CHAPTER 1

Introduction

1.1 PHOTOREFRACTIVE EFFECT:

The photorefractive effect [1-4] refers to the field induced change in refractive index of an optical material. Where, the field results from a light induced redistribution of electrons and holes. Thus a photorefractive (PR) system [5-7] is one which is simultaneously photoconductive and electro optic. Diffraction gratings or holograms can be produced in a photorefractive material [8] by the photo-generation, drift or diffusion and subsequent trapping of mobile charges.

The attracting feature of PR materials [9-10] is the large effective nonlinearity even at low laser powers. One of the features also includes inherent optical real time information processing properties using all three dimensions in space.

1.1.1 Origin of Photorefractive Effect

In 1966, a defect was found in LiNbO$_3$ crystal by Ashkin et al. [11] which caused a distortion of the wavefront. It was discovered when it ruined the phase – matching condition in a second-harmonic generation experiment. In that experiment, the LiNbO$_3$ used was “optically damaged” after irradiation by a laser beam. It was proposed by the authors that the defect was caused through spatial variation in refractive index. This light induced modification of the refractive index form the basis of photorefractive effect.
Fig. 1.1 Migration of charges from bright to dark regions.

Fig. 1.2 The spatial variation of the light intensity, space charge field and the induced index change.
1.1.2 Principle of Photorefractive Effect

The photorefractive effect is induced by non-uniform illumination of light, such as focussed laser beams or intensity interference patterns. Free carriers are photo ionized from the deep traps to the conduction band and are transported due to electric field.

The most useful formation of the photorefractive effect emerged from Kukhtarev [12] and his co-workers in 1979 in the form of band transport model.

This band transport model is summarized as four processes:

(a) Electrons or holes are liberated from donors or traps via photo-ionization. These charges may be provided by lattice defects or dislocations or in case of nominally doped crystals by traces of impurities.

(b) The liberated or excited charges, now in the materials conduction band, migrate to darker regions where they are subsequently re-trapped as shown in Fig.1.1 [3]. Migration process starts from three different charge carrier transport processes.

(i) Diffusion – Charges move towards a space of lower charge concentration owing to their thermal ability.

(ii) Drift – Action of externally applied field.

(iii) Photovoltaic effect – a drift effect caused by an internal electric field which has in turn been created by the light pattern itself.

(c) The now spatially non-uniform charge distribution results in strong electrostatic space charge fields.

(d) A refractive index change occurs due to the linear electro-optic effect which results from space charge field formed. The magnitude of this index change is proportional to the local electric field strength.
Band transport model is formulated by a set of equation as:

\[
\frac{\partial N_D^+}{\partial t} = (N_D - N_D^+)(sl + \beta) - \gamma_R N_D^+ n
\]  \hspace{1cm} (1.1)

\[
\frac{\partial n}{\partial t} = \frac{\partial N_D^+}{\partial t} + \nabla \cdot (D \Delta n + \mu n E)
\]  \hspace{1cm} (1.2)

\[
\nabla \cdot \varepsilon E = e(N_D^+ - N_A - n)
\]  \hspace{1cm} (1.3)

Where \(\Delta n = \frac{n_0^3}{2} r_{\text{eff}} E\) \hspace{1cm} (1.4)

\(N_D^+\) = ionized trap density

\(N_D\) = total density of traps

\(sl\) = photo-ionization cross section(s) \(\times\) light intensity (I)

\(\beta\) = rate of thermal excitation

\(\gamma_R\) = recombination constant

\(n\) = number density of free charges

\(D\) = diffusion constant

\(E\) = electric field

\(\mu\) = carrier mobility

\(N_A\) = number density of acceptor sites

\(\varepsilon\) = static permittivity

\(\Delta n\) = refractive index change

\(n_0\) = background refractive index

\(r_{\text{eff}}\) = effective value of electro optic coefficient

These equations correspond to the steps of basic band transport model.

First three equations (1.1) – (1.3) are nonlinearly interlinked and useful for determining the properties of any space charge field. They are also termed as
material rate equations. Equation (1.4) gives the change in refractive index due to linear electro-optic effect (Pockel’s effect).

1.2 ELECTRO-OPTIC EFFECT

The electro-optic effect [4, 13] and photoconductivity are the fundamental phenomena underlying the photorefractive effect. Electro-optic effect referred to the effect where the application of electric field results in refractive index modulation in an electro-optic material. Most photorefractive crystals are anisotropic (their properties are different along different directions), and even those that are not, become anisotropic under the action of an externally applied electric field.

The electro-optic effect in photorefractive materials is of the highest importance, because it is responsible for mapping the space-charge field modulation onto an index of refraction modulation.

For electro-optic materials refractive index (n) is a function of electric field (E)

Two different types of electro-optic effect is given as:

linear electro-optic effect (Pockels effect):

$$n(E) = n - \frac{1}{2} r \cdot n^3 E$$

quadratic electro-optic effect (Kerr effect,):

$$n(E) = n - \frac{1}{2} s \cdot n^3 E^2$$

where $r$ and $s$ are the linear and quadratic electro-optic coefficients.

In photorefractive materials, Pockel’s effect is responsible for the index variation.

The formation of refractive index grating in a photorefractive material is shown in Fig. 1.2 [14].
1.3 FORMATION OF VOLUME HOLOGRAM

The space-charge field modulation produces a refractive index modulation. This phenomenon results in a phase grating of real-time nature and thus records a hologram [4, 15]. This phase grating diffracts the light during the recording process and modifies the recording pattern of light. This modification in turn affects the recorded grating and thus forms a feedback process. This feedback process is referred as self-diffraction.

Coupled wave theory for fixed grating

In the photorefractive effect, the change in refractive index occurs in areas between the bright and dark positions of the interference fringe. As a result the phase of index grating is shifted from that of interference pattern by angle $\phi_g$ as shown in fig 1.3 [4]. This characteristic of photorefractive effect results in asymmetric energy transfer among input beams as shown in fig 1.4 [16]. The formation of hologram in the PR material results from the interference of two coherent beams inside the material.

For two co-polarized input waves of irradiance $I_1$ and $I_2$, the modulation index of the interference pattern formed is given as,

$$m = \frac{2I_1 I_2}{I_1 + I_2}$$

The incident optical irradiance due to interference is of the form,

$$I = I_0 (1 + m \cos k_g z)$$

where $k_g$ is the grating wave number and $I_0$ is the average irradiance.
The index change $\Delta n$ caused by a space charge field is given as (pockel's effect),

$$\Delta n = \frac{1}{2} n_0^3 r_{\text{eff}} E_{\text{SC}}$$

Where $n_0$ is the background refractive index and $r_{\text{eff}}$ is the effective electro optic coefficient.

Under steady state condition with linear approximation, neglecting the effect of photovoltaic field and detuning of beams, the space charge electric field $E_{\text{SC}}$ is given by [8, 12, 17]

$$E_{\text{SC}} = E_Q \left| \frac{E_0^2 + E_D^2}{E_0^2 + (E_D + E_Q)^2} \right|^{1/2}$$

The phase shift between interference pattern and refractive index grating in the steady state is given by [18]

$$\tan \phi_g = \frac{E_D}{E_Q} \left| 1 + \frac{E_D}{E_Q} + \frac{E_0^2}{E_D E_Q} \right|$$

Where $E_o = $ applied electric field

$E_D = $ the diffusion field

$E_Q = $ maximum amplitude of the electric field

Diffraction of an incident beam from thick holograms has been studied through coupled wave theory by Kogelnik [19]. The coupled differential equations as derived by Kogelnik were based on the diffraction process from fixed gratings. Kogelnik theory was later used to estimate the diffraction efficiency from dynamic gratings in PR crystal [20]. The dynamic theory takes into account the possible changes of the fringe pattern along the crystal length due to the intensity redistribution between the writing beams [12].
Fig. 1.3 Recording of a fixed volume index-of-refraction hologram that is phase shifted by $\Phi_g$ with respect to interference fringes.

Fig. 1.4 Asymmetric energy exchange in a photorefractive grating.
1.4 PHOTOREFRACTIVE MATERIALS

Photorefractive materials [2, 9, 21] are classified basically into following groups

1. Ferroelectric Oxides (LiNbO$_3$, BaTiO$_3$, Sr$_x$Br$_{1-x}$Nb$_2$O$_6$, KNbO$_3$, etc)

2. Cubic Oxides (sillenites such as BSO, BTO)

3. Semiconductor Materials (GaAs, InP etc.)

4. Organic Materials (Polymers)

5. Hybrid Materials

6. Other Materials

Thus a variety of photorefractive materials have been found, which can be selected according to their properties and applications. The wavelength selectivity region of different materials is shown in Fig. 1.5 [2].

1.4.1 Ferroelectric oxides

The special features and properties of some ferroelectrics are discussed in the coming subsections.

1.4.1.1 Lithium Niobate

Lithium niobate (LiNbO$_3$) was the first electro-optic material to be utilized as a photorefractive holographic recording medium. This material is still one of the most extensively investigated [22-24]. Its low dark conductivity makes it applicable for efficient holographic data storage [25-26] with storage times up to years. Doping LiNbO$_3$ improves its storage capability and two-wave mixing coupling constant.
Generally, iron is used for doping but good results have been also obtained with other elements [27]. LiNbO$_3$ is also used for the easy formation of low loss waveguides and embedded waveguides.

![Fig. 1.5 wavelength selectivity region of different materials.](image-url)
1.4.1.2 Barium Titanate

Barium titanate (BaTiO$_3$) is a tetragonal crystal with 4mm point group symmetry at room temperature. The particular advantage of BaTiO$_3$ for photorefractive applications relies on its very large value of dielectric permittivity and electro-optic tensor coefficients [28-29], allowing very high gain to be achieved in two beam coupling experiments. BaTiO$_3$ has been used to demonstrate a double phase conjugate mirror, an oscillator that couples incoherent optical beams in a bidirectional holographic link [30]. Moreover, image amplification has been successfully demonstrated in BaTiO$_3$ crystals [31] by means of two and four wave mixing with high gain factors.

1.4.1.3 Potassium Niobate

Potassium niobate (KNbO$_3$) possesses a strong electro-optic effect and its two beam coupling properties has been widely studied [32]. This material find application in reflection gratings. Fe-doped crystals are used for reflection grating based phase conjugators [33-34]. KNbO$_3$ shows a shorter dark storage time but has a larger photosensitivity which allows faster recording. These high sensitivities have been observed especially in cerium-doped potassium niobate crystals.

1.4.2 Sillenite Crystals

The crystals of sillenite family includes: Bi$_{12}$GeO$_{20}$ (BGO), Bi$_{12}$SiO$_{20}$ (BSO), and Bi$_{12}$TiO$_{20}$ (BTO) [35]. They are cubic noncentrosymmetric crystal and belong to point
group 23 symmetry. They are inherent piezo-electric [36], electro-optic, and elasto-optic and optically active.

Because of its inherent optical activity [37], the sillenite crystals possess interesting polarization properties [38]. To study its properties [39] the two basics configuration used are Kg $||$ <001> and Kg $\perp$ <001> as shown in Fig. 1.6 and Fig. 1.7 [40 - 41]. In these two configurations the piezoelectric and photoelastic properties are not much effective [42]. Optical activity is important for interferometric applications and cannot be neglected for diffusion recording [43].

Fast response time (1–$10^{-3}$ s) of sillenites make it applicable for dynamic holography, real time interferometry [44 - 45] and optical information processing. Yellow and green regions are strongly absorbed (absorption $\alpha = 1.5 \text{ cm}^{-1}$ at $\lambda = 0.63 \mu\text{m}$) by the sillenite crystals. They are transparent in the red and infrared regions [46] (low absorption $\sim 0.03 - 0.05 \text{ cm}^{-1}$ at $\lambda = 632.8 \text{ nm}$).

The 23 point group symmetry of sillenites facilitates natural optical activity and piezoelectric effect. The feature can be used in electric and magnetic sensors and various piezoelectric devices. The coupling coefficient of sillenite crystals is rather small but can be enhanced by detuning one of the beams [47] or by applying external field across the crystal [48]. Doping in sillenites affects its photoconductivity and holographic properties [49].
Fig. 1.6 The Kg\(\parallel\) <001> crystal orientation of Bi\(_{12}\)SiO\(_{20}\) for volume holography.

Fig. 1.7 The Kg \(\perp\) <001> crystal orientation of Bi\(_{12}\)SiO\(_{20}\) for volume holography.
1.4.3 Photorefractive Semiconductors

Optically induced refractive index changes have been observed in various semiconductors, such as Gallium Arsenide (GaAs), Indium Phosphide (InP), Cadmium Telluride (CdTe), Zinc Telluride (ZnTe), ternary compounds such as AlGaAs, and other materials. Short response time of photorefractive semiconductors make them suitable for fast holographic processing of optical data in the infrared region of spectrum [7-8, 50]. Different enhancement techniques are used to make them applicable for potential applications such as optical phase conjugation [51-53], design of optical interconnects [54], laser-based ultrasonics detection with adaptive interferometers [55-56] etc.

1.4.4 Organic photorefractives

The mechanism of the photorefractive effect in polymers [57] is the same as in inorganic materials, requiring generation of mobile carriers as a response to the incident light pattern, transport of generated charges with one carrier more mobile than the other, and refractive index change of the material by the local electric field. However, in organic materials [58], an additional effect is present, the so-called orientation enhancement effect. The process of PR grating formation in most organic materials can be viewed as a space-charge field formation followed by a noninstantaneous reorientation of birefringent chromophores, in response to the total local field arising from both the space charge field and the applied dc field. These materials are finding potential applications in various fields [59].
1.4.5 Hybrid Photorefractive Materials

New photorefractive hybrid materials are gaining importance because of hybridization of material properties. G. Cook et al. [60] have worked on hybridization of inorganic photorefractives and organic liquid crystals. They have found that the net gain of the hybrid cells is significantly greater than the product of the individual gains of the Ce : SBN (inorganic pr crystal) and the liquid crystal layers respectively. The liquid crystal layer has increased the overall gain of the system while preserving the attractive phase shift, trap density and wide beam angle characteristics of the inorganic substrate.

1.4.6 Other materials

Although the phrase ‘photorefractive effect’ has traditionally been used for such effects in electro-optic materials, unconventional materials photopolymers, holographic polymer dispersed liquid crystals (H-PDLC) and photosensitive glasses, have been developed in recent years and are playing important roles in optical fiber communication systems [14]. Photopolymers, in combination with liquid crystals (LCs) are ideal materials for wavelength selective tunable devices. The improved optical quality and large dynamic range of photopolymers make them promising material for holographic recording.
1.5 WAVE MIXING IN PR MATERIALS

Wave mixing is a process or technique in which two or more waves interact inside the medium. There are two types of wave mixing technique basically use to study photorefractive effect and applications.

Two – wave mixing

Four – wave mixing

According to grating orientation with respect to the input crystal surfaces, there are two types of interaction geometry: transmission and reflection. Both of them have been intensively investigated.

1.5.1 Two - wave mixing (TWM)

TWM [61-63] involves the coupling of two electromagnetic waves and the coupling between them. Two input beams are considered one referred as pump (reference) and other as signal. In transmission geometry [64], the two input signals co-directional (Fig. 1.8 (a)) i.e. on the same side of the crystal. When the signal and pump are contra-directional (Fig. 1.8 (b)) i.e. on the opposite sides, the grating formed is reflection grating [65].

Formulation of coupled wave equations for TWM [66]

Two beams of same frequency (degenerate) interfering in the photorefractive crystal forms a stationary interference pattern. Let the electric field of the two interfering waves be given as

\[
E_1 = A_1 e^{i(o_1-k_1.r)}
\]  
(1.5)

\[
E_2 = A_2 e^{i(o_2-k_2.r)}
\]  
(1.6)
Where $A_1$ and $A_2$ are the wave amplitudes, $\omega$ is the angular frequency; $k_1$ and $k_2$ are the respective wave vectors. Both beams are assumed to be polarized perpendicular to the plane of incidence i.e. they are s-polarized.

The intensity of the electromagnetic radiation can be written as

$$I = |E|^2 = |E_1 + E_2|^2 \quad (1.7)$$

Substituting equation (1.5), (1.6) in (1.7)

$$I = |A_1|^2 + |A_2|^2 + A_1^* A_2 e^{-K r} + A_2^* A_1 e^{K r} \quad (1.8)$$

Where $K = k_2 - k_1$ is the grating vector. The magnitude of the vector $K$ is $2\pi/\Delta$, where $\Delta$ is the period of the fringe pattern.

Including the photorefractive effect, the index of refraction can be written as

$$n = n_0 + \frac{n_1}{2} e^{i\phi} \frac{A_1^* A_2}{I_0} e^{-iK r} + c.c. \quad (1.9)$$

Where $I_0 = I_1 + I_2 = |A_1|^2 + |A_2|^2$

$n_0$ is the index of refraction of the material when no light is present

$\phi$ is the phase shift between interference pattern and refractive index grating. $\phi$ is $\pi/2$ for the case of diffusion regime (when no field is externally applied). $n_1$ depends on material properties, grating spacing and its direction.

For getting the form of coupled wave equation, $E = E_1 + E_2$ is substituted from (1.5) and (1.6) and index of refraction from (1.9) into the following wave equations

$$\nabla^2 E + \frac{\omega^2}{c^2} n^2 E = 0 \quad (1.10)$$
Fig. 1.8 (a) Two wave mixing: transmission geometry.

Fig. 1.8 (b) Two wave mixing: reflection geometry.
Now solving the above equation considering the slowly varying approximation so that
\[
\left| \frac{d^2 A}{dz^2} \right| \ll \left| \beta \frac{dA}{dz} \right|
\]
(1.11)

We get the corresponding equations as
\[
2i\beta_1 \frac{dA_1}{dz} = \frac{\omega^2 n_0 n_1}{c^2 I_0} e^{-i\phi} A_2^* A_2 A_1
\]
(1.12)
\[
2i\beta_2 \frac{dA_2}{dz} = \frac{\omega^2 n_0 n_1}{c^2 I_0} e^{i\phi} A_1^* A_1 A_2
\]
(1.13)

Where \( \beta_1 \) and \( \beta_2 \) are the z components of the wave vectors \( k_1 \) and \( k_2 \) inside the medium.

The energy coupling depends on the relative sign of \( \beta_1 \) and \( \beta_2 \).

**Case I : Transmission geometry (Co-directional TWM)**

We have \( \beta_1, \beta_2 > 0 \)

Considering the case when the two laser beams enter the medium from the same side at \( z = 0 \).

Writing the complex amplitudes of the beams as
\[
A_1 = \sqrt{I_1} e^{-i\psi_1}
\]
(1.14)
\[
A_2 = \sqrt{I_2} e^{-i\psi_2}
\]
(1.15)

Where \( \psi_1 \) and \( \psi_2 \) are respective phases of amplitudes \( A_1 \) and \( A_2 \)

Now the coupled wave equation for this case can be formulated as
\[
\frac{dI_1}{dz} = -\gamma \frac{I_1 I_2}{I_1 + I_2} - cI_1
\]
(1.16)
\[
\frac{dI_2}{dz} = \gamma \frac{I_1 I_2}{I_1 + I_2} - cI_2
\]
(1.17)
\[
\frac{d\psi_1}{dz} = \beta \frac{I_2}{I_1 + I_2}
\]  
(1.18)

\[
\frac{d\psi_2}{dz} = \beta \frac{I_1}{I_1 + I_2}
\]  
(1.19)

\(\alpha\) is the absorption coefficient. \(\gamma\) and \(\beta\) are the intensity and phase coupling coefficients.

**Case II: Reflection geometry (Contra-directional TWM)**

Considering the case when the two beams enter the medium from opposite faces, \(\beta_1 = -\beta_2\), coupled wave equations can be written as

\[
\frac{dI_1}{dz} = -\gamma \frac{I_1 I_2}{I_1 + I_2} - \alpha I_1
\]  
(1.20)

\[
\frac{dI_2}{dz} = -\gamma \frac{I_1 I_2}{I_1 + I_2} + \alpha I_2
\]  
(1.21)

and

\[
\frac{d\psi_1}{dz} = \beta \frac{I_2}{I_1 + I_2}
\]  
(1.22)

\[
\frac{d\psi_2}{dz} = -\beta \frac{I_1}{I_1 + I_2}
\]  
(1.23)

### 1.5.2 Four Wave Mixing (FWM)

In four-wave mixing [67], other than two input beams, a third beam is used to read out the volume hologram. Thus the writing and reading process occur simultaneously. To satisfy the Bragg condition, this third beam must be counter-propagating relative to one of the input beam.
Fig. 1.9 (a) Four wave mixing : transmission geometry.

Fig. 1.9 (b) Four wave mixing : reflection geometry.
Case I: The transmission grating in FWM:
In the case of transmission geometry (Fig. 1.9 (a)), the holograms are formed by the interaction of waves incoming from the same input crystal faces. The photorefractive crystal is illuminated by two counter-propagating pump waves pump1, pump2 and a probe wave called signal. The index grating (phase hologram) is formed by pump1, and the signal. A fourth beam is generated that propagates backward relative to the signal and is a time reversed replica of that beam. This phase conjugation by means of four-wave mixing is referred as real – time holography.

Case II: The reflection geometry in FWM:
In this case (Fig. 1.9 (b)), the phase hologram is formed due to the interaction of waves incoming from the opposite crystal faces.

1.6 APPLICATIONS
Photorefractive materials are one of the most promising materials being used in potential applications such as optical signal processing [68], real-time holography, adaptive interferometry, image amplification, optical interconnections, dynamic holographic memory, etc.

1.6.1 Spatial Light modulator
Spatial light modulator (SLM) is a optical processing device capable of modifying the amplitude (or intensity), phase, or polarization of an optical wavefront as a function of position across the wavefront. These devices can perform a wide variety of functions such as formatting interfaces, incoherent-to-coherent converters and optical interconnects. Photorefractive material for SLM has proved to yield good sensitivity and a large spatial resolution bandwidth.
A. Marrakchi [69-70] have demonstrated photorefractive spatial light modulation based on Doppler-enhanced two-beam coupling in BSO. The author has shown that the polarization properties of optically active BSO crystals enhance the signal to noise ratio. L. J. Cheng et al. [71] have presented the optically addressable GaAs spatial light modulator using the photorefractive effect. They have utilized a special configuration of beam coupling in GaAs in which there was no net energy transfer, but rotation in the polarization of the two beams was achieved.

1.6.2 Holographic Data Storage

Photorefractive materials are widely used for volume holographic storage material [3,72]. In holographic data storage, an entire page of information is stored at once as an optical interference pattern within a photorefractive material. This is done by interfering two laser beams within the storage material. The first, called the object beam, contains the information to be stored; the second, called the reference beam, is designed to be simple to reproduce. The resulting optical interference pattern causes refractive index change in the photorefractive medium.

A basic holographic data storage system is shown in fig. 1.10 [72]. In this figure the storage material is the photorefractive material. The use of photorefractive crystals for holographic recording present advantages like ongoing self-proceeding of recording medium and indefinite reusability.
1.6.3 Optical Computing

Four wave mixing in photorefractive media has drawn tremendous interest due to applications in various optical computing functions [73 - 74] including optical convolution and correlation, image subtraction, image division, image differentiation, matrix addition, edge enhancement, contrast reversal, spatial light modulation, optical switching, and logic etc. Photorefractive materials are most suitable as the recording medium for such applications because of their high sensitivity and erasable nature.
1.6.3.1 Digital logic operations

Parallelism of optics is utilized for performing arithmetic and logic operations.

Fig 1.11 schematics of (a) OR-signal beam saturation (b) AND-signal beam saturation (c) NOR-pump depletion mode (d) NEGATION controlled two-beam coupling (e) NOR-controlled two-beam coupling. BS is a beam splitter and PBS is a polarization selective beam splitter.
Authors have proposed various techniques [75] for binary addition and subtraction by all optical switching system. F. Garzia et al. [76] presented an electro-optical device that acts as a multifunction logical gate based on BSO photorefractive crystal. Fainman et. al. [77] have worked on the nonlinear phenomenon of signal beam saturation or pump beam depletion as well as optically controlled coupling coefficient in two-beam interaction in photorefractive BaTiO$_3$. They have discussed about the saturation and depletion modes of operation and utilized them in performing different logic operations of OR, NOR, AND and NOT for parallel digital optical computing as shown in Fig. 1.11. H. Rajbenbach [78] has demonstrated a real-time parallel half-adder circuit with the use of nonlinear interactions in photorefractive media.

### 1.6.3.2 Associative memories

A combination of holography and optical resonator using PR material can be used for the implementation of optical associative memories in which one can retrieve a complete optical image from a partial version of the image.
To reconstruct an image, a partial version of that image illuminates the hologram, which reconstructs the reference beam for that image. The reconstructed reference beam is sent back to the hologram using a phase conjugator which reconstructs the original image [79].

Xu et al. [80] demonstrated real time holographic associative memory system using photorefractive KNSBN: Co crystal and liquid crystal electrooptic switches.

Zheng et al. [81] have grown Sc: Fe: LiNbO₃ crystal to be used as recording material and phase conjugate mirror to realize holographic associative memory. They have demonstrated principle scheme of holographic associative memory as shown in Fig. 1.12.

1.6.3.3 Optical interconnects

Optical interconnections linking laser arrays and detector arrays play a key role in optical computing. High parallelism, speed and non interference are the inherent advantage properties of optical interconnection configurations. PR materials with their reconfigurable capability allow the implementation of dynamic holographic interconnections [82 - 83]. The combined parallelism optics, and storage capability of the PR media allow large number of interconnections which are independent of each other. The use of dynamic arrangement for interconnection allows the pattern to change upon request during computation.
1.6.4 Optical Phase Conjugation (OPC)

Phase conjugation is a nonlinear mechanism that reverses both the direction of propagation and the phase of an aberrated wavefront. The generation of the conjugate beam can be viewed as a dynamic holographic recording process. Such an unconventional optical device is known as a phase conjugator or a nonlinear phase conjugate mirror (PCM).

Fig 1.13 Compensation of the aberrations due to a phase distorting media by wavefront reflection on a phase conjugate mirror.

One interesting application of OPC is its ability of phase aberration correction [6] as shown in Fig. 1.13 [84]. This excellent property can be used in various cases such as: photolithography, laser resonator using PCM and imaging through distorting media etc. A versatile application of the PCM is imaging through phase distorting medium. In all the cases, signal is passed through an aberrated medium and as the PC wave retraces its own path, it cancels the aberration leaving behind the pure object
information. The distortion correction ability of the phase conjugate wave also has the properties of lensless imaging.

1.6.5 Photorefractive Optical Beam Splitter

This beam splitter is based on the higher diffraction order of a phase grating formed via the photorefractive effect. D. Gong et al. [85] have made the beam splitter by two-beam coupling at a small incident angle in a crystal of Fe: LiNbO$_3$. They have split multi-wavelength input (632.5, 532.0 and 488.0 nm) into multi-output beams by the beam splitter as shown in Fig. 1.14.

The photorefractive beam splitter is characterized by low cost light distribution solution with small form factor, high reliability, multi-output, wide wavelength range, broad angular acceptance, large operating temperature range and easy operation.

Fig. 1.14 optical beam splitter.

1.6.6 Holographic Interferometry

Holographic Interferometry (HI) is a technique which was developed for measuring the static deformation of various structures. Now it is widely used for dynamic cases
also. The capability of HI makes it useful in metrology techniques [86] for engineering and industrial applications. Based on HI principles [87], there are various techniques such as real time HI, double exposure HI and time-average HI.

Photorefractive crystals of the sillenite family present interesting properties for real time holographic interferometry. They present a much faster hologram buildup and provide less noisy holographic images. M. R. R. Gesualdi [44-45] et al. have demonstrated the developments in phase-stepping real-time holographic interferometry using photorefractive sillenite crystal.

**Compact and portable holographic camera**

Photorefractive materials are not only limited to experimental and theoretical analysis of their properties but people are realizing practical applications by making devices.

![Fig. 1.15 compact holographic camera.](image)

One of such devices is presented by M.P. Georges et al. [88] as shown in Fig 1.15. They have developed a compact holographic interferometer that uses a photorefractive crystal of the sillenite family as a holographic recording medium. This instrument is useful in various metrological problems. One of the application of this device is the measurement of the coefficient of temperature expansion of carbon-fibre hollow rods.
1.6.7 Adaptive Interferometry

Photorefractive dynamic hologram not only adapts the object wave front to the reference one but is also self-adapted to slow temporal variations in the phase difference, this type of optical system is referred to as adaptive interferometry [89].

Adaptive interferometry is one of the most promising techniques in the non-destructive testing of materials and elements of technical constructions. They are also used in laser ultrasound systems [90] for the non-destructive remote control of internal defects inside materials and constructions. Some of the areas of application adaptive interferometry can be listed as stabilization of fiber-optical interferometric sensors, real time analysis of deformations and vibrations of technical constructions, molecular recognition etc. Adaptive interferometer contains a medium in which a dynamic hologram is continuously being recorded, instead of just simple beam combining in conventional interferometers.

Adaptive interferometers based on two-wave mixing in photorefractive crystals are used for optical detection of ultrasonic surface displacements. K. Shcherbin et al. [91] have experimentally demonstrated adaptive interferometer based on two-wave mixing in photorefractive crystal without applying external field.

1.6.8 Fiber Optic Devices (Flat – topped tunable filter)

C. Gu. et al [14] have designed a flat – topped tunable filter for wavelength division multiplexing (WDM) optical networks as shown in Fig. 1.16.
WDM is used for increasing the information capacity of optical fiber communications. Wavelength selective filters is one of the major components for WDM. Their design consists of a liquid crystal waveguide, whose index of refraction can be tuned by an applied electric field. There is a layer of holographic material (such as photorefractive liquid crystal/polymer) on the top of liquid crystal waveguide. This holographic material can be used to fabricate the DBR mirrors optically.

1.7 OUTLINE OF THESIS

Chapter 1 introduces the basic principle underlying the photorefractive effect. One of the most acceptable model i.e. band transport model is being discussed. It outlines the different photorefractive materials and some of their special features. The specific features of photorefractive Sillenite crystals which makes it applicable for various applications is being discussed. It provides an overview of the techniques such as two-wave mixing and four-wave mixing, used to study photorefractive materials. Transmission and reflection geometry used for photorefractive analysis is being introduced in this chapter. It also deals with the basic coupled wave equations for two-wave mixing. Some of the valuable applications of the photorefractive
materials are summarized. Chapter is concluded with the outline of the present thesis.

Two-wave mixing in photorefractive crystal of Sillenite family is investigated in Chapter 2. Diffusion regime is considered for the analysis when there is no externally field is applied. The coupled wave equations are solved using fourth-order Runge-kutta method and the results are represented graphically. The effects of various parameters such as crystal thickness, optical activity, coupling coefficient, absorption and input polarization have been studied on output beam components. The results have been compared for BSO and BTO crystals.

Chapter 3 deals with the study of higher – order self diffraction in optically active BSO crystal. The generation of higher order diffraction beams is considered to be unidirectional in case of diffusion regime. The parameters responsible for the generation of different components of higher diffraction orders are studied such as polarization state of pump beam, optical activity, off-Bragg parameter, coupling coefficients, absorption, thickness of crystal, etc. The real coupled wave equations are solved numerically using fourth-order Runge-kutta method. Graphical results are presented and analyzed.

Chapter 4 analyzes the generation of two newly generated higher diffraction orders in BTO crystals. The effect of input beam polarization is studied on the higher order beams generated. The graphical results are obtained by solving coupled wave equations including two higher diffraction orders on the same side of output beams. The comparison of results is being done for BSO and BTO crystals.

Applying external electric field to the photorefractive crystal changes the phase shift (between interference pattern and refractive index grating) to be other than $\pi/2$. 
Chapter 5 analyzes the effect of phase shift on the higher order generated on both sides of output beams. The analysis is done for different values of pump to signal beam ratio. The chapter represents the investigation for optically active photorefractive Sillenite crystals (BSO and BTO). The results are represented and analyzed graphically by solving complex coupled wave equations.

Chapter 6 concludes the whole analysis done in the present work. It includes the control of polarization properties in photorefractive Sillenite crystals. This chapter also summarizes the various applications of the present work. Finally, the suggestions for future work are proposed. This includes research on some new materials such as hybrid materials. The possibility of the present work in doped sillenites is also proposed.
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