SOME STUDIES ON DEVELOPMENT OF DIFFERENT ALL-OPTICAL LOGIC, ARITHMETIC AND ALGEBRAIC PROCESSORS

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“Some Studies on Development of Different All-Optical Logic, Arithmetic and Algebraic Processors”

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by

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Dedicated

to my

Reverend Parents
To whom it may concern

This is to inform to all concerned that the thesis entitled, “Some Studies on Development of Different All-Optical Logic, Arithmetic and Algebraic Processors,” is a sincere and bonafide work done by Mr. Debajyoti Samanta towards the award of the Ph.D. degree. This work was studied under my supervision. The thesis has covered many new approaches and techniques in the field of ‘optical parallel computation’. No portion of it, except the reviews and background work, was included in any Ph.D. level thesis or in any dissertation work.

I believe, the readers will certainly get many new interesting ideas from it.

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Preface

The practical limitations of conventional electronic digital computers have led to the invention of a new technology which uses optics in computation. All-optical data processing has been the subject of most research interest during the last few decades. The area of optical computing provides a challenge to the researchers as it is a multidisciplinary area and the field is expanding rapidly. During my post graduate classes I had come to know about ‘optical computing’. After knowing the advantages of optical parallel computation I became interested in this new promising and flourishing field of study. Gradually I had dreamt of doing something new in this field. I would like to take this opportunity to thank all those persons who have been directly or indirectly involved with the preparation of this thesis. I have also taken help of some academic institution and research organizations. Without such assistance it would not be possible to write this thesis.

With a deep sense of gratitude I express my sincerest respect, thanks and regards to Prof. Sourangshu Mukhopadhyay, Professor, Department of Physics, The University of Burdwan, who was my teacher in post graduate classes as well as my supervisor, for providing me the opportunity to undergo this identified field of research work described in this thesis. Language fails me how to express my indebtedness to him for his inspiration, blessings, encouragement, invaluable advice and continuous patient guidance throughout this research work.

I bow to my parents Mrs. Rekha Samanta and Dr. Dilip Samanta. I would not be in a position to write this thesis without their blessing and support. My deepest regards, gratefulness are due to them.

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I acknowledge the help from the SPIE University of Calcutta students’ chapter for providing some study materials. I also like to thank Department of Science and Technology, New Delhi for extending some financial assistance to present a paper in an international conference held in Japan.

I also like to thank my grandparents Mrs. Lilarani Samanta and Mr. Ramkrishna Samanta and other relatives and well wishers for their inspiration, affection and goodwill extended to me during these years. I convey my sincere thanks to my beloved brother Mr. Dhrubajyoti Samanta for his constant inspiration and also providing some study materials to me. It would be incomplete if I do not acknowledge my dear wife Aparna. I wish to express my heartfelt thanks to her for the cooperation, support and sacrifice extended to me to complete this thesis.

In this thesis some approaches towards some developments on different optical logic and data processing are described. The whole content is divided into thirteen chapters. First two chapters are preliminary discussions. From ‘chapter-3’ through ‘chapter-12’ different proposed optical schemes are depicted. In ‘chapter-13’ a general conclusion is given. Finally at the end a list of some important reference and my publications are attached.

Date: ................................................

Place: Department of Physics (Mr. Debajyoti Samanta)

The University of Burdwan,
Bardhaman.
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CHAPTER - 1

Introduction to Optical Logic, Arithmetic and Algebraic Processing and Objective of the Proposed Thesis

Abstract

The rate of data transfer is increasing enormously day by day. As a result the demand is also increasing for such systems which can keep real link with such rate of increase in data traffic. In this context logic processing, data processing, image processing with optics as information carrying signal have shown a high degree of potentiality. It is well established that optics can go far beyond electronics. It is mainly because of the inherent advantages in optical signal. The field of optical computing had appeared as a part of a new, promising and vast filed of research interest. A large number of papers to utilize optical signal in computing have been reported to date. In this chapter a general introduction to optical computing is represented. The advantages of using optics in computing along with some important steps taken towards the implementation of an optical parallel computer are illustrated. Again the chapter also accommodates the objective of my contributed works in the thesis.
1.1. Introduction

With the advancement in technology computational techniques also have achieved a new dimension. Improvement of electronics has increased the level of performance of conventional computing machines. By miniaturizing the size of the electronic components to sub-micron level the speed has increased. But this is limited by the interconnection problem. Again electron has a speed limit (According to Einstein’s relativity principle electron cannot move faster than light). So scientists were looking for an alternative. In the seventies of the last century there was a revolutionary change in the area of data processing. Optics had expressed itself as a potential candidate for data processing. Here photon is the information carrier instead of electron in electronic systems. Due to some inherent advantages optics appeared to be lucrative technique over conventional electronic systems. Scientists then started an effort to replace the conventional electronic systems with the optical counter parts. This was a beginning of a new era of optical computing. Since then the field of optical computing has flourished in many directions. Researches in optical computing have opened new possibilities in high speed computing, communication and parallel algorithm designing. Lots of improvements are being reported by the researchers in every corner of the world. Initially optical computing was in analog nature. Then digital optical data processing has become a success. Now the role of the optics is known to entire scientific community. Today researchers are working all over the world to fully utilize the advantages of optical signal in computation as well as in communication [20, 141, 191, 148, 254, 301, 302]. Already lots of developments are reported to implement different optical systems in various techniques.

In this chapter we describe the advantages of optics or photonics in computing over electronics. Recent innovations in optical computing are also summarized. Lastly a brief description of the proposed work is given.

1.2. Advantages of optics over electronics in data processing, computation and in communication.

Some advantages of optics over electronics have made optics so popular. When electronic transistor was invented a new dimension was achieved in data processing. Scientists looked for a higher speed of data processing but a smaller size of the device. The conventional electronic systems have a band width limit, called the ‘bottle
neck’ problem, above which more speed cannot be achieved. Where as in electronic system a maximum speed of operation is $10^{10}$ Hz, in case of optical system up to $10^{15}$ logic operations per second can be performed. As optical signal can travel at a very high speed there will be no propagation delay among the different parts of an optical system. Thus light does not have time response limitation of electronics. So a real time operational speed can be expected from an all-optical device. Electronic devices also generate heat which can damage the components. Photon does not interact with an electric or magnetic field, as electron does. Therefore there will be no distortion due to electric and magnetic field during optical data communication. Optical signals do not interfere among them. Thus the problem due to cross-talk and short-circuit can be removed. Different optical signals (of different frequency or colour) can easily propagate simultaneously. So an all-optical system can perform multiple data operations at a time. The inherent advantage of parallelism associated with optical signal has made it so popular for high speed communication and data and logic processing [166, 167]. As channel requirement is lower in optics the system volume would be smaller. Optical system can avoid the inconvenience of using only binary logic. Wavelength division multiplexing is also a remarkable advantage in parallel processing of optical data and also in computation.

Optics can reduce the energy required for transmission [251]. In optical connection there is no need to charge the optical lines to signal voltage. Thus the optical system will be more efficient, compact in size, lighter in weight and more cost effective. So in respect of speed, size, complexity optics is favored far advantages than electronics.

1.3. Optical or photonic computing and its need.

Before invention of the electronic transistor data and logic processing was very hard. The computers were very slow and large in size. Transistors made the electronic computers faster and smaller in size [300]. After that digital data processing was started. With the development of electronics the sizes of the devices were reduced greatly. A speed of the order of GHz can be achieved by Very Large Scale Integration (VLSI) Technology. Unfortunately for integration complexity and interconnection delay more speed of computation cannot be realized with electronics. Among the limitation of VLSI circuits are limited number of pin and low bandwidth for
interconnection. But the demand for speed of operation is increasing enormously day by day.

Now using all-optical system can be a way to get rid of the problem. The new technology of using optics in the field of computation and parallel processing is generally called as optical or photonic computing. Optical signals and optical integrated circuits have several advantages as described earlier. Apart from these the advantages of using optics in computing are limited not only to communication of data but also memory storage capacity, 2-D and 3-D holography, Fourier transform, correlation, optical pattern recognition, image edge detection, neural networking, artificial intelligence, multiplexing-demultiplexing, channel based and channel free operation, fuzzy logic operation and many more can be achieved. It can be said that photonic technology is dedicated to generate, control, detect and utilize photons for the development of mankind and civilization. By replacing electrons and wires by photons and optical fiber, scientists hope to generate a new generation of optical computer.

1.4. Optical architecture in optical computation.

In optical systems photon is the carrier of data instead of electron in electronic systems. The performance of the computing systems can be enhanced by increasing clock rate of serial data processing or by using parallel data processing. Due to inherent parallelism in optics parallel processing is much more desirable. However digital optical systems were not demonstrated at the very beginning of optical era. The journey started with optical analog data and image processing systems. Often photographic transparencies were used for processing of data in the form of 2-dimensional images [299]. Then spatial light modulators (SLMs) were developed to replace photographic films. SLMs were used massively for optical computing [75].

Optical and optoelectronic processing deal with the performance of computation, algebraic analysis, artificial intelligence. The area of optical parallel data processing can be divided into four sub-areas like (i) technique: this part falls within the area of physics, electronics and computer engineering; (ii) algorithm: is a mathematical topic; (iii) architecture: the design of optical circuit involving computer scientists; and (iv) application. So this is an interdisciplinary area of research interest. Therefore it demands for its success the collaboration of researchers from different
disciplines such as engineering, computer architecture, material research, chemistry and physics.

For any optical device to fabricate optical counter part of every system is required. To develop an optical processor we need optical logic and arithmetic unit, optical memory unit, optical buses, optical input/output ports, optical power sources, optical encoders, decoders, optical detectors are required. Logic gates are the building block of any digital system. So for developing an optical arithmetic or algebraic processor optical logic gates are essential.

Optical system is to be developed for performing mathematical operations like addition, subtraction, multiplication, division etc. For performing addition operation half-adder and full-adder are required to be developed. For binary addition the rules followed are 0+0=00, 0+1=01, 1+0=01 and 1+1=10. The addition is carried out bit wise from the right hand side bit towards left. The carry bit is carried to the next adder circuit.

Optical memory is also needed to support the high rate of data processing by optical processors [135, 136, 211]. Using the inherent parallelism large number of data bit can be stored (or received) simultaneously into (or from) an optical memory. Two types of optical memory can be found like arrays of one bit store element and mass storage like hologram. Flip-flop circuits are common digital memory. Electromagnetically induced transparency (EIT), fiber delay line (FDL), optical cavities can also be used for optical memory. EIT is caused due to interference of coherences excited in the atom by the electromagnetic fields [25]. As a result an initially opaque medium may become transparent. Quantum states of photons are transferred to collective excitations of the medium. Hence EIT medium can act as quantum memory for photon [106, 165]. Holographic memory can provide a real time high recording density as well as high data access rate [97-100, 103, 122-125, 134]. Holography is a method in which the amplitude and phase of light wave is recorded in a photo-sensitive medium by interference. For formation of hologram basically a coherent light beam coming from a laser is divided into two beams (‘figure -1.1’). One beam illuminates an object from which we get ‘object beam’. The other beam is reflected from a plane mirror and serves as a ‘reference beam’. These two beams interfere between them in the space where they superpose. A photo sensitive medium is made to record the interference pattern is called hologram.
With the development of optical device for high speed computation the interconnection technology is also to be developed at the same time. Wavelength division multiplexing (WDM) is a suitable tool for optical interconnect [43]. Optical time division multiplexing (OTDM) and dense wavelength division multiplexing (DWDM) are two mention worthy techniques in this context. In OTDM technique optical data stream are constructed by time multiplexing a number of lower bit rate optical streams [8]. Again very high bit rate optical signal is demultiplexed to many lower bit rate optical signals at the receiver end of the system. In WDM different optical signals of different wavelengths (like $\lambda_1$, $\lambda_2$ and $\lambda_3$ in ‘figure -1.2’) can be multiplexed on a single optical fiber. It is often also termed as frequency division multiplexing. Multiplexer and demultiplexer can be implemented with diffraction grating, fiber Bragg grating etc. Fiber nonlinearity limits the number of channels can be multiplexed in WDM.

Fig. 1.1: Schematic diagram for recording of hologram.
In conventional WDM system only few channels are accommodated in single optical fiber. If laser has very narrow line width then more channels can be multiplexed into a single optical fiber. This leads to DWDM technique.

Scientists first thought of an optical computer observing the nonlinearity in optical nonlinear material. They needed some optical device which would replace the electronic transistor in electronic computer. In a junction transistor electric current (flow of electron) is controlled by another current. Optical bistable devices and logic have been developed later. In these devices one light beam (flow of photon) is controlled by another light beam. Bistable devices can be very small in size but offer a very high operational speed. Optical bistable devices or optical flip-flops can be used in optical communications and computing for threshold function, demultiplexing, optical memory etc. Optical logic gates should be able to function at very small power and at room temperature. That means optical nonlinear materials with larger nonlinearity term are required. To make the energy per logic operation lower the volume of the device material is to be minimized. The materials should have short response and relaxation time. Some semiconductors, organic and photorefractive materials can serve the purpose. Multi-layered photorefractive polymeric devices, as the phase conjugation reflectivity depends on the incident beam polarization, can be used in optical logic devices [113]. Electrons or photons with energies above the
band-gap energy can affect the electronic and optical properties of semiconductors. Thus many semiconductors can be used for implementation of electronic, optical or opto-electronic devices [300]. Optical bistability can be observed in many semiconductors like GaAs, CuCl, CdS, InSb, ZnS etc.

For implementation of logic devices with optical signal the devices should satisfy some criterion [251]. The output of any logic devices should be such that it can be used as the input of another device. That means the logic devices will be cascadable [260]. The optical logic device should have fan-out of at least two i.e. the output of first device will be capable to drive the inputs of at least two subsequent logic devices. If the optical signal quality becomes worse the logic level should be restored in the concerned stage. Apart from these an optical device should have separate input and output beams, should have an operating point which can be easily established and the logic level should be independent of transmission loss. Future optical logic devices should operate consuming energy only of the order of autojoules. The optical devices are to be made efficient to this extend. As optics has passive components zero energy logic is possible.

1.5. Different encoding/decoding processes.

A conventional computing machine cannot understand the mathematical digits like 0 and 1 (for binary). Hence it is necessary to encode the mathematical data by different optical symbols. For data communication from one unit to other part of a system and for conducting various computing operations several symbolic coding and decoding techniques can be adopted to use the parallelism of optical signal. In some reports the use of tri-state or other multivalued logic has also been observed.

Different techniques for encoding and decoding of data may be used to implement optical data processor. These methods can be like intensity, phase, polarization or frequency based encoding [259].

In intensity based coding one can assume presence of a prefixed intensity of light signal beam as ‘logic 1’ (high) state and absence of any light signal as ‘logic 0’ (low) state (in binary). Alternatively input array can be represented by a number of pixels in intensity coded symbolic substitution. Here a transparent pixel can be represented by ‘logic 1’ and ‘logic 0’ is denoted by an opaque pixel. There are several research works which have used intensity based encoding/decoding process. This is a
convenient method of encoding/decoding. But there may arise some situation where the intensity of the light signal beam may fall due to absorption, scattering etc. This may lead to bit error problem.

The spatial encoding technique has been used successfully for implementation of various logic and arithmetic operations [163]. In this method the input is encoded by the combination of presence and absence of light signal in a spatially represented coded mask. For two input variables (A and B) each rectangular half of the input variables is spatially encoded (‘figure-1.3’). When ‘A’ is ‘logic 0’ it can be assumed that the upper rectangular half is transparent and lower half is opaque. Again ‘A’ assumes ‘logic 1’ when upper half is opaque and lower half is transparent. Similarly input ‘B’ can be assumed as ‘logic 0’ or ‘logic 1’ when left and right half is transparent respectively.

Instead of using this type of coding one can use polarization based coding [119]. Besides these two techniques one can describe an optical signal as logic 0 (low) of logic 1 (high) if the beam has a predefined phase relationship with respect to a reference signal. Again in case of frequency based encoding technique one can represent two light signal of two different frequencies as ‘logic 0’ (low) and ‘logic 1’ (high) state.
Fig. 1.3: Spatial input coding for two variables.
1.6. Optical switching systems.
Optical switching systems are the most important elements for implementing all-optical devices. Several types of switches are reported [284]. Some of the switches are electro-optic where as some are all-optical. Electro-optics systems are limited by the speed of the electronic part. Here optical signal is converted to electronic signal. After switching operation the electronic signal is again converted to optical one. Due to repeated conversion process the effective switching operation become slower. Also the cost of the switching device is higher due to the presence of the electronic parts. All-optical components have advantages over electro-optic components. The general principle of all-optical switches are controlling of light signal with another light signal. So conversion of optical to electronic and electronic to optical signal is not required in this case. There are different types of optical switches.

1.6.1. Micro-electro-mechanical systems (MEMS)
Micro-electro-mechanical systems (MEMS) are small integrated systems consisting of electrical and mechanical parts. Advantages like batch fabrication, small size, integratability etc. have made this type of switches popular. MEMS have small movable mirrors which can be moved by the application of external current. The switching speed of this type of switch is low as it involves movement of the mirrors. There are two types of MEMS optical switches like 2D and 3D switches. In 2D switches mirrors are arranged in a crossbar configuration. Mirrors are placed at the intersections of light paths between inputs and outputs (‘figure -1.4’). Each mirror can reflect the light beam (‘ON’ position) or let the light beam to pass unaffected (‘OFF’ position). In 3D switches mirrors can rotate about two axes and thus can redirect the light beams to multiple angles in space.
Fig. 1.4: Schematic diagram of a 2D MEMS optical switch.

- Mirror in ON position
- Mirror in OFF position
1.6.2. Optical add-drop multiplexer (OADM)

Optical add-drop multiplexer (OADM) can add or drop an optical signal into or from an information channel. It is used in wavelength division multiplexing systems. This device consists of two circulators connected by a fiber. A fiber grating placed in the fiber can reflect a signal of particular wavelength. Let there are ‘n’ number of wavelengths \( (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{i-1}, \lambda_i, \lambda_{i+1}, \ldots, \lambda_n) \) at the input (‘figure -1.5’). The fiber grating reflects a particular wavelength \( (\lambda_i) \). This wavelength reenters the ‘circulator -1’ and leaves the circulator at the drop port. The remaining wavelengths \( (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{i-1}, \lambda_{i+1}, \ldots, \lambda_n) \) enter to the ‘circulator -2’. A signal which is absent in the input of ‘circulator -2’ can be added here. So the dropped wavelength \( (\lambda_i) \) is injected through the ‘add’ port to the ‘circulator -2’. The signal is now added to the mainstream and exit with all other wavelengths at the output.

![Schematic diagram of an optical add-drop multiplexer.](image)

Fig. 1.5: Schematic diagram of an optical add-drop multiplexer.
1.6.3. *Liquid crystal (LC) switch*

Liquid crystal (LC) switches are another type of optical switch. These materials are of much interest as they show sensitivity to applied electrical field, consume less power, have long lifetime and are cheaper. The operation of this type of switch is controlled by applying voltage to the liquid crystals. These switches depend on the wavelength of the signal. The operation of a LC switch is shown ‘figure -1.6’.

![Diagram of a liquid crystal switch](image)

Fig. 1.6: Schematic diagram of a liquid crystal switch
A birefringent plate in the input determines the polarization state of the input as desired. The LC cell can pass the light with the state of polarization unaltered when no biasing voltage \( (V=0) \) is applied to the cell [29]. The light beam is now passed thought the polarization beam splitter and thus the output is received in ‘output -1’. When voltage is applied to the LC it changes the polarization of the light beam passing through it. For a specific voltage \( (V=V_0) \) it rotates the polarization state by \( \pi/2 \) (\( \uparrow \) is changed to \( \cdot \)). Now the polarization beam splitter reflects the light beam to the ‘output -2’. Thus the LC can act as a switch. There are different mechanisms for utilizing liquid crystal switch such as based on total internal reflection, polymer containing nematic LC droplets etc. [60, 61, 104, 144-146].

1.6.4. Semiconductor optical amplifier (SOA)

The semiconductor optical amplifier (SOA) is similar to a semiconductor laser. SOA are compatible with monolithic integration and hence are of low cost. SOA can be used for all-optical functional applications like in line optical amplifier, optical switching, wavelength conversion, pulse generation and logic gate [66, 91, 108, 126, 155, 180, 182, 186, 200, 221, 265, 291, 304]. SOA can amplify a light signal by stimulated emission. An external electric current provides the necessary energy for the gain. In SOA electrons or carriers are injected into the active region (‘figure -1.7’) from an external source. Large optical bandwidth can be expected in SOA. SOAs are of two types namely Fabry-Perot SOA (FP-SOA) and travelling-wave SOA (TW-SOA). In FP-SOA the signal passes many times through the amplifier due to the reflections from the end facets. In TW-SOA reflection is negligible and the signal passes only one time. SOA gate arrays can be used for high-speed switching. Four types of nonlinearities seen in SOA are cross gain modulation (XGM), cross phase modulation (XPM), self phase modulation (SPM) and four wave mixing (FWM) [130].
1.6.5. Interferometric switch

An interferometric switch has two 3-dB couplers. Input beam is split into two arms of equal length at the first coupler. The second coupler combines the beams and finally splits again. A phase difference is introduced between the two beams. This results in interference between the two beams. Depending on the path difference there will be constructive or destructive interference between the two beams. Light beam propagations in Michelson, Mach-Zehnder and Sagnac interferometer are shown schematically in ‘figure -1.8’. Mach-Zehnder interferometer, ultrafast nonlinear interferometer and nonlinear optical loop mirror are different types of interferometric switches [206].
Fig. 1.8: (a) Michelson interferometer, (b) Mach-Zehnder interferometer
(c) Sagnac interferometer
Mach-Zehnder interferometer (MZI) based switch is a very commonly used interferometric optical switch [264]. It consists of a nonlinear medium, generally an SOA. The SOA is placed in the arms of the interferometer (‘figure -1.9’). An optical control signal is used to change the carrier density in the SOA. This causes refractive index change. Thus a phase difference is introduced. Depending upon the interference (constructive or destructive) between the two beams the data signal is diverted to ‘output -1’ or ‘output -2’.

Fig. 1.9: MZI based optical switch.
Ultrafast nonlinear interferometer (UNI) is in general a single arm polarization interferometer. UNI works depending on the phase difference between the two polarization components of the data signal. The input signal is split into two orthogonal polarization components with a time-delay between them (‘figure -1.10’). This can be done by a polarization split and delay (PSD) which consists of a polarization beam splitter (PBS) and a polarization maintaining fiber (PMF) [69]. The SOA introduces a phase difference between the two components. The phase difference is controlled by a control signal. An identical PSD is placed at the exit of the SOA. This removes the delay between the components and forces the components to interfere at the PBS. In absence of control pulse the data signal goes to ‘output -1’ and in the presence of control pulse the data signal is received at the ‘output -2’. Thus switching action is achieved.

Fig. 1.10: A schematic diagram for UNI gate.
A nonlinear optical loop mirror (NOLM) is basically a Sagnac interferometer in optical fiber with a nonlinear medium inserted in the loop (‘figure -1.11’). A nonlinear fiber is used in the loop. Input signal is split into two components at the input 3 dB coupler. One component propagates in the clockwise direction and the other travels in the anti-clockwise direction. After recombining at the neck the signal interferes constructively at the input side but interferes destructively at the output side. Thus the signal appears to be reflected to the input. So when the phase difference is zero the interferometer seems to be a mirror. Phase difference can be changed by a control pulse inserted to the loop through a second coupler. When a phase difference of $\pi$ is introduced between the two components the data signal will be transmitted to the output.

![Fig. 1.11: Schematic diagram of a nonlinear optical loop mirror (NOLM).](image-url)
1.6.6. *Terahertz optical asymmetric demultiplexer (TOAD)*

Again Terahertz Optical Asymmetric Demultiplexer (TOAD) can be used for high-speed switching [304]. It can also demultiplex a high speed optical time division multiplexing (OTDM) stream. In TOAD switching is achieved by placing a SOA asymmetrically from the center of an optical fiber loop mirror (‘figure -1.12’). Data signal is injected to the loop through a 50:50 coupler. The clockwise and anticlockwise propagating data signals arrive asynchronously at the SOA. A control pulse is injected via a second coupler and is timed such that it arrives after one data pulse but just before the other data pulse. Due to the phase change when the two counter-propagating data signals components interfere on their return to the input coupler, data pulse is switched out.

![Fig. 1.12: TOAD as optical switch.](image-url)
1.6.7. Optical isotropic nonlinear material (NLM)

Optical isotropic nonlinear materials can also play a great role in optical switching. These materials show Kerr type of nonlinearity. The refractive index of this type of material changes with the intensity of the optical signal passing through the material. As a result if the input light beam has two different intensity levels (at different time) then the output will be received from two different output channels corresponding to the two different input levels. For example when the intensity of the input light beam ‘AO_1’ is a prefixed intensity ‘I’ then output is received at ‘Y_2’ (‘figure -1.13’). Now no light will be received at ‘Y_1’. Again when the input intensity changes to ‘2I’, the refractive index of the linear material (LM) remains unaltered but that of the NLM is changed (increased in this case). So the light beam is now travels through the channel ‘Y_1’ causing no light in the channel ‘Y_2’. So these materials can be used for all-optical switching [229]. Optical switching using this type of isotropic nonlinear material is discussed in ‘chapter -3’ in detail.

Fig. 1.13: Optical isotropic nonlinear material used as a switch.
For performing all-optical switching operations pulsed Nd:YAG laser sources are massively used in many schemes. But high electrical power is required for production of Nd:YAG laser. Tunable diode lasers can also produce the required laser pulse for optical switching. Therefore such nonlinear materials are required which have larger nonlinearity so that it can provide significantly high nonlinear effect even if a laser beam of low intensity travels through it. The all-optical switching with nonlinear material utilizing Kerr effect the nonlinear absorption is also to be low [184]. For chalcogenide glasses the third order susceptibility ($\chi^3$) is noticed 1000 times higher than the silica glass. Q-switching technique may be adopted to produce high peak power pulse beam from continuous wave laser.

1.6.8. Quantum dot switching

Quantum Dots (QDs) can also be used for optical switching [87, 226, 257, 285]. QDs show nonlinearity due their delta function intensity states. Sharp excitonic peak having larger peak absorption than bulk or quantum wells can be seen in QDs. Different states of QD are shown in ‘figure -1.14’) Generally QD-SOA based Mach Zehnder interferometer is used to utilize quantum dots based optical switching. The QD-SOA is placed in the arms of the MZI. Quantum dots are excited by external pump beam. This leads to a variation in the phase difference. This results in the switching of the MZI.
1.6.9. *Electro-optical absorption switching*

Electro-optical absorption can also be used for optical switching. This type of switching is based on shift of the absorption band edge of a semiconductor. It can be achieved by Quantum Confined Stark Effect (QCSE). Quantum well shows electro-optic effects due to birefringence and Kerr effects from QCSE near the excitonic absorption edge [227]. Extension of wave function outside of the quantum well makes the absorption band gap narrower. A reversed bias is applied to a p-n junction. A pulse is absorbed in the junction area resulting in generation of carriers. The carriers diffuse and cancel increase in the absorption area for the next pulse. So the next pulse is not absorbed but transmitted.
1.7. **Objective of the proposed work.**

The importance of using optics in computing is already established. Optics has been being used in computation as well as communication since the last few decades. Several approaches have been seen to increase the performance of computing systems. Many optical logic, arithmetic and algebraic processors have been reported but the search for new technology remains. Here we have attempted to make some contribution to the wide field of optical computing. The broad target of our present work is to develop different all-optical logic, arithmetic and algebraic processor in some advantageous method.

Light is considered as a transverse electromagnetic wave consisting of vibrating electric and magnetic field vectors at right angles to each other and also at right angles to the direction of propagation of light. When the electric vector of a light is confined to a definite direction then the light is called ‘plane polarized light’ (‘figure -1.15’). The plane in which the electric vector and the propagation vector are confined is known as ‘plane of vibration’ and the plane perpendicular to the plane of vibration is called ‘plane of polarization’. Light signal can be represented in terms of the state of polarization of the light beam. Advantage of this technique is that the state of polarization of the optical signal is not generally changed of its own. During long distance transmission of data signal the intensity of the light signal may decrease due to various reasons. In case of intensity based coding the receiving system cannot recognize the optical signal whose intensity is changed from the predefined value. Therefore it becomes difficult for an optical system, operating on intensity based coding, to work properly. In polarization based encoding this problem can be avoided. Here one may consider a light signal polarized in the plane of paper as ‘logic 1’ (high) state and a light signal polarized perpendicular to the plane of paper as ‘logic 0’ (low) state. The powers in the two polarization states are equal. Optical isotropic nonlinear material based switches are used in many cases for developing the optical system. High speed all-optical logic gates are essential elements to fabricate high-speed optical networks for performing optical signal processing functions. It is seen that there is a scope to develop the all-optical logic gates in a different technique using polarization based encoding and as well as the switching capacity of the optical isotropic nonlinear material. As the polarization based coding method have some own advantages therefore using this technique it is helpful to design an optical logic.
system. Again in the polarization encoded data the average byte power is always same whatever the number of ‘1’s’ and ‘0’s’ in the byte, but in intensity encoded data it is not seen.

The objective of the proposed work is to develop a method of implementing (i) an integrated logic and arithmetic unit in an alternative approach, (ii) polarization encoded optical logic gates, (iii) an optical system for maintaining a prefixed intensity of light signal, (iv) a photonic astable multivibrator, (v) polarization encoded optical S-R flip-flop and M-S J-K flip-flop, (vi) optical polarization encoded adder, subtractor etc., (vii) optical polarization encoded multiplexer, demultiplexer etc.

In ‘chapter -1’ an introduction to optical logic, arithmetic and algebraic data computing is given. We have discussed advantages of optical computing, architecture of optical systems, how optical switches can be developed in various methods and some approaches for an all-optical computer. In ‘chapter -2’ we shall have a short tour in the avenues of some important works to reach the goal of superfast computing.
using optics. An all-optical, arithmetic and algebraic processor is proposed in ‘chapter -3’. It can perform any logical, arithmetic or algebraic operations. In ‘chapter -4’ a method of developing a prefixed light intensity for a logic signal bit is described. Further in ‘chapter -5’ the all-optical logic gates using polarization based encoding are illustrated. Polarization encoded new optical S-R flip-flop and an M-S J-K flip-flop are presented in ‘chapter -6’ and ‘chapter -7’ respectively. Sometimes it may require achieving a polarization encoded data bit from an intensity encoded data bit or vice versa. Such techniques are described in ‘chapter -8’. A method of generating a single optical pulse using electro-optic modulator is presented in ‘chapter-9’. An astable vibrator is discussed in ‘chapter-10’. In ‘chapter -11’ an all-optical technique for developing optical multiplexer using polarization encoded logic gates is depicted. In ‘chapter -12’ we have discussed a method to implement an optical parity generator and checker. Finally in ‘chapter -13’ an overall conclusion is given and future scope of work is discussed. At the end of this chapter a list of references is given. Lastly the list of my publication and presentations are given.

1.8. Conclusion
In near future all-optical signal processing will be necessary to meet the increasing demand for higher speed and larger capacity based optical communication networks. Though a general purpose all-optical computer is very difficult to be practical, but the technology is changing. The optical nonlinear materials and semiconductor optical amplifier are playing important role to perform optical nonlinear operations. Many approaches have been proposed to achieve all-optical logic functions based on the nonlinear effects in semiconductor material, in optical fibers or in waveguides. With new innovations with polarization encoding and optical nonlinear material it will be helpful to arrive at the new world of higher speed of operation. Promising nanotechnology like nanoresonators, nanometallics, plasmonics, quantum dots etc. can give a light of hope towards the realization of an optical computer.
Background Review of Some Important Works
Related to Optical Computing

Abstract

Information all over the world is expanding every day. Simultaneously the rate data transfer is also increasing day by day. Therefore it is necessary to develop such computing system which can provide such tremendous speed of operation. Shifting to the optical domain from the conventional electric one is the only way for such upgradation. Already many approaches have been seen to achieve the goal of high speed computation with optical signal. In this chapter a short review of such development has been made.
2.1. Introduction
Optical device has become an interesting tool because of its many advantages in
different applications. It can solve many problems associated with conventional
electronic computing hardware. The limitation on the speed of the conventional
electronic technology can be overcome by the use of the photonic technology. All-
optical parallel computation is the key feature of optical network as well as part of
optical computer. All-optical systems have much higher speed of operation compared
to the electro-optic systems. Scientists and researchers in different corners of the
world are leaving no stone unturned to make the dream of an optical computer a
reality. In recent years numbers of optical logic gates, optical switches, optical
interconnections and optical memory have been developed. All-optical parallel
computing and data processing basically depends on the material nonlinearity. That is
why researchers are testing possibilities of using different materials for all-optical
logic. The twenty first century is expected to become the age of photonic materials
and optical technology. Different techniques have their advantages over other and
some limitations too. The operational speed as well as the power required for
operation is the main attention of the researchers. For any optical computation
systems optical memory elements are also significant for proper functioning of the
system. In optical computing signal synchronization is important. Many approaches
have also been seen where an unconventional method is explored for optical
computation.

2.2. Some approaches for optical computing.
Optics has successfully established itself as a promising technique for data computing.
Electronic computers generally perform some number of serial operations. On the
other hand all-optical parallel computation is possible with the inherent parallelism of
optical signal. Data can be communicated in parallel by incorporation of optics for
organizing an optical computer. So a higher rate of information processing can be
achieved for decision making and computing. Different approaches have already been
seen to reach the goal. Now it is established that optics can be successfully used for
implementing arithmetic, algebraic and data processing operations as well as in
communications.
The earliest computer could do only some prefixed operations. A stored programmed computer was an improvement over earlier program-controlled machines like electronic numerical integrator and computer (ENIAC). A von Neumann machine has four parts like (i) processing unit, (ii) memory unit, (iii) control unit and (iv) I/O unit. As the instruction and data streams share the same bus this limits the operational speed of the computer.

In a computer architecture depending upon the number of simultaneous instructions (or control) and data streams available, the system can be classified into four classes like single instruction single data stream (SISD), single instruction multiple data stream (SIMD), multiple instruction single data stream (MISD) and multiple instruction multiple data stream (MIMD) [2]. SISD processing is like Von Neumann architecture. SIMD can be divided into array processor, pipelined processor and associative processor.

For implementation of optical computing machine the four units have to be replaced by optical systems. To develop an optical computer an optical data processor is needed. Optical numeric processor and optical nonnumeric processors are being developed. Optical logic, arithmetic unit, correlator are numeric processors. On the other hand nonnumeric processors perform optical text processing and optical knowledge based processing [41]. For processing of data optical switching device is an important element. Lot of proposals, analysis and new findings has been reported in the last few decades to use optical signal in computations. The journey was started with the discovery of LASER in around 1960. Solid state ruby laser and He-Ne gas laser were reported at that time. Consequently semiconductor laser, dye laser etc. were demonstrated followed by a revolutionary change in the area of data processing. Researchers realized that classical optics could be utilized for the digital optical computer [4]. It was supposed that if optical nonlinearity would not be significantly high, then optical logic devices with satisfactory speed, size, and energy consumption would not be implemented. Symbolic substitution was an important technique for image processing. It was used to develop an elementary computer. Now laser diodes, as a source of coherent light, are being produced in large scale. Optical CD is now very common in computers.

Different approaches are seen to develop different logic, arithmetic and data processors. Lots of logic and data processors have been implemented using different techniques so far [14, 23, 31, 53, 70, 72, 76, 139, 147, 149, 172, 174-176, 187, 188,
Heinz et al. have reported an optical method for matrix multiplication [1]. A real-time optical parallel processor for binary addition with a carry is proposed by Mukhopadhyay et al. [6]. In some proposals the use of tristate logic is found [13, 17]. The concept of modified signed-digit (MSD) number system has been introduced in this context [7, 30]. The problem of ‘carry’ and ‘borrow’ based operations in conventional adder, subtractor can be avoided by using MSD. Beside this a negative number can be handled easily in MSD. Negative numbers are the logical complement of the positive number.

Though some uncertainties about the future of optical computer have arisen [3], optical computing remains a promising field of research [176]. The field of optical computing is progressing rapidly. As a result of numerous developments integrated optical logic has become practical and interesting. Two passive logic gates (XOR and COINC) have been demonstrated [109, 156]. These consume no power in principle.

Different encoding and decoding techniques are used in different reports for fabrication of optical system. Alam et al. have designed an efficient combinational logic circuit using polarization encoded optical shadow-casting [18]. Polarization based encoding is used in some cases [19, 170, 171]. Zaghloul et al have reported unforced polarization-based optical implementation of Binary logic [171]. A technique for complete all-optical processing polarization based binary logic gates is reported by them [170]. They have introduced the orthoparallel optical logic architecture to design and implement different binary logic gates like AND, OR, NAND etc. An OR gate, introduced by them, is shown in the ‘figure - 2.1’. They have represented the ‘logic 1’ and ‘logic 0’ by linearly polarized waves at +45° and -45° respectively. There are two branches logic zero branch (LZB) and logic one branch (LOB). Only one beam is active at a time.
Different optical switches have been seen to be used for implementation of optical systems. All-optical data processing and computing operation technique basically depends on nonlinearity of material constituting the device. Optical isotropic nonlinear material based switching is used in many cases. Pahari et al have proposed an all-optical method for the addition of binary data by nonlinear materials [79].

For development of information processing architectures, the role of various analog and digital data comparison is very important [225]. An all-optical comparison scheme between two multi-bit data with optical nonlinear material has been proposed. With proper laser source and optical nonlinear material an operational speed of 1-10 Tb/s can be expected. Pahari et al. have developed a new method of all-optical data comparison scheme with nonlinear material using 1’s compliment method [166]. Caulfield et al. have proposed generalized optical logic elements (GOLEs) and directed logic [190]. It is a device that can do any of the 16 Boolean logic operations on signals in an optical beam with very fast switching among functions. A Mach-Zehnder interferometer with two mutually coherent inputs can perform lossless computing.
All-optical switching has been demonstrated using in a laterally coupled GaAs-AlGaAs microring resonators [44]. Nonlinear polarization switch can be used for developing all-optical logic [114].

Optical tree architecture (shown in ‘figure - 2.2’) can be found in many applications [86, 223, 247]. It uses the switching capacity of optical nonlinear material. The switch is managed in such a way that in the absence of controlling optical signal ‘P’ the light signal in the branch ‘A’ (which comes from a constant laser source (CLS)) goes to the lower branch ‘C’. When there is a control optical signal ‘P’ then the signal beam in the branch ‘A’ is refracted to the upper channel ‘B’. Similarly the control signal ‘Q’ in the branches ‘B’ and ‘C’ determines whether the light signal in the concerned branch will travel to the respective lower branches or switch over to the upper branches. Different output states for different control signal are depicted in the ‘table - 2.1’.

![Optical tree architecture](image)

**Fig. 2.2: Optical tree architecture.**
Table - 2.1: Output states of tree architecture.

<table>
<thead>
<tr>
<th>Control inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Q</td>
<td>D E F G</td>
</tr>
<tr>
<td>0 0</td>
<td>0 0 0 1</td>
</tr>
<tr>
<td>0 1</td>
<td>0 0 1 0</td>
</tr>
<tr>
<td>1 0</td>
<td>0 1 0 0</td>
</tr>
<tr>
<td>1 1</td>
<td>1 0 0 0</td>
</tr>
</tbody>
</table>

Semiconductor optical amplifier (SOA) based switches play an important role in many cases [50, 59, 71, 73, 118, 189, 217, 232]. It is very similar to a laser. All-optical logic gates based on the nonlinear effects in semiconductor optical amplifiers (SOAs), like cross-gain modulation (XGM), cross-phase modulation (XPM), four-wave mixing (FWM) and cross-polarization modulation are promising due to SOA’s high gain in the optical power, strong change of the refractive index and potential for photonic integration. M. Kalyvas has reported a 40 Gb/s all-optical write/store memory using a single semiconductor optical amplifier-based logic gate [35].

With the use of an integrated SOA based Mach Zehnder interferometer with a differential modulation scheme an all-optical XOR has been demonstrated [112]. XOR logic gate can also be implemented by four-wave mixing in SOA [117, 120].

Mach-Zehnder interferometers with the help of SOAs can provide very high-speed all-optical switching [28, 33, 52, 78, 121, 280]. XOR logic gate can also be constructed based on Sagnac interferometric structure where SOA serves as the nonlinear medium [47, 48, 157]. All-optical logic gates based on nonlinear optical loop mirrors can also be found [162]. SOA in nonlinear optical loop mirrors or sagnac interferometer is also used for data format conversion and other operations [49, 164].

An all-optical 40 Gbit/s NOR logic gate has been presented using SOA and an optical bandpass filter [177]. All-optical AND and NAND logic gates based on semiconductor microresonators have been constructed [68]. Multiple ring based logic devices are advantageous for cascading in photonic circuit because more ports are
available. Photonic logic NOR gate has been also constructed based on symmetric GaAs-AlGaAs microring resonators [84]. The switching energy of the gate is reported as 20 pJ/pulse. It can be integrated to a large scale photonic circuit. As microring resonators are ultracompact, they can be useful for developing optical logic gates [67, 261, 270].

The polarization shift keying modulation format is used in many schemes. Based on an asymmetric nonlinear directional coupler all-optical logic gates have been developed by Fraga et al [173]. All-optical logic OR gate using SOA and delayed interferometer is implemented by Wang et al [175]. Mondal et al have developed a method of conducting an all-optical NAND logic operation controlled from a long distance [187].

Zhang et al have implemented optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals [195]. The operating principle is based on the interference of reflected and transmitted self-collimated beam. The device is applicable for photonic integrated circuits. Liu et al have designed theoretically the all-optical logic gates based on two-dimensional low-refractive index nonlinear photonic crystal slabs [267]. They have demonstrated ultracompact all-optical AND, NAND, OR, and NOR gates with two-dimensional nonlinear photonic crystal slabs. They have showed that all-optical logic gates with low pump-power in the order of tens of MW/cm² can be achieved.

All-optical Boolean logic gates can also be realized using azo-dye doped polymer film [158]. Bovino et al. have implemented an optical polarization based logic function (XOR or XNOR) with nonlinear gallium nitride nanoslab [238]. They have presented the scheme based on non phase-matched noncollinear second harmonic generation from Gallium nitride. The polarization of the noncollinear generated beam is a function of the polarization of both pump beams.

Periodically poled lithium niobate (PPLN) have been used in many reports [45, 193, 216, 234, 245, 262, 282]. Single PPLN based simultaneous half-adder, half –subtractor and OR logic gate are proposed by Wang et al. Bogoni et al have developed 640 Gbit/s photonic logic gates. They have used pump depletion in a periodically poled lithium niobate waveguide. Again Wang et al. have developed an ultrafast all-optical three-input Boolean XOR operation for differential phase-shift keying signals using periodically poled lithium niobate [216].
Fok et al. have experimentally developed an all-optical XOR gate with optical feedback using highly Ge-doped nonlinear fiber and a terahertz optical asymmetric demultiplexer [268]. The XOR gate is achieved based on cross-polarization rotation in nonlinear fiber, while the optical feedback employs a terahertz optical asymmetric demultiplexer (TOAD). The TOAD simultaneously cleans up the XOR output and converts the wavelength of the feedback signal to allow proper feedback operation. Optical soliton can also be used for logic operation and data processing [138, 143, 230].

Half adder and half subtractor are essential in data computing. The ‘sum’ or ‘difference’ can be achieved by XOR logic operation between the two input variables (‘figure – 2.3’). While the ‘carry’ bit is generated by AND operation between the two variables, the ‘borrow’ bit is received by the AND logic operation of one variable with the complement of the other variable. An ultrahigh-speed all-optical half adder based on four-wave mixing in semiconductor optical amplifier is reported by Li et al. [172].

Yang et al have developed a function-lock strategy in OR/NOR optical logic gates based on cross-polarization modulation effect in semiconductor optical
amplifier [196]. Leyder et al. have designed a polarization controlled optical gates by interference of coherent polariton beams in microcavities [197]. Because of the interference between coherent polaritons, this process is observed in the case of polaritons generated from two collinearly polarized coherent pump beams. On the contrary, if the beams are cross polarized, the scattering is suppressed. Emary et al. report an optically controlled logic gates for two spin qubits in vertically coupled quantum dots [198]. RayChaudhuri et al. have suggested molecular level all-optical logic with chlorophyll absorption spectrum and polarization sensitivity [205]. Molecular devices can be used for photonic information processing and storage due to their small size and light weight. The photochromic protein bacteriorhodopsin is important in this context. Optical switching operation can be performed with bacteriorhodopsin (‘figure - 2.4’) [96, 116, 140, 159, 293]. The probe beam is focused by the lens onto the sample. The pump and probe beams overlap on the sample. Changing the intensity of the beams switching properties are studied.

![Schematic diagram of the experimental set up for optical switching with bacteriorhodopsin film sample.](image)

Fig. 2.4: Schematic diagram of the experimental set up for optical switching with bacteriorhodopsin film sample.
Chattopadhyay et al. have proposed an all-optical conversion scheme for representing a binary to quaternary and vice versa [236]. Clark et al. have reported an all-optical fiber polarization based quantum logic gate [237]. Ma et al. report a high speed all optical logic gates based on quantum dot semiconductor optical amplifiers [257].

Half adder/subtractor arithmetic operation can also be found by using dark-bright soliton conversion control within an all-optical circuit consists of microring and nanoring devices [279]. Here ‘logic 0’ and ‘logic 1’ are represented by dark and bright soliton respectively. An all-optical half adder based on cross structures in two-dimensional photonic crystals is implemented by Liu et al. [215].

With the use of optical nonlinear material based switching and spatial input encoding binary addition and subtraction operation can be performed [163]. Polarization coding technique and nonlinear total reflectional optical switches are also used for optical half adder and full adder operations [253].

Gayen et al. have proposed an all-optical adder/subtractor based on terahertz optical asymmetric demultiplexer [239]. They have exploited the advantages of terahertz optical asymmetric demultiplexer based optical switch to design an integrated all-optical circuit which can perform binary addition and subtraction.

All-optical half adder has been demonstrated with interferometric SOA gates [111]. This all-optical device generates simultaneously four Boolean operations at 10 Gb/s.

All-optical flip-flop, designed as bistable elements, can serve as temporary memory elements and help in realizing optical networks. Flip-flops have been proposed in different ways by many researchers [150]. Flip-flop memory based on two coupled nonlinear polarization switches is reported [65]. The principle of polarization dependent semiconductor optical amplifier gain is applied to a nonlinear polarization switch.

Designing of all-optical flip-flop is also reported using directionally coupled bistable laser diode [110]. The nonlinear effects of the saturable absorber and the directional coupler are utilized to demonstrate the flip-flop. Multimode interference bistable laser diodes are also used to establish flip-flop operation [107, 160].

Optical bistability in a SOA or distributed feedback SOA can be employed to achieve all-optical flip-flop operation [115].
Again flip-flop is designed depending upon coherent nonlinear feedback [181]. The nonlinearity is due to interference of two coherent optical fields. The lasers remains above the lasing threshold always and thus carrier density changes are lower. This makes the transient times reduced.

All-optical flip-flop has been designed based on single distributed feedback laser diode [208-210]. A bistability is achieved due to the spatial hole burning effect by injecting continuous wave light in the laser diode. Switching time below 75 ps and repetition rates of 2 GHz are reported by using pulses with energies below 200 fJ.

Using of multivalued logic in optical computing can increase the logic density. In trinary system memory elements also have much importance for better performance [228]. A trinary flip-flop is different from a binary flip-flop. While a binary flip-flop has two stable states, a trinary flip-flop has three states.

New conducting polymers are being used to develop transistor like switches [40, 41]. These switches are smaller and faster than the silicon transistors. We can dream for an optical transistor which can operate with a single photon [224]. Now all-optical transistor can be expected in reality [161, 250, 252]. As the rate of data transmission is increasing sharply demand for optical technology is also strengthening. Optics is now being used in long distance telecommunication as well as in shorter distance interconnection [251].

There are also many more all-optical processors already developed by different workers.

2.3. Conclusion
Since the birth of the optical computing technique it has become much matured today. Yet it seems to be in competition with the electronic computing. With the invention of new optical and optoelectronic technologies the goal of superfast computing with optics can be achieved. The field of quantum computing, based on quantum nature of photon, is also flourishing. Linear optical logic devices can be utilized to develop an optical quantum computer. All-optical digital data processing seems to be the technology for the new generation computing systems in the optical domain. Again optical computing technique is believed to be highly useful in quantum cryptography.
A Proposal for Developing an Integrated All-Optical Logic and Arithmetic Unit Using the Kerr - Nonlinearity

Abstract

The advantages of using optical signal in logic, data and arithmetic processing are now well known to the optical community over the globe. Some optical isotropic nonlinear materials can play an important and essential role in developing such logic and arithmetic processors. This type of nonlinear materials can be successfully used also as an optical switch. Different all-optical logic gates using this type of switching are already reported several times. Here in this chapter a new method to develop an integrated, compact and dedicated all-optical system is described. This system can perform many logic and arithmetic operations in parallel as required for the purpose of processing of optical data.

Publications related to this chapter -


3.1. Introduction

Since the middle of seventies there started an effort to implement data processors with optical signal instead of so-called electronic signal. This is because of tremendous inherent processing advantages with optics as information carrying signal. Optical signal has a strong role in parallelism. Very high speed operation (for above the THz limit) can be achieved if optics is suitably used. Even a femto-second pulse can be used as an optical data bit if required. In last three decades lots of proposals already came forward where logic operations, arithmetic operations, algebraic operations, data processing, computation and image processing are done by either optical signal alone (i.e. all-optical) or by opto-electronic mechanism. To implement the above all-optical system we have seen the massive use of optical nonlinear material based optical switches, photo-refractive and electro-optical material based optical switches etc. Nonlinear material based switches have also several applications. Working principle of this type of switches depends on the intensity level of the light signal existing at the time of passing the information carrying signal through the nonlinear material. Most all-optical logic and arithmetic operations can successfully be implemented by some isotropic nonlinear materials [79, 127-129]. Here a new approach is proposed to accommodate several all-optical systems in a single, compact and integrated architecture for performing different logic and arithmetic operations. To develop it the inherent all-optical switching capacity of optical isotropic nonlinear material is used as far as practicable.

3.2. Use of nonlinear material for implementation of optical logic system.

3.2.1. Optical isotropic Kerr nonlinear material (NLM) used as a switch

There are some isotropic nonlinear materials (NLMs) which can show also Kerr type of nonlinearity. This type of materials can exhibit the character of self-focusing [303]. For this type material the 2\textsuperscript{nd} order nonlinear term, in the expression of polarization ($\vec{P}$), has a significant value and cannot be no longer neglected. Considering up to the 2\textsuperscript{nd} order nonlinear term and neglecting the higher order terms the expression for dielectric polarization becomes

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E} \vec{E} + \varepsilon_0 \chi^{(3)} \vec{E} \vec{E} \vec{E}$$

(3.1)

For isotropic materials
Hence the above equation becomes

\[ \vec{P}(-E) = -\vec{P}(E) \]  

\[ \vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + a_3 E_0^2 \vec{E} \]  

where \( a_3 = \varepsilon_0 \chi^{(3)} \). Now the displacement vector \( \vec{D} \) can be expressed as

\[ \vec{D} = \varepsilon \vec{E} = \varepsilon_0 \vec{E} + \vec{P} = [\varepsilon_0 (1 + \chi^{(1)}) + a_3 E_0^2] \vec{E} \]  

Hence the refractive index of the isotropic nonlinear material becomes

\[ n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \sqrt{1 + \chi^{(1)} + a_3 E_0^2 \varepsilon_0} \]

\[ n \approx \sqrt{(1 + \chi^{(1)}) \left[ 1 + \frac{a_3}{2 \varepsilon_0 (1 + \chi^{(1)})} E_0^2 \right]} \quad \text{as} \quad \left[ \frac{a_3 E_0^2}{\varepsilon_0 (1 + \chi^{(1)})} \right] \ll 1 \]

So,

\[ n = n_0 + n_2 I \]  

Here \( n_0 = \sqrt{(1 + \chi^{(1)})} \) is the constant linear refractive index term, \( n_2 = \frac{a_3}{2 \varepsilon_0 \sqrt{(1 + \chi^{(1)})}} \) is the nonlinear correction term and \( I = E_0^2 \) is the intensity of the light signal passing through the NLM.

In ‘equation - 3.5’ it is seen that if the intensity ‘I’ increases the refractive index of the nonlinear material also increases linearly. This character of the NLM can be used to implement an all-optical switch shown in ‘figure - 3.1’. Let us consider a light beam AO, of intensity ‘I’ is made incident from air to an ordinary glass made linear material (LM) interface at the point ‘O1’ of a LM-NLM block. After refraction the beam propagates through the linear material and then it is incident at the boundary of linear and non-linear material (at the point ‘O2’). The beam is now refracted through the NLM and leaves the NLM at the point ‘O4’. So this beam is received in the channel ‘Y2’. If the intensity of the light beam incident at ‘O2’ (originally it falls at ‘O1’) changes from ‘I’ to ‘2I’ value, then the refractive index of the NLM increases according to ‘equation - 3.5’. As a result the light beam now leaves the NLM from the point ‘O3’ and it is then received through the channel ‘Y1’, instead of the channel ‘Y2’. Thus the NLM can be used as an optical switch, where the change of the outcoming channel of the light signal from the NLMs depends on its intensity level.

Fused Silica glass, carbon di sulphide (CS2) and many other dielectric materials can be used as a non-linear device. For fused silica, \( n_0 = 1.458 \), \( n_2 = 2.7 \times 10^{-20} \text{ m}^2 / \text{W} \) and for CS2, \( n_0 = 1.63 \) and \( n_2 = 514 \times 10^{-20} \text{ m}^2 / \text{W} \) [309]. For an
example the deviation of the light signal passing through CS₂ for different intensity level of the light beam can be calculated very easily. For an ordinary CW laser of 100mW power and 50µm² beam cross-section the intensity becomes $2 \times 10^9 \text{ W/m}^2$. Now if the above continuous wave (CW) beam is changed to a pulsed beam of pulse duration $10^{-9}$s the pulse power reaches a value of $2 \times 10^{18} \text{ W/m}^2$. This pulsating beam can be obtained by the use of a suitable Q-switching or mode locking mechanism.

Considering the average intensity of the pulse $I = 2 \times 10^{18} \text{ W/m}^2$ the value of ‘n’ becomes 11.91 for CS₂. Now considering the angle of incidence of the pulsed light at LM and NLM interface as $45^\circ$ one can find the value of the angle of refraction in the NLM ($\theta_2$) as $4.529^\circ$. The above value of $\theta_2$ can be easily obtained from Snell’s law. Now if the intensity of the light passing through it is made doubled then ‘n’ reaches the value of 22.19 and the value of $\theta_2$ goes to $2.429^\circ$. So the change of the angle of refraction ($\Delta \theta_2$) is $2.1^\circ$, for the doubling of intensity.

![Diagram](image)

Fig. 3.1: Optical nonlinear material used as a switch.
For 1cm thickness of the NLM the separation between the two exit points ('O₀' and 'O₄') of the NLM (i.e. the lateral separation between the two channels 'Y₁' and 'Y₂') becomes 0.3mm for that value of \( \Delta \theta_2 = 2.1° \). This is a very large separation in case of a micro-device. Therefore this type of NLM can be made useful for implementing all-optical logic devices as a suitable channel can be selected by using a proper laser intensity of a pulse having the order of nanosecond duration. The logical systems are to be operated certainly in digital/pulsating mode of the signal otherwise the high amount of power is required to exploit the nonlinear switching character. There are some nonlinear materials which can show very fast response time even in sub-picoseconds range. Already several proposals of all-optical logic systems using this type of switching have been reported.

There are also some nonlinear materials for which the refractive index is expressed by the following equation

\[
n = n_0 - n_2 I \quad \text{... (3.6)}
\]

For this type of material the effect will be reverse of the aforesaid nonlinear material i.e. for increase in the intensity of the light beam passing through the NLM the refractive index decreases.

The nonlinear material referred here in this thesis is only the first type of nonlinear material. Different all-optical logic gates can be successfully implemented by such type of optical isotropic nonlinear material. The logic states can be encoded by the intensity level variation of the light signal. Here the presence of a light signal of some predetermined intensity 'I' is considered as 'logic 1' (high state) and the absence of light (zero intensity) is considered as 'logic 0' (low state).

3.2.2. Optical NOT logic gate using NLM

An optical NOT logic gate using nonlinear material is shown in ‘figure - 3.2’. Here ‘A’ is the input and ‘CLS’ is a constant laser source. The operation of the scheme is similar to the operation of the scheme shown in ‘figure - 3.1’. Here the input channel ‘A’ and the constant light source (CLS) are combined together and the combination is incident at the point ‘O₁’ on the linear material (LM). Then it is incident at the point ‘O₂’ on the interface of the linear and nonlinear materials and finally it is refracted through the NLM.
Now if $A=0$ then the intensity of the combined beam incident at the point ‘$O_1$’ (and also at ‘$O_2$’) is ‘$I$’ only. So this light beam is refracted through the NLM along the continuous line shown in the figure and leaves the NLM at the point ‘$O_4$’. Therefore at the output ‘$Y$’ a light beam of intensity ‘$I$’ (which is because of the intensity of the CLS) is received. Again if the input $A=1$ then the intensity of the combined light beam incident at the point ‘$O_1$’ becomes ‘$2I$’ and as a result of this the light beam the refractive index of the NLM increases. So the light beam is now refracted through the NLM along the dotted line shown in the ‘figure - 3.2’ and leaves the NLM at the point ‘$O_3$’. Therefore no light (logic 0) is received at the output ‘$Y$’. Thus the NOT logic operation is performed.

### 3.2.3. Optical AND and Ex-OR logic gates using NLM

Using the similar method other optical logic gates can also be implemented. How an all-optical 2-input AND logic gate and an Ex-OR logic gate can be realized is shown in the ‘figure - 3.3’. ‘A’ and ‘B’ are the two input channels. These two light beams are combined and made incident at the point ‘$O_1$’. After passing though the LM the light
beam is incident at the point ‘O₂’ on the interface of LM and NLM. Then the light beam is refracted through the NLM and leaves the medium at the point ‘O₃’ or at the point ‘O₄’ according to the intensity of the combined light beam.

When A=B=0 i.e. no light is given to the inputs ‘A’ and ‘B’ then the intensity of the combined light beam is zero. Therefore no light is obtained at the output channels ‘Y₁’ and ‘Y₂’. So for the input condition A=B=0 the output Y₁=0, Y₂=0.

When A=0 and B=1 or A=1 and B=0 the intensity of the combined light beam incident at the point ‘O₁’ is ‘I’ only. This light beam passes through the LM and is incident at the point ‘O₂’ on the LM and NLM boundary surface. Now this light beam propagates through the NLM along the continuous line shown in the figure and leaves the NLM at the point ‘O₄’. This light beam is received in the channel ‘Y₂’. Therefore no light is found in the channel ‘Y₁’. Hence for the 2nd and 3rd input conditions the output yields the result Y₁=0 and Y₂=1.

Fig. 3.3: All-optical AND and Ex-OR logic gates using nonlinear material.
For the last input condition A=B=1 i.e. both the input gets light of the prefixed intensity ‘I’. So the intensity of the combined light beam becomes ‘2I’. The refractive index of the LM does not change with intensity. So the combined light beam travels through the LM in the same path as earlier and finally is incident at the point ‘O₂’ on the LM and NLM interface. Now as the refractive index of the NLM increases with the intensity of the light beam the combined light beam is refracted through the NLM along the dotted line shown in the ‘figure - 3.3’. Finally this beam leaves the NLM at the point ‘O₃’ and is traced at the channel ‘Y₁’. This results no light in the channel ‘Y₂’. So for this input condition the outputs become Y₁=1 and Y₂=0.

Thus it is seen that only when both the two inputs ‘A’ and ‘B’ get light (high state) then only output Y₁=1 (high state) and for the other input conditions Y₁=0. So output ‘Y₁’ gives the output of AND logic gate. On the other hand when only one of the inputs gets light (high state) then only the output Y₂=1 (high state) and for the input conditions A=B=0 and A=B=1 the output channel ‘Y₂’ gets no light (low state). Therefore the output channel ‘Y₂’ gives the result of Ex-OR logic operation between the two inputs ‘A’ and ‘B’.

3.3. An integrated scheme of implementing optical logic and arithmetic processor (OLAP) with NLM.

Here an all-optical integrated scheme is proposed. The system can perform different logic operations as well as some arithmetic operations. Using this scheme optical logic expressions in Sum of Product (SOP) form can be implemented. This scheme can also be parallely used as an arithmetic processor. The scheme is shown in the ‘figure - 3.4’. Here ‘A’, ‘B’, ‘C’ are three input variables. From these inputs the ‘Ā’, ‘B’, and ‘C’ signals are generated using NOT logic gates. There are eight other optical blocks in the ‘figure - 3.4’. The blocks (1-8) are made of optical linear and nonlinear materials.

The internal architecture of each block is shown in ‘figure -3.5’. Here ‘x’ represents the serial number of the blocks (x=1, 2,…., 8). ‘A’, ‘B’, ‘C’, ‘Ā’, ‘B’, and ‘C’ are the respective input data channels of each block. There are also seven control inputs like xA, xB, xC, xĀ, xB, xC and Px. If the control channel ‘Px’ is made high (logic 1) by giving light in the input terminal the corresponding block will be
activated otherwise the corresponding block will not work. When ‘P_x’ is high then the output of the block will be the product of two or more terms among A, B, C, \(\overline{A}\), \(\overline{B}\) and \(\overline{C}\). Which terms appear in the output depend on the status of the corresponding control input channel. The terms A, B, C, \(\overline{A}\), \(\overline{B}\) or \(\overline{C}\) will appear in the output only if the corresponding control terminal xA, xB, xC, x\(\overline{A}\), x\(\overline{B}\), x\(\overline{C}\) respectively are high (logic 1). For example if the SOP term is \(\overline{A}B\overline{C}\) then to get the respective result of the product we require 1 \(\overline{A}\), 1B, 1\(\overline{C}\) and \(P_1\) control terminals as “1” (high state) and remaining control terminals as low for the block-1 in ‘figure -3.4’. On the other hand if the control input ‘P_x’ is at low (logic 0) state then the corresponding block will not function and output of the block will be low.

In ‘figure - 3.5’ it is seen that \(P_x\) is one of the inputs of the last AND gate. Now for ‘block-1’ (x=1) if \(P_1=1\) then only the block is activated and output ‘\(Y_1\)’ gives the desired result. Now the function of each block is described. Let us consider the ‘block-1’. The control input ‘1A’ and the ‘data A’ are combined by an AND logic gate and parallelly ‘1A’ control terminal and a constant light source (CLS) of intensity ‘1’ are also combined together by an NOT logic gate. ‘G’ and ‘H’ give the output of the AND logic gate and the NOT logic gate respectively. If light is applied (logic 1) to the control input ‘1A’ then the data ‘A’ can be recovered in the channel ‘G’. Now the channel ‘H’ remains at the ‘logic 0’ state (i.e. no light is obtained in the channel ‘H’). Again if the control input ‘1A’ gets no light signal (logic 0) then the output ‘G’ remains at ‘logic 0’ state (i.e. no light is available in the channel) and the output ‘H’ goes to ‘logic 1’ state. The other control input channels in the block also function in the same manner. The channels ‘G’ and ‘H’ are combined together (by OR operation) to get the channel ‘J’. Similarly, the same type of channels can be formed by combining the every AND and NOT logic output channels for other control inputs in the same block. Thus the channels ‘K’, ‘L’, ‘M’, ‘N’ and ‘O’ are obtained. These channels and the control channel ‘\(P_1\)’ (here \(P_1=1\)) are connected to the inputs of the final AND logic gate of the block producing the output ‘\(Y_1\)’. In such way other outputs (\(Y_2, Y_3,..., Y_8\)) from other blocks of ‘figure -3.4’ can be obtained.

The outputs of the blocks are added (by OR operation) as shown in ‘figure -3.4’ by suitable beam combining system to get the final output ‘\(Y\)’. There are also two more control inputs ‘Q_1’ and ‘Q_2’ in ‘figure - 3.4’. In some specific application of the scheme ‘Q_1’ and ‘Q_2’ are made high (logic 1) and then the output is to be taken at the...
channels ‘S/D’ and ‘C\textsubscript{0}/B\textsubscript{0}’ (shown as dotted lines) respectively instead of getting the output at ‘Y’.

A logical processor can be implemented using this integrated scheme. For this purpose the instructions which are to be followed are Q\textsubscript{1}=Q\textsubscript{2}=0. The control channel P\textsubscript{x} (where x=1, 2,..., 8 for respective blocks) is to be made high (logic 1). The number of blocks which are to be activated is the number of minterms present in the given expression which is to be executed. For the first term in the expression, the block-1 is activated by making P\textsubscript{1}=1. Then the control inputs (among 1A, 1B, 1C, \(\bar{A}\), \(\bar{B}\), \(\bar{C}\)) corresponding to the variables (among A, B, C, \(\bar{A}\), \(\bar{B}\), \(\bar{C}\)) in the term are made to be high. Similarly other blocks are also activated if required. Data are given in the input channels ‘A’, ‘B’, ‘C’. Now at the final output ‘Y’ (in ‘fig. - 3.4’) the required result of digital operation can be achieved. Thus the system can be used to implement the logical expression given in SOP form, under three-variable scheme.

The same integrated scheme can also be used as a half adder for adding two data bits ‘A’ and ‘B’. The truth table of half adder is given in ‘table - 3.1’. To use the scheme as a half adder the instructions which are to be followed are (i) Q\textsubscript{1}=Q\textsubscript{2}=1, (ii) P\textsubscript{1}= P\textsubscript{2}= P\textsubscript{5}=1, (iii) \(\bar{A}\)=1B=1, (iv) 2\(\bar{A}\)=2\(\bar{B}\)=1, and (v) 5A=5B=1. As the controlled inputs ‘Q\textsubscript{1}’ and ‘Q\textsubscript{2}’ are made high (logic 1) so no light signal can now be retrieved at the terminal ‘Y’. Rather the output is to be taken from the terminals ‘S/D’ and ‘C\textsubscript{0}/B\textsubscript{0}’. For this operation only block -1, block-2 and block-5 are activated by making the control inputs ‘P\textsubscript{1}’, ‘P\textsubscript{2}’ and ‘P\textsubscript{5}’ high. After executing the above instructions the scheme becomes ready for the half adder operation. Now if the data (augend and addend) is applied at the input channels ‘A’ and ‘B’ the sum(S) is obtained at the output channel ‘S/D’ and the carry (C\textsubscript{0}) at the channel ‘C\textsubscript{0}/B\textsubscript{0}’.

To use the scheme as a full adder (i.e. for adding the data ‘A’, ‘B’, and ‘C’) the required instructions which are to be followed are (i) Q\textsubscript{1}=Q\textsubscript{2}=1, (ii) P\textsubscript{1}= P\textsubscript{2}= P\textsubscript{3}= P\textsubscript{4}= P\textsubscript{5}= P\textsubscript{6}= P\textsubscript{7}=1, (iii) \(\bar{A}\) =1\(\bar{B}\) =1C=1, (iv) 2\(\bar{A}\)=2\(\bar{B}\)=2\(\bar{C}\)=1, (v) 3A=3\(\bar{B}\)=3\(\bar{C}\)=1, (vi) 4A=4B=4C=1, (vii) 5A=5B=1, (viii) 6B=6C=1, (ix) 7C=7A=1. The truth table of the full adder is given in ‘table - 3.2’. Now the data is to given in the input channels ‘A’, ‘B’, ‘C’ and then the sum (S) is obtained at the output channel ‘S/D’ and the carry (C\textsubscript{0}) is received at the output channel ‘C\textsubscript{0}/B\textsubscript{0}’ (shown in ‘fig.- 3.4’). The truth table is exactly supported.
Again the integrated scheme (‘fig. - 3.4’) can be used as a half subtractor also. For this purpose the instructions which is to be followed are i) $Q_1=Q_2=1$, ii) $P_1= P_2= P_3=1$, iii) $1 \overline{A} =1B=1$, iv) $2A=2 \overline{B} =1$, v) $5 \overline{A} =5B=1$. Now if we give the data (minued and subtrahend) at the input channels A and B we get the difference bit (D) at the output channel ‘S/D’ and the borrow bit ($B_0$) at the channel ‘$C_0/B_0$’. The truth table is given in ‘table - 3.3’.

Similarly a full subtractor can also be implemented using the same integrated scheme. To do this the necessary instructions which to be followed are i) $Q_1=Q_2=1$, ii) $P_1= P_2= P_3= P_4= P_5= P_6= P_7=1$, iii) $1 \overline{A} =1B =1C=1$, iv) $2 \overline{A} =2B=2 \overline{C} =1$, v) $3A=3 \overline{B} =3 \overline{C} =1$, vi) $4A=4B=4C=1$, vii) $5 \overline{A} =5B=1$, viii) $6 \overline{A} =6C=1$, ix) $7B=7C=1$. The truth table for the full adder is given in ‘table - 3.4’. Now one requires to put the data at the input channels A, B, C. Then the difference bit (D) can be taken from the output channel ‘S/D’ and the borrow bit ($B_0$) from the channel ‘$C_0/B_0$’. Here also the truth table given in ‘table - 3.4’ is supported.
Fig. 3.4: An integrated all optical logic and arithmetic processor using nonlinear material.
Fig. 3.5: The internal architecture of each of the block (1-8) in fig.-3.4.
(x=1, 2, …, 8; beam splitters and beam combiners are not shown in the fig.)
Table – 3.1: Truth table for a half adder.

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Table – 3.2: Truth table for a full adder

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Table – 3.3: Truth table for a half subtractor

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Table-3.4: Truth table for a full subtractor.

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3.4. Conclusion

The above integrated system is all-optical in nature. The whole unit uses the strong parallelism of optics as far as possible. Not changing the internal architecture of the system, but only applying optical signal in proper terminals, and in proper control-channels of the blocks used in the scheme one can receive any desired logic and arithmetic operation as and when necessary. For example if we like to get a full addition between three optical bits we should first apply the optical signal carrying the instructions for performing the addition of bits, then optical signals for data-bit values. Similarly with the same system we can get the result of full subtraction and that of any logical expression.

The architecture shown above can also be minimized. It could be minimized more if a single block is used in replacement of multiple blocks. As the whole scheme is all-optical one therefore the real-time speed of operation can be expected from here. The system can be implemented properly if a suitable laser source and nonlinear material are available. Semiconductor optical amplifier and the necessary diode laser can be mentioned in this regard.

There is a drawback of the logic gates with the intensity level dependent encoding of the data signal. However this problem is resolved later. The scheme may be successfully used for different logic and arithmetic operations.
A Method of Developing a Prefixed Intensity Level for any Logic Input/ Output Signal Bit

Abstract

Optical isotropic nonlinear materials can be used as successful optical switch to implement a logic or arithmetic processor. Optical systems can be developed very easily using this type of optical switch. These switches act on changing the intensity level of an optical signal. The primary requirement for proper functioning of such nonlinear material based logic devices is a fixed intensity level of the optical signal against a specific logic state. In this chapter a technique for obtaining fixed intensity level of optical signal against a specific logic state is illustrated for the purpose of optical data processing.

Publications related to this chapter -

4.1. Introduction

Optical signals are seen to be used widely since the last few decades to implement data and image processing operations [26, 27, 34, 36, 37, 39, 42, 54-58, 62, 64, 77, 81, 82, 89, 93-95, 101, 102, 105, 131, 137, 151, 152, 178, 199]. This is due to the tremendous inherent advantages of optical signal in comparison to the conventional electronic signal. Naturally when optical signal is used for communication of data, one feels the necessity for encoding and decoding of the data bits. This can be done with various optical/ opto-electronic techniques. For example the variation of levels of intensity, polarization or phase of a light signal can be used for encoding or decoding of data bit. In intensity based encoding technique generally the absence of any light signal is treated as ‘logic 0’ (low) state and the presence of a predetermined intensity of light signal is considered as ‘logic 1’ (high) state. To implement optical data processors using the intensity based encoding technique, optical nonlinear materials and photo-refractive materials have been widely used in many proposals [83, 90, 142, 274, 287, 305]. Several papers are also published where tri-state and quaternary state logic operations are seen to be implemented with optical data. In those systems where nonlinear material based switches are used, the intensity of the optical signal is very important for proper functioning of the switches. This is because the refractive index of the isotropic Kerr type of nonlinear material varies with the intensity of the optical signal passing through it. This mechanism is utilized to develop optical switch. Now if there is a loss due to the absorption during propagation of the light signal or any other reasons, the intensity of the data signal may change. This can cause problems in the switching operation of the nonlinear material based switch and consequently the cascaded system may lead to a malfunction. Therefore the intensity of the optical signal against a specific bit is to be kept constant with a predetermined value for getting a desired operation. Here in this chapter a new concept is reported for maintaining a fixed intensity level of the light signal against specific logic state in case of all-optical data processing.

4.2. All-optical method for controlling the intensity of the light signal: the circuit description.

The proposed scheme is shown in ‘figure - 4.1’. The scheme is developed using the switching capacity of the optical isotropic nonlinear material. The refractive index of
this type of nonlinear material depends on the intensity of the light signal passing through the material. The scheme is designed in such a way that the output of the scheme will give a fixed intensity value ‘I’ of light signal when there is a light signal at the input and there will be no light at the output when there will be no light signal at the input. Four constant intensity laser sources (CLS) are used in the scheme. The intensity of the light emitted from a constant laser sources CLS-1, CLS-2, CLS-3 and CLS-4 are ‘I/2’, ‘I/4’, ‘I’ and ‘I/4’ respectively where ‘I’ is a prefixed value of intensity of the laser light. The respective intensities of the constant laser sources are to be ensured constant for achieving the specific intensities for specific bits.

Let it is assumed that an optical data signal, after travelling through a long distance, arrive at the input of the aforesaid (‘fig.-4.1’) system. As the beam moves through a long distance it may undergo losses, thereby a decrease in the intensity may occur.

Now the given light signal is fed to the input channel ‘A’. Let it is considered first that the intensity of this light beam is ‘I₁’. This light beam is split into two beams at the point ‘B’ by a 50:50 beam splitter. So the intensity of each of the two beams becomes ‘I₁/2’. The first component is incident on a nonlinear material (NLM) at the point ‘C’. Only if the intensity of this component equals ‘I/2’ then it goes to the channel ‘D’. Otherwise the beam is refracted through other direction and does not propagate through the channel ‘D’. This is because the refractive index of the material changes with the intensity of the light beam passing through it. The other component of the input light is added to the light from CLS-3 at the point ‘H’.

The light signal coming from channel ‘D’ is combined with the light signal coming from CLS-1 at the point ‘E’. This combined beam is now incident at the point ‘O₁’ at the boundary of linear material (LM) and nonlinear material (NLM) of a LM-NLM block. Therefore the beam (of intensity ‘I’') is refracted through the channel ‘F’ and received at the output ‘Y’. If the light from channel ‘D’ is absent, then the light only from the CLS-1 is refracted through the channel ‘G’ which results in absence of light in the channel ‘F’.

On the other hand the combined light beam at the point ‘H’ is made incident at the point ‘O₃’ at a LM and NLM boundary. When there is no light at the input ‘A’ then the beam is refracted through the channel ‘J’; otherwise it does not go through the channel ‘J’. This beam (of intensity ‘I’') from the channel ‘J’ is now combined
with the light coming from CLS-4 and is made incident at the point ‘O4’ on a LM and NLM boundary. The refracted beam goes to the channel ‘K’ only when there is no light in the channel ‘J’. The light beam (of intensity ‘I/4’) coming from the channel ‘K’ is now combined with the light from CLS-2 and the light (of intensity ‘I/2’) from the channel ‘G’ at the point ‘L’. Only if all of these three light beams are present then the combined beam, after incidence at the point ‘O2’ at a LM and NLM boundary is refracted through the channel ‘R’. The channels ‘R’ and ‘F’ are combined at the point ‘S’ and the final output is obtained at the point ‘Y’.

4.3. Description of operation of the system.

The functioning of the scheme is described as follows. The whole operation is discussed in three different cases, i) when $I_1 = I$, ii) when $I_1 \neq I$, and iii) when $I_1 = 0$.

i) When the input light intensity $I_i$ is equal to $I$

First let us consider that a light beam of intensity $I_1$ (=I) falls on the input ‘A’. This beam is split into two sub-beams (each of intensity ‘I/2’) at the point ‘B’. Here we assume that there is no loss of light in the system as the volume of the whole system is small enough. Now as depicted earlier, the first component at the point ‘C’ goes to the channel ‘D’ as its intensity is ‘I/2’. As a result the combined beam at the point ‘E’ is of intensity ‘I’ and is refracted through the channel ‘F’. On the other hand, due to presence of the second component at the point ‘H’, no light is obtained in the channel ‘J’. This will, in turn, result in a light beam of intensity ‘I/4’ at the channel ‘K’. Now at the point ‘L’ only two beams, one from CLS-2 and other from channel ‘K’, prevail while no light comes from the channel ‘G’. So the combined incident light beam at the point ‘O2’ will not be refracted through the channel ‘R’. Therefore at the point ‘S’ only the light from the channel ‘F’ prevails. This offers a light signal of intensity ‘I’ at the output ‘Y’.

ii) When the input light intensity $I_i$ not equals $I$

In the second case, if the intensity of the input light beam at the point ‘A’ is $I_1 \neq I$, then no light will be received at the channel ‘D’. Therefore the light from CLS-1 will be refracted through the channel ‘G’ while no light will be obtained at the channel ‘F’. On the other hand, similar to the previous case, a light of intensity ‘I/4’
will be received in the channel ‘K’. Now in this case, as all of the three beams are present at the point ‘L’, the combined beam of intensity ‘I’ will go to the channel ‘R’. So, at the point ‘S’ only the light from the channel ‘R’ exists. This beam now produces a light of intensity ‘I’ at the output ‘Y’.

Thus it is seen that, the light of intensity ‘I’ is obtained at the output ‘Y’ for any value of intensity of the input beam at the point ‘A’.

Fig. 4.1: Scheme to obtain a fixed intensity for a signal bit.

**iii) When the input channel accepts no light**

Now if there is no light at the input ‘A’, no light will be received in the channel ‘D’. This will result in, similar to the second case, no light in the channel ‘F’. On the other hand, at the point ‘H’ no light comes from the point ‘B’. So the beam incident at ‘O3’ (due to CLS-3 only) now goes to the channel ‘J’. This will result in no light in the channel ‘K’. Therefore, at the point ‘L’ only two light beams one from the channel ‘G’ and the other from CLS-2 prevail. As a result the combined beam,
incident at ‘O₂’, will not be refracted through the channel ‘R’. So at the point ‘S’, light from neither the channel ‘F’ nor the channel ‘R’ prevails. This leads to no light at the final output ‘Y’, when no light is given at the input ‘A’.

The proposed system can not only be useful for developing all-optical logic circuits, it can be used in multiplexing and de-multiplexing of optical data too. There already exists some scheme of optical multiplexer, demultiplexers, data converters etc. in the area of optical computing and parallel processing. If this scheme or a modified version of this scheme is used in such multiplexers, demultiplexers, data converters etc., the proper intensity values against each bits or digits of the multiplexed or demultiplexed data can be ensured and this will help transmission with less noise, i.e. with high signal to noise (S/N) ratio and with very low probability error.

In a brief it can be said that the proposed system can ensure no light if no light signal comes at the input of the proposed scheme and at the same time it ensures also a fixed intensity ‘I’ of light beam whatever the input light intensity becomes. That means it offers the ‘I’ intensity of light at the output if the input light intensity is equal to, greater or less than ‘I’ except zero intensity.

4.4. Conclusion
The above scheme is all-optical one. So anyone can certainly expect a real time speed of operation of the scheme. The system must be operated with high pulse power digital signals to exploit the material nonlinearity for optical switching. As the scheme ensures the specific intensity value of data ‘bit 1’ or of ‘bit 0’, it may be highly useful in any nonlinear material based digital optical processing system. In case of digital optical communication one can use this scheme successfully both at the input and at the output ends and specially also at the repeater stations. This will help also for readjusting the intensity values of bits to avoid the problem of intensity falling when optical bits travel a long distance. Using the scheme the signal to noise ratio can be improved at a high level and the bit error rate can be reduced. The scheme may be extended to specify the intensity value of digits of tristate, quaternary state or even decimal states of logic system.
A New Proposal of Implementing the Polarization Encoded Optical Logic Families

Abstract

Optics has already been established as a meaningful signal in logic, algebraic and data processing. Several all-optical data processors are reported in last few decades. Different techniques and methods are utilized to develop the data processors. A new concept of implementing all-optical logic gates is proposed in this chapter where the logic states of bits are represented by different states of polarization of an optical signal. As the state of polarization of the light signal is very much suitable and advantageous for encoding and detecting the input as well as output bits of data of a digital signal so the scheme can certainly extend some wide applications both in all-optical parallel computation and information processing.

Publication related to this chapter -
5.1. Introduction
Optical signal has a strong role in parallelism. Very high speed operation can be
achieved if the inherent advantages of optics are properly exploited. That is why, a
strong effort to implement data processors with optics as information carrying signal
instead of electronic signal is being tried in almost every corner of the world. In the
last few decades lots of proposals have already come forward where logic, arithmetic,
algebraic operations, data processing, computation and image processing are done by
either optical signal alone or by opto-electronic mechanism [9, 46, 74, 85, 88, 92,
131-133, 153, 169]. To implement the Boolean logic operations using nonlinear
material as switching element, the variation of intensity level of the used light signal
is generally considered to indicate the logic states. So, to represent any logic state,
there, it is highly required to fix a specific intensity level of the light signal in favour
of each bit. Still there lies a problem. In long distance communication of optical signal
the intensity of the signal may change due to various reasons. Then the logic
processor which operates on the basis of the intensity level of the signal fails to work
properly in the detecting side. This difficulty may be avoided if the principle of
polarization based encoding/decoding technique is adopted. Use of optical
polarization state for implementing logic family is already proposed by Lohmann et al
[4, 5]. In this chapter polarization based encoding / decoding technique of bits and the
switching activity of some 2nd order nonlinear materials are jointly used to implement
some important and dedicated Boolean logic gates, like AND, OR, NAND, and EX-
OR gates.

5.2. Polarization based encoding and decoding technique.
In this technique of encoding and decoding the logic states are defined on the basis of
the state of polarization of the optical data signal. Here one orthogonally polarized
light beam (say, polarized along perpendicular to the plane of paper (●)) is assumed as
‘logic 0’ (low) state and the other orthogonally polarized light beam (say, polarized in
the plane of paper (∥)) is represented as the state of ‘logic 1’ (high).

A half-wave plate or a λ/2 plate is usually made of thin sheets of split mica or
of quartz crystal cut parallel to its optic axis, which introduces a phase difference of
‘π’ between two orthogonal polarized components, if a suitable wavelength of the
light is used. Thus when a light polarized perpendicular to the plane of paper, passes
through a half-wave plate, it becomes polarized in the plane of paper and vice-versa at the outlet. So a half-wave plate can act as an all-optical NOT gate.

As the NLM is isotropic one and the light beam passing through it is not splitted into ordinary and extra-ordinary components, so the NLM will not change the state of polarization of the light beam during its propagation though NLM, what a half-wave plate does. Here it is also assumed that the light beams at the inputs are of ‘I’ intensity each, whatever their polarizations become i.e. polarized perpendicular to the plane of paper (♦) or polarized in the plane of paper (†). The inputs can be taken from a coherent source.

5.3. Use of polarization based encoding/decoding technique and nonlinear switching technique to implement optical logic gates.

Here AND, OR, NAND and Ex-OR logic gates are proposed by the proper use of the techniques of polarization encoding /decoding and that of the non-linear switching. These gates extend the fundamental logic operations, which can be very useful for all-optical computation or data processing.

5.3.1. Implementation of a 2-input AND logic gate

The truth table for 2-input AND gate is given in ‘table - 5.1’ and the respective schematic diagram is depicted in ‘figure - 5.1’. ‘A’ and ‘B’ are two inputs and Y is the output. A dot (♦) on a line in the figure signifies that there is a connection (may be by a beam combiner or splitter) between the beam lines. The polarizer ‘P₁’ and ‘P₂’ can pass the light polarized perpendicular to the plane of paper (♦) and polarizers ‘P₃’ and ‘P₄’ can pass the light polarized in the plane of paper (†). Each of the inputs ‘A’ and ‘B’ are splitted into two beams of equal intensity (‘I/2’) by a 50:50 beam splitter. Between the two parts driven from the input ‘A’ the first one is passed through the polarizer ‘P₁’ and second through ‘P₄’. First beam now is combined with a component of the input ‘B’, and the combined beam is passed through ‘P₂’. On the other hand the other portion of the input beam ‘B’, after passing through ‘P₃’ is combined with the beam coming from ‘P₄’ at the point ‘J’. This combined light beam is now made incident on the linear and non-linear material (LM-NLM) boundary. If this light beam is of intensity ‘I/2’ or ‘I’, it is then refracted along the channels ‘S’ or ‘R’
respectively. This is because of the dependence of the refractive index of the NLM on the intensity of the light signal passing through it.

On the other hand the output from the polarizer ‘P₂’ is also made incident on a similar LM-NLM block. If the intensity of this light beam is ‘I/2’ (or ‘I’) then the beam is received in the channel ‘E’ (or ‘F’) after refraction through the NLM. The light from the channel ‘E’ is combined with the light from the constant laser source (CLS) emitting light of intensity ‘I/2’ and polarized perpendicular to the plane of paper (●). Now the combined beam is made incident on boundary of another LM-NLM block. If the intensity of this combined light beam is ‘I/2’ (or ‘I’) then the beam is received in the channel ‘H’ (or ‘G’). The channels ‘G’ and ‘F’ are combined together at the point ‘Q₁’. The light beam from ‘Q₁’ and the channel ‘R’ are now combined at the point ‘Q₂’. This combined beam produces the final output of AND gate at ‘Y’. The beam splitters and mirrors are not shown in the figure for clarity.

Table-5.1: Truth table for the 2-input AND logic gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0 (●)</td>
<td>0 (●)</td>
</tr>
<tr>
<td>0 (●)</td>
<td>1 ( угол)</td>
</tr>
<tr>
<td>1 ( угол)</td>
<td>0 (●)</td>
</tr>
<tr>
<td>1 ( угол)</td>
<td>1 ( угол)</td>
</tr>
</tbody>
</table>

The operation of the scheme is now described in brief.

(i) When A=B=0, both inputs ‘A’ and ‘B’ gets light having ‘●’ polarization (logic 0). As the polarizers ‘P₁’ and ‘P₂’ pass only light having ‘●’ polarization, one gets at the output of polarizer ‘P₂’ a light beam of ‘●’ polarization. The intensity of the light beam is ‘I’ because of the contribution of the two parts (each of intensity ‘I/2’) from the two input beams. So the light beam is refracted through the channel ‘F’. As
the channel ‘E’ gets no light only the light from the CLS (intensity ‘I/2’) is incident on the LM-NLM boundary. Therefore the beam is refracted to the channel ‘H’. As a result no light is obtained in the channel ‘G’. Thus at the point ‘Q₁’ only light from channel ‘F’ is received. On the other hand P₃ and P₄ block the light from the inputs. Therefore light can be received neither in the channel ‘R’ nor in the channel ‘S’. So at the point ‘Q₂’ only light (●) from the point ‘Q₁’ is available. As a result at the final output ‘Y’ the light beam polarized perpendicular to the plane of paper (●) is observed.

(ii) For the second input condition A=0, B=1, as ‘P₁’ and ‘P₂’ can only pass the light of ‘●’ polarization, so the output of ‘P₂’ can have light of ‘●’ polarization (of intensity ‘I/2’). Now the light beam is refracted through the channel ‘E’ while no light is obtained in the channel ‘F’. So a light beam of ‘●’ polarization (and intensity I) is received in the channel ‘G’ as well as at the point ‘Q₁’. On the other hand a part of the light from input ‘B’ (having ‘♩’ polarization) passes through P₃. But P₄ don’t pass any

Fig. 5.1: Polarization encoded 2-input AND logic gate.
light in this case. So the light beam (of intensity I/2) is refracted through the channel ‘S’. And no light is available in the channel ‘R’. Therefore at the point ‘Q_2’ only the light beam from ‘Q_1’ prevails. As a result at the output ‘Y’ only the light of (•) polarization is observed.

(iii) For the third input condition A=1, B=0, the light beam from ‘A’ cannot pass through ‘P_1’ but pass through ‘P_4’. Again light from ‘B’ cannot pass through ‘P_3’ but it passes through ‘P_2’. So similar to the second condition, in this case no light is obtained in the channels ‘F’ and ‘R’. At the point Q_2 the light beam from ‘G’ only is present. Therefore one gets at the output ‘Y’ a light of ‘•’ polarization (logic 0).

(iv) The last input condition is A=B=1. Here ‘P_1’, ‘P_2’ block the light beams. So at Q_1 no light is received. Polarizer ‘P_3’ and ‘P_4’ pass the light of ‘↑’ polarization. As this combined beam at the point ‘J’ is of intensity ‘I’ it is refracted therefore to the ‘R’ channel. This leads the output ‘Y’ to get a light of polarization ‘↑’ (logic 1). Thus the truth table of AND logic gate is satisfied for the operation of the AND logic system given in ‘fig.-5.1’.

5.3.2. Implementation of a 2-input OR logic gate

The truth table for a 2-input OR logic gate is given in ‘table - 5.2’ and the schematic diagram for the OR operation is given in ‘figure - 5.2’. In ‘table - 5.2’ it is seen that the output light beam is a ‘•’ polarized one when both the input is ‘•’ polarized and the output is ‘↑’ polarized for all other cases. In ‘fig.-5.2’ it is depicted that the scheme of OR gate has a little bit difference to that for the AND gate. Here the difference is that the polarizers ‘P_1’ and ‘P_2’ pass only the ‘↑’ polarized light beam and polarizers ‘P_3’ and ‘P_4’ can pass only light having ‘•’ polarization. The operation is similar to that of the scheme in ‘fig.-5.1’.

Now the operation of the scheme of ‘fig.-5.2’ is described.

(i) When the inputs A=B=0, polarizers ‘P_1’ and ‘P_2’ don’t pass any light (••) coming from inputs. So no light signal is traced in the channels ‘E’, ‘F’ and ‘G’. Light beam from the CLS is refracted to the channel ‘H’. On the other hand ‘P_3’ and ‘P_4’ pass the light signals obtained from the inputs. So the intensity of the combined beam at the point ‘J’ is ‘I’. When this beam is passed through the NLM it is refracted to the channel ‘R’. This beam results a light signal of intensity ‘I’ at the final output ‘Y’ and it is polarized perpendicular to the plane of paper (•) (logic 0).
Table 5.2: Truth table for the two-input OR logic gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>(B)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>1 (↑)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>1 (↑)</td>
</tr>
</tbody>
</table>

Fig. 5.2: Polarization encoded 2-input OR logic gate.
(ii) When A=0, B=1, input light beam ‘A’ (●) cannot pass through ‘P₁’ but passes through the polarizer ‘P₄’. Again the input beam ‘B’ (↑) passes through ‘P₂’ but fails to cross ‘P₃’. Therefore the light beam at the point ‘J’ is of intensity ‘I/2’. It goes to the channel ‘S’ after refraction through the NLM. This results no light signal in the channel ‘R’. On the other hand the output beam from the polarizer ‘P₂’ is of intensity ‘I/2’ and polarized in the plane of paper (↑). It is now refracted to the channel ‘E’. This beam is combined with the light (of intensity ‘I/2’ and polarized in the plane of paper) from the constant light source (CLS). This combined beam is now refracted to the channel ‘G’. No light is detected in the channel ‘F’ and ‘H’. So at the point ‘Q₂’ only the light beam from the channel ‘G’ is available. This beam yields ‘↑’ polarized light at the output ‘Y’. Thus the output light beam ‘Y’ is (of intensity ‘I’ and) polarized in the plane of paper (↑) (logic 1).

(iii) For the third input condition, A=1, B=0, input light beam ‘A’ (↑) can pass through ‘P₁’ and ‘P₂’ but cannot passes through the polarizer ‘P₄’. Again the input beam ‘B’ (●) passes through ‘P₃’ but fails to cross ‘P₂’. So in this case a light beam (of intensity ‘I’ and) polarized in the plane of paper (↑) (logic 1) is obtained at the final output ‘Y’. This output comes for the light transmitted through ‘E’ and combined with CLS. This ultimately goes to ‘Q₁’ passing through ‘G’ where as no light comes from ‘R’ for joining at ‘Q₂’.

(iv) For the input condition A=B=1, no input light beam can pass through the polarizers ‘P₃’ and ‘P₄’. So one cannot receive any light in the channel ‘R’ and ‘S’. On the other hand the output of the polarizer ‘P₂’ is of intensity ‘I’ and polarized in the plane of paper (↑), due to the contribution of the two components from the inputs ‘A’ and ‘B’. This beam is now refracted to the channel ‘F’ and no signal is produced at the channel ‘E’. So a light beam from the CLS to refract along the channel ‘H’ contributing no light in the channel ‘G’. Therefore at the output ‘Y’, due to the beam from the channel ‘F’, one gets a light signal (of intensity ‘I’) polarized in the plane of paper (logic 1). Thus the truth table for the OR logic operation as given in ‘table – 5.2’ is supported.
5.3.3. Implementation of a 2-input universal NAND logic gate

The truth table for the NAND gate is shown in ‘table-5.3’ and the scheme is shown ‘figure - 5.3’. In the truth table one can see that the output ‘Y’ gets light of ‘↑’ polarization (logic 1) when any one or both the two inputs A and B gets light of ‘•’ polarization (low, logic 0) and the output gets light of ‘•’ polarization only when both the inputs gets light of ‘↑’ polarization (high state or logic 1). To implement a NAND logic gate the output of an AND gate (of ‘fig.-5.1’) is sent through a half-wave plate. The half-wave plate introduces a ‘π’ phase differences between the components of the light at the output ‘Y’. This plate changes the light signal of ‘•’ polarization (logic 0) to a light signal of ‘↑’ polarization (logic 1) and vice-versa. Thus for the first three input conditions, while the output of a AND gate was described by ‘•’ polarized light, then the output for the NAND gate here produces a ‘↑’ polarized light (logic 1 or high state) at the output. Similarly for the last input condition A=B=1, light having ‘•’ polarization (logic 0 or low state) is obtained at the output ‘Y’ (‘fig.-5.3’). This scheme supports the truth table of a NAND gate satisfactorily.

Table-5.3: Truth table for the two-input NAND logic gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>0 (•)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>1 (↑)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>1 (↑)</td>
</tr>
</tbody>
</table>
5.3.4. Implementation of 2-input Ex-OR logic gate

Proceeding in the same way an Ex-OR logic gate can also be developed. In the ‘table - 5.4’ the truth table for a two-input Ex-OR gate is shown and the proposed scheme is shown in ‘figure- 5.4’. The polarizers ‘P₁’ and ‘P₂’ allow only the ‘↑’ polarized light to pass through them and the polarizers ‘P₃’ and ‘P₄’ only pass the ‘•’ polarized light beam. The operation of the scheme is described as follows.

(i) For the first input condition A=B=0, polarizers ‘P₁’ and ‘P₂’ block the input light beam and ‘P₃’ and ‘P₄’ pass the respective light beams. So no light is obtained at ‘Q₁’. Now each of the two light beams coming through polarizers ‘P₃’ and ‘P₄’ are ‘•’ polarized and of intensity ‘I/2’. So at the point ‘Q₂’ they combine to give a light beam of intensity ‘I’. The combined beam is now refracted through the NLM along the channel ‘T’. Thus at the point ‘Q₂’ the light of ‘•’ polarization (and intensity ‘I’) is received. Therefore the output ‘Y’ gets the light signal of ‘•’ polarization (logic 0).
(ii) For the second input condition A=0, B=1; polarizers ‘P₁’ and ‘P₄’ block the light and polarizers ‘P₂’ and ‘P₃’ allow the light signal to pass. It results at O₁ the light of ‘\( \uparrow \)’ polarization (of intensity ‘I/2’). As a result this beam is refracted through the NLM along ‘S’ channel. Thus at ‘R’ no light is seen. At Q₁ a light of ‘\( \uparrow \)’ polarization is obtained because of the presence of light both at the channels ‘S’ and CLS. On the other hand at O₂ we get light of ‘\( \bullet \)’ polarization. As intensity of this beam is ‘I/2’, it is refracted along the channel U giving no light at Q₂. Therefore the output Y gives only a light of ‘\( \uparrow \)’ polarization.

(iii) For the third input condition, A=1, B=0, the polarizers P₁ and P₄ pass the light and P₂ and P₃ block the light signal. This case is nearly similar to that of the second condition. At O₁ we get light of ‘\( \uparrow \)’ polarization. Because of the presence of light both at the channels ‘S’ and CLS, this combined light signal is refracted through channel ‘V’ to ‘Q₁’. On the other hand, at O₂ we get a light of ‘\( \bullet \)’ polarization which goes to the channel ‘U’. Therefore at the output Y the light of ‘\( \uparrow \)’ polarization is obtained.

(iv) For the last condition A=B=1, P₁ and P₂ pass the light signal and P₃ and P₄ block the light signal. Therefore at O₂ and so in the channel T no light is obtained but the point O₁ gets light of ‘\( \uparrow \)’ polarization having intensity ‘I’ (for the combination of two beams). So the beam is refracted to the channel R giving no light at S. The light beam after traveling through the half-wave plate becomes ‘\( \bullet \)’ polarized. Therefore ultimately at the output Y we get light having ‘\( \bullet \)’ polarization for the application of ‘\( \uparrow \)’ polarization light at the inputs. Thus the truth table of Ex-OR operation is satisfied and the scheme acts as an Ex-OR logic gate.
Table 5.4: Truth table for the two-input Ex-OR logic gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0 (⊗)</td>
<td>0 (⊗)</td>
</tr>
<tr>
<td>0 (⊗)</td>
<td>1 (↕)</td>
</tr>
<tr>
<td>1 (↕)</td>
<td>0 (⊗)</td>
</tr>
<tr>
<td>1 (↕)</td>
<td>1 (↕)</td>
</tr>
</tbody>
</table>

Fig. 5.4: Polarization encoded optical 2-input Ex-OR logic gate.

~ 73 ~
5.4. Conclusion
As the basic and fundamental logic gates are implemented by the above mechanism, therefore the any other all-optical logic operations can also be implemented successfully with the same methodology. The all-optical switching speed with Kerr type of nonlinear materials is very fast. On the other hand the polarization of light is a property of the light signal which normally does not change during communication unless we do it. Again the powers in the two polarization states are equal. The above schemes use therefore the advantages of both the nonlinear optical material based systems and polarization encoded system. If the inputs are drawn from a suitable laser source and the other optical components are suitably used the schemes can be implemented to execute any desired logical result. These schemes can be directly used in developing optical arithmetic and algebraic units. Again combinational and sequential logic systems can be developed using the schemes discussed in this chapter.
An All-Optical Method of Developing an S-R Flip-Flop for Storing a Set of Digital Inputs

Abstract

Optical storage device is an essential part to implement an all-optical computing system. S-R flip-flop is a primary circuit of different digital storage device. Here in this chapter an all-optical method for developing a polarization encoded S-R flip-flop is proposed. For this purpose a special optical scheme is also used. This scheme can be used to maintain a prefixed intensity level against the polarization encoded optical bits. For developing the all-optical S-R flip-flop the switching character of optical isotropic nonlinear material and the special optical scheme are jointly utilized.

Publication related to this chapter -


6.1. Introduction

Many logic gates and data processors are already reported where different optical methods of encoding and decoding are used [5, 51, 128, 219, 233, 240, 244, 258, 266, 305]. Among all the encoding techniques intensity based encoding is used most extensively. Here Boolean states (1, 0) are represented by different intensity levels of the light signal. To implement the optical logic units and logic based systems based on intensity based encoding mechanism, optical nonlinear materials and photorefractive materials can be used successfully. Electro-optic materials, Mach-Zehnder interferometer, semiconductor optical amplifier can also be used for this purpose.

There lies also many works which use polarization or frequency of a light signal for encoding or decoding purpose of bits. Polarization encoding technique is found advantageous than intensity encoding as the state of polarization of a light signal cannot change of its own unless it is compelled to do so. Therefore during the propagation of light signal through a long distance the information can remain intact in case of polarization encoding. Since the last few decades lots of contributions using polarization encoding is reported [18, 19, 22, 75, 119, 201, 306].

In ‘chapter - 5’ different all-optical logic gates based on polarization encoding technique are discussed. Again a method to maintain a fixed intensity level of light signal against a logical bit required for a digital optical processor of nonlinear material based switches has been described in ‘chapter-4’. This is very important for a system which works depending on the intensity of light signal. As the optical nonlinear material (NLM), used for switching, is isotropic one and the light beam passing through it is not split into ordinary and extra-ordinary components, so the NLM will not ordinarily change the state polarization of the light beam during the propagation though it, what the half-wave plate does.

Based on the two systems an optical S-R flip-flop with polarization encoded light signal is described here. In this scheme also it is assumed that the light beam polarized along perpendicular to the plane of paper (•) represents ‘logic 0’ state and light beam polarized in the plane of paper (↑) represents the state of ‘logic 1’, i.e. ‘1’ and ‘0’ are encoded with two orthogonal polarized light beams. So a half-wave plate can act as an NOT gate. Flip-flops are basically bistable multivibrators. They can provide a strong role in implementation of optical computer. Flip-flop can be used to store optical data. At first a scheme to get a desired value of intensity for a
polarization encoded light bit is described. Then using the scheme the method of implementing polarization encoded the optical S-R flip-flop is discussed.

6.2. A scheme to get a specified intensity level for a polarization encoded light beam.

The scheme is shown in ‘figure - 6.1’. It can be used to increase or to maintain the same intensity level of a polarization encoded light signal. The operation of the scheme is now described. Let a light beam of intensity ‘I’ is given. The light beam may be polarized either in the plane of the paper (زواری) or perpendicular to the plane of paper (پریش). The signal beam is coming in the channel ‘A’. Now our first goal is to raise the intensity of this given signal to a specific value of intensity ‘2I’.

The light beam is splitted into two beams at the point ‘B’ by a 50:50 beam splitter. These two beams are now made incident on two polarizers ‘P₁’ and ‘P₂’. ‘P₁’ can pass only light beam polarized in the plane of paper (زواری) and only the light beam polarized perpendicular to the plane of paper (پریش) can pass through ‘P₂’. As the intensity of the light beam from channel ‘A’ is ‘I’ so each of the two beams coming from ‘B’ is assumed to have an intensity level ‘I/2’. ‘CLS-1’ and ‘CLS-2’ are two constant laser sources which emit light beam of predetermined intensity. ‘CLS-1’ emits light beam polarized in the plane of paper (زواری) and the light beam from ‘CLS-2’ is polarized perpendicular to the plane of paper (پریش).

Now, in the first case, if the light beam coming from ‘A’ is polarized in the plane of paper (زواری) then the polarizer ‘P₁’ allows the light beam to pass through it and ‘P₂’ blocks the light beam. Therefore light of intensity ‘I/2’ arrives at the point ‘C’. This beam is now combined with the light beam of intensity ‘3I/2’ (polarized as (زواری)) coming from a constant laser source (CLS-1) as shown in the figure. This combined light beam is incident at the point ‘O₁’ at the linear material (LM) and nonlinear material (NLM) boundary. As the intensity of the incident beam is ‘2I’ it is refracted to the channel ‘E’ having the less angle of refraction then that of ‘F’ channel [dedicated for transmission of light beam of intensity ‘3I/2’]. On the other hand no light passes through ‘P₂’ in this case. So at the point ‘D’, only the light from ‘CLS-2’ prevails. The light beam from the ‘CLS-2’ has intensity level ‘3I/2’ [and is polarized perpendicular to the plane of paper (پریش)]. Therefore the light beam, after incidence at the point ‘O₂’ at the second LM and NLM boundary, is refracted to the channel ‘H’.
Naturally no light is obtained at the channel ‘G’. Thus at the point ‘S’ only the light beam from the channel ‘E’ is received. This light beam will yield light of intensity ‘2I’ with ‘\( \frac{\pi}{4} \)’ polarization at the output ‘Y’.

In the second case, the light coming from ‘A’ is assumed to have intensity ‘I’ and polarized perpendicular to the plane of paper (\( \bullet \)). Similar to the first case, this light beam is splitted into two beams with each of intensity level ‘I/2’ at the point ‘B’. The first component cannot pass through the polarizer ‘P_1’ (as it can pass only ‘\( \frac{\pi}{4} \)’ polarized beam). So the light beam incident at ‘O_1’ is of intensity ‘3I/2’ (due to ‘CLS-1’ only) and refracted through the NLM to the channel ‘F’. Thus it contributes no light signal at the point ‘S’. On the other hand the second component of the light beam from the point ‘B’ passes through the polarizer ‘P_2’ and reaches at the point ‘D’. This beam is now combined with the light beam (of intensity ‘3I/2’ and ‘\( \bullet \)’ polarized)
coming from the ‘CLS-2’. Thus the combined light beam incident at the point ‘O₂’ has the intensity level ‘2I’ and refracted through the NLM to the channel ‘G’. This beam only arrives at the point ‘S’ now. Thus the output ‘Y’ gives a light beam of intensity ‘2I’ with † polarization.

Thus the scheme can provide a desired level of intensity of the input light beam. When there is no light signal in the input channel ‘A’ then no signal is available at the output ‘Y’.

6.3. Method of maintaining a prefixed intensity level of a polarization encoded light signal.

In the previous scheme one can keep the intensity level of the given signal at the same level as that of the input signal or can increase the intensity level. But the scheme cannot be used to decrease the intensity level of the optical signal to a specified value.

In the ‘section - 4.2’ and in ‘section - 4.3’ a scheme to obtain a prefixed intensity of light signal has already been illustrated. The scheme provides a prefixed intensity of light signal at its outlet irrespective of the intensity of the input signal. When there is no light in the input of the system then no light is obtained at the outlet of the scheme. This scheme is shown in ‘fig.-4.1’ and also in ‘figure - 6.2’. This scheme can also be extended to maintain a prefixed intensity level for a polarization encoded light signal. The extended scheme is shown in ‘figure - 6.3’. The internal architecture of the ‘block-1’ and ‘block-2’ shown in ‘fig.-6.3’ are similar to the scheme depicted in ‘fig.-4.1’. These blocks represent the aforesaid scheme. Only difference between the two blocks is that the constant light sources (CLS) used in ‘block-1’ give light signal polarized perpendicular to the plane of paper (●) whereas the CLS used in block-2 give light signal polarized in the plane of paper (†).

Now the given optical signal is coming from the channel ‘A’. As before this light signal may be either polarized perpendicular to the plane of paper (●) or polarized in the plane of paper (†). The output ‘Y’ of the scheme shown in ‘fig.-6.3’ should be of a prefixed intensity ‘I’ irrespective of the intensity of the given input beam but should have same polarization state as the input signal.
Fig. 6.2: Scheme to obtain a fixed intensity for a signal bit.

Fig. 6.3: Scheme to maintain the intensity level of a polarization encoded light signal.
Let a light signal (of any intensity) polarized perpendicular to the plane of paper (•) is given to the input ‘A’. Now this beam is splitted by beam splitter at the point ‘B’ into two beams. The polarizer ‘P₁’ can only pass light signal polarized perpendicular to the plane of paper (•) whereas the polarizer ‘P₂’ can pass only the light signal polarized in the plane of paper (†). So the component of the input beam from the point ‘B’ cannot pass through ‘P₂’. The other component passes through ‘P₁’ and enters the ‘block-1’. ‘Block-1’ provides, at its output, a light signal of a prefixed intensity ‘I’ and polarized perpendicular to the plane of paper (•). As no light enters to the ‘block-2’ therefore this block does not produce any light signal at the outlet of it. The operation of these blocks is similar to the scheme of ‘section-4.3’. So at the point ‘C’ only light from ‘block-1’ comes. Thus when input ‘A’ is a light polarized perpendicular to the plane of paper (•) the output ‘Y’ assumes to get a light signal having same polarization state having a prefixed intensity ‘I’.

Similarly when a light beam polarized in the plane of paper (†) is given to the input ‘A’ the beam cannot pass through ‘P₁’. It passes through ‘P₂’ and enters into ‘block-2’. Now the ‘block-1’ gives no light at the outlet of it. But ‘block-2’ produces a light signal of intensity ‘I’ and polarized in the plane of paper (†) at the point ‘C’ and also at the output ‘Y’.

Thus the scheme shown in ‘fig.-6.3’ gives, at the output ‘Y’, a light signal having a prefixed intensity ‘I’ and having the same polarization state as that of the input light beam. When there is no light in the input ‘A’ then no light comes out at the output ‘Y’.

Thus using the above scheme the intensity of a polarized encoded light beam can be maintained or raised at a desired level. The strength of the CLS guides whether the signal intensity level would be kept same or increased. So the intensity as well as the polarization of a light signal both can be maintained simultaneously by the proper application of the proposed method. This scheme will be very useful in logic processors where a prefixed intensity level of a signal with proper polarization is required for digital operation. This scheme can support the strengthening of the intensity level of a signal whatever its state of polarization is (‘†’ or ‘•’), i.e. keeping the state of input polarization conserved.

Here a scheme for optical S-R flip-flop by polarization encoded light signal is described. To implement this scheme optical isotropic nonlinear material and half-wave plate can be used jointly. The proposed scheme is shown in the ‘figure - 6.4’. ‘S’ and ‘R’ are the two inputs whereas ‘Q’ is the output of the S-R flip-flop and ‘\( \overline{Q} \)’ is the inverted output. ‘\( P_1 \)’, ‘\( P_2 \)’, ‘\( P_3 \)’ and ‘\( P_4 \)’ are the four half-wave plates. ‘Block-3’ and ‘block-4’ includes the same scheme as described in ‘fig.-6.3’. The scheme works as follows.

(i) At first if no light is given to the inputs ‘S’ and ‘R’, no light will be received at the outputs ‘Q’ and ‘\( \overline{Q} \)’.

(ii) When a light beam polarized along perpendicular to the plane of paper (\( \bullet \) (assumed as logic state 0) is given to the input ‘S’ and another light beam polarized in the plane of paper (\( \downarrow \) (logic state 1) is applied to the input ‘R’ the scheme will function as follows. The input light beam at ‘S’ after passing through the half-wave plate ‘\( P_1 \)’ will be polarized in the plane of paper (\( \downarrow \)) at the point ‘A’. This light beam after passing through the half-wave plate ‘\( P_2 \)’ will be again polarized along perpendicular to the plane of paper (\( \bullet \)). Therefore the output ‘Q’ will receive the light polarized along perpendicular to the plane of paper (\( \bullet \)). Similarly the light beam from the input ‘R’ (polarized in the plane of paper (\( \downarrow \))) after passing through two half-wave plates ‘\( P_3 \)’ and ‘\( P_4 \)’ will result a light beam polarized in the plane of paper (\( \downarrow \)) at ‘\( \overline{Q} \)’. Thus for the input condition S=0 and R=1 the outputs become Q=0 and \( \overline{Q} \)=1.

Now if the inputs are withdrawn (that means no light signal is given to the inputs) at that instant the intensities of the light beam entering the ‘block-3’ and ‘block-4’ will tend to be reduced. Now the blocks will maintain the intensity level of the signal as described in the scheme shown in ‘fig.6.3’. So the output of the ‘block-3’ will be a light beam of a prefixed intensity ‘I’ (and polarized along perpendicular to the plane of paper (\( \bullet \))) whereas the ‘block-4’ will produce at the output of it a light beam of a prefixed intensity ‘I’ (and polarized in the plane of paper (\( \downarrow \))). Now at the point ‘B’ only the light beam from the outlet of ‘block-4’ comes. No light comes from the point ‘A’ as there is no light signal in the input ‘S’. Thus the intensity of the light beam incident at the point ‘O_1’ on a linear material (LM) – nonlinear material (NLM)
boundary is only ‘I’. Therefore the light beam is refracted through the channel ‘D’. This light beam after passing through the half-wave plate ‘P₂’ produces a light beam polarized perpendicular to the plane of paper (⊥) at the output ‘Q’.

Similarly the light beam (of intensity ‘I’ and polarized as (⊥)) emerges from ‘block-3’ and incident at the point ‘O₂’ in another NL-NLM boundary surface. After refraction this beam propagates through the channel ‘K’ (as there is no light from ‘R’) as intensity of it is ‘I’ only. This beam passes through the half-wave plate ‘P₄’. It results a light beam polarized in the plane of paper (↑) at the output ‘Q’. Therefore even when the inputs are withdrawn the output continues to maintain at the last achieved states Q=0 and \( \overline{Q} = 1 \).

Fig. 6.4: Schematic diagram of a polarization encoded S-R flip-flop.
(iii) If now the input states are interchanged that means a light beam polarized in the plane of paper (\(\uparrow\) or logic 1) is given to the input ‘S’ and a light beam polarized perpendicular to the plane of paper (\(\downarrow\) or logic 0) is applied to the input ‘R’ the outputs will be altered accordingly. The light beam which is applied to ‘S’ will result in a light beam polarized perpendicular to the plane of paper (\(\downarrow\)) at the point ‘A’. So, now at the point ‘B’ two light beams; one from point ‘A’ and another from the ‘block-4’ are combined together. Therefore the intensity of the beam incident at the point ‘O₁’ increases and the beam is now refracted through the channel ‘C’, whereas no light is obtained through the channel ‘D’. So only the light beam (\(\ast\)) from the point ‘A’ arrives at the point ‘E’. This beam after passing through ‘P₂’ produces a light signal (\(\uparrow\)) at the point ‘F’ and at the final output ‘Q’. A similar process occurs for the input ‘R’. The input light beam (\(\ast\)), from the input ‘R’, produces a light beam (\(\uparrow\)) at the point ‘G’. A portion of this beam and the light beam coming from ‘block-3’ are combined at the point ‘H’. Due to this joint beam refractive index of the NLM increases and the combined light beam, which is incident at the point ‘O₂’, is refracted through the channel ‘J’. This results the absence of any light signal in the channel ‘K’. Thus the only light beam from the point ‘G’ arrives at the point ‘L’. This beam, after passing through ‘P₄’, again produces a light beam (\(\ast\)) at the point ‘M’ and at the output ‘\(\overline{Q}\)’. Thus for the input condition S=1 and R=0 the output becomes Q=1 and \(\overline{Q}=0\).

Similar to the condition described earlier if now the input light beams are withdrawn, no light will be obtained at point ‘A’ and ‘G’. The intensity of the light beams at the points ‘F’ and ‘M’ tend to be reduced at that moment when the inputs are just withdrawn. Immediately the ‘block-3’ and ‘block-4’ maintain the intensity levels of their inputs beams. The output of ‘block-3’ gives now a light beam polarized in the plane of paper (\(\uparrow\)) and of intensity ‘I’ and the ‘block-4’ produces a light beam (\(\ast\)) of intensity ‘I’. Then the light coming from ‘block-4’ is incident at the point ‘O₁’ and refracted through the channel ‘D’. This beam after passing through ‘P₂’ results in a light beam (\(\uparrow\)) (of intensity ‘I’) at the point ‘F’ and passes it to the output ‘Q’. Similarly the beam coming from ‘block-3’ is incident at ‘O₂’ and refracted through the channel ‘K’. This beam now produces a light beam (\(\ast\)) at ‘M’ and sends it to ‘\(\overline{Q}\)’. Thus the output takes Q=1 and \(\overline{Q}=0\) even after the withdrawal of the signal input S=1 and R=0 that is the flip-flop maintains the last state here also.
Table - 6.1: Truth table of the polarization encoded S-R flip-flop

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>( R )</td>
</tr>
<tr>
<td>● (0)</td>
<td>( \uparrow ) (1)</td>
</tr>
<tr>
<td>( \uparrow ) (1)</td>
<td>● (0)</td>
</tr>
<tr>
<td>● (0)</td>
<td>● (0)</td>
</tr>
<tr>
<td>( \uparrow ) (1)</td>
<td>( \uparrow ) (1)</td>
</tr>
<tr>
<td>No light</td>
<td>No light</td>
</tr>
</tbody>
</table>

(iv) Thus the scheme follows the function of a polarization encoded all-optical S-R flip-flop and its truth table given in ‘table - 6.1’. The input condition, when both the input receives same logic state \( S=R=1 \) and \( S=R=0 \), are forbidden.

6.5. Conclusion

The above scheme of S-R flip-flop is an all-optical one. So real time speed of operation can be achieved from the scheme. Again the system accommodates the polarization encoding techniques which has many advantageous sides over intensity encoding. Here each logic state caries same amount of light power (intensity) whether the logic state indicates ‘0’ or ‘1’. Therefore at the time of transmission of polarization encoded data the average power of a ‘byte’ remains constant and it does not change on the number of ‘zeroes’ and ‘ones’ in it. This polarization encoded flip-flop can act as a real time memory cell also. So the storage of optical data bits can be easily achieved by this unit. The mechanism can be extended to develop some other improved version of polarization encoded optical flip-flops. It is important to say that the nonlinear materials in the flip-flop can be replaced by semiconductor optical amplifier (SOA), if necessary. This replacement can implement the flip-flop at a very low power.
All-Optical Method for Developing Master-Slave J-K Flip-Flop with Polarization Encoded Light Signal

Abstract

Memory elements are the essential part of a digital optical system. These elements can store binary information. Flip-flops can also be treated as storage device of one bit of binary information. Depending on the working procedure flip-flops are of different types. Here in this chapter a method to develop an all-optical polarization encoded Master-Slave J-K flip-flop is discussed. To implement the flip-flop polarization based encoding technique with optical signal is used. Also the switching capacity of isotropic nonlinear material is utilized for the scheme.

Publication related to this chapter -

7.1. Introduction

Invention of electronic digital computer has made the computing process very much easier. But increasing demand for higher and higher speed of computation has compelled researchers to switch to optical domain. Optical signal has been being used since long ago for data processing and communication [168, 185, 192, 202, 218, 256, 263, 269, 281, 283, 292]. To achieve real time speed of operation scientific community are trying to develop all-optical logic and data processing system. Due to many inherent advantages, optics is found to be more suitable in data processing as well as in communication.

To achieve an optical computer development of an optical memory is essential. In a sequential circuit flip-flops are used as memory cells. Flip-flops can store a binary data until an input signal is applied to change the binary state. The basic flip-flop is an S-R flip-flop. In ‘chapter -6’ a method to implement an S-R flip-flop is described. There are also other types of flip-flops like J-K flip-flop, D flip-flop and T flip-flop etc. The differences among various flip-flops are in the number of inputs of the flip-flops and in the way how the input signal affects the output. Here in this chapter a process for developing a polarization encoded optical M-S J-K flip-flop is illustrated. Master-Slave J-K flip-flop is constructed by adding an R-S flip-flop to a J-K flip-flop. The J-K flip-flop circuit acts as ‘master’ and the other performs as ‘slave’. The J-K flip-flop is a modification over the S-R flip-flop described in the previous chapter. In J-K flip-flop the input ‘J’ is used to ‘set’ the flip-flop (similar to the input ‘S’ in S-R flip-flop) and input ‘K’ is used instead of ‘reset’.

Encoding and decoding of optical signal by its variation of the state of polarization is one convenient method. Here the light signal polarized along the perpendicular to the plane of paper (*) is considered as ‘logic 0’ (low) state whereas the light signal polarized in the plane of paper (†) is treated as the ‘logic 1’ (high) state. In ‘chapter-5’ different polarization encoded all-optical logic gates are depicted. Here a polarization encoded optical M-S J-K flip-flop is developed using the polarization encoded logic gates.

7.2. Polarization encoded all-optical M-S J-K flip-flop.

In ‘section-5.3.3’ a 2-input polarization encoded optical NAND gate is described. This logic gates have been implemented using proper use of the switching capacity of
the optical isotropic nonlinear material. For developing the Master-Slave (M-S) J-K flip-flop here a 3-input NAND logic gate is described first. As the earlier concept this NAND gate also uses polarization based encoding of data signal. Finally the above logic gates are used to develop an M-S J-K flip-flop.

7.2.1. Polarization encoded 3-input NAND logic gate

The scheme for 3-input NAND logic gate is shown in ‘figure - 7.1’ and the truth table is shown in ‘table - 7.1’. The scheme for 2-input NAND logic gate is extended to develop a 3-input NAND gate. ‘A’, ‘B’ and ‘C’ are the three inputs and ‘Y’ is the output. Inputs can be either a light signal perpendicular to the plane of paper (⊥) (logic 0) or a light beam polarized in the plane of paper (∥) (logic 1) where each with a prefixed intensity ‘I’. The polarizer ‘P1’, ‘P2’, ‘P3’ and ‘Ps’ can pass the light signal polarized perpendicular to the plane of paper (⊥). Again polarizers ‘P4’, ‘P6’ and ‘P7’ can pass the light polarized in the plane of paper (∥). Each of the inputs ‘A’, ‘B’ and ‘C’ are splitted into two beams of equal intensity (‘I/2’) by using 50:50 beam splitters. Between the two components from the input ‘A’ the first one is passed through the polarizer ‘P1’ and second through ‘P7’. Similarly the two components from input ‘B’ are passed through polarizer ‘P2’ and ‘P5’ respectively. One component from the input ‘C’ is passed through ‘P4’ and the other component is combined with the beam coming from the polarizer ‘P2’.

This combined been is now passed through the polarizer ‘P3’ and then is incident on a linear material (LM) –nonlinear material (NLM) boundary. When the intensity of the incident beam is ‘I/2’ or ‘I’ then the beam is refracted through the channel ‘F’ or ‘E’ respectively. At the point ‘Q5’ the beam ‘E’ is divided into two equal parts. One part goes to the channel ‘L’. The signal channels ‘F’, ‘L’ and the beam from ‘P1’ are combined together at the point ‘Q1’. This combined beam is now made incident at a LM-NLM boundary. When the intensity of this beam is ‘I’ or ‘I/2’ then the beam is refracted through the channel ‘H’ or ‘G’ respectively. The channel ‘G’ is then combined with the light beam coming from a constant laser source (CLS). The CLS emits a light beam polarized perpendicular to the plane of paper (⊥) and of intensity ‘I/2’. This combined beam is now incident on another LM-NLM boundary. This beam refracted to the channel ‘K’ when its intensity is ‘I’ and travels through
channel ‘J’ when its intensity is ‘1/2’. Channel ‘H’ and ‘K’ are combined at the point ‘Q_2’.

On the other hand the output channels of the polarizer ‘P_4’ and ‘P_5’ are combined at the point ‘Q_3’. This combined light beam is now made incident on another boundary of linear and nonlinear material. When the intensity of this combined beam is ‘1/2’ or ‘1’ it is refracted to the channel ‘S’ or ‘R’ respectively. If the light signal in the channel ‘S’ is polarized in the plane of paper (\(\perp\)) then only it can pass through the polarizer ‘P_6’ and reaches the point ‘Q_4’. At this point it is combined with the channel coming from the polarizer ‘P_7’. If the intensity of this combined beam becomes ‘1’ only then it is refracted to the channel ‘T’, otherwise it goes to the channel ‘U’ when its intensity remains ‘1/2’.

Fig. 7.1: A 3-input polarization encoded optical NAND logic gate.
The light from the channel ‘T’ and from the point ‘Q_4’ are combined at the point ‘Q_6’. Finally this beam passes through a half-wave plate and yields the final output ‘Y’.

Now the function of the scheme is described as follows. (i) When A=B=C=0 no light is obtained at ‘Q_4’ as well as in the channel ‘T’. Intensity of the light beam at the output of ‘P_3’ is ‘I’. So it goes to channel ‘E’ resulting no light in the channel ‘F’. Now the beam ‘E’ is splitted by a beam splitter and a portion (of intensity I/2) is taken in the channel ‘L’. Finally at the point ‘Q_1’ the intensity of light beam is ‘I’ because of the two beams coming from ‘L’ and ‘P_1’. So the combined beam is refracted through ‘H’. No light is obtained in the channel ‘G’ and ‘K’. The light from the CLS is refracted to ‘J’. So at the point ‘Q_6’ only light from the channel ‘H’ is obtained. It is now passed through the half-wave plate. Therefore at the output ‘Y’ a light beam of ‘↑’ polarization (and of intensity I) is obtained.

(ii) When A=0, B=0 and C=1, then light from ‘A’ passes through ‘P_1’ and cannot pass through ‘P_7’. The intensity of the light beam at the output of ‘P_3’ is ‘I/2’.

Table 7.1: Truth table of polarization encoded 3-input NAND gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0 (•)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>0 (•)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>1 (↑)</td>
</tr>
<tr>
<td>0 (•)</td>
<td>1 (↑)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>0 (•)</td>
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<tr>
<td>1 (↑)</td>
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<td>1 (↑)</td>
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<td>1 (↑)</td>
<td>1 (↑)</td>
</tr>
</tbody>
</table>

~ 90 ~
So it propagates through the channel ‘F’. No light is obtained in ‘E’. Similar to the previous case intensity of the light beam at ‘Q₁’ is ‘I’. So ‘•’ polarized light (of intensity I) is received at ‘Q₂’. On the other hand the desired light passes through ‘P₄’ and ‘P₅’. These beams are combined at ‘Q₃’. As these two beams are coherent the intensity of the combined beam becomes ‘I’. So it is refracted to ‘R’. As a result no light is obtained in ‘S’ and also in ‘T’. Therefore at ‘Q₆’ only light from ‘H’ is present. This results a light beam of ‘†’ polarization (and of I intensity) at the output ‘Y’.

(iii) When A=0, B=1 and C=0, similar to the previous case light from input ‘A’ passes through ‘P₁’ and cannot pass through ‘P₇’. Light from input ‘B’ cannot pass through either ‘P₂’ or ‘P₃’. The intensity of the light beam at the output of ‘P₃’ is ‘I/2’ as before. As a result this beam is refracted to the channel ‘F’. Similar to the previous case a light beam polarized along perpendicular to the plane of paper (‘•’) is received in the channel ‘H’. On the other hand no light signal can reach the point ‘Q₃’. So no light signal is received at the channel ‘T’. Thus only the light signal from the channel ‘H’ is available at the point ‘Q₆’. This beam now passes through the half-wave plate. Therefore at the output ‘Y’ light of ‘†’ polarization (logic 1) is received for the input condition A=0, B=1 and C=0.

(iv) When A=0, B=1 and C=1, only light from ‘A’ is present at the point ‘Q₁’. Intensity of this beam is ‘I/2’. So this beam is refracted through ‘G’ which results no light in the channel ‘H’. Now the light from the channel ‘G’ is combined with the light coming from CLS (emitting light of intensity I/2 and ‘•’ polarized). This generates a light beam (of intensity I) in the channel ‘K’. On the other hand at the point ‘Q₃’ only the light signal from the input ‘C’ is available. So this beam (of intensity I/2) is refracted through the nonlinear material to the channel ‘S’. This crosses ‘P₆’ and arrives at the point ‘Q₄’. As no light comes through ‘P₇’ the light beam from ‘S’ is now refracted to the channel ‘U’. So no light is obtained in the channel ‘T’. Thus at the point ‘Q₆’ only the light signal from the channel ‘K’ prevails. Therefore in this case also the output ‘Y’ gets logic 1 state (a light beam of ‘†’ is received at Y).

(v) For the input condition A=1, B=0 and C=0, light from ‘A’ passes through ‘P₇’. This light beam (of intensity I/2) is now refracted to ‘U’, as because the light beam from ‘B’ passes through ‘P₃’ but cannot pass through ‘P₆’. Again light signal from input ‘C’ cannot pass through ‘P₄’. Therefore no light is obtained in ‘T’.

~ 91 ~
Because of the joint effect of two beams coming from inputs ‘B’ and ‘C’ the intensity at the output of ‘P3’ is ‘I’. This beam goes to ‘E’. So at the point ‘Q1’ only light (of intensity I/2) from ‘L’ is available. Similar to the fourth case a light beam polarized along perpendicular to the plane of paper (\(\uparrow\downarrow\)) (and of ‘I’ intensity) is obtained in the channel ‘K’. This beam after passing through the half-wave plate generates a light beam polarized in the plane of paper (\(\uparrow\downarrow\)). Therefore for this input condition the output ‘Y’ also receives logic 1 state.

(vi) When A=1, B=0 and C=1 then, only light from input ‘B’ is received at the point ‘Q1’. As the intensity of this beam is ‘I/2’ it is refracted through the nonlinear material to the channel ‘G’. So, as depicted before, in the channel ‘K’ a light beam of ‘\(\uparrow\downarrow\)’ polarization (and of intensity I) is obtained. No light is received in the channel ‘H’. On the other hand ‘P7’, ‘P5’ and ‘P4’ pass the corresponding light beams. So at ‘Q3’ the combined light intensity becomes ‘I’. Therefore it is refracted through the channel ‘R’. As a result at ‘Q4’ only light (of intensity ‘I/2’) from ‘P7’ is available. This light beam is refracted to ‘U’. So no light can be traced in ‘T’. Thus in this case also at the output ‘Y’ a light beam polarized in the plane of paper (\(\uparrow\downarrow\)) (and of intensity ‘I’) is received (logic 1).

(vii) When the inputs are A=1, B=1 and C=0 then, at the point ‘Q4’ only light signal (of intensity ‘I/2’) from the output of ‘P7’ is available. This beam, after refraction through the isotropic nonlinear material, goes to the channel ‘U’. So no light is received in the channel ‘T’. On the other hand at ‘Q1’ the light intensity is I/2 because of the only light coming from input ‘C’ (that is from ‘F’). So as before, at the point ‘Q6’ only light from ‘K’ is present. Thus output ‘Y’ gets a light beam polarized in the plane of paper (\(\uparrow\downarrow\)) (and of intensity I). Therefore for the input condition A=1, B=1 and C=0 the output becomes Y=1.

(viii) For the last input condition A=1, B=1 and C=1, light beam from input ‘A’ passes through ‘P7’ but cannot pass through ‘P1’. Input beam from ‘B’ can pass neither through ‘P2’ nor through ‘P3’. Again light signal from input ‘C’ can pass through ‘P4’ but unable to pass through ‘P3’. Thus no light beam can arrive at the point ‘Q1’. So at the point ‘Q2’ no light signal is present. On the other hand at ‘Q3’ only light (of intensity I/2) from ‘P4’ is available. So this beam is refracted to the channel ‘S’ and passes through ‘P6’. This beam is now combined with the light signal coming through ‘P7’. Therefore at ‘Q4’ the intensity of the combined light beam becomes ‘I’. So this beam of ‘\(\uparrow\downarrow\)’ polarization is now refracted through the nonlinear
material to the channel ‘T’. As a result now only the light from ‘T’ is present at the point ‘Q0’. This beam is now passed through the half-wave plate. So finally at the output ‘Y’ one gets a light beam of intensity ‘I’ and polarized along perpendicular to the plane of paper (‘*’) (logic 0). So for this input condition one gets Y=0 when A=B=C=1. Thus the scheme serves as a 3-input polarization encoded NAND logic gate.

7.2.2. Developing the Master-Slave J-K flip-flop

Now the NOT and NAND logic gates discussed before can be used properly to implement the M-S J-K flip-flop. The scheme is shown in ‘figure - 7.2’ and the function (truth) table is shown in ‘table - 7.2’.

![Logic diagram of a polarization encoded optical M-S J-K flip-flop.](image-url)
Table 7.2: Function table of M-S J-K flip-flop

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>K</td>
</tr>
<tr>
<td>0 (*)</td>
<td>0 (*)</td>
</tr>
<tr>
<td>0 (*)</td>
<td>1 (↑)</td>
</tr>
<tr>
<td>1 (↓)</td>
<td>0 (*)</td>
</tr>
<tr>
<td>1 (↑)</td>
<td>1 (↓)</td>
</tr>
</tbody>
</table>

An M-S J-K flip-flop is constructed by adding a inverted clocked S-R flip-flop at the output of another ordinary J-K flip-flop. ‘J’ and ‘K’ are the inputs of the M-S J-K flip-flop and ‘Q_n’ and \overline{Q_n} are the outputs. CLK is the clock signal. The NAND gates shown in the blocks are same as the scheme shown in ‘fig-7.1’ and ‘fig-5.3’. The first part of the optical circuit (consisting of four 3-input NAND gates) acts as the ‘master’ part. And the last part serves as the ‘slave’. A half-wave plate functions as a NOT gate. The slave is provided an inverted clock. Thus when clock signal to the master part is high then it is low for the slave part and vice versa. Both of the ‘master’ and ‘slave’ flip-flops work only when the clock provided to them is high (‘↑’). Thus when CLK=1 the ‘master’ part is active and when CLK=0 then the ‘slave’ part is active. Preset (PR) and clear (CLR) terminals are used for setting the initial values of ‘Q_n’ and \overline{Q_n}.

If one makes the inputs J=0 and K=1, when the CLK becomes ‘1’ then the output of the master flip-flop ‘C’ gets ‘logic 0’ (and output ‘D’ goes to ‘logic 1’) state. At the moment the slave flip-flop is disabled as the clock for this part is low. When CLK becomes ‘0’ (low) then the master part is inactive and the ‘slave’ is active. Now the output of the master part is transmitted to the output of the slave part. So the output ‘Q_n’ gets the logic state ‘0’ and \overline{Q_n} (the inverted output) is ‘1’ for J=0, K=1. These outputs are feeded back to the input ‘J’ and ‘K’. But until CLK becomes high, the master part is isolated from the taking of ‘J’ and ‘K’ inputs.

Now the data inputs are made J=K=0 when Q_n=0 and \overline{Q_n}=1. Then as before when CLK=1 the output of the master part becomes C=0 and D=1. When CLK=0 this
information is carried to the output of the slave. So the final output becomes \( Q_n = 0 \) and \( \overline{Q}_n \) becomes ‘1’. Therefore the flip-flop maintains the last state for the input condition \( J=K=0 \). When \( Q_n=1 \) and \( \overline{Q}_n=0 \), the outputs remain same if \( J=K=0 \). This condition tells that the flip-flop acts also as memory cell, as it maintains the last state of values at the outputs when the inputs are made ‘0’.

Similarly for the other input conditions the flip flop works according to the function table. Now if the inputs are given as \( J=1 \) and \( K=0 \), ‘master’ flip-flop does not respond to the input till the clock becomes high. When \( CLK=1 \), the information at the input ‘J’ and ‘K’ are transmitted to the output of the ‘master’ part. This has no effect on the ‘slave’ part until \( CLK \) becomes ‘0’. When \( CLK=0 \) slave is active and the output of the ‘master’ is transferred to the output of the ‘slave’. Thus the outputs become \( Q_n=1 \) and \( \overline{Q}_n=0 \), for \( J=1 \) and \( K=0 \).

Now if the inputs are made as \( J=K=1 \), on arrival of the next clock \( CLK=1 \), the previous outputs states are transferred to the ‘master’ part. Thus output of the ‘master’ changes. When clock becomes \( CLK=0 \), this information is transferred to the ‘slave’. So outputs of the slave change to its inverted values. After the application of the next clock the outputs will be again changed from \( Q_n=1/0 \) and \( \overline{Q}_n=0/1 \) to \( Q_{n+1}=0/1 \) and \( \overline{Q}_{n+1}=1/0 \). Thus for the input condition \( J=K=1 \), the output will toggle after application of every clock signal. Thus the scheme acts as an M-S J-K flip-flop.

### 7.3. Conclusion

The method for implementing the M-S J-K flip-flop is all-optical one. Again due to polarization encoding technique both the logic bit gets same amount of optical power. The beam splitters and mirrors used in the schemes are not shown in the figures to avoid complexity. A dot (‘•’) on any line in the figures implies that there is a connection between the optical channels. All the inputs are to be either a light beam polarized perpendicular to the plane of paper (‘•’) for ‘logic 0’ state or a light beam polarized in the plane of paper (‘ RTP’ for ‘logic 1’ state. As the input signals serve both as the power supply and data inputs for the flip-flop, so the flip-flop stores the data bit till there are light signal at the inputs. If the input signals are withdrawn then the flip-flop fails to work.
All-Optical Technique of Conversion of Polarization Encoded Data Bit to an Intensity Encoded Data Bit and Vice Versa

Abstract

Among different techniques for encoding and decoding of data bit, intensity based encoding and polarization based encoding techniques are two important methods. So both the two methods have wide applications. Depending on the encoding methods the digital optical systems are named different. Their operation techniques are also different. Now if the situation demands that the output data signal of an optical data processor which works on intensity coding, is to be processed by an optical polarization encoded data processor then the later system cannot function properly. The reverse is also true. Here in this chapter two optical systems are described which transforms intensity encoded data bit to a polarization encoded data bit and vice-versa.

Publication related to this chapter -

8.1. Introduction
The use of optical signal in logic and data processing is not new in the present day’s technological context. Since the seventies of the last century lots of proposals have been reported using the light beam as the signal carrier instead of electronic signal [10, 154, 246, 286, 288, 290]. Different techniques have been incorporated for encoding and decoding of optical data signal. Among these various methods intensity based and polarization based coding mechanisms are two important techniques. In the intensity based coding technique one may assume the presence of a prefixed intensity (I) of light signal as the ‘logic 1’ (high) state and absence of light signal as ‘logic 0’ (low) state. On the other hand in the polarization based encoding technique one may assume a light beam polarized perpendicular to the plane of paper (•) as the ‘logic 0’ (low) state and its orthogonal light beam polarized in the plane of paper (تاح) as ‘logic 1’ (high) state. So there are many optical devices in which intensity based coding is used. At the same time there are also some devices which works on polarization based coding technique. Often it is necessary to cascade two types of devices. Then if the output of the intensity encoded data processor is applied into the input of a polarization encoded data processor then the later device cannot give proper result. The reverse condition is also true. In such situations the output data bit from the intensity encoded device is to be first converted to a polarization encoded data bit and then is to be applied to the input of the polarization encoded device. Similarly when the output of a polarization encoded data processor goes to the input of an intensity encoded data processor, it needs the conversion of the polarization encoded data bit to the corresponding intensity encoded data bit. Here in this chapter a scheme is described to obtain polarization encoded optical data bit from intensity encoded optical data bit. Similarly another method is illustrated to get an intensity encoded data bit from a polarization encoded data bit. To implement the schemes the switching capacity of isotropic nonlinear material [38, 127, 305] is utilized. The properties of this type of nonlinear materials are already described in ‘section-3.2.1’.

8.2. All-optical scheme for obtaining a polarization encoded data bit from intensity encoded data bit.
The scheme is shown in ‘figure - 8.1’. ‘A’ is the data input. The input signal is intensity encoded. So it can be done either by a light signal of a prefixed intensity ‘I’
(for logic 1) or absence of the light signal (for logic 0). The input signal beam is now combined with the light coming from a constant laser source (CLS-1) at the point ‘B’. CLS-1 emits light of a prefixed intensity ‘I’ and polarized perpendicular to the plane of paper (•). This combined light beam is now made incident on a linear material (LM) and nonlinear material (NLM) block. Only when there is no light in the input ‘A’ then this beam is refracted through the NLM such that it is received in the channel ‘C’. Otherwise the intensity of the combined beam is greater than the prefixed intensity level ‘I’ and is not refracted to the channel ‘C’. Again the light signal from the channel ‘C’ is combined at the point ‘E’ with the light coming from another CLS (CLS-2). CLS-2 also emits light of prefixed intensity ‘I’ and polarized perpendicular to the plane of paper (•). This combined beam (from ‘E’) is again made incident on a LM-NLM boundary. When the intensity of combined light beam is ‘I’ and ‘2I’ then it is refracted to the channel ‘F’ and ‘G’ respectively. The light beam from the channel ‘F’ is passed through a half wave plate. On the other hand the signal from the channel ‘G’ is splitted by 50:50 beam splitter and one part goes to the channel ‘H’. Now this light beam is combined with the signal from the half-wave plate at the point ‘J’. This combined light signal gives the final output at ‘Y’.

Now the operation of the scheme is depicted. When the input ‘A’ gets no light (for ‘logic 0’) then at the point ‘B’ only the light from ‘CLS-1’ prevails. This beam is made incident on a LM-NLM boundary. As the intensity of the beam is ‘I’ so it is refracted through the NLM to the channel ‘C’. Now at the point ‘E’ this beam is combined with the light beam (of intensity ‘I’ and ‘•’ polarized) coming from ‘CLS-2’. So the intensity of the combined beam is now ‘2I’. Therefore when this combined beam is made incident on the other LM-NLM block it is refracted through the NLM to the channel ‘G’. On the other hand no light is obtained in the channel ‘F’. The light beam from ‘G’ is splitted by the 50:50 beam splitter. So the intensity of the signal in the channel ‘H’ is ‘I’. This beam produces the output at ‘Y’. So as a result at the output ‘Y’ a light beam, polarized perpendicular to the plane of paper (•) (and of a prefixed intensity ‘I’), is received (logic 0). Thus from the intensity encoded ‘logic 0’ data bit applied in the input channel ‘A’ one gets a polarization encoded ‘logic 0’ data bit at the output ‘Y’.
When the input ‘A’ gets a light of prefixed intensity ‘I’ (for ‘logic 1’) then the intensity of the combined beam at the point ‘B’ becomes ‘2I’. So when this beam is passed through the NLM this is refracted to the channel ‘D’. As a result no light signal is propagated into the channel ‘C’. So at the point ‘E’ only the light (‘•’ polarized) from the ‘CLS-2’ is available. Intensity of this beam is ‘I’. As a result when this beam is passed through the NLM it is refracted to the channel ‘F’. Now there is no signal in the channel ‘G’. The beam from the channel ‘F’ is now passed through a half wave plate. Due to birefringence property the half wave plate introduces a phase change of ‘π’. After passing through the half wave plate the light beam becomes polarized in the plane of paper ( представляет собой). This gives the output ‘Y’. Thus for a data bit of ‘logic 1’ (intensity encoded) in the input, one gets a polarization encoded ‘logic 1’ signal bit at the output.

Fig. 8.1: Scheme to obtain polarization encoded optical data bit from intensity encoded data bit.
8.3. All-optical scheme to get an intensity encoded data bit from a polarization encoded data bit.

The scheme for obtaining an intensity encoded data bit from a polarization encoded data bit is shown in ‘figure - 8.2’. Here ‘A’ is the input which receives either a light beam polarized perpendicular to the plane of paper (\(\bullet\), logic 0) or a light beam polarized in the plane of paper (\(\uparrow\), logic 1). The input beam is passed through a polarizer ‘P<sub>1</sub>’. The polarizer is oriented in such a way that it can pass only the light beam perpendicular to the plane of paper (\(\bullet\)). The light beam which is passed by ‘P<sub>1</sub>’ is now combined at the point ‘B’ with the light beam (of a prefixed intensity ‘I’) coming from a constant laser source (CLS). Now the combined light beam is made incident on the boundary surface of linear (LM) and nonlinear material (NLM). When the intensity of the combined beam is ‘I’ only (that means when no light passes through ‘P<sub>1</sub>’) then the beam is refracted towards the channel ‘C’. Light beam from channel ‘C’ provides the output ‘Y’.

![Scheme to obtain intensity encoded optical data bit from polarization encoded data bit.](image)

When the input ‘A’ gets a light beam polarized perpendicular to the plane of paper (\(\bullet\)) (logic 0) then this input light beam is passed through ‘P<sub>1</sub>’. Now the light
beam is combined with the light from CLS. So the intensity of this combined beam is
greater than a prefixed intensity ‘I’. As a result the beam is not refracted to the
channel ‘C’. Therefore no light is obtained in the output ‘Y’, which signifies intensity
encoded ‘logic 0’ state.

On the other hand when the input ‘A’ receives a light beam polarized in the
plane of paper (↑) (logic 1) then this light beam is not passed through the polarizer
‘P1’. So at the point ‘B’ only the light beam of intensity ‘I’ from CLS is obtained.
That is why the beam is now refracted through the NLM to the channel ‘C’. Therefore
at the output ‘Y’ a light beam of intensity ‘I’ is received (logic 1). Thus one can get an
intensity encoded data bit from a polarization encoded data bit.

8.4. Optical system for conversion of an optical intensity encoded
data to polarization encoded data.
The optical scheme depicted in ‘fig.−8.1’ can be extended for conversion of an optical
intensity encoded (n-bit) data to polarization encoded data (as shown in ‘figure −
8.3’). ‘A1’, ‘A2’, ….. , ‘An−1’ and ‘An’ are the data inputs. The input signals are
intensity encoded. So these can be done either by a light signal of a prefixed intensity
‘I’ (for logic 1) or absence of the light signal (for logic 0). ‘Y1’, ‘Y2’, …. , ‘Yn−1’ and
‘Yn’ are the corresponding data outputs. The operation of the scheme is similar to that
depicted in ‘section − 8.2’. Every input signal beam is combined with the light coming
from a constant laser source (CLS). These CLSs emit light of a prefixed intensity ‘I’
and polarized perpendicular to the plane of paper (•). The combined light beams are
now made incident at different points on a linear material (LM) and nonlinear
material (NLM) block. The outputs are polarization encoded. The output becomes low
(•) or high (↑) according the status of the corresponding input.
Fig. 8.3: Scheme to obtain polarization encoded optical data from intensity encoded data.
8.5. Conclusion

The above method is all optical one. So real time operational speed can be achieved from the scheme. The mirrors and the entire beam splitters used in these schemes are not shown in the figures to avoid complexity in representation. This scheme may be useful where one optical system running with intensity encoding mechanism is connected to a polarization encoded optical system, and vice versa.
An All-Optical Approach for Developing a Single Optical Pulse Generator

Abstract

It is established that optics has lots of advantages over an electronic signal as information carrier. Optics has strong use in data processing. Lot of all-optical data processors has been proposed in last few decades. Again it is well-known that in many practical cases an optical pulse is very much useful to trigger an optical data processing circuit. In this chapter a method of generating a sub-nanosecond optical pulse is described for the use as triggering pulse. Electro-optic modulator and nonlinear material have been exploited here to generate the pulse.

Publication related to this chapter -

9.1. Introduction
Optics is found as a strong and potential candidate in information and data processing. Several all-optical data processors are already been proposed in last few decades [11, 15, 179, 194, 207, 222, 241, 272, 273, 275-277]. For implementation of such data processors, different techniques are used. Some of these used intensity based coding technique whereas polarization based coding of the optical signal is used in some systems. Optical nonlinear material is used in many systems for switching purpose. For such systems the intensity of the optical signal is kept in a prefixed value for proper operation [307]. To implement an all-optical processor, the massive use of isotropic optical nonlinear material and photo-refractive material based optical switches are seen in many communications. Here the presence of a prefixed intensity of light (‘I’) represents the ‘logic 1’ (high) state and the absence of light represents the ‘logic 0’ (low) state. There are also many other materials which are used in many communications using different techniques. In electronic and photonic data processing systems the role of single pulse is very much essential. This single pulse is generally required for triggering an electronic, opto-electronic or all-optical photonic circuit. For organizing a time controlled data processing operation in spatial domain one requires the single pulse very much to generate the starting signal. In this situation the power of a single pulse is so high, that it can activate easily a circuit with a power far above its threshold requirement. The on time duration of the pulse can be made lower to enhance the pulse power higher. This upliftment of pulse power can also be done by Q-switching or mode-locking mechanism of laser radiation. A method of developing an all-optical circuit for generating a high powered optical pulse is described in this chapter. To generate such a pulse the character of optical modulation of nonlinear material and also that of electro-optic material are exploited.

9.2. Use of electro-optic modulator for phase delay.
The electro-optic effect has a wide application in many optical and opto-electronic devices for modulation (amplitude, phase, and frequency) of light. In this effect an externally applied electric field alters the refractive indices of the crystal or alters the birefringence property of the crystal. Lithium niobate (LiNbO₃) and lithium tantalate (LiTaO₃) are two very commonly used important electro-optic materials. These are trigonal crystal of point group 3m. Lithium niobate is a negative uniaxial crystal (nₒ>
n_e) whereas lithium tantalate is a positive uniaxial crystal. When an external electric field $E_z$ is applied along the optic axis (chosen as the z-axis) of the lithium niobate or lithium tantalate crystal, the refractive indices for a light wave polarized along the crystallographic x, y and z directions are given by

$$n_x = n_o - \frac{1}{2} n_o^3 r_{13} E_z$$

$$n_y = n_o - \frac{1}{2} n_o^3 r_{13} E_z$$

$$n_z = n_e - \frac{1}{2} n_e^3 r_{33} E_z$$

.....9.1

where $r_{13}$ and $r_{33}$ are the electro-optic coefficients of the respective material [308]. When the external electric field is applied, the crystal becomes biaxial. So if it is assumed that the light beam is propagating along the y-direction and that of the incident light is linearly polarized at 45° to the z-direction in the x-z plane, then it can be considered to have two components of light, one along x and other along z axes. Therefore a phase difference will be introduced between the z and x components of the light at the outlet of the crystal. The function of an electro-optic material based system is shown in ‘figure - 9.1’.

![Fig. 9.1: Biasing of an electro-optic modulator.](image-url)
9.3. An integrated scheme to generate a single sub-nanosecond pulse.

A scheme for an optical single pulse generation is depicted here. The scheme (shown in ‘figure- 9.2’) is developed with the use of electro-optic material and nonlinear material. To implement such scheme a constant light source (CLS) of some prefixed intensity ‘2I₀’ is used. Coherent light beam coming from the CLS is passed successively through a polarizer P₃, ‘electro-optic modulator (EOM)-1’ and then through another polarizer P₄. The pass axes of the two polarizers P₃ and P₄ are mutually perpendicular to each other and oriented at an angle 45° to the x-axis on the ‘x-z’ plane. When a voltage equal to Vₚ is applied to the crystal (electro-optic modulator-1) it rotates the polarization of the light signal passing through it by 90°. As a result only when a voltage equal to ‘Vₚ’ is applied to the electro-optic modulator, the light from the CLS can reach the point ‘R’. This beam is now splitted into two rays (each of intensity ‘I₀’) by a beam splitter at the point ‘R’. These two rays are incident on the two different LiNbO₃ crystals through the two polarizers P₁ and P₂. The pass axes of the polarizers ‘P₁’ and ‘P₂’ are ‘z’ and ‘x’ axes respectively. Let the intensity of each of these two beams incident on the ‘EOM- 2’ and ‘EOM- 3’ is ‘I’ (I = I₀ cos² 45°). Here it is considered that the light beam propagates along y-direction and the external electric field is applied along z-direction. Due to the applied electric field these two components along x and z-axes which are in phase at the plane of incidence will suffer a phase difference at the outlet of the crystals. So the phase difference between the two beams after emerging from the crystals at the points A₁ and A₂ is different than that between the two beams entering the crystals. The light beam emerged at A₂, after passing through a ‘λ/2 plate’ (which rotates the plane of polarization of the incident beam by π/2), is combined with the light beam coming from A₁ at the point ‘S’. The combined light beam is made incident at the boundary surface of linear and nonlinear material (i.e. at ‘O’). This produces the Ex-OR logic output at ‘Y’ between the two beams coming from A₁ and A₂.
If the voltage \( V_\pi \) is not applied to the ‘electro-optic modulator-1’, then no light is received at the output ‘Y’ i.e. the output Y is at ‘logic 0’ (low) state. Now the two predetermined voltages \( V_1 \) and \( V_2 \) are applied across the two crystals (electro-optic modulator-2 and electro-optic modulator-3 respectively) along their optic axes (z-axis) and a voltage \( V_\pi \) across the ‘electro-optic modulator-1’. Then the light beam from the CLS arrives at the point ‘R’. The beam is polarized along the pass axis (that is along a direction 45° to the x-axis) of the polarizer \( P_4 \). The light beam is now splitted into two components as depicted earlier. As the refractive indices are different for two light beams vibrating along x and z directions, the times required to travel the length ‘\( l \)’ of the crystals are different for the two beams. Thus one of the two beams reaches the point ‘S’ before another. So a light beam is received at the output ‘Y’ for the ray which comes first at ‘S’ due to its higher velocity, i.e. the output is at ‘logic 1’ (high) state. After a very small interval of time \( \Delta t \), the other component of the light beam reaches at the point ‘S’. So the light beam incident at the point ‘O’ is now

![Diagram of optical pulse generation](image-url)
refracted through the channel ‘T’ as its intensity is nearly double because of the joint effect of the two beams. Therefore no light is obtained through the output channel ‘Y’ after the arrival of the second (slower) beam at ‘S’. This makes the output ‘Y’ low (logic 0) level when both the beam comes at ‘S’. Thus a single light pulse of width $|\Delta t|$ can be found at the output ‘Y’ when the voltage $V_{\pi}$ is applied to the ‘electro-optic modulator-1’. This time $\Delta t$ can be calculated as

$$\Delta t = \frac{l}{c} (n_x - n_z)$$

$$= \frac{l}{c} \left[ (n_o - n_e) - \frac{1}{2d} (n_o^3 r_{13} V_1 - n_e^3 r_{33} V_2) \right] \quad \ldots 9.2$$

where ‘c’ is the speed of light in vacuum and ‘d’ is the width of the crystals along z-axis.

Here it is seen that the time $\Delta t$ depends on the voltages $V_1$ and $V_2$. If one keeps any one of $V_1$ and $V_2$ (let $V_1$) fixed and vary the other (let it is $V_2$), or varies both the $V_1$ and $V_2$ then one can change $\Delta t$ as desired. For LiNbO$_3$, $n_o=2.297$, $n_e=2.208$, $r_{13}=8.6$, $r_{33}=30.8$. If someone assumes $l=1$ cm, $d=1$ cm and $V_1=76.1$ V and $V_2=23.9$ V then $|\Delta t|=12.75 \times 10^{-9}$ s.

9.4. Conclusion

The above scheme may extend many important applications in the area of data processing. This method may be applied to the cases, where only a single pulse is required for triggering or starting the operation of a circuit or system. As and when a voltage $V_{\pi}$ is applied to the ‘electro-optic modulator-1’ a single optical pulse is obtained through the output channel ‘Y’. In the above scheme we may get the dimension of the pulse as required, and it can be done very easily by changing only the input level voltages applied to the ‘EOM-2’ or ‘EOM-3’. The pulse duration can be made narrower according to the requirement. In the above scheme all the conventional losses have been ignored. The time lag suffered by the light beam during passing through the $\lambda/2$ plate is not also considered. This time lag is adjusted by the path difference in the two wings of the system. The scheme can be implemented successfully by the joint application of electro-optic modulator and non-linear material with a suitable laser.
A New Scheme of Developing an All-Optical Astable Multivibrator

Abstract

In any computation the need of an oscillator is very much essential. The astable multivibrator is often used for oscillatory signal generation. In this chapter a method to develop an all-optical astable multivibrator is illustrated. The scheme generates oscillation with the joint use of electro-optic modulator and optical nonlinear material.

Publication related to this chapter -

10.1. Introduction

Due to several advantages optical systems have become popular over the electronic systems. Different optical logic, arithmetic and algebraic processors using different techniques are already proposed during last few decades [12, 16, 183, 203, 204, 213, 214, 220, 243, 248]. Due to inherent parallelism very high speed operation can be achieved with the optical system. The systems are either all-optical or electro-optic. Optical nonlinear material and electro-optic material can be used in this context [32, 63, 80, 278]. In the previous chapter the electro-optic effect was utilized to get a single optical pulse. In electronics and as well as in optical data-processing system the role of astable multivibrator is very much important. Here a new concept to implement an optical astable multivibrator is described. The scheme is constructed using electooptic material and optical nonlinear material. Optical isotropic nonlinear materials can be successfully used for switching operation. This is already described in the ‘section-3.2’. These nonlinear materials can also be used for implementing different logic operations.

A half-wave plate or a λ/2 plate is usually made of thin sheets of split mica or of quartz crystal cut parallel to its optic axis. This plate introduces a phase difference of π between the two components of the light beam for a certain wavelength of the light. Thus the half-wave plate alters the direction of vibration of plane-polarized light by an angle 2θ, where θ is the angle between the incident vibrations and the principal section. Therefore when a light, linearly polarized perpendicular to the plane of paper, passes through a half-wave plate, it becomes polarized in the plane of paper and vice-versa at the outlet.

10.2. Phase modulation by electro-optic modulator.

The electro-optic effect has been described in ‘section-9.2’. In this effect an externally applied electric field alters the refractive indices of the crystal or alters the birefringence property of the crystal for the wave passing through it [308]. When an external electric field is applied, the crystal becomes biaxial. So if we assume that the light beam is propagating along the y-direction and that of the incident light is linearly polarized at 45° to the z-direction in the x-z plane, then it can be considered to have two components along x and z axes. Therefore a phase difference will be introduced
between the $z$ and $x$ components of the light at the output of the crystal. The biasing of an electro-optics modulator is shown in ‘figure - 10.1’.

![Fig. 10.1: Biasing of an electro-optics modulator.](image)

The phase difference between the two components at a distance $L$ from the input plane will be

$$
\Delta \Phi = \frac{2\pi}{\lambda_0} (n_z - n_x)L
$$

$$
= \frac{2\pi}{\lambda_0} [(n_e - n_o) - \frac{1}{2d} (n_o^2 r_{33} - n_o^2 r_{13})V] L
$$

Where $V=E_xd$ is the applied voltage. Therefore a phase modulated light beam will be obtained at the output of the crystal. The half-wave voltage (the voltage required to introduce a phase difference of ‘$\pi$’ between the two components) of this modulator is lower than that of KDP crystal and it depends on the ratio $(d/L)$. If the field of the input light beam is expressed as $A_x = A_{x0} \cos \omega t$ then the wave emerging from the crystal will be given by

$$
A_x(y = L) = A_{x0} \cos \left( \omega t - \frac{2\pi}{\lambda_0} n_x L \right)
$$
\[ A_x = A_{x0} \cos \left( \omega t - k_0 n_0 L + \frac{1}{2} n_0^3 r_{13} k_0 L \frac{V}{a} \right) \]

Where \((2\pi/\lambda_0) = k_0 = (\omega/c)\). Now if an alternating potential \(V = V_0 \sin \omega_m t\) is applied across the electro-optic modulator then the above equation becomes

\[ A_x = A_{x0} \cos(\omega t - k_0 n_0 L + \zeta \sin \omega t) \]

Here \(\zeta = (\omega L/2cd)n_0^3 r_{13} V_0\) is the phase modulation index. Thus a sinusoidal applied electric field results a sinusoidal phase variation at the output. If we use the following identities,

\[
\cos(\zeta \sin \omega_m t) = J_0(\zeta) + 2J_2(\zeta) \cos 2\omega_m t + 2J_4(\zeta) \cos 4\omega_m t + \ldots
\]

\[
\sin(\zeta \sin \omega_m t) = 2J_1(\zeta) \sin \omega_m t + 2J_3(\zeta) \sin 3\omega_m t + \ldots
\]

then we have,

\[
A_x(y) = A_{x0}[J_0(\zeta) \cos(\omega t - k_0 n_0 L) - J_1(\zeta) \cos((\omega - \omega_m) t - k_0 n_0 L)]
\]

\[
+J_1(\zeta) \cos((\omega + \omega_m) t - k_0 n_0 L) + J_2(\zeta) \cos((\omega + 2\omega_m) t - k_0 n_0 L) + \ldots
\]

From the above equation we can see that at the output of electro-optic modulator we can recover several optical frequencies like \(\omega, \omega \pm \omega_m, \omega \pm 2\omega_m\) etc.

### 10.3. Scheme for development of an all-optical astable multivibrator.

To implement the scheme for an astable multivibrator the electro-optic material and nonlinear material are jointly used. The scheme is shown in ‘figure- 10.2’. A constant light source (CLS) of a prefixed intensity ‘2I’ is used. Now at the point ‘C’ the coherent light beam coming from the CLS is combined with the light beam coming from the channel ‘T’, which is a second output channel. Now the combined beam is made incident at the LM and NLM boundary at the point ‘O1’. This beam is now refracted to the channel ‘D’ if its intensity is ‘2I’ or to the channel ‘E’ if its intensity is ‘4I’. The light beam taken from ‘D’ is now splitted into two rays of intensity ‘I’ each. These two rays are passed through two polarizers P1 and P2 and then incident on two different LiNbO3 crystals. The pass axes of the polarizers ‘P1’ and ‘P2’ are z and x axes (mutually perpendicular) respectively. Here it is assumed that the beam is propagated to the ‘y’ direction through the electro-optic modulator and the external electric field is applied along the ‘z’ direction by applying two proper voltages \(V_1\) and \(V_2\) respectively. The two light beams whose vibrations are along ‘z’ and ‘x’
directions, are in phase, when they are incident at the electro-optic modulator input. When the field is given the electro-optic materials become biaxial. So the two light beams suffer a phase difference at the outlet of the crystals. Thus the phase difference between the two beams after emerging from the crystals at the points ‘A₁’ and ‘A₂’ is different from that between the two beams while entering the crystals. The light beam emerged at A₂, after passing through the half-wave plate (which changes the ‘x’ polarized light to ‘z’ polarized light beam) is combined at the point ‘S’ with the light beam coming from ‘A₁’. The combined light beam is now made incident at the boundary surface of another LM and NLM (at ‘O₂’) block. This produces at the output ‘Y’ an Ex-OR logic output between its two incoming beams from ‘A₁’ and ‘A₂’. When both the beams from ‘A₁’ and ‘A₂’ are present, the refracted beam through the NLM goes to the channel ‘T’ causing no light at ‘Y’. The light beam from ‘T’ is passed through a medium of high refractive index and suffers multiple reflections there by two parallel mirrors. Therefore a delay (let t₂) is introduced to the beam. Finally the beam is combined with the light beam coming from the CLS at the point ‘C’.

Now the operation of the astable vibrator is described. When the CLS is made off, no light is received at the output ‘Y’ and also at ‘T’. Therefore the output is at ‘logic 0’ (low) state. Now the two predetermined voltages V₁ and V₂ are applied across the two crystals. Then the CLS is switched on. As at the beginning no light is coming from ‘T’, thus the intensity of the light beam incident at ‘O₁’ is only ‘2I’. As a result, it is refracted to the channel ‘D’. This beam is splitted into two rays as depicted earlier. As the electro-optic materials offer different refractive indices for the two light beams polarized along ‘z’ and ‘x’ directions, the time required to travel the length ‘L’ of the crystals is different for the two beams. Thus one of the two beams reaches at the point ‘S’ earlier than another. This causes a light at the output ‘Y’ for a very small time. Thus the output ‘Y’ goes to ‘logic 1’ (high) state for the faster moving ray. In this condition the channel ‘T’ gets no light for that time. After a time Δt, the other component of the light beam also arrives at the point ‘S’. Now the light beam (of intensity ‘2I’) is incident at O₂ and therefore it is refracted through the channel ‘T’. So the output Y goes to ‘logic 0’ state after the time Δt. The light beam coming from ‘T’ arrives at ‘C’ after a delay time t₂. Then the light incident at ‘O₂’ is refracted to the channel ‘E’ (due to increase of the intensity of the light beam at ‘C’) causing no light at ‘D’. This will ultimately result no light at ‘Y’ and ‘T’ both.
Therefore no light will go from ‘T’ to the point ‘C’ in this time. This will reduce the intensity of the light beam incident at ‘O₁’ to ‘2I’ (due to CLS only). So the light beam is now again refracted through ‘D’. This makes the output Y high (logic 1) again similar to the situation when the CLS was made on at the beginning.

Fig. 10.2: Scheme for an all-optical astable multivibrator.
The above process is cumulative in nature. Thus an optical rectangular pulse train is obtained at the output ‘Y’. The on-time of the wave is $\Delta t$ and off time is $2t_2$. The time $\Delta t$ can be calculated as

$$\Delta t = \frac{L}{c} (n_r - n_i)$$

$$= \frac{L}{c} \left[ (n_o - n_r) - \frac{1}{2d} (n_o r_{13} V_2 - n_c r_{33} V_1) \right]$$

......(10.1)

Here ‘$c$’ is the speed of light in vacuum and ‘$d$’ is the width of the crystals along z-axis.

The above equation shows that the time $\Delta t$ depends on the voltages $V_1$ and $V_2$. So if any one of $V_1$ and $V_2$ is kept fixed and the other is varied, or both is changed then $\Delta t$ can be changed as desired. For LiNbO$_3$, $n_o=2.297$, $n_c=2.208$, $r_{13}=8.6$, $r_{33}=30.8$.

If we assume $L=9.5$ mm, $d=0.25$ mm and $V_1= V_2=40$ V then we get $\Delta t = 5.76 \times 10^{-4}$ s

. Again if we fix $V_1=10$ V and $V_2=30$ V then $\Delta t = 11.95 \mu$s . The off time can also be varied if needed.

10.4. Conclusion

In the above scheme all the conventional losses are ignored. The time lag suffered by the light beam during passing through half-wave plate is not also considered and it is adjusted in the path and the two wings. The scheme exploits the joint advantages of electro-optic modulator and nonlinear material. If suitable material and Laser beams are available the scheme can be implemented successfully and the system can be used nicely for pulse generation in different all-optical devices. The pulse duration can also be controlled. It is also important to mention that the pulsating nature of optical output can be received at ‘T’ and ‘E’ channels also. This method can provide pulsating output in Mega-Watt range.
An All-Optical Polarization Encoded Multiplexer Using Optical Nonlinear Material Based Switches

Abstract

Optics has been used since last few decades in data and logic processing. The inherent parallelism and many other advantages have made optics a strong candidate as information carrying signal in computing. Till now lot of research proposals are reported which use optical signal for implementation of several optical logic devices. Again encoding and decoding of data bits on the basis of different states of polarization of optical signal is a highly advantageous and a popular method over intensity based encoding. In this chapter a new technique to realize a polarization encoded optical multiplexer is illustrated. This multiplexer is based on different polarization encoded optical logic devices which are already described earlier. Optical isotropic nonlinear material based switches take the key role for implementing this multiplexer.

Publication related to this chapter -

11.1. Introduction

The concept of computation with optics instead of electronics as information carrying signal is not new. The inherent parallelism and many other advantages of optical signal can be exploited to achieve the goal of building the architecture of an optical superfast computer and data processor.

Logic gates are the building blocks of any data processing circuit. To develop an optical computing system optical logic gates are primarily essential. Already many optical encoding and decoding techniques have been proposed [271, 306, 310]. In this context, optical isotropic nonlinear materials, optical bistable materials, SLMs, semiconductor optical amplifiers etc. are successfully used for the required switching actions. All optical logic systems like AND, OR, NOT, NAND, Ex-OR etc. are developed following Boolean methodology. Several approaches are seen also where tri-state and quaternary state logic operations are physically implemented with optical data. Many non-Boolean logic systems with wider advantages have been developed with optics.

Optical arithmetic and algebraic processors can also be very easily developed once the all optical logic gates are implemented. Since the last few decades many optical arithmetic, algebraic, image and data processors have been developed and reported. Some of them followed the techniques of conventional arithmetic operations in Boolean mechanism, whereas some alternative approaches are developed to implement arithmetic and algebraic operations, i.e. optical symbolic substitution technique, space variant technique and residue technique etc. which extend many new advantages in data processing. In all those drives optics successfully replaced electronics as signal carrier to do the arithmetic and algebraic operations.

In any communication and computation mechanism multiplexer and demultiplexer are the essential part for proper channel selection. Hence optical computer needs an optical parallel multiplexer and demultiplexer. In this chapter an all-optical method for developing a polarization encoded multiplexer is described.
11.2. Polarization encoded logic gate with the use of optical nonlinear material based switch.

The technique for using an optical isotropic nonlinear material as a switch is already described in the previous chapters. Among different techniques for encoding and decoding of optical signal, polarization based encoding and decoding is an important and popular one. Encoding and decoding of light signal based on polarization of light signal may be a very convenient technique. Here if the light signal polarized along perpendicular to the plane of paper (⊔) is considered as ‘logic 0’ state then the light beam polarized in the plane of paper (_CNTL) is treated as the state of ‘logic 1’. Different all-optical polarization encoded logic gates are also implemented with the help of optical nonlinear material based switching. In the ‘section- 5.3.1’ and ‘section- 5.3.2’ a polarization encoded 2-input AND logic gate and a polarization encoded 2-input OR logic gate respectively have been depicted. Here a polarization encoded 3-input AND logic gate is illustrated.

11.2.1. Polarization encoded all-optical 3-input AND logic gate

The schematic diagram for the polarization encoded 3-input AND logic gate is shown in ‘figure - 11.1’ and the truth table is shown in ‘table - 11.1’. ‘A’, ‘B’ and ‘C’ are the three inputs and ‘Y’ is the output. Inputs can be either a light signal polarized along the perpendicular to the plane of paper (⊔) (logic 0) or a light beam polarized in the plane of paper (_CNTL) (logic 1) but each of a prefixed intensity ‘I’. The polarizer ‘P₁’, ‘P₂’, ‘P₃’ and ‘P₅’ can pass the light signal polarized perpendicular to the plane of paper (⊔). Again the polarizers ‘P₄’, ‘P₆’ and ‘P₇’ can pass the light signal polarized in the plane of paper (_CNTL). Each of the inputs ‘A’, ‘B’ and ‘C’ are splitted into two beams of equal intensity (‘I/2’) by three beam splitters. Between the two components from the input ‘A’ the first one is passed through the polarizer ‘P₁’ and second through ‘P₇’. Similarly the two component channels from input ‘B’ are passed through polarizer ‘P₂’ and ‘P₃’. One component from the input ‘C’ is passed through ‘P₄’ and the other component is combined with the channel coming from the polarizer ‘P₂’.

This combined channel is now passed through the polarizer ‘P₃’ and then is incident on a linear material (LM) – nonlinear material (NLM) boundary. When the intensity of the incident beam is ‘I/2’ or ‘I’ then the beam is refracted through the channel ‘F’ or ‘E’ respectively. At the point ‘Q₅’ the beam ‘E’ is divided into two
equal parts. One part goes to the channel ‘L’. The signal channels ‘F’, ‘L’ and the beam from ‘P_1’ are combined at the point ‘Q_1’. This combined beam is now made incident at a LM-NLM boundary. When the intensity of this beam is ‘I’ or ‘I/2’ then the beam is refracted through the channel ‘H’ or ‘G’ respectively. The channel ‘G’ is then combined with the light beam coming from a constant laser source (CLS). The CLS emits a light beam polarized perpendicular to the plane of paper (●) and of intensity ‘I/2’. This combined beam is now incident on another LM-NLM boundary. This beam is refracted to the channel ‘K’ only when its intensity is ‘I’ and travels through channel ‘J’ when its intensity is ‘I/2’. Channel ‘H’ and ‘K’ are combined at the point ‘Q_2’.

Fig. 11.1: A polarization encoded optical 3-input AND logic gate.
On the other hand the output channels of the polarizer ‘P₄’ and ‘P₅’ are combined at the point ‘Q₃’. This combined light channel is now made incident on another boundary of linear and nonlinear material. When the intensity of this combined beam is ‘I/2’ or ‘I’ it is refracted to the channel ‘S’ or ‘R’ respectively. If the light signal in the channel ‘S’ is polarized in the plane of paper (†) then only it can pass through the polarizer ‘P₆’ and reaches the point ‘Q₄’. At this point it is combined with the channel coming from the polarizer ‘P₇’. If the intensity of this combined beam becomes ‘I’ only then it is refracted through the NLM to the channel ‘T’, otherwise it goes to the channel ‘U’ when its intensity remains ‘I/2’.

The light from the channel ‘T’ and the point ‘Q₂’ are combined at the point ‘Q₆’. This combined beam yields the final output ‘Y’.

Now the function of the scheme is described as follows. (i) When A=B=C=0, no light signal is obtained at the point ‘Q₄’ as well as in the channel ‘T’. On the other hand the intensity of the light beam at the output of the polarizer ‘P₃’ is ‘I’ because of the two components from inputs ‘B’ and ‘C’. So this beam goes to channel ‘E’ after refraction through the NLM. It results no light in the channel ‘F’. Now the beam ‘E’ is splitted by a 50:50 beam splitter and a portion (of intensity I/2) is taken in the channel ‘L’. Finally at the point ‘Q₁’ the intensity of light beam is ‘I’ because of the two beams coming from ‘L’ and ‘P₁’. So the combined beam is refracted to the channel ‘H’. No light is obtained in the channel ‘G’ and ‘K’. The light from the CLS is refracted to ‘J’. So at the point ‘Q₆’ only light from the channel ‘H’ is obtained. Therefore at the output ‘Y’ a light beam polarized along the perpendicular to the plane of paper (•) (and of intensity ‘I’) is obtained.

(ii) When A=0, B=0 and C=1, then light from ‘A’ passes through ‘P₁’ and cannot pass through ‘P₇’. The intensity of the light beam at the output of ‘P₃’ is ‘I/2’. So it propagates through the channel ‘F’. No light is obtained in the channel ‘E’. Similar to the previous case intensity of the light beam at ‘Q₁’ is ‘I’. So ‘•’ polarized light (of intensity I) is received at ‘Q₂’. On the other hand the input light beams from ‘C’ and ‘B’ pass through ‘P₄’ and ‘P₅’ respectively. These beams are combined at the point ‘Q₃’. As these two beams are coherent the intensity of the combined beam becomes ‘I’. So it is refracted to the channel ‘R’. As a result no light is obtained in ‘S’ and also in ‘T’. Therefore at ‘Q₆’ only light from ‘H’ is present. This results a light beam polarized along the perpendicular to the plane of paper (•) (and of ‘I’ intensity) at the output ‘Y’.
Table 11.1: Truth table of a 3-input AND logic gate

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0(●)</td>
<td>0(●)</td>
</tr>
<tr>
<td>0(●)</td>
<td>0(●)</td>
</tr>
<tr>
<td>0(●)</td>
<td>1(‖)</td>
</tr>
<tr>
<td>0(●)</td>
<td>1(‖)</td>
</tr>
<tr>
<td>1(‖)</td>
<td>0(●)</td>
</tr>
<tr>
<td>1(‖)</td>
<td>0(●)</td>
</tr>
<tr>
<td>1(‖)</td>
<td>1(‖)</td>
</tr>
<tr>
<td>1(‖)</td>
<td>1(‖)</td>
</tr>
</tbody>
</table>

(iii) When A=0, B=1 and C=0, similar to the previous case light from input ‘A’ passes through ‘P₁’ and cannot pass through ‘P₇’. Light from input ‘B’ cannot pass through either ‘P₂’ or ‘P₅’. Input signal from ‘C’ cannot pass through polarizer ‘P₄’ but passes through ‘P₃’. The intensity of the light beam at the output of ‘P₃’ is ‘I/2’ as before. As a result this beam is refracted to the channel ‘F’. Similar to the previous case a light beam polarized along perpendicular to the plane of paper (‘●’) is received in the channel ‘H’. On the other hand no light signal can reach the point ‘Q₃’. So no light signal is received at the channel ‘T’. Thus only the light signal from the channel ‘H’ is available at the point ‘Q₆’. Therefore at the output ‘Y’ light beam polarized along the perpendicular to the plane of paper (‘●’) (logic 0) is received for the input condition A=0, B=1 and C=0.

(iv) When A=0, B=1 and C=1, only light from ‘A’ is present at the point ‘Q₁’. Intensity of this beam is ‘I/2’. So this beam is refracted through the NLM to the channel ‘G’. This results no light in the channel ‘H’. Now the light from the channel ‘G’ is combined with the light coming from CLS (emitting light of intensity I/2 and ‘●’ polarized). This generates a light beam (of intensity I) in the channel ‘K’. On the other hand at the point ‘Q₃’ only the light signal from the input ‘C’ is available. So this beam (of intensity I/2) is refracted through the nonlinear material to the channel
S. This beam crosses through the polarizer ‘P₆’ and arrives at the point ‘Q₄’. As no light comes through ‘P₇’ the light beam from ‘S’ is now refracted to the channel ‘U’. So no light is obtained in the channel ‘T’. Thus at the point ‘Q₅’ only the light signal from the channel ‘K’ prevails. Therefore in this case also the output ‘Y’ assumes ‘logic 0’ state (a light beam polarized along the perpendicular to the plane of paper (\(\star\))).

(v) For the input condition A=1, B=0 and C=0, light from ‘A’ passes through ‘P₇’. Again light signal from input ‘C’ cannot pass through ‘P₄’. The light beam from the input ‘B’ passes through polarizer ‘P₅’ and goes to the channel ‘S’. Now it cannot pass through ‘P₆’. So the at the point ‘Q₄’ only signal from ‘P₇’ is present. This light beam (of intensity I/2) is now refracted to ‘U’. Therefore no light is obtained in ‘T’.

(vi) When A=1, B=0 and C=1 then, only light from input ‘B’ is received at the point ‘Q₁’. As the intensity of this beam is ‘I/2’ it is refracted through the nonlinear material to the channel ‘G’. So, as depicted before, in the channel ‘K’ a light beam of ‘\(\star\)’ polarization (and of intensity I) is obtained. No light is received in the channel ‘H’. On the other hand polarizers ‘P₇’, ‘P₅’ and ‘P₄’ pass the corresponding light beams. So at the point ‘Q₃’ the combined light intensity becomes ‘I’. Therefore it is refracted through the channel ‘R’. As a result at ‘Q₄’ only light (of intensity ‘I/2’) from ‘P₇’ is available. This light beam is refracted to ‘U’. So no light signal can be traced in ‘T’. Thus in this case also at the output ‘Y’ a light beam polarized along perpendicular to the plane of paper (\(\star\)) (and of ‘I’ intensity) is obtained in the channel ‘K’. This beam produces the output ‘Y’.

(vii) When the inputs are A=1, B=1 and C=0 then, at the point ‘Q₄’ only light signal (of intensity ‘I/2’) from the output of ‘P₇’ is available. This beam, after refraction through the isotropic nonlinear material, goes to the channel ‘U’. So no light is received in the channel ‘T’. On the other hand at ‘Q₁’ the light intensity is I/2 because of the only light coming from input ‘C’ (that is from ‘F’). So as before, at the point ‘Q₅’ only light from ‘K’ is present. Thus output ‘Y’ gets a light beam polarized...
along the perpendicular to the plane of paper (\(\oplus\)) (and of intensity I). Therefore for the input condition \(A=1, B=1\) and \(C=0\) the output \(Y=0\).

(viii) For the last input condition \(A=1, B=1\) and \(C=1\), light beam from input ‘A’ passes through ‘\(P_7\)’ but cannot pass through ‘\(P_1\)’. Input beam from ‘B’ can pass neither through ‘\(P_2\)’ nor ‘\(P_5\)’. Again light signal from input ‘C’ can pass through ‘\(P_4\)’ but unable to pass through ‘\(P_3\)’. Thus no light beam can arrive at the point ‘\(Q_1\)’. So at the point ‘\(Q_2\)’ no light signal is present. On the other hand at ‘\(Q_3\)’ only light (of intensity I/2) from ‘\(P_4\)’ is available. So this beam is refracted to the channel ‘S’ and passes through ‘\(P_6\)’. This beam is now combined with the light signal coming through ‘\(P_7\)’. Therefore at ‘\(Q_4\)’ the intensity of the combined light beam becomes ‘I’. So this beam of ‘\(\downarrow\)’ polarization is now refracted through the nonlinear material to the channel ‘T’. As a result now only the light from ‘\(T\)’ is present at the point ‘\(Q_6\)’. So finally at the output ‘\(Y\)’ one gets a light beam of intensity ‘I’ and polarized in the plane of paper (\(\uparrow\)) (logic 1). Thus the scheme serves as a polarization encoded 3-input AND logic gate.

11.3. Polarization encoded optical multiplexer.

The all-optical polarization encoded logic gates can be now utilized to implement a polarization encoded optical multiplexer. A half-wave plate can act as a polarization encoded NOT as described earlier.

11.3.1. Polarization encoded 4×1 optical multiplexer

A schematic diagram of an optical multiplexer is shown in the ‘figure - 11.2(a)’ along with the block diagram of a 4×1 optical polarization encoded multiplexer in the ‘figure - 11.2(b)’. Here ‘A’ and ‘B’ are the control signal inputs. ‘\(X_1\)’, ‘\(X_2\)’, ‘\(X_3\)’ and ‘\(X_4\)’ are the data signal inputs. All input signals are polarization encoded. So the signal can be either polarized along the perpendicular to the plane of paper (\(\oplus\)) or polarized in the plane (\(\downarrow\)) of paper. The data signal inputs go to four different polarization encoded optical 3-input AND logic gates. The internal structure of these AND gates are similar to that shown in the ‘fig.-11.1’. The control input signal ‘A’ is connected directly to the inputs of ‘AND gate-3’ and ‘AND gate-4’ and is inverted before connecting to the inputs of ‘AND gate-1’ and ‘AND gate-2’. Similarly the control input signal ‘B’ is connected directly to the inputs of ‘AND gate-2’ and ‘AND
gate-4’ and is inverted before connecting to the inputs of ‘AND gate -1’ and ‘AND gate-3’. The outputs of the ‘AND gate-1’ and ‘AND gate-2’ go to the inputs of the ‘OR gate-1’. The outputs of the ‘AND gates 3’ and ‘AND logic gate- 4’ are connected to the inputs of the ‘OR logic gate-2’. The outputs of these two OR gates are connected to the inputs of a 3rd 2-input OR logic gate. The output of this OR gate gives the final output at the terminal ‘Y’ of the multiplexer.

Fig. 11.2(a): Scheme for polarization encoded optical 4×1 multiplexer.
(i) When $A=B=0$, $\overline{A} = \overline{B} = 1$. The output of the ‘AND gate-1’ (‘$Q_1$’) gives the data signal ‘$X_1$’. But for the other three AND gates, as any one or both the two control input is ‘0’, each output becomes ‘0’. Now for the ‘OR gate-1’ one input (‘$Q_1$’) is ‘$X_1$’ and other is logic 0 (‘0’). This causes the output of ‘$Q_1$’ to be ‘$X_1$’. In case of the ‘OR gate-2’ both the two inputs are at low state (‘0’). As a result the output of this gate is ‘logic 0’. So in the channel ‘$Q_3$’ the data ‘$X_1$’ is available whereas in the channel ‘$Q_6$’ ‘0’ is received. Therefore in the output ‘Y’ the data ‘$X_1$’ is retrieved.

(ii) When $A=0$ and $B=1$, both the two control inputs for the ‘AND gate-2’ are high (‘1’). So output of this AND gate ‘$Q_2$’ gives the data signal ‘$X_2$’. In this case the other three AND gates give the low (‘logic 0’) outputs. So the output of the ‘OR logic gate-1’ becomes data signal ‘$X_2$’. In this case also the output of the ‘OR logic gate-2’ will be ‘logic 0’ signal. Thus the output of the ‘OR logic gate- 3’ will produce data signal ‘$X_2$’ at the output ‘Y’.

(iii) When $A=1$ and $B=0$, only for the ‘AND gate-3’ both the two control inputs are high. As a result for this AND gate the output ‘$Q_3$’ gives the data signal
'X₃'. On the other hand the outputs of the three other AND gates become low (‘logic 0’) as before. Now the output of the ‘OR gate-1’ becomes ‘logic 0’ (light signal polarized along the perpendicular to the plane of paper). On the other hand the output of the ‘OR gate- 2’ is now the data bit ‘X₃’. Therefore in the output channel ‘Y’ one can get the data ‘X₃’.

(iv) When A=B=1, only for the ‘AND gate-4’ both the two control input is high (logic 1). So the output of the gate ‘Q₄’ gives the data signal ‘X₄’. On the other hand the outputs of the other three AND gates are low (‘logic 0’ state). Similar to the previous case now in the output ‘Y’ the data ‘X₄’ is retrieved.

Thus the scheme can function as an optical 4×1 multiplexer.

11.3.2. Polarization encoded 8×1 optical multiplexer

A polarization encoded optical 8×1 multiplexer can be implemented using the 4×1 multiplexer described earlier. The scheme for the 8×1 multiplexer is shown in the ‘figure - 11.3’. The two blocks, indicated as ‘MUX-1’ and ‘MUX-2’, include two 4×1 multiplexers. The internal architectures of these two blocks are same as described in ‘fig.-11.2(a)’. The outputs of ‘MUX-1’ and ‘MUX-2’ are ‘Y₁’ and ‘Y₂’ respectively.

For an 8×1 multiplexer there are three control inputs ‘A’, ‘B’ and ‘C’. ‘B’ and ‘C’ control inputs are directly connected to the control inputs of the two 4×1 multiplexers. One can get the inverted signal ‘Å’ by passing the control input signal ‘A’ through a half-wave plate (served as a NOT logic gate). AND logic operations is performed between each of the first four data input signals ‘X₁’, ‘X₂’, ‘X₃’ and ‘X₄’ and the inverted control input signal ‘Å’ by four 2-input AND logic gates. The four outputs from these four AND gates are connected to the four data inputs of the MUX-1. Similarly AND logic operation is executed between each of the data signals ‘X₅’, ‘X₆’, ‘X₇’ and ‘X₈’ and the control signal ‘A’ by four other polarization encoded optical 2-input AND logic gates. The outputs from these four AND gates are connected to the four data inputs of MUX-2. Now the outputs ‘Y₁’ and ‘Y₂’ are connected to the inputs of a polarization encoded 2-input OR logic gate. The output of this gate gives the final output ‘Y’ of the 8×1 multiplexer. An 8×1 multiplexer has 8 control input states (000, 001, 010, 011, 100, 101, 110 and 111). For the first four control input conditions of a 8×1 multiplexer (when A=0 (or Å=1)) the data inputs ‘X₁’, ‘X₂’, ‘X₃’ and ‘X₄’ are available at the outputs of the respective AND gates and
can reach the data inputs of the MUX-1. So MUX-1 now gives result at the output ‘Y₁’ according to the control inputs ‘B’ and ‘C’. At this time the remaining four data input signals ‘X₅’ through ‘X₈’ cannot reach to the outputs of the respective AND gates as one of two inputs for each AND gate is low (logic 0 state). So all of the data inputs for MUX-2 are low (logic 0). Therefore for the first four control input conditions the output of MUX-2 becomes low (logic 0). Similarly for last four control input conditions (100 through 111 when A=1) all of the data inputs for MUX-1 are low (logic 0) and the data inputs ‘X₅’ to ‘X₈’ can reach successfully the data inputs of ‘MUX-2’.

Fig. 11.3: Scheme for a polarization encoded optical 8×1 multiplexer.
(i) When A=0, B=0, C=0, the data inputs signals ‘X₁’, ‘X₂’, ‘X₃’ ‘X₄’ can reach the data inputs of MUX-1. Now MUX-1 acts similar to the scheme described in the ‘section- 11.3.1’. So for B=C=0 the output ‘Y₁’ produces the data signal ‘X₁’. On the other hand all the data inputs for MUX-2 are low (logic 0). Hence the output ‘Y₂’ of this 4×1 multiplexer is a light signal polarized along the perpendicular to the plane of paper (*) (logic 0). Therefore at the output ‘Y’ of the 8×1 multiplexer one can retrieve the data signal ‘X₁’ for the first control input condition A=B=C=0.

(ii) When A=0, B=0, C=1, the data inputs signals ‘X₁’, ‘X₂’, ‘X₃’ ‘X₄’ can reach to the data inputs of MUX-1 as before. For the condition B=0, C=1 the output ‘Y₁’ gives the data signal ‘X₂’. In this case also the output ‘Y₂’ is low. So the output ‘Y’ retrieves only the data ‘X₂’.

(iii) When A=0, B=1, C=0 the data inputs signals ‘X₁’, ‘X₂’, ‘X₃’ ‘X₄’ can reach the data inputs of MUX-1. As the control inputs of MUX-1 are B=1 and C=0 so output ‘Y₁’ carries the data signal ‘X₃’. On the other hand ‘Y₂’ is low as before. Therefore logic OR operation between ‘Y₁’ and ‘Y₂’ gives the data signal ‘X₃’ at the output ‘Y’.

(iv) When A=0, B=1, C=1 the data inputs signals ‘X₁’, ‘X₂’, ‘X₃’ ‘X₄’ can reach the data inputs of MUX-1. Here for the condition B=1, C=1 the output ‘Y₁’ gives the data signal ‘X₄’. The output ‘Y₂’ is also low in this condition. So the final output ‘Y’ retrieves the data signal ‘X₄’.

(v) When A=1, B=0, C=0, the first four data inputs signals ‘X₁’, ‘X₂’, ‘X₃’ ‘X₄’ cannot reach to the data inputs of MUX-1. Whereas the last four data input signals ‘X₅’, ‘X₆’, ‘X₇’ and ‘X₈’ can reach the data inputs of MUX-2. So in this case the output ‘Y₁’ of MUX-1 is low (logic 0). But now for the condition B=C=0 the MUX-2 carries the data signal ‘X₅’ at the output ‘Y₂’. Therefore at the output ‘Y’ one can receive the data signal ‘X₅’.

(vi) When A=1, B=0, C=1, similar to the condition (v) as all of the inputs of the ‘MUX-1’ are at logic low state, the output ‘Y₁’ becomes low (logic 0). For the control inputs B=0 and C=1 for the ‘MUX-2’ the output ‘Y₂’ produces the data signal ‘X₆’. Now at the output ‘Y’ also the data ‘X₆’ is available.

(vii) When A=1, B=1, C=0, the last four data input signals ‘X₅’, ‘X₆’, ‘X₇’ and ‘X₈’ can reach to the data inputs of MUX-2. The output ‘Y₁’ is low as before and output ‘Y₂’ gives the data signal ‘X₇’ for the condition B=1 and C=0. Thus at the output ‘Y’ one can get the data signal ‘X₇’.
(viii) When A=1, B=1, C=1, all the data inputs of MUX-1 are low. So ‘Y1’ is also low (logic 0). On the other hand last four data signals ‘X5’, ‘X6’, ‘X7’ and ‘X8’ can reach the data inputs of MUX-2. Thus for B=C=1 ‘MUX-2’ yields the data signal ‘X8’ at the output ‘Y2’. Therefore one can retrieve the data signal ‘X8’ at the output ‘Y’ for the control input condition A=B=C=1.

Thus the scheme serves as an optical polarization encoded 8×1 multiplexer.

11.4. Conclusion

The operation of the scheme is all-optical. So a real time operational speed can be achieved from the system. Using the scheme optical demultiplexer can also be implemented. One can very easily develop a higher input multiplexer and demultiplexer expanding this proposed scheme just accommodating some additional 4×1 multiplexers and AND logic gates. The whole system can operate smoothly if nonlinear material with higher ‘n2’ is used as an optical switch. A single nonlinear material block can be used to accommodate all the logic gates required for a multiplexer. So an optical embedded system can be developed for developing an integrated scheme of multiplexer.
An All-Optical Polarization Encoded Parity Generator and Checker

Abstract

Polarization based encoding of data signal is an important method for implementation of optical logic and data processor. Again to avoid any unwanted error in data signal sometimes it becomes essential to check the data signal, especially during transmission of data through large distance. Checking of the parity of the data signal during transmission and reception is one way to ensure errorless transmission of data. A method to implement an all-optical parity generator and checker, using polarization encoded light signal, is proposed and described in this chapter. The scheme uses the switching capacity of isotropic nonlinear material, where the 1\textsuperscript{st} order nonlinearity is absent but the 2\textsuperscript{nd} order nonlinearity is present. This scheme can be used to check whether any error is occurred during transmission of optical data signal. As parity checking is an essential component in any communication system and it ensures the correctness of the sending data at the receiving point, so the all- optical system can exhibit a strong application in optical communication as well as in computation.

Publication related to this chapter -
12.1. Introduction

As photon is a charge-less particle and therefore it does not create cross-talk problem like electrons and supports its inherent parallelism during information processing and computing. Because of these advantages of optical signal over electronic signal scientists have been trying to implement optical systems replacing the conventional electronic systems. Already several methods have been reported for implementing optical logic, arithmetic and algebraic systems [21, 24, 212, 231, 242, 249, 289, 294-296]. Again during transmission of light signal through a long distance if an optical data is changed due to some noise or error then the logic processor which uses this signal cannot respond properly. A parity bit is used to detect the errors during transmission of binary information. It is an extra bit included with the binary information to make the number of ‘1’s’ either odd or even [297, 298]. The parity of the information as a bit is also transmitted with the data. At the receiving end the parity is again checked. If the parity is same as that of the transmitted signal at the transmitting end then it may be concluded that there is no error during transmission. The circuit which generates the parity in the transmitting end is called ’parity generator’ and the circuit that checks the parity at the receiving end is called ’parity checker’ [129]. An all-optical method to implement a parity generator and parity checker with polarization encoded light signal is depicted in this chapter.

To implement the scheme optical isotropic nonlinear material and polarization based encoding are used. As the polarization of the optical signal is not generally changed during propagation at a long distance being non-guided , and also when it is guided through a polarization maintaining optical fiber ,so the encoding and decoding of light signal based on its polarization property can be a very convenient technique. Polarization encoding has been used in many works. Here the light signal polarized along the perpendicular to the plane of paper (•) is considered as ‘logic 0’ state and the light beam polarized in the plane of paper (↑) is treated as the state of ‘logic 1’. A simple half wave plate can act as a polarization encoded NOT logic gate. This plate introduces a phase difference of π if the wavelength of the light signal remains constant. Thus when a light signal polarized perpendicular to the plane of paper (•) (logic 0), passes through the half-wave plate, it becomes polarized in the plane of the paper (↑) (logic 1) and vice-versa. A polarization encoded 2-input Ex-OR logic gate was discussed in the ‘section- 5.3.4’.
12.2. Method of implementing an all-optical parity generator and checker for polarization encoded light signal.

The block diagram of the all-optical polarization encoded parity generator is shown in ‘figure - 12.1(a)’ and the detail internal structure of the block is shown in ‘figure - 12.1(b)’. The block diagram for the parity checker is shown in the ‘figure - 12.2’. In these figures the Ex-OR and NOT logic gates, which are shown by some blocks, represent the polarization encoded all-optical logic gates. The circuit incorporated at the transmitting end (‘fig.-12.1(a)’) is called parity generator and the similar circuit (‘fig.-12.2’) used at the receiving end is called parity checker.

A, B, C, D are the four bits of an optical binary data which is to be transmitted. In the input ‘P₁’ one can give either ‘1’ (\(\uparrow\); a light signal polarized in the plane of paper) or ‘0’ (•; a light signal polarized along the perpendicular to the plane of paper) data signal by a modulator ‘M’. Ex-OR operation is performed between the data ‘A’ & ‘B’ and between the data ‘C’ & ‘D’. The outputs from these two Ex-OR operations are applied to the inputs of another all-optical polarization encoded Ex-OR gate. The output of this gate is passed through a half-wave plate which acts as a NOT logic gate. The output of this optical NOT gate and the signal from the input ‘P₁’ are again made to go to the input of another polarization encoded Ex-OR gate. One gets the output at ‘P₂’ depending on ‘P₁’ and the parity of the data. The bit ‘P₂’ is also transmitted along with the data bits. At the receiving end the system shown in ‘fig.-12.2’ is incorporated. Here the signal bit ‘P₂’ is applied to the input ‘P₃’. Viewing the resulting output at ‘P₄’ one can know if the data is transmitted correctly or any error has been occurred.

If for P₁=0 one get P₂=1 then one can conclude that the data has even parity. The same conclusion can be drawn if for P₁=1 one receives P₂=0. If someone gets the result P₂= P₁ then the data has an odd parity. Let for example the data has even parity and at the transmitting end one sets P₁=0. As a result one gets P₂=1 in the parity generator circuit at the transmitting end. So, one can conclude that the data has even parity. Now the data along with the parity bit ‘P₂’ is transmitted. At the receiving end, for the parity checker circuit the data ‘P₂’ is treated as ‘P₃’. Thus P₃=1. Therefore one should get P₄=0 for the even parity of the data signal. If one gets this result then it can be decided that no error has been occurred during transmission. Because, the transmitted data has even parity as it has been confirmed by the parity generator.
circuit. If one does not get this result it is decided that an error has been occurred during transmission of the data.

Fig. 12.1(a): All-optical polarization encoded parity generator used at the transmitting end.
Fig. 12.1(b): Scheme for all-optical polarization encoded parity generator.
Fig. 12.2: All-optical parity checker at the receiving end.

12.3. Conclusion

Polarization encoded data communication is being popular more and more in all optical communication, as the encoding technique bears some basic advantages. The scheme offers an all-optical technique by which one can check a polarization encoded optical data as well as it can generate a polarization encoded optical data which is useful in optical communication. As the scheme uses polarization encoding technique, same power can be considered for both ‘logic 1’ and ‘logic 0’ states. Therefore the average power of a byte remains same whatever be the number of ‘0’s and ‘1’s. The beam splitters and mirrors are not shown in the figure for simplicity. One can use a different point on the surface of a single LM-NLM block instead of using multiple LM-NLM blocks for increased number of switches as shown in the ‘figure- 12.1(b)’. Hence this scheme may extend a wide application in optical communication.
General Conclusion and Future Scope of Works

Abstract

Optics has been being used in logic and data processing since last few decades. The field of optical computing is still flourishing. Although lots of research proposals are already reported, still there are many more scopes to do for completely utilizing the advantages of optics. In this chapter an overall conclusion on the whole thesis is given and scopes of future works are discussed.
13.1. Introduction

The use of optical signal in logic and data processing was started few decades ago. Since then optics has established itself as a potential candidate in optical computing and optical communications. The study of optical computing spreads over a multidisciplinary area in both science and engineering. Scientists and researchers all over the world from different fields are continuously working to deploy optics in computing. As a result of their effort a rapid growth has been noticed in the implementation of different optical systems. This is because of highly expanding field of applications. This has been made possible by introducing different techniques, optical material etc. Optical components are very much useful in digital optical computer. In optical parallel computation optical switches play an important role. In this regard optical nonlinear material based switch is used in many systems. Optical logic gates are the basic building block of any optical digital logic circuit. In the previous chapters few approaches for the optical logic, arithmetic and data processing are discussed. As these schemes can provide very fast speed of operation and can be fabricated in a small volume, so it can be expected that these will be very much helpful in superfast processing.

13.2. Overall conclusion on the thesis

With the ever increasing demand for higher speed of computing operation the search for such efficient optical systems continues. Optical logic processors are the key elements of such optical systems. In this thesis, I have tried to describe some optical techniques for developing a few optical logic, arithmetic, algebraic and data processors. Conclusions related to specific schemes are given in the respective chapters. The all-optical schemes may offer real time speed of operation. As polarization based encoding and decoding technique has some advantages, it has been used in many of these optical processors. The two polarization based logic states have equal energy. The figures, which describe different optical scheme, are schematic only. These may have to be slightly shifted for practical situation. In some of the schematic diagram for implementing the optical processors, the beam splitters and mirrors are not shown for simplicity. In the background review section only some of the sensible proposals for implementation of optical processors are mentioned. There are no doubt many other related important works which are not referred in thesis due
to page limitation. A logic and arithmetic processor described in ‘chapter-3’ can be used to perform different operations only changing the control signal i.e. without changing the system configuration. The volume of the optical systems can also be smaller than they look in the diagrams, if different points on a single optical linear-nonlinear material block can be used for multiple switching operations. This is possible as optical signal beams do not interact with each other. For the implementation of the schemes utilizing the Kerr effect in optical isotropic nonlinear material, proper laser sources are required. In some cases the conventional loss was not considered. The intensity maintaining scheme proposed in ‘chapter-4’ can be useful for cascading of optical devices working on intensity based encoding technique. The polarization encoded 2-input optical logic gates described in ‘chapter-5’ can be extended for higher input logic gates. These polarization based logic gates can be cascaded. Proposed flip-flops (in ‘chapter-6’ and ‘chapter-7’) are all-optical and hence are very fast. The scheme in ‘chapter-8’ can be useful for cascading intensity encoded optical system with a polarization encoded optical system. I believe that the schemes depicted in ‘chapter-9’ through ‘chapter-12’ will also find a wide application.

13.3. Future scope of works

Since the seventies of the last century already lots of research works are reported using optical signal for computing of data. Some all-optical approaches for implementing different optical systems are depicted in this thesis. In the present thesis we have just reached our initial target and a large amount of work beyond this is left for our future study.

In ‘chapter-3’ an integrated scheme for optical logic and arithmetic processor (OLAP) is described. Similarly an integrated optical scheme can be developed which will be able to perform any logic, arithmetic or algebraic operation as directed through the control signal. This optical system may function depending on polarization based encoding technique. The scheme for obtaining a prefixed intensity of light, illustrated in ‘chapter-4’, can be extended to specify the different intensity levels of a multi-valued logic system. In multi-valued logic system the increase of logic density can provide extra information through each connection. Different polarization encoded optical logic gates have been developed. Now with the help of these optical logic
gates optical register, counter, demultiplexer etc. may be developed. A compact optical polarization encoded scheme for performing various logic, arithmetic and algebraic operations may be developed. Polarization encoded optical astable, monostable multivibrator may also be constructed. Optical isotropic nonlinear material has a key role in developing optical switch. In addition new materials are being investigated to use their nonlinearity for switching action. Semiconductor optical amplifier can also be used for optical computational purpose. We can also show the results of the different schemes by simulation process. Again there is a vast scope left for preparing proper nonlinear materials with organic materials which can serve the above logic purposes due to their high material nonlinearity. Therefore I think there is a lot of scope for my future works.
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