Realization of optical logic gates using thermal lens effect

This chapter describes how Optical logic gates can be implemented using thermal lensing technique. A dual beam thermal lens method using low power cw lasers in a dye-doped polymer is used as an alternate technique to perform logical functions such as NAND, AND and OR employing appropriate modes of data deduction.
6 Realization of logic gates

6.1 Introduction

Computers have modernized human life to a great extent. The first practical computer based on vacuum tubes was large in size but small in computing capacity. The invention of transistors in 1947 provided smaller, faster and more efficient circuit elements. The speed of conventional computer is achieved by the development of the Very Large Scale Integration Technology and this has revolutionized the electronics industry and established the 20th century as the computer age. But further miniaturization of lithography introduced several problems such as dielectric breakdown, hot carriers and short channel effects. Since electronic circuits reached this limit, the speed of computers has now become a pressing problem. The rapid growth of internet demands faster speeds and larger bandwidths than electronic circuits can provide. In this situation, optical interconnections and optical integrated circuits provide a way out of these limitations to computational speed and complexity inherent to conventional electronics [1-6].

Optical computing received a great advancement after the invention of lasers in 1960. The characteristics of this light source allowed numerous computations to be realized by optical means. Optical computing represents a very stimulating challenge for optics that is better suited than electronics for highly parallel computing. The fact is that through a large number of small optical processors tied together by a powerful connecting network, optical signals can travel as light rays in free space. Optical computers use photons instead of electrons to perform appropriate functions. Optical interconnections and optical integrated circuits have several advantages over their electronic counterparts. Optical computing has inherent advantages such as massive connectivity, fast
speed and freedom from electromagnetic interference over electronic computers. Optical components do not need insulators because they do not experience cross talk. They are free from electrical short circuits. They have low loss transmission and provide large bandwidth. They are compact, lightweight and inexpensive to manufacture and more facile with stored information than magnetic materials. Another benefit of optical methods over electronic ones for computing is that optical data processing can be done by much easier and less expensive methods. Another advantage results from the fact that photons are uncharged and do not interact with one another as in the case of electrons. Hence, unlike electrical signals, light signals can cross paths without affecting the information that is to be received at their destinations. Information can also be multiplexed, with possibly as many as 1,000 separate channels in a single pulse.

At present most of the photonic devices are based on hybrid technology, which is an amalgam of optical and electronic hardware components [7-11]. In a typical hybrid configuration, the optical system performs its function efficiently and all other decisions and interfacing are done by flexible electronic components. This will limit the capabilities of optical processors. Hence most of R & D activities are concentrated on identifying proper photonic materials and optical signal processing techniques to develop all-optic computing elements [12, 13].

According to their functionality, optical computing systems can be divided into two categories: special purpose analog and general purpose digital systems. Recently, digital optical computing has been emphasized more because of the advances in photonic materials, which make energy-efficient ultra fast digital switching. They are based on nonlinear optical effects and they mimic the existing electronic computers having logic gates and memory elements.
Logic operations are nonlinear and hence nonlinear optics plays a vital role in the realization of a digital optical computer. Availability of coherent optical sources along with the realization of various nonlinear optical phenomena has made it possible to implement optics based computing and memory elements. It is now possible to control a light beam with another using nonlinear optical effects. Usually the method of implementation of binary logic elements uses nonlinear effect, where the nonlinearity consists of a threshold located at some input level [14-17]. This has helped in developing various types of optical logic elements based on optical phase conjugation [18, 19], optical bistability [20-26], optical interference [27], image subtraction [28], shadow casting logic or Spatial light modulators [29], etc.

Logic elements built from a four-wave mixing optical phase conjugator are based on the dependence of the output on three input beams. Pump beams represent two inputs. The probe is the readout beam and its conjugate the output. The conjugate beam is created as a result of the interaction of all three input beams in a nonlinear medium.

Optical bistability characterizes an optical system with two possible output states for a single input. The phenomenon of changes in refractive index due to the variation of the intensity of light, have been used to fabricate optical bistable devices. They are of two types (1) all-optical type and (2) the hybrid type. In the former type of Fabry-Perot resonator bistable device a nonlinear optical material is placed in the cavity and refractive index varies as light intensity varies. When the intensity is increased, constructive interference takes place and the intensity buildup occurs inside the resonator cavity. Even if the intensity falls, the device again approaches the resonance condition and the intensity goes up which is the high transmission state. When the intensity is lowered it does not immediately affect the intensity buildup in the resonator. When the input intensity is lowered
far enough, the intensity in the resonator is not sufficient to maintain constructive interference, and therefore the intensity in the resonator decreases sharply and the system switches back to the low-transmission stable state. Since the nonlinear coefficient is too small, large optical power is required to confirm bistability. In the hybrid type configuration an electro-optic controlled element is inserted in a Fabry-Perot resonator and the transmitted optical power is converted into voltage through the optical detector. This type does not require large optical power. Recently nonlinear guided waves to obtain bistability has developed in which an optical waveguide can be considered as very thin resonant cavity whose thickness is of the order of light wavelength. Such optical devices that utilize intensity-dependent index changes are expected to operate at high bit rates not attainable by electronic elements.

Another way of implementing optical switches is to shift and combine optical interference fringes [30]. In these studies, nonlinear optical materials are utilized to generate necessary phase changes, which in turn induce the shifting operation and interference fringes. Unfortunately efficient nonlinear materials that can respond at low power levels are not presently available.

An alternate approach is the one that does not require nonlinear optical materials or shifting operation of interference fringes, but simply utilizes a well-known photothermal phenomenon called thermal lens (TL) effect, which introduces intensity dependent refractive index [31-33]. In TL effect, thresholding phenomenon [14] is achieved due to the aberration of thermal lens. Above a certain threshold laser intensity, refractive index gradient in the medium becomes so large that thermal lens is created and the probe beam through the lens gets diverged to form a bottle like shape [34] with a central dark region surrounded by bright regions as shown in the figure 6.1. The central rays are deflected more
than the peripheral rays. From the figure it is clear that the appearance of dark central part depends both on the pump power as well as the position of detector along the beam axis. In the present experiment, the position of detector is fixed so that the variable parameter is the pump power. Such modifications of the probe beam shape can be used to implement optical logic gates due to the existence of threshold like phenomenon. Changes in the optical intensity at the center of the probe beam at far field due to thermal lens effect can be used as the thermal lens signal. The exact level of the threshold determines which Boolean function appears at the output. One can modify the scheme of data detection to realize various types of logic gates. [35].

Figure 6.1 The ray diagram representing the distortion of beam cross-section due to thermal lens effect
Figure 6.2 Cross section of the probe beam showing TL for $I < I_{\text{thresh}}$

Figure 6.3 Cross section of the probe beam undergoing thermal blooming for $I > I_{\text{thresh}}$
6.2 Materials

6.2.1 Polymers

Organic materials can perform functions such as switching, signal processing and frequency doubling using less power than inorganic materials. Polymers are familiar materials found throughout everyday life. Polymer molecules consist of many repeat units and the enormous range of possible repeat units give an almost unlimited variety of polymeric materials. This gives great diversity and applications of polymers, ranging from compact disks to car tyres. Biological polymers such as DNA, proteins and cellulose form the basis of life itself. Some other polymers show conducting or semiconducting electrical properties thus providing the basis for a new approach to electronics [35, 36]. One of the key reasons for the wide spread use of man-made polymers is the ease with which they can be processed into any desired shape or form. A further advantage of polymers is that modifying their chemical structure can control their properties. A number of solid organic polymeric matrices have been described in literature [37, 38]. Of these, the use of poly methyl methacrylate (PMMA) host presents additional advantages such as better compatibility with organic laser dyes and inexpensive fabrication techniques. These characteristics when combined with their lightweight would facilitate miniaturization and the design of integrated optical systems [23,39-42]. The optical medium selected for the present investigation is chemically stabilized Rhodamine 6G doped PMMA, due to its best optical transparency and resistance to laser damage [43-45]. Details of the method of preparation of the material are given elsewhere [46].
6.3 Experimental

The experimental setup for dual beam thermal lens method for realizing logic gates is shown in figure 6.4. Laser radiation at 532 nm wavelength from a Diode Pumped Nd: YVO₄ laser (Uniphase BWT-50) is split into two beams I₁ and I₂. These pump beams are later spatially overlapped in the medium and modulated using a chopper to generate thermal lens effect. The excitation beam was focused using a 400 mm focal length lens.

Figure 6.4 Schematic diagram of the experimental set up for realizing logic gates. BS₁, BS₂ - Beam Splitters, C - Chopper, L₁, L₂ - Lens, DM - Dichroic Mirror, S - Sample, F - Filter, PD - Photodiode, D - Detector.
A low power (1 mW) intensity stabilized He-Ne laser source of wavelength 632.8 nm is used as the probe beam which was focused by a 200mm focal length lens. Sample in the form of a disc (thickness 3 mm and 1 cm diameter), is kept in the path of the pump beam. The probe beam is made to pass collinearly through the sample using a dichroic mirror.

A filter is placed in the path of the emergent beams, which allows only the 632.8 nm wavelength to reach the photodiode. The signal is measured using a power meter (Liconix 55PM)

6.4 Results and discussion

For the realization of digital optical computing, the very basic building block is an optical gate capable of performing universal logic functions such as NAND, AND and OR gate.

Figure 6.5 Power dependence of TL effect (sample concentration: $4 \times 10^{-3} \text{ mol l}^{-1}$)
All other functional devices can be built by employing different combinations of such basic gates. A simple implementation of these optical logic gates is achieved using nonlinear effect (TL effect), where the nonlinearity consists of a threshold located at some input level. The threshold like behavior of aberrated thermal lens effect monitored by the photodiode output is shown in the figure 6.5.

### 6.4.1 NAND gate

In the experiment to realize NAND gate, when the both pump beams ($l_1$, and $l_2$) are absent, the output corresponds to the intensity of probe beam itself. This is detected by the photodiode and is represented by the first condition in Table 1.

**Table 1. NAND gate**

(monitoring the photodiode output; $l_1$, $l_2 < l_s$, $l_1 + l_2 > l_s$)

<table>
<thead>
<tr>
<th>$l_1$ (input)</th>
<th>$l_2$ (input)</th>
<th>Photodiode output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Realization of logic gates

If the input of either beam is below the threshold, there is a high output (second and third conditions of Table 1). If both inputs are present and the input is above threshold, thermal blooming is so strong that aberration of thermal lens takes place. In this condition, the output of photodetector is low, which is taken as zero. The input-output relations of the TL experiment, using the photodetector output as the signal, satisfy NAND gate type relation as shown in Table 1. Similar experimental setup using pthalocyanine film is described in a work done by NASA in 2000 [47].

6.4.2 AND gate

In order to implement AND gate, the thermal lens signal for different pump powers is obtained and is shown in figure 6.6.

![Figure 6.6 Input-output characteristics for AND gate.](image-url)
From the figure it is clear that when both pump beams (inputs) are absent, there occurs no thermal lens phenomenon, and hence the thermal lens signal is zero, which gives the first condition of Table 2. If the inputs are below the threshold \( I_s \), i.e., either \( I_1 \) or \( I_2 \) is less than \( I_s \), the thermal lens signal is low and can be considered as zero. \( I_1 \) and \( I_2 \) together produce aberrated thermal lens, which gives maximum thermal lens signal that corresponds to the last condition of Table 2. Saturation of intensity, \( I_s \), depends on the concentration of the dye in the matrix.

Table 2. AND gate

(monitoring the TL signal; \( I_1, I_2 < I_s, I_1+I_2 > I_s \))

<table>
<thead>
<tr>
<th>( I_1 )</th>
<th>( I_2 )</th>
<th>TL output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

6.4.3 OR gate

By adjusting the pump powers we can implement the OR gate also. When both the inputs are low, the TL signal is low. Adjust the inputs such that \( I_1 \) or \( I_2 \) is greater than \( I_s \) and the output is high, as is evident from Table 3.
Absorbed power must not be so large to introduce photodegradation of the dye. It is a well-established fact that the PMMA matrix does not undergo any change in its chemical or any other physical properties at very low laser powers as we have used in the present investigation [45-47].

6.5 Conclusion

At present, all-optical digital computer is only at its infancy and there does not exist any complete systems. Intensive research is currently being pursued to attain this goal. Most of the optical devices and concepts of the present day are based on hybrid technology. Newer advances have produced a variety of thin films and optical fibers that make optical interconnections and devices practical. The thermal lens technique has been successfully implemented for realizing basic logic gates. The advantage of this technique is that basic logic gates can
be realized with optical beams of moderate intensity. In contrast to other optical logic gates, this method does not require any nonlinear optical materials, apart from being sensitive. The sample used for the present work is Rhodamine 6G doped PMMA, which is photochemically stable at moderate laser powers.

References

6 Realization of logic gates