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Photorefractive Effect and Applications

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Optical Computing and Image Processing: Role of Nonlinear Photorefractive Crystals

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SUMMARY

Coherent optical processing plays an important role in various fields of science and engineering, with its numerous applications in optical computing and image processing etc. The real-time implementation of various processing and computing operations are made possible by the use of nonlinear photorefractive (PR) crystals, with their ability to record dynamic volume holograms. In this review article, we present a brief survey of PR wave mixing, PR crystals and their various applications. A wide range of applications are covered. However, the emphasis has been laid on the importance of PR crystals in optical computing and image processing. The general topics covered are; PR effect, two- and four-wave mixings, and materials and their properties. The applications included for discussion are optical phase conjugation, optical interconnects, optical computing, imaging through phase distortions, image amplification, image processing, image convolution and correlation, optical subtraction and addition, and associative memories. Also mentioned in brief are the topics of interferometry, photolithography, novelty filters, multiple image storage, phase locking of lasers, and optical oscillators.

All-optical information processing devices are being investigated in the recent years incorporating photorefractive (PR) materials as the real-time recording media. Optical processors have the inherent capability of processing in parallel, two-dimensional arrays of data. Development of devices incorporating the parallel processing capability of optics and the real-time operation nature of the PR materials have thus revolutionized the activities in optical computing and image processing.

The PR effects allow efficient interactions between light waves leading to a series of nonlinear effects in which light waves can be controlled by other optical beams. This makes the PR materials useful for a series of all-optical devices in optical phase conjugation, light amplification, optical information

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processing and computing, and dynamic holography etc. The whole range of image processing operations has been implemented using PR materials. These include image amplification, image subtraction, addition, multiplication and division, image correlation and convolution, edge enhancement, band pass filtering, pattern recognition, image restoration, image conversion, image transmission and many more. The use of bulk materials and hence the three-dimensional nature of the optical beam interactions within the crystal volume has increased the information processing capacity of the devices.

1. THE PHOTOREFRACTIVE EFFECT

The literal meaning of 'photorefractive effect' is 'a change in the refractive index of a material, caused by light'. Originally, this photoinduced change in refractive index was discovered as undesirable optical damage in nonlinear electro-optic crystals, but later this optical damage effect was effectively applied for holographic recording in electro-optic crystals. Recently, the term 'photorefractive effect' has been used only for such refractive index changes in which incident light produces mobile charge carriers by photoionization, the carriers drift and diffuse, thus forming a local field variation, and the electric field modulates the refractive index of the material through electro-optic (Pockel's linear) effect [Günter 1982a, Solymar et al. 1984, Eichler et al. 1986, Rupp 1987, Günter and Huignard 1988, Feinberg 1988, Pepper et al. 1990].

The photorefractive (PR) effect has been observed in a variety of electro-optic materials including lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$), barium titanate ($BaTiO_3$), potassium niobate ($KNbO_3$), $K(TaNb)O_3$, $Ba_2NaNb_5O_{15}$, strontium barium niobate ($Sr_xBa_{1-x}SrNb_2O_6$), $Bi_{12}(Si, Ge, Ti) O_{20}$, KH_2PO_4, $Ba_{2-x}Sr_xK_{1-y}Na_yNb_5O_{15}$ (BSKNN), $Sr_{2-x}Ca_xNaNb_2O_{15}$ (SCNN), $Pb_{0.57}Ba_{0.43}Nb_2O_6$ (PBN57), barium strontium titanate ($Ba_{1-x}Sr_xTiO_3$) and (Pb, La) (Zr, Ti) O_3 i.e. PLZT ceramics, GaAs, InP, GaP, InAs, CdTe, CdS, CdSe and other compound semiconductors. In principle, any electro-optic material in which light can produce free charge carriers may be photorefractive. Depending on the band-gap of the material and the energy levels of the donor or acceptor levels of the impurity ions involved, the PR effect may be induced by ultra-violet, visible or infrared radiation [Günter 1987].

The photoinduced changes in the refractive index of the electro-optic materials i.e. the PR effect, result from the generation of charges by nonuniform illumination and the transport of photogenerated charges. The generation of photocurrent depends on the presence of suitable donor and acceptor sites inside the material. For the charge transport in PR material, two separate approaches have been formulated. (i) The band transport model [VonderLinde and Glass 1975, Glass 1978] assumes that electrons (or holes) are optically excited from filled donor (acceptor) sites to conduction (or valence) band, where they migrate to dark regions in the crystal by drift or diffusion before recombining into any empty trap. (ii) The hopping model [Feinberg et al. 1980] assumes that the carrier transport occurs via hopping from a filled intrinsic site to a neighbouring empty trap. In both models, the transported charges result in an ionic space charge grating that is, in general, out of phase with the incident

irradiance. Although producing similar results to the band transport model for special cases, such as vanishing charge transport lengths or low mobilities, the hopping model appears to be less general of the two. These models have later been modified to take into account transient effects [Valley 1986a, Heaton and Solymer 1988, Valley and Smirl 1988, Osipov and Sturman 1990], and high modulation depths [Vachss and Hesselink 1988, Au and Solymar 1990] etc.

Recent models of the PR effect assume the presence of shallow traps in addition to deep traps [Tayebati and Mahgerefteh 1991]. The consideration of shallow traps is necessary to explain the experimentally observed light and intensity-dependence of PR grating strength, dark decay of PR gratings [Strohkendl 1989], and intensity dependence of optical absorption [Brost et al. 1988] etc. Cudney et al. [1991] have also established the presence of at least two PR levels in $BaTiO_3$ and also the presence of absorption gratings.

1.1 General properties

The presence of suitable donors or traps in the material and efficient charge migration are necessary for large PR effect [Günter 1982a, Valley et al. 1988]. In undoped crystals, the traps are provided by small traces of impurities. In most of the ferroelectrics, Fe impurities are the most important donor and trapping centers. The dopant acts as a donor-acceptor trap via intervalence exchanges such as $Fe^{2+} \Leftrightarrow Fe^{3+}$ [Clark et al. 1973, Staebler and Philips 1974]. Later studies showed that the simple model of $Fe^{2+} \Leftrightarrow Fe^{3+}$ interconversion cannot explain all phenomena connected with photorefraction and that also other defects such as oxygen vacancies, self-trapped electrons and colour centers play an important role [Kratzig 1978, 1990, Jullien et al. 1990].

The band transport model can describe grating formation in a PR material under the influence of a periodic illumination [Günter 1982a, Günter and Huignard 1988, Valley and Klein 1983]. Upon illumination, there is

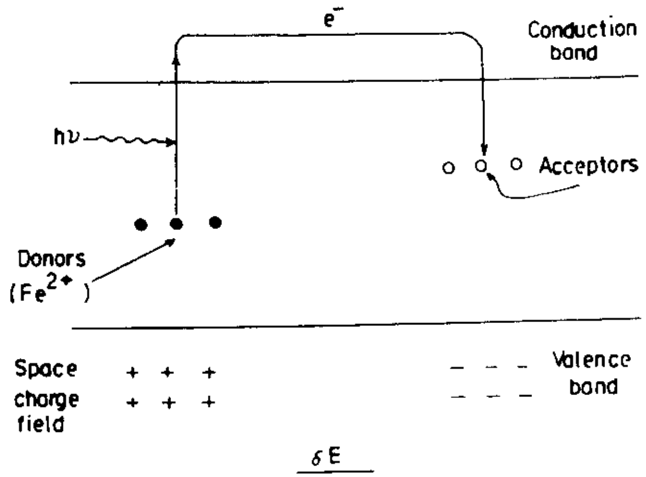


Fig. 1 Space-charge field formation in PR material

photo-ionization (Fig. 1). Photogenerated carriers diffuse and drift in the local electric field and are retrapped, resulting in an ionic space charge grating. The periodic space charge is balanced by a periodic space charge field in accordance with Poisson's equation. This space-charge field modulates the refractive index through electro-optic effect (Fig. 2). The movement of the photoexcited free carriers can be affected by three different mechanisms: diffusion, drift (when

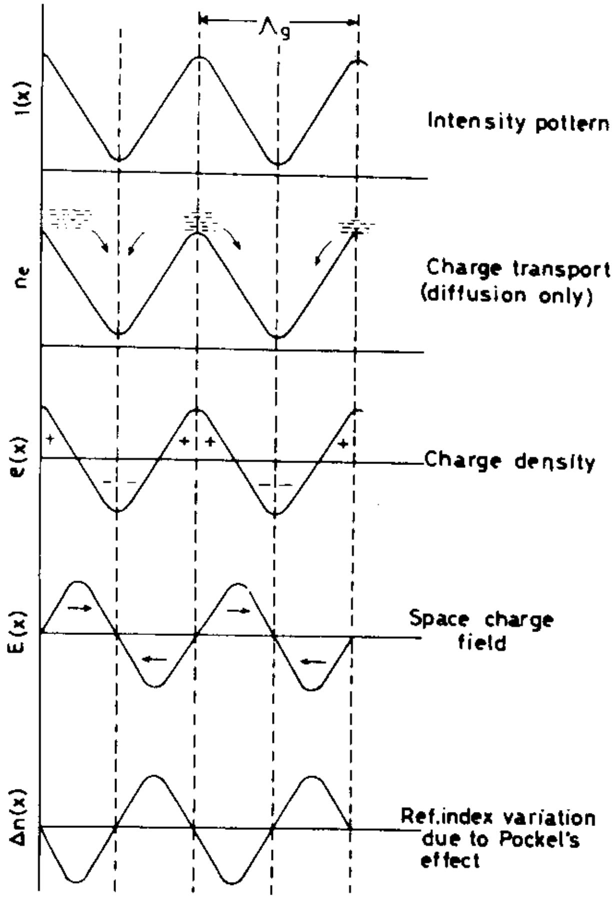


Fig. 2. Buildup of refractive index modulation (After Fisher 1983, p. 422)

an electric field is externally applied) and the photovoltaic effect. In the diffusion case, i.e. with no externally applied electric field, the resulting space charge electric field distribution E_{sc} is shifted in phase by $\pi/2$ with respect to the light intensity. In the drift case, displacement of the electron distribution is achieved by static electric field. The spatial modulation of free carrier density results in a space-charge electric field which is shifted in phase relative to the incident irradiance. In photovoltaic effect, photoelectrons are excited into the

charge transfer band with a preferential direction of the velocity along the direction of the polar axis [Günter and Huignard 1988, 1989].

1.2 Hologram Formation

The formation of hologram in the PR material results from the interference of two coherent beams inside the material. In the basic geometry (Fig. 3) the

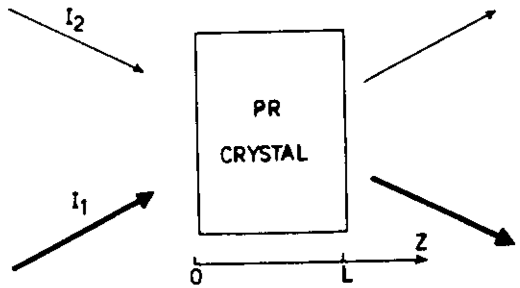


Fig. 3. Two-wave mixing geometry

interference of a reference wave I_1 and signal wave I_2 produces the resulting refractive index modulation through the PR effect. The incident optical irradiance due to interference is of the form,

$$I = I_0(1 + m\cos K_g z) \tag{1}$$

where m is the modulation index, K_g is the grating wave number and I_0 is the average irradiance. For two copolarized input waves of irradiances I_1 and I_2

$$m = 2(I_1 I_2)^{1/2}/(I_1 + I_2) \tag{2}$$

The index change Δn caused by a space-charge field is given [Günter 1982a, Ewbank et al. 1987, Günter and Huignard 1988] by

$$\Delta n = 1/2n^3 r_{eff}\delta E \tag{3}$$

where n is the background refractive index and r_{eff} is the effective electro-optic coefficient.

The steady-state index change reached is given by,

$$\Delta n_{ss} = 1/2\, n^3 r_{eff} m E_{sc} \tag{4}$$

The space-charge electric field E_{sc} is given [Kukhtarev et al. 1979a, b, Valley 1987, Kukhtarev 1988] by

$$E_{sc} = E_Q \left| \frac{E_O^2 + E_D^2}{E_O^2 + (E_D + E_Q)^2} \right|^{1/2} \tag{5}$$

The phase shift between I and δE in the steady state is given by

$$\tan\phi = \frac{E_D}{E_Q}\left|1 + \frac{E_D}{E_Q} + \frac{E_O^2}{E_D E_Q}\right| \qquad (6)$$

with,

E_O = applied electric field

$E_D = 2\pi k_B T/\Lambda_g e$, the diffusion field

$E_Q = e\,\Lambda_g N_E/2\pi\varepsilon$, is the maximum amplitude of the electric field that can be obtained in a material in which the trapped charge density is N_E. e is the charge of the electron, Λ_g is the grating period of the optical interference pattern, ε is the dielectric constant of the material, K_B is the Boltzman constant and T is the absolute temperature.

The diffraction efficiency η which is the ratio of the diffracted intensity to the incident intensity is given by,

$$\eta = \exp(-\alpha L)\sin^2(\pi\Delta n L/\lambda) \qquad (7)$$

where λ is the wavelength of radiation and L is the interaction length, α being the linear absorption coefficient.

Diffraction of an incident beam from thick holograms has been studied through coupled wave theory by Kogelnik [1969]. The coupled differential equations as derived by Kogelnik were based on the diffraction process from fixed (nonerasable) gratings (Diffraction of interfering beams themselves from the formed dynamic volume holograms leads to energy transfer between the beams). Kogelnik theory was later used to estimate the diffraction efficiency from dynamic gratings in PR crystals [Staebler and Amodei 1972a, Magnusson and Gaylord 1976]. 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 [Moharam and Young 1977, Kukhtarev et al. 1979 a, b, Vinetskii et al. 1979].

The readout of hologram recorded in a BSO type crystal with a beam of wavelength even far from the region of strong absorption can lead to a distortion of the holographic gratings. In such cases of high intensity readout, the classical Kukhtarev model does not hold good. Rustamov [1991] proposed a two-level model, which considers the involvement of luminescent levels into optical transitions allowing the distortion of holographic gratings. Investigations on the diffraction efficiency of strong volume holograms have been done by Hong et al. [1990]. In this case the diffraction efficiency is a periodic function of the index perturbation amplitude-thickness product.

Zhivkova and Miteva [1990] studied the formation and behaviour of holographic gratings in sillenite crystals especially in BTO with simultaneous involvement of electron and holes. The formation of a compensated positive charge grating gives rise to a fixing process which is exploited for image subtraction, edge enhancement, intensity inversion operations etc., and for a

holographic interferometric microscope [Tontchev et al. 1990, Zhivkova and Miteva 1991].

2. WAVE MIXINGS IN PR CRYSTALS

The ability of PR materials to transform an interference pattern into a refractive index pattern with nonlocal response has led to efficient coupling between the interfering beams. Two- and four-wave mixings are the most efficiently used wave mixing techniques with their wide ranging applications in dynamic holography, information storage, parallel signal processing, real-time image processing, phase conjugation, and optical resonators etc.

2.1 Two-wave mixing and self-diffraction

Beam coupling in two-wave mixing (TWM) results from the process of self-diffraction. In self-diffraction, the processes of writing and reading happen simultaneously. When the interfering beams propagate through the self-induced refractive index grating, they undergo Bragg scattering [Yeh 1989]. One beam scatters into the other and vice versa. The occurrence of a phase shift of $\pi/2$ between the intensity pattern and the ref. index pattern in PR media (i.e. nonlocal response) and an additional phase shift of $\pi/2$ which occurs during the diffraction on a phase grating [Kogelnik 1969], allows the amplification of one beam at the expense of the other [Staebler and Amodei 1972 a, b]. However, in the transient case, energy transfer in two-wave mixing is possible in local as well as nonlocal response media. This comes due to the occurrence of phase shift during the hologram formation [Kukhtarev et al. 1977, 1980, Odoulov and Soskin 1989]. The self-diffraction and energy transfer from one beam to the other occurs when the angle between the beams is large enough or the grating spacing is small [Marrakchi et al. 1986]. For small interaction angle, new waves in the form of higher diffraction orders are generated [Eichler et al. 1987, Sanchez et al. 1988, Au and Solymar 1988 a,b, 1990, Khoo et al. 1989, Roy and Singh 1992]. Experimental studies have been carried out by Erbschloe et al. [1989] of transients in higher diffracted orders in a BSO crystal. The interaction of the principle waves produces higher-order waves and their presence forms further gratings which assist power transfer between the principle beams. Erbschloe et al. (1988) also studied TWM in reflection holograms.

The signal amplification process is commonly expressed in terms of the PR gain [Rak et al. 1984, Klein and Valley 1985], the measurement of which is done using the geometry shown in Fig. 3. The amplification of the signal beam I_2 is due to its interference with a reference beam I_1 inside a PR material and the consequent energy coupling due to diffraction of reference beam from the photoinduced grating. The crystal c-axis needs to be oriented appropriately to provide maximum gain for the signal beam I_2 [Fainman et al. 1986a]. The signal beam gain is given by,

$$\frac{I_2(L)}{I_2(O)} = \frac{[I_2(O) + I_1(O)]\exp\{(\Gamma - \alpha)L\}}{I_1(O) + I_2(O)\exp(\Gamma L)} \qquad (8)$$

For negligible depletion of the pump (reference) wave $[I_2(O) \exp(\Gamma L) << I_1(O)]$,

$$I_2(L) = I_2(O) \exp\{(\Gamma - \alpha) L\} \quad (9)$$

Quantitative measurements on signal beam gain are generally made in terms of effective gain

$$\gamma = \frac{I_2(L) \text{ with reference beam}}{I_2(L) \text{ without reference beam}}$$

$$= \frac{(1 + \beta) \exp(\Gamma L)}{[1 + \beta \exp(\Gamma L)]} \quad (10)$$

where $\beta = I_2(O)/I_1(O)$ is the incident beam intensity ratio. The exponential gain coefficient Γ is related to the maximum value of the index modulation due to the PR effect as,

$$\Gamma = 4\pi \Delta n/\lambda \quad (11)$$

Deriving the two interacting beam intensities from the charge transport and coupled wave equations, the expression for gain coefficient Γ in terms of the space-charge field can be obtained [Kukhtarev et al. 1979a,b] as,

$$\Gamma = (2\pi/\lambda) n^3 r_{eff} E_{sc} \quad (12)$$

The beam coupling process due to PR effect can be used for measuring fundamental material properties. The specific advantage of the PR effect for such measurements is that it can be used to generate internal electric fields without the use of contacts. In the simple TWM geometry, a knowledge of the polarity of the crystal c-axis and the energy transfer direction yields the sign of the dominant charge carriers [Feinberg et al. 1980]. Observations on steady state beam coupling can be used to measure the concentration of empty traps, electro-optic coefficient, fractional poling of the crystal, relative conductivity, Debye length, and charge carrier mobility etc. [Ducharme and Feinberg 1984, Klein and Valley 1985, Pierce et al. 1990, Pauliet et al. 1990].

Theoretical analysis of the energy coupling between the incident beams considering the different possible experimental conditions, are done through the derivation of the coupled wave equations [Kogelnik 1969, Staebler and Amodei 1972a, Vahey 1975, Günter and Huignard 1989].

$$dI_1/dz = -2\Gamma (I_1 I_2)/(I_1 + I_2) - \alpha I_1 \quad (13)$$

$$dI_2/dz = +2\Gamma (I_1 I_2)/(I_1 + I_2) - \alpha I_2 \quad (14)$$

The nonlinear coupled wave equations are analytically solvable in the simple cases (e.g. small beam coupling, similar polarization and no absorption loss etc.). However, a solution through numerical analysis could be necessary for solving the coupled wave equations for considering complex experimental situations [Ja 1982, Roy and Singh 1990]. Ja [1982-1988] and Das and Singh

[1989-1991] have made several attempts to make numerical solutions more simple and well fitting to the experimentally expected values. One main advantage of using the numerical techniques is that no special conditions such as low beam coupling, non-depleting beams and non-absorbing materials need be assumed. Also, intensity-dependent coupling [Das and Singh 1990a] and many-grating mechanisms [Das and Singh 1989, 1990b] can be safely incorporated. Recently Lee (1991) made a detailed numerical calculation on the two-beam coupling gain in $BaTiO_3$ crystal.

It has been established theoretically [Yeh 1987, 1988] and verified experimentally [Cheng and Yeh 1988, Chang et al. 1988] that the PR semiconductors such as GaAs and InP can provide cross-polarization coupling effects for a wide range of beam geometries. Competitive effects of cross and parallel coupling have been studied by Roy and Singh [1990a,b] in degenerate TWM. It has been found that the presence of parallel coupling suppresses the cross coupling effect to a large extent and vice versa. The output polarization can be modified by the proper choice of input polarizations. TWM gain in PR media can be controlled by the use of a biasing illumination [Roy and Singh 1990c, d].

2.2 Four-wave mixing and phase conjugation

The degenerate four-wave mixing (DFWM), which generally is the basic geometry for the generation of an optical phase conjugate (OPC) wave, [Hellwarth 1977, Yariv and Pepper 1977, Feinberg and Hellwarth 1980, Cronin-Golomb et al. 1984] is shown in Fig. 4. In this case for the simultaneous self-diffraction of the incident beams, the phase shift required for energy transfer arises automatically even in locally nonlinear media. In the degenerate backward FWM, two collinear pump beams 1 and 2 enter a nonlinear sample from opposite sides. The nonlinear mixing of these waves with a signal wave 4 generates the phase conjugate wave 3 [Pepper 1982].

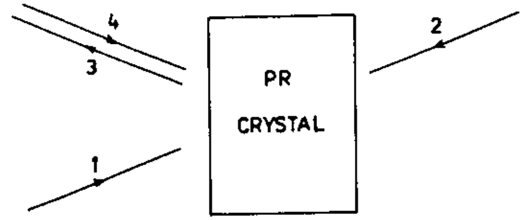


Fig. 4. Four-Wave mixing geometry

OPC can be realized through other processes such as stimulated Brilluoin scattering (SBS) [Zel'dovich 1985], stimulated Raman scattering (SRS) and photon echoes [Pepper 1982, Fisher 1983, Shen 1984] and also via three-wave mixing. The three-wave mixing process as proposed by Yariv [1976] has the inherent problem of serious phase matching condition which limits its practical use. SBS, SRS and photon echoes processes require high power lasers for the generation of PC waves and the output is not a true PC of the input field due to the inherent frequency shift. The process of degenerate FWM as proposed by Hellwarth [1977] produces PC with low power lasers, it is automatically phase matched and it produces exact conjugate of the input field [Zel'dovich 1985, Fisher 1983]. In the holographic analogue [Yariv 1978a, b], the fourth wave is generated due to diffraction of one of the pump beams from the photoinduced gratings formed by the other two beams [Giuliano 1981, Fisher 1983, Pepper 1982]. The gratings of importance are the two transmission gratings formed between 1 and 4 and 2 and 3 beams and two reflection gratings formed between 2 and 4 and 1 and 3.

Phase conjugation via FWM has been investigated quite extensively by many researchers especially in nonlinear media with local response. These nonlinear media include CS_2, Na vapour, SF_6, different polymers such as polydiacetylenes and polyphenylacetylenes [Blau 1987], organic dyes [Fisher 1983, Flytzanis 1983, Ravindrakumar et al. 1989], liquid crystal light valves [Marom and Efron 1987], and liquid crystals [Khoo 1986, Khoo and Liu 1987]. FWM has also been used as a tool for studies on the third-order susceptibilities of the nonlinear materials [Chemla and Zyss 1987, Reintjes 1984, Kobayashi 1989].

The increased interest in FWM using the PR materials is because, the PC reflectivities that can be achieved using PR materials are quite high, and there is low power level operation. Earlier works on OPC by DFWM in PR materials were done in BSO [Huignard et al. 1979, 1980], $LiNbO_3$ and $LiTiO_3$ crystals [Kukhtarev and Odulov, 1980]. Later, the whole range of PR materials has been examined for the generation of PC waves by DFWM. Highly efficient PR materials such as $BaTiO_3$ and SBN can work as self-pumped phase conjugators (SPPC). In SPPC the pump beams for FWM are not to be supplied externally, rather they are self-generated inside the crystal itself or within a cavity. The SPPC has been demonstrated in PR materials using a variety of geometries. PC mirrors via DFWM and SPPC find applications in image processing, interferometry, image transmission, and optical computing etc. [Giuliano 1981, Fisher 1983, Pepper 1985, Lindsay and Dainty 1986, Lindsay 1987, Chang and Sato 1987, Günter and Huignard 1989, Dunning and Giuliano 1990, Dunning et al. 1991].

Earlier demonstrations of the SPPC used external mirrors for the self-generation of pump beams via stimulated amplified scattering (beam fanning) [Feinberg 1982, White et al. 1982, Cronin-Golomb et al. 1982]. A ring configuration for the SPPC was demonstrated by Cronin-Golomb et al. [1983]. By proper alignment of the crystal with respect to the incident beam, the interacting beams can be contained within the crystal by total internal reflection from the crystal faces themselves. Such self-contained SPPC has been studied by Feinberg [1982b], Jahoda et al. [1984], Kwong et al. [1984], Lam [1985], Kwong and Yariv [1986], Goff and Brody [1988], Chang et al. [1988], Venkateshwarlu et al. [1989, 1990] and many others. Phase conjugation of two beams which are mutually incoherent can be done through double phase conjugators (DPC) [Sternklar et al. 1987, Smout and Eason 1987, Ewbank 1988, Yeh et al. 1988a, Statman and Liby 1989, He and Duthie 1990, Tikhonchuk et al. 1991]. Eason and Smout [1987] have studied bistability and noncommutative behaviour of multiple-beam self-pumping in $BaTiO_3$. Studies by Honda and Matsumoto [1991] on a $BaTiO_3$ SPPC mirror for two mutually coherent beams showed that the time response of such a PC mirror is much shorter than the rise time of PC wave.

On the theoretical front, the FWM process and the generation of PC waves have been investigated by many, on the basis of coupled wave analysis [Kogelnik 1969]. The intensity changes of the interacting beams for the cases of transmission and reflection gratings can be derived by solving the coupled wave equations [Kukhtarev and Odulov 1980, Cronin-Golomb et al. 1984, Peterson and Johanson 1988, Roy and Singh 1991a, b].

The optimization of the wavefront reflectivity or PC reflectivity (PCR) depends on different experimental conditions and the material properties. Experimentally an enhanced PCR has been realised with moving interference fringes [MacDonald and Feinberg 1985, Goltz et al. 1988a] or with tilted pump waves [Denz et al. 1989]. The use of orthogonally polarized pumps in DFWM [Kong et al. 1988, Stepanov and Petrov 1988] can result in a high PCR with a smaller coupling length [Shaw and Cronin-Golomb 1988, 1989, Bledowski and Krolikowski 1988]. Bistability and multistability in DFWM (Bledowski et al. 1986, Das and Singh 1991a, Odoulov et al. 1991] are important aspects for PR PC device applications.

Many-grating mechanism cannot be avoided in geometry of the SPPC. A careful choice of the amplitudes of all the relevant gratings may sometimes improve the reflectivity [Krolikowski 1986, Krolikowski and Belic 1988, Das and Singh 1989]. Asymmetric configuration (i.e. non equal angles of incidence) of the DFWM may be a common experimental situation and if the angles of incidence are altered, the coupling parameters and at the same time absorption of the interacting beams will be modified. As a result the PC wave generation will differ from the usual symmetric configuration [Das and Singh 1990c]. Similar to the case of TWM, intensity-dependent coupling effects in DFWM predict some adverse features in the PC signal [Das and Singh 1990a]. Angle-dependence of the PCR in the two-grating operation is strongly nonlinear and establishes a beneficial influence over the single grating case [Das and Singh 1990e]. Influence of cross polarization coupling effects on the PCR in transmission and reflection types of DFWM has been studied for the case of PR semiconductors such as GaAs and InP etc. by Roy and Singh [1991].

3. PHOTOREFRACTIVE MATERIALS AND PROPERTIES

PR effect has been noticed and studied in detail in wide ranging classes of electro-optic materials. The dominant classes include ferro-electric oxides, cubic oxides of sillenite family and semi-insulating compound semiconductors. Most of the work towards the understanding of the effect has been concentrated on oxygen-octahedra ferroelectrics, mainly because of their larger electro-optic effects. In fact $LiNbO_3$ is the material in which the 'PR effect' in the form of an 'optical damage' was discovered for the first time. The ferro-electric oxides such as $BaTiO_3$ and $LiNbO_3$ etc. have large electro-optic coefficients but are very slow in response. The sillenites such as $Bi_{12}SiO_{20}$ and $Bi_{12}GeO_{20}$ have smaller electro-optic coefficients but they have relatively fast response. The compound semiconductors such as GaAs and InP have electro-optic coefficients similar in magnitude to the sillenites. They are near the theoretical limit in sensitivity, but the present materials are mostly sensitive in the near IR only [Valley et al. 1988].

The requirements associated with the PR materials have been (i) presence of sufficient density of deep levels to create a space-charge field and (ii) lack of an inversion center of symmetry leading to a Pockels electro-optic effect. While choosing an electro-optic material for the PR applications, the important material requirements which are to be taken into account are, PR sensitivity [Johnson and Tanguay 1989], dynamic range (maximum refractive index change) and the response time [Valley and Klein 1983, Cronin-Golomb 1991]. Depending on the experimental situations, the other requirements are the spatial frequency and electric field dependence, wavelength range, and resolution etc. The formation of PR gratings and the self-diffraction are very much influenced by the electron-hole competition during the illumination of the material [Valley 1986a, Bernado et al. 1990].

The PR sensitivity tells how efficiently a material uses given amount of optical energy. A figure of merit for characterizing the PR sensitivity of material describes energy needed to give one percent diffraction efficiency for 1 mm thick material. This is mainly useful in hologram storage applications. The dynamic range of a phase storage medium is its maximum possible photoinduced change of the refractive index. It determines the highest diffraction efficiency that can be given by a crystal of a given thickness, and the number of different holograms that can be recorded in a given volume.

Response time is a useful figure of merit for applications in which the available energy limits the illumination time, or in which the grating is to be written or erased in a set time scale. The response time of a PR material depends not only on illumination intensity but also on the interference fringe spacing. According to the widely used results of Kukhtarev [1977], the grating formation time is expected to be inversely proportional to the laser intensity. However, experiments performed on $BaTiO_3$ have shown that the response time varies sublinearly with intensity [Ducharme and Feinberg 1984]. Brost and Motes [1990] have explained this sublinear dependence of response time on the basis of secondary PR centers. Experimental studies showed that for BSO, the response time increases with decrease of grating spacing [Mullen and Hellwarth 1985], while for $BaTiO_3$ the behaviour is opposite [Feinberg et al. 1980]. The difference between characteristics is interpreted in terms of the difference in the diffusion length [Hirao and Sawada 1991]. To improve the response time of PR materials, the methods employed are: increased intensity, higher temperature [Rytz et al. 1988] and applied electric fields [Sayano et al. 1990].

3.1 Ferroelectric oxides

Ferroelectric oxides are the most thoroughly studied of all the PR materials. These studies have been concentrated on $LiNbO_3$, $LiTaO_3$, $KTa_{1-x}Nb_xO_3$ (KTN), $BaTiO_3$, $KNbO_3$, $Sr_{1-x}Ba_xNb_2O_3$ (SBN), $Ba_2NaNb_5O_{15}$ (BNN) and $Ba_{2-x}Sr_xK_{1-y}Na_yNb_5O_{15}$ (BSKNN), largely for their holographic recording capabilities [Neurgaonkar et al. 1987, 1990]

Commonly, ferroelectric oxides are most sensitive at the visible wavelengths. Their linear and nonlinear dielectric properties are inherently temperature-dependent because of their ferroelectric nature. As materials are cooled below their melting point, they undergo a structural phase transition to a ferroelectric phase [Lines and Glass 1977]. Additional transitions may occur in the ferroelectric phase upon lowering the temperature further. A poling process is generally done to obtain a single domain crystal for the most efficient use of the electro-optic properties of the ferroelectric oxides.

Lithium niobate

Lithium niobate is the most extensively studied of all the electro-optic materials mainly because of its important applications as an electro-optic modulator. From room temperature to the Curie temperature T_c = 120°C, the point group symmetry of $LiNbO_3$ is 3 m. During the preparation the most commonly used dopant is Fe [Kratzig and Kurz 1977]. It enters the lattice either as Fe^{2+} or Fe^{3+}. If the PR process, the Fe^{2+} ions are occupied traps and the Fe^{3+} ions are empty traps. The relative Fe^{2+}/Fe^{3+} population ratio will determine the electron and hole contribution to photoconductivity and they determine the PR behaviour of the crystals [Orlowski and Kratzig 1978, Kratzig and Orlowski 1980, Odoulov et al. 1985].

$LiNbO_3$ is well suited for holographic storage [Staebler and Amodei 1972b, Staebler and Philips 1974], with storage times exceeding one month. Its PR sensitivity is relatively small and its response time is relatively long. The PR response characteristics of the material are largely influenced by doping. Most influential dopants are Fe [Clark et al. 1973, Kratzig 1978] and Mg [Arizmendi et al. 1987, Feng et al. 1990].

Barium titanate

The very large optical nonlinearities which can be obtained in barium titanate because of the very large value of its electro-optic tensor component r_{42}, makes it a particularly advantageous crystal for the PR applications [Townsend and Lamacchia 1970, Feinberg et al. 1980, Chang and Hellwarth 1985, Klein and Schwartz 1986]. This large value of r_{42} leads to large values of grating efficiency, beam coupling gain and FWM reflectivity.

$BaTiO_3$ is a member of the perovskite family of ABO_3 compounds [Lines and Glass 1977]. Top seeded solution growth (TSSG) is the technique widely used for the growth of $BaTiO_3$ crystal samples for PR purposes. $BaTiO_3$ has the prototype cubic perovskite structure (point group m3m) above 120°C. In the cubic phase its structure is a simple one with Ba^{2+} ions at the cube corners, Ti^{4+} ions at the body centers and O^{2-} ions at the face centers (Fig. 5). Many of the dielectric and optical properties of $BaTiO_3$ are determined by the characteristics of the basic TiO_6^{8-} octahedron. Below 120°C it transforms successively to three ferroelectric phases: first to 4 mm tetragonal, then to mm2 orthorhombic at about 9°C and finally to a 3 m trigonal phase below – 90°C [Klein 1988].

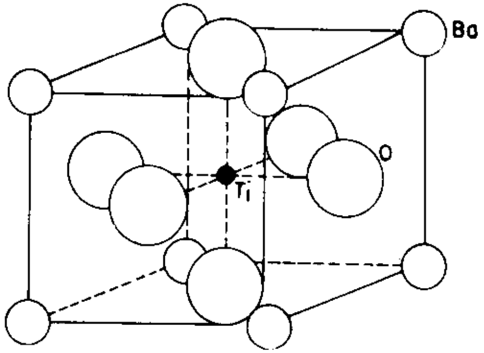


Fig. 5 $BaTiO_3$ unit cell

The cubic tetragonal phase transition near 120°C is a displacive one, the most important change being a shift of the Ti^{4+} ion from the center of the octahedron towards an oxygen ion at one of the face centers of the cubic unit cell. This shift produces a spontaneous polarization in the direction of motion. The polar nature of $BaTiO_3$ leads to a variety of well-known properties, including the piezo-electric effect, the pyro-electric effect, the electro-optic effect and second harmonic generation. The reversibility of polarization in $BaTiO_3$ leads to its ferroelectric properties.

To exploit the electro-optic effects in a $BaTiO_3$ crystal a single domain crystal is necessary, which is achieved through the process of poling [Wemple et al. 1968]. Poling techniques involve application of mechanical and/or electrical fields and often require several stages to achieve the single domain state.

The origin of the PR effect in $BaTiO_3$ i.e., the exact nature of the microscopic centers responsible for the effect, is still not perfectly understood. The main experimental difficulty regarding this problem is in controlling the doping of single crystal of $BaTiO_3$ [Schunemann et al. 1988, Burns et al. 1990]. Studies on the PR properties of $BaTiO_3$: Co by Rytz et al. [1990] have shown that a high PR gain is achieved due to Co doping.

For beam coupling experiments in PR $BaTiO_3$ crystal, the largest electro-optic coefficient r_{42} is exploited and the maximum gain is obtained by using an extraordinary polarized input beam. However, recently James and Eason [1991] conducted experiments on self-pumped (CAT) phase conjugator in $BaTiO_3$ and showed that for certain input geometries it is possible to double the PCR by the inclusion of an ordinary-polarized component in the input beam.

While studying the response time of the PR effect in $BaTiO_3$ at elevated temperature, Kirilov and Feinberg [1991] discovered that, in addition to the usual PR grating caused by the light-induced migration of holes in the crystal, a second grating appeared and was especially noticeable at temperatures above 80°C. This second grating persisted after the crystal was cooled to room temperature and then it could not be erased by light. Lam et al. [1984] have studied the formation of PR gratings in $BaTiO_3$ using nanosecond pulses.

Dielectric and electro-optic properties $BaTiO_3$

The PR performance of $BaTiO_3$ is significantly influenced by its dielectric and electro-optic properties [Ducharme et al. 1987]. $BaTiO_3$ at room temperature is in a tetragonal phase with uniaxial optical and dielectric behaviour. The large values of the electro-optic tensor components in $BaTiO_3$ are responsible for its high beam-coupling coefficient. The relatively long time constants in $BaTiO_3$ are partially the result of the high values of dielectric constant. The response time of $BaTiO_3$ is strongly temperature-dependent [Rytz et al. 1988]. The PR effect and absorption of $BaTiO_3$ are found to be intensity-dependent giving rise to some anomalous behaviour in the coupling process [Klein and Valley 1985, Motes and Kim 1987a,b, Motes et al. 1988]. The speed of PR effect in $BaTiO_3$ is found to have a sublinear dependence on the intensity of incident light [Ducharme and Feinberg 1984].

Some of the important dielectric and electro-optic properties of $BaTiO_3$ are listed in Table 1.

Table 1.

Parameter	$BaTiO_3$	BSO
Background index, n	2.4	2.5
Dielectric constant, ε	4300 (ε_{11}) 168 (ε_{33})	56
Electrooptic coefficient, r_{ij} (pm/V)	1640 (r_{42}) 80 (r_{33})	5 (r_{41})
Donor number density, N_D (cm^{-3})	–	10^{19}
Trap number density, N_A (cm^{-3})	2×10^{16}	10^{16}
Photoionization cross- section, S (cm^{-2})	5×10^{-8}	1.6×10^{-19}
Recombination coefficient (cm^3/s)	–	2×10^{-11}
Mobility, μ (cm^2/V s)	0.5	0.03

Strontium barium niobate and Potassium niobate

PR strontium barium niobate ($Sr_xBa_{1-x}Nb_2O_6$ or SBN) is an attractive material for PR applications because of its large r_{33} electro-optic coefficient [Voronov et al. 1980, Ducharme et al. 1987, Liu et al. 1987, Neurgaonkar and Cory 1986, Sayano et al. 1989a, b, c]. It is a ferroelectric with the tungsten bronze structure. SBN is a mixed crystal in which the temperature for transition to the ferroelectric tetragonal phase can be adjusted linearly with concentration; when x varies from 0.25 to 0.75, T_c decreases from 200°C to 60°C. At room temperature SBN has a tetragonal symmetry with point group 4 mm. Its PR applications are similar to that of $BaTiO_3$ [Wood et al. 1987, Ewbank et al. 1987, Redfield 1988, Rytz et al. 1989, Sayano et al. 1990, Neurgaonkar et al. 1990, Vazquez et al. 1991].

In the quest for new efficient PR materials, $KNbO_3$ has received considerable attention in the recent years [Zgonik et al. 1991, Polzib and Kimble 1991]. $KNbO_3$ has been investigated for its PR properties as an undoped material [Medrano et al. 1988] and when doped with Fe and Mn [Günter and Micheron 1978, Günter 1982b, Zha and Günter 1985]. Recently, Clement and Gilbreath [1991] have studied for PR effect in tantalum doped $KNbO_3$. The magnitude of r_{42} coefficient (~ 380 pm/V) in $KNbO_3$ is low compared to $BaTiO_3$. However, $KNbO_3$ has the advantage of potentially offering larger apertures.

3.2 Sillenite Family Crystals [$Bi_{12}(Si,Ge, Ti)O_{20}$]

These materials are paraelectric, electro-optic and photoconductive. In the absence of an applied electric field they are optically isotropic with point group symmetry 23. With the application of an electric field, the crystal becomes birefringent. These crystals are strongly optically active ($\rho_0 = 45°\ mm^{-1}$ at $\lambda =$ 514.5 nm for BSO) [Huignard and Micheron 1976, Herriau et al. 1978, Herriau et al. 1985].

In the PR experiments, the electrons are shown to be the photo induced carriers in BSO. The beam coupling and the diffraction efficiency are strongly dependent on the crystallographic axes [Günter 1982a]. Two optimum geometries have been found for each effect [Marrakchi and Huignard 1981, Herriau and Huignard 1986]. One gives a maximum diffraction efficiency and the other gives better beam-coupling which is useful for light amplification and OPC. In sillenites, photoconductivity is n-type and dark conductivity is p-type. The linear electro-optic effect in the sillenites is characterized by three equal coefficients r_{41}, r_{52} and r_{63}. Table 1 gives some of the important dielectric and electro-optic properties of BSO.

Because of the low electro-optic coefficients, the beam coupling efficiency in the diffusion case is very small in sillenites [Ja 1982a]. Hence, in PR sillenites, a technique which employs an externally applied electric field (drift case) and moving the fringe pattern at a constant velocity, is used [Huignard and Marrakchi 1981a, b, Stepanov et al. 1982, Valley 1984, Refregier et al. 1985, Huignard 1987, Harriau et al. 1987, Kawata et al. 1990, Walsh et al. 1990]. In a TWM configuration, such a displacement increases the amplitude of the $\pi/2$ phase-shifted component of the index modulation, and therefore an efficient energy transfer from the reference beam to the low intensity probe beam can be obtained [Rajbenbach et al. 1983]. Application of an ac electric field can also lead to enhancement in beam coupling [Stepanov and Petrov 1985, Gan et al. 1988, Imbert et al. 1988, Ghosh et al. 1989].

To enhance the two-beam coupling interaction in PR crystals, Mathey et al. [1991] applied pulsed electric field to a photorefractive BGO crystal. In this gain enhancement technique, the maximum gain is not limited by the crystal PR trap density. Due to the inherent optical activity and electric field induced birefringence in sillenite crystals, polarization of the interfering beams is a factor of importance in wave mixing experiments [Sakai 1988]. Polarization properties of self-diffraction and that of wave mixing under alternating electric field have been studied by Marrakchi et al. [1987] and Pauliat et al. [1989] respectively. Sawada and Ujihara [1989] studied the influence of optical activity on PC in a BSO crystal.

The origins of the PR and photoconductive effects in these crystals are still under investigation. Recently Attard [1991] has made a thorough investigation into this aspect. His observations combined with the previously reported observations of photoconductivity, photoresistivity, photosensitivity and mobility modulation, a model theory of transport has been developed that requires multiple sources of defect/impurity energy levels. It is observed that much of the phenomena in BSO can be explained through interaction between the multiple defect/impurity energy levels.

3.3 Compound semiconductors

Semiconductor materials such as GaAs, GaAs:Cr, InP, InP:Fe, CdS, SbSi, GaAs, and CdTe etc. have been shown to produce PR effects [Klein 1984, Glass et al. 1984, Valley et al. 1986b, Glass and Strait 1988, Fabre et al. 1988, Rajbenbach et al. 1989a]. These materials have good photoconductivities due to large carrier mobilities, are very photosensitive, and show fast recording speed in the near infrared wavelength range from 0.95-1.35 μm. However, the electro-optic coefficients are rather small and therefore the photoinduced refractive index changes are relatively small.

While the sensitivity of the PR semiconductors is many times that of PR oxides, the small value of the Pockel's electro-optic coefficient in semiconductors results in small values of beam coupling gain coefficient and diffraction efficiency under diffusion recording conditions. In order to compensate for the small electro-optic coefficients and to achieve larger gain coefficients, researchers have investigated many methods of increasing the magnitude of the PR space charge field. Various techniques such as application of an external electric field [Albanese et al. 1986, Liu et al. 1988], moving grating technique [Kumar et al. 1987a, Imbert et al. 1988], application of an electric field [Kumar et al. 1987b, Klein et al. 1988] and use of a temperature dependent resonance [Picoli et al. 1989] have been used. To enhance the two-beam coupling gain in InP:Fe crystal, Mainguet [1988] applied a dc electric field of 8 kV/cm and the method by Gravey et al. [1989] involved Peltier cooling technique and applying a dc electric field of 10 kV/cm. Ozkul et al. [1990, 1991] obtained very high gain in InP:Fe crystal by controlling the temperature of the crystal and applying an external dc field, by using an auxiliary incoherent beam and also by using a negative thermal gradient.

Electron and hole mobilities in semiconductors are much larger than in the oxides. Hence, the dark conductivity, which is proportional to the mobility, is much larger and dark decay times are shorter. Because of this, the compound semiconductors are not useful for long term holographic storage. Large mobilities give rise to very large PR sensitivity which is near the theoretical limit in semiconductors, because charge carriers can diffuse or drift many grating periods before recombination. Currently, research work in semiconductor PR materials centers on the following areas: [Albanese et al. 1986, Valley et al. 1986b, Kumar et al. 1987a, b, Smirl et al. 1988] (a) moving grating and ac field techniques to enhance the nonlinearity of existing materials (b) doping techniques to increase the donor/acceptor/trap density (c) picosecond pulse observations that take advantage of the large mobility and hence short diffusion time and (d) use of the effect to measure properties of the materials.

Recently, Partovi and Garmire [1991] have investigated the PR effect in semiconductors near the band edge. Application of an electric field will change the refractive index of the material near the band edge, which is called electrorefraction. The space-charge field generated in PR semiconductors through the usual drift and diffusion processes with the participation of deep levels to form electro-refractive gratings to obtain electrorefractive-photorefractive (ERPR) effect. This method has the additional advantage that in the proper geometry, the conventional electro-optic grating can also add to eletro-refractive grating to result in larger nonlinearities.

4. APPLICATIONS OF WAVE-MIXING IN PR MATERIALS

4.1 Optical phase conjugation (OPC)

OPC has been the subject of intense investigation over the past decade for applications such as lensless imaging, precision pointing and tracking, laser resonators, image processing and imaging through fibers etc. PR crystals have been the most widely used materials for the OPC applications. However, the poor performance of PR systems with respect to output image fidelity and response time has hindered the development of useful devices. Another importance of the PC is due to its simultaneous amplification and energy transfer between two mutually incoherent beams. The current research in the area of phase conjugation is mainly concentrated on the areas of, (i) imaging through phase distortions such as fibers, (ii) high fidelity PC, (iii) fast response time in PC, (iv) double PC (DPC) and SPPC and (v) optical processing and computing.

The fidelity of OPC [Fleck and Kiessling 1991] is an important factor for its various applications. The use of diverging pump beams and nonstationary recording of gratings, for high fidelity image amplification and PC in a BSO crystal has been demonstrated by Vainos and Gower (1991). They could obtain wide-angle, large space-bandwidth product coherent image amplification with a flat spatial frequency response. Studies on the fidelity fluctuations in a stimulated Brillouin scattering PC have been done by Ottusch and Rockwell [1991].

An important issue in the applications of PR effect is the speed of the grating formation. The search for new materials and the modification of existing materials are two efforts currently being pursued to improve the response time [Neurgaonkar and Cory 1986, Klein and Schwartz 1986, Ducharme and Feinberg 1984, 1986]. For presently available materials, three other methods have been used; increased intensity, higher temperature [Rytz et al. 1988, 1989] and applied electric fields [Sayano et al. 1990, Clark III et al. 1990]. Recently Salamo et al. (1991) experimentally demonstrated that the response time for beam fanning, SPPC and DPC can be shortened by more than an order of magnitude without a significant reduction in the coupling strength by using a cylindrical lens to focus the incident laser light into a PR crystal. During the wave mixing process in BSO and $BaTiO_3$ crystals, the dependence of PR response time on index grating spacing has been studied in detail by Hirao and Sawada (1991).

Research in SPPC and DPC has gained momentum recently because of their unique applications. The importance of the SPPC is due to its ability to produce PC wave without the need for externally driven pump beams and that of DPC is due to its ability to couple beams from two lasers which are incoherent to each other. Chang et al. (1990) employed mutually pumped phase conjugation (MPPC) in a PR $BaTiO_3$ for spatial mode clean-up of a pulsed laser. The idea is based on MPPC between the pulsed laser (Nd:YAG) beam and a *cw* Ar+ reference, thereby transferring the desirable spatial mode of the *cw* beam onto the pulsed beam. In an experiment, MacCormack and Eason [1991] used an SPPC mirror in a self-injection locking geometry to obtain a single-lobe output from a 20-stripe diode-laser array. Gruneisen et al. [1991] conducted experimental studies on DPC mirror to examine the effects of laser coherence on its coupling efficiency. Such studies on laser coherence are significant to laser phase-locking applications where changes in the coupling intensity can affect the quality of phase locking.

A theoretical approach on the SPPC has been made by Eliseev [1991], where he considered the geometry of one-mirror SPPC in the frame work of a three-dimensional theory, predicting that the phase conjugator acts as an amplifier. In a two-dimensional approach Zozulya [1991] showed that a DPC is a convective amplifier rather than an oscillator as proposed through one-dimensional theories.

Mamaev [1991] proposed and demonstrated a geometry with two interconnected ring mirrors for the conjugation of mutually incoherent beams. Studies by Chomsky et al. [1991] showed that DPC in a PR semi-insulating GaAs has its special features of self-frequency detuning and large coupling coefficient compared to two-beam coupling. Owechko and Soffer [1991] proposed that the SPPC mirrors could be employed as an alternative holographic interconnection method for neural networks. This approach greatly reduces crosstalk and each connection weight is distributed among many angularly and spatially multiplexed gratings. Recently, as an application of neural network, Aisawa et al. [1991] proposed and experimentally tested a method for classifying remote images through multimode optical fiber using neural networks. This method achieves rotation-invariant pattern recognition with a compact optical set-up.

4.2 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 advantageous properties of optical interconnection configurations [Weiss et al. 1986, Goodman 1989, McAulay 1989]. PR materials with their reconfigurable capability allow the implementation of dynamic holographic interconnections (Fig. 6) [Anderson and Lininger 1987, Yeh et al. 1988c, Shudong et al. 1990] The combined parallelism of optics, and storage capability

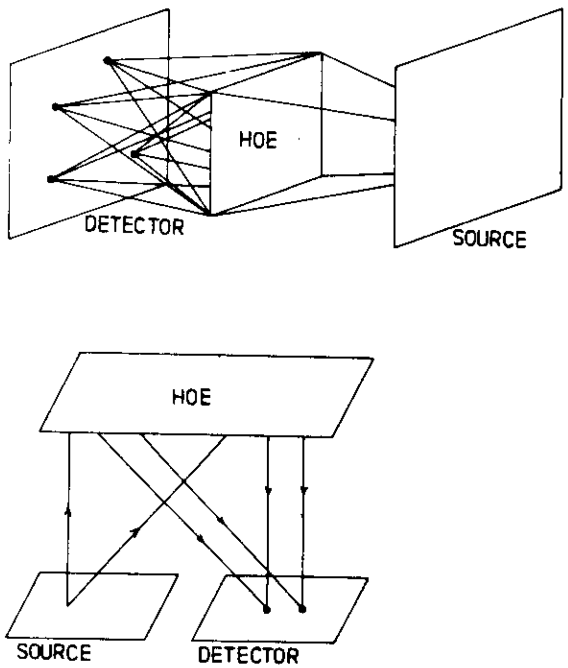


Fig. 6. Transmission and reflection type HOE interconnects (After Arsenault 1989, p. 262)

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 [Wilde et al. 1987, Psaltis et al. 1988].

Optical matrix-vector multiplication [Fig. 7, 8] can be used for the implementation of interconnections liking laser arrays and detector arrays [Yeh et al. 1989]. Chiou and Yeh [1990] have done the recording at Fourier transform plane to achieve high energy efficiency of ~ 40% in a PR optical interconnection. The diffraction properties of volume holograms are useful for reconfigurable interconnections by either wavelength tuning or spatial division techniques. The use of SPPC mirrors for optical interconnection has been analyzed by Owechko and Soffer [1991]. Lin et al. [1991] presented a system composed of a stack of single-transverse-mode slab waveguides for highly parallel multilayer interconnection. The use of wavelength multiplexing for interconnections of two-dimensional neural arrays has been studied by Weverka et al. [1991].

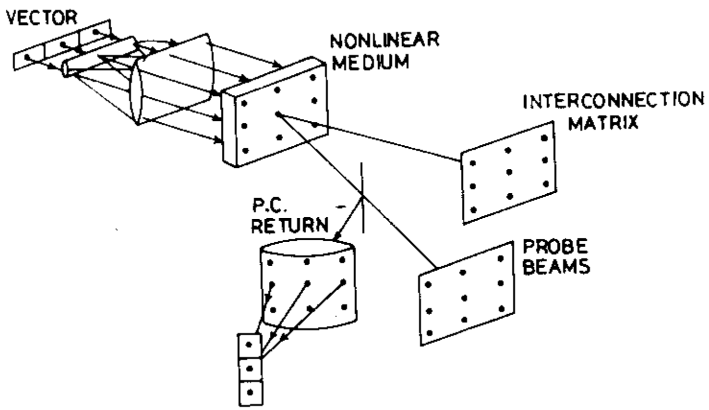


Fig. 7. Optical matrix vector multiplication (Yeh et al. 1989)

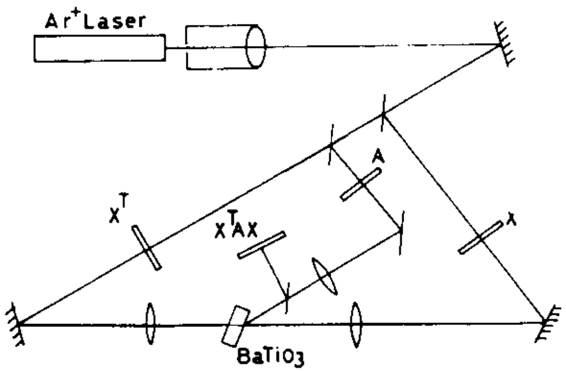


Fig. 8. Optical vector-matrix-vector multiplication

4.3 Optical computing

The much attention received by 'Optical computing systems' in the recent years over 'Electronic computing systems' is due to the massive parallelism and large interconnection capabilities of optics. In optical computing, 'photons' play the role of 'electrons' in an electronic computer. The capabilities of optical systems for high speed parallel processing, logic operations, analog and digital multiplication, convolution, matrix operations, bistable devices and learning process etc. have been demonstrated [Gibbs 1985, Yeh et al. 1989, Arsenault et al. 1989, Feitelson 1990]. The importance of parallelism in optical computer architecture is well recognized as a means of overcoming the limitations of current electronic computer technology.

There are two optical methods to implement the high speed optical computation, the parallel processing and the sequential processing. The use of transparencies, spatial light modulators, digitalization of the data, development of appropriate algorithm schemes etc. play the role in optical parallel processing. The sequential processing has been the counterpart of high speed electronic devices and to be implemented using photonic switches. As a whole, the approach of photonic computing and processing can be summarized as in Fig. 9.

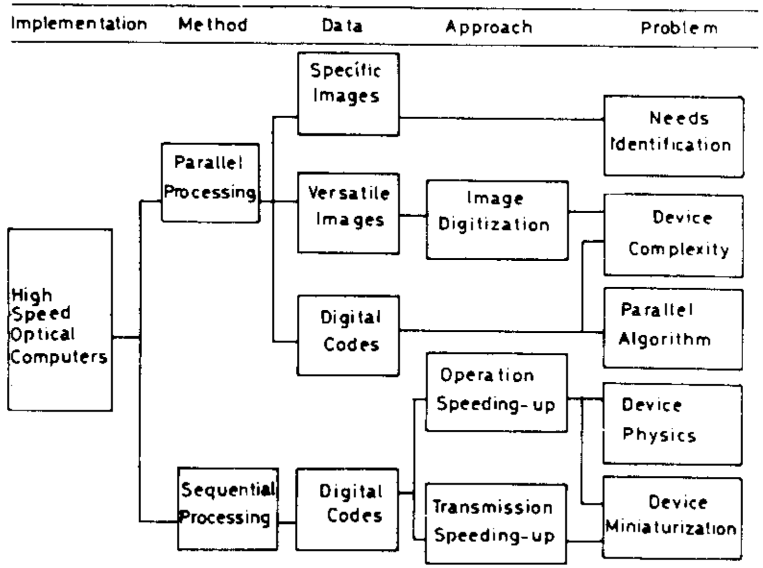


Fig. 9. Optical computer allabout (After Ishihara 1990, p. 4)

Optical parallel active elements play an important role to implement parallel optical computation. These active elements, which use the nonlinear optical response of materials, allow the possibility of manipulating the propagation of an optical beam by another beam of light [Yeh et al. 1989]. The nonlinear optical manipulation offer unique capabilities in holographic interconnection, parallel image subtraction, phase conjugation, optical data storage spatial light modulators, bistable optical devices, optical switches, matrix multiplications, associative memories and neural networks [Yeh and Chiou 1987a, Gookin 1987, Rajbenbach 1987, Rajbenbach et al. 1987, Vainos et al. 1988, Mandel et al. 1987, Gustafson and Smith 1988, Arrathoon 1989, Arsenault et al. 1989, Zozulya et al. 1989, Martellucci and Chester 1990, Gibbs et al. 1990, Ishihara 1990, Murdocca 1990, Midwinter 1990].

Another approach worth mentioning, towards the implementation of optical computing is via neural networks. Basically a neural computer contains a large number of simple processing units, called 'neurons' and each neuron is connected to many others (Fig. 10). The neural network is programmed for a learning process also [Psaltis et al. 1988, 1989]. For a neural computer, there

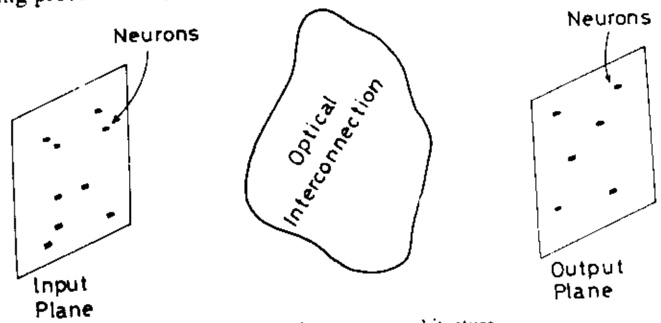


Fig. 10. Neural computer architecture

are two basic components that are needed to be implemented; neurons and interconnections. The neurons can be implemented by simple thresholding elements electronically or optically. The massive interconnectivity between several thousands of neurons is relatively difficult to achieve electronically. However, optics is well suited for the massive parallelism and large connectivity needed. Modifiable interconnections can very well be realized using PR materials so that learning can take place (Fig. 11).

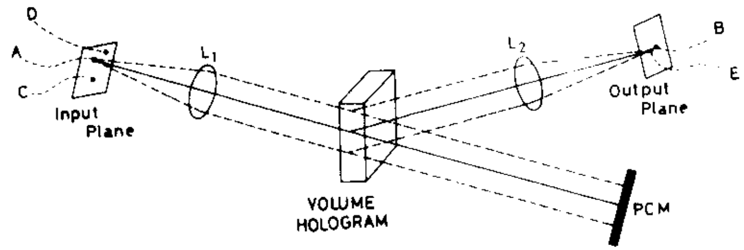


Fig. 11. Modifiable interconnections using PR materials

Generally, the basic architecture of a neural computer consists of spatial light modulators as neurons, where as holograms, transparencies, and PR materials etc. comprise the optical interconnecting system [Abu-Mustafa and Psaltis 1987, Yeh et al. 1989, Ishikawa 1990, Dunning and Giuliano 1990a,b]. Dunning et al. [1991] presented an optical interconnection method based on mutually pumped PC in a PR crystal. Adaptive bidirectional optical interconnection between planes has been realized by Schamschula et al. [1991] using

DPC mirrors. Zhang et al. [1991] employed quadratic interconnection between neurons to increase the association capability of neural network without decreasing the processing speed of the machine. Aisawa et al. [1991] used a neural network system for classifying remote image through a multimode optical fiber.

Electronic circuits are limited in complexity and/or speed by the difficulty of implementing extremely large numbers of connections between their individual components. A potentially attractive way of implementing such large numbers of connections (typically thousands or even millions) is by means of photonic interconnects. The key ways to achieve this is by using either lenslet-array [Yu et al. 1991a] or holographic interconnections. The basic distinction between these techniques is that lenslet interconnection is essentially an incoherent system, whereas the holographic interconnection is coherent. Although using incoherent light has the advantage of suppressing coherent noise, the lenslet array interconnection suffers from low light efficiency, which limits large scale operations. This shortcoming can be alleviated by using a mirror-array interconnection as demonstrated by Yu et al. [1991b]. Other promising types of interconnections are realized using holographic techniques [Peterson et al. 1990]. Weighted interconnections between inputs and outputs, as essential in neural nets, are realized using an optical vector-matrix multiplier and interconnection holograms [Jang et al. 1988].

Hologram multiplexing in PRs gives another alternative. But this interconnect system exhibits deleterious interference effects when multiple optical beams are fanned into a single beam with the use of multiplexed gratings. Elimination of such effects is possible by using incoherent readout, temporal sequencing, random phase modulation of readout beams or allocated volume configurations [Marrakchi and Hubbard 1991]. PR crystals, when used for DPC mirror set-up, can be employed to implement connections between planes [Schamschula et al. 1991], which are self-establishing and self-adaptive to the changes in the optical medium i.e., thermal, vibrational, and other environmental fluctuations can be compensated for. This scheme helps to establish bidirectional interconnections using different wavelengths.

With the blooming interest in neural network models which itself permeates a diverse assortment of disciplines, a recent upsurge of activity in an allied field of optical associative memory has resulted. An optical implementation of associative recall has recently received considerable interest. Soffer et al. [1986] have discussed a holographic implementation of the associative memory for storing images, in which the correlation between the input and the stored image was subjected to a nonlinear operation through a phase conjugator. Athale et al. [1986] gave a mathematical model for incorporating controllable nonlinearity in the correlation domain which provides flexibility of rapidly and arbitrarily changing the strengths of the stored states in an associative memory. White et al. [1988] considered digital and analogue implementations of optical associative memories. Both techniques rely on the holographic manipulation of optical information. In the digital scheme, which is based on an optical

version of the Hopfield model, computer generated holograms achieve this, while for the analogue processor FT holograms are used. They also discuss the extension of this model to incorporate learning algorithms which are required by the more flexible, and useful, neural network architectures.

A real-time holographic associative memory implemented with PR crystal as the memory element and a liquid crystal electro-optic switch array as the reflective thresholding device was demonstrated by Xu et al. [1990]. In this experiment, it is shown that real-time multiple-image storage and recall function is possible. An associative memory with a dynamic threshold level to decide the closest match of an incomplete input is proposed. A 2-D hybrid holographic associative memory using single memory hologram, computer controlled electronic circuit and liquid crystal television is demonstrated by Mu et al. [1990]. An orthogonalized model is described for this system that makes the holographic recording spatially separate and hence there are no losses in the diffraction efficiency. Lu et al. [1990] have proposed and demonstrated a real-time all optical associative memory system which combines Fe:$LiNbO_3$ crystal holographic memory element and $BaTiO_3$ SPPC mirror.

As discussed by Ishikawa et al. [1990], 'optical associatron' consisting of two microchannel spatial light modulators (MSLMs) as optical analog processing devices, works as electro-optical hybrid system of auto-associative memory (Fig. 12.). The system has versatile capabilities and adaptivities, especially a method of orthogonal learning. By applying multiwave mixing strategy in PR crystals, real-time associative memory phenomenon can be realized [Yulin et al. 1990].

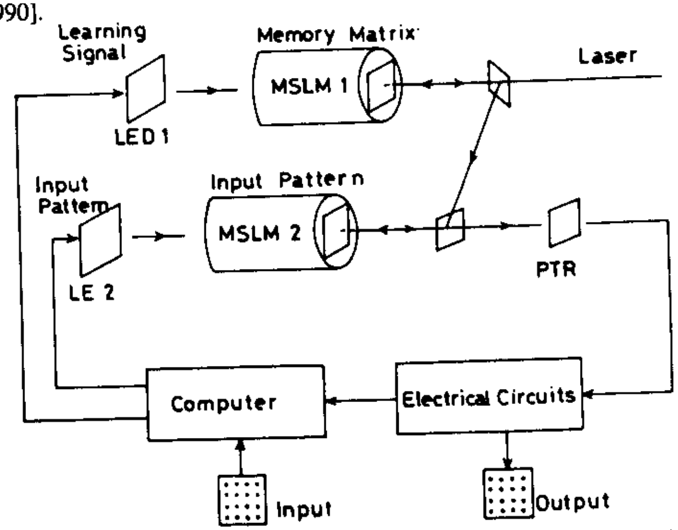
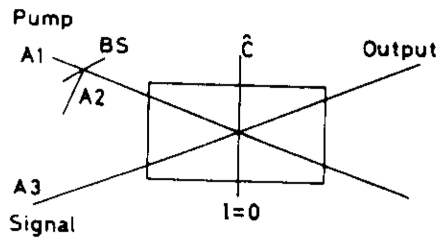


Fig. 12. Block diagram of optical association (After Ishikawa et al. 1990, p. 180)

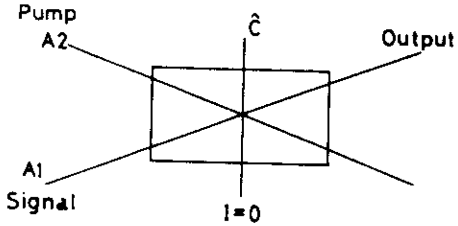
All the above holographic associative memory systems suffer from low light efficiency. A new system based on two new concepts is described by Paek ad Jung (1991) using thermoplastic plates: the system utilizes second-order diffraction efficiency and a novel angle-tuning recording. As a result, system size is reduced by one half with a remarkable increase (as much as approx. 100 times) in light efficiency compared with that of the conventional systems, and the need for critical alignment is eliminated. In another concept, associative memory is realized by using optical ring resonators [Anderson and Erie 1987], using a PR crystal. One important factor determining recall ability is the diffraction efficiency. Particularly, this quantity is also a function of the polarization of the read-out beam.

One important application of wave mixing in photorefractive materials is the optical implementation of digital logic operations. The nonlinear phenomena of signal beam saturation, pump depletion and optically controlled coupling coefficient of two-beam interaction in PR materials are used for the success of these operations. We have carried out OR and AND operations using two-wave mixing in $BaTiO_3$ using the experimental set-up of Fig. 14. The schematic diagram for these operations is shown in Fig. 13. Fig. 15 shows the results of these operations.



OR

A1	A2	Out
0	0	0
0	1	1
1	0	1
1	1	1



AND

A1	A2	Out
0	0	0
0	1	0
1	0	0
1	1	1

Fig. 13. Schematic diagram for OR and AND operations by two-beam coupling (After Fainman 1986 b)

Optical implementation of neural nets has been burgeoning in recent years. The attraction of neural networks lies in what they appear to offer for brain-like processing problems such as pattern recognition, language acquisition, motor control, knowledge processing, and so on. Neural network models have been abstracted to many forms. Because of their brain-like architecture as well as processing capability, implementation of these models is termed as "neuromorphic processor". There is an overlap between requisite features of network

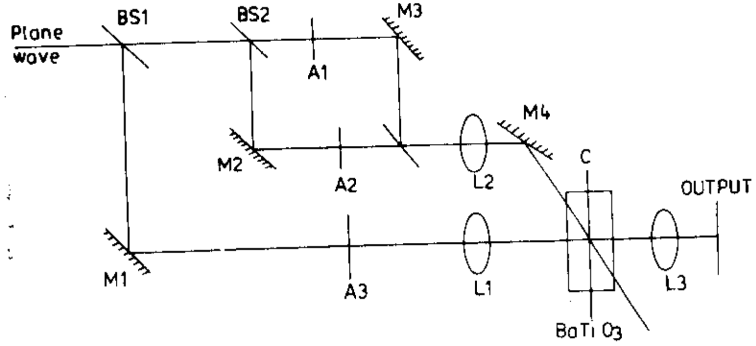


Fig. 14. Experimental set-up for performing logic operations (After Fainman 1986 b)

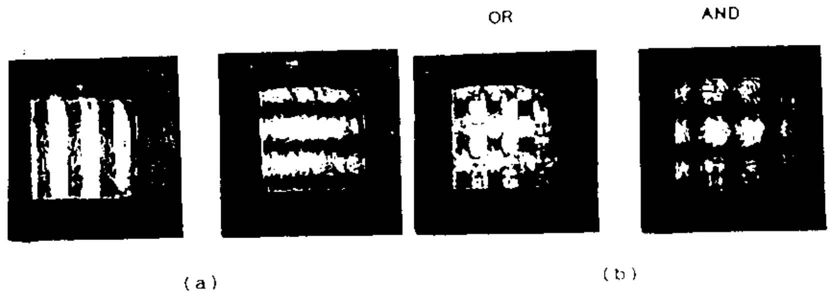


Fig. 15. Results of logic operations (a) Input function (b) OR and AND operations

models and the neural domains of the optical regime, such as parallel and distributed processing.

Increasingly, computers are being asked to do tasks that were formerly only done by their biological counterparts. And digital computers, as often as not, cannot do those tasks. The question then arises as to whether we can make electronic architectures that are more like neuro-biological architectures for treating fuzzy and ill-defined problems, like face recognition or the decoding of natural language.

Several architectural proposals and toy-sized experiments exist in literature for implementing neural network architecture. Most deal with Hebbian learning using either programmable SLMs or PR crystals. Large number of connections as required for network, which are mathematically represented by matrix elements are implemented as holographic grating, which can be realized in real-time by using PR medium. There is an additional reason for implementing neural networks in PR crystals; grating naturally decays and this can be exploited as beneficial adaptive process in neural network modeling. Psaltis et al. [1988] designed a multilayer architecture of several PR crystals to implement back-propagation algorithm with hidden units. Angular multiplexing was used to store the connection strength in gratings. Peterson et al. (1990) presented a single crystal architecture that is versatile enough to host a class of supervised learning algorithms, all of which handle hidden units. Their setup employed spatial multiplexing, which implies large rescattering and beam depletion effects for large grating strength and large number of neurons.

A PR interconnect system with coherently erasable synapses (PISCES) is described by Marrakchi et al. [1990]. They analyzed grating erasure in PR material for implementation of optical interconnects with analog weights. The PISCES includes Fresnel zone plates for spot generation, amplitude and phase SLM based on liquid crystal technology and detector arrays in addition to PR crystal.

It is shown that optoelectronic setup can perform pattern association with single-layer perceptron type neural networks, despite large errors due to the optical hardware used in the implementation [Robinson et al. 1990]. Furthermore a computer model of the hardware shows that errors do not severely affect the system performance, even when scaled to accommodate large input vector dimensions of 200 single-layer machines. Zhang et al. [1991] modified the original single-layer design to permit quadratic interconnections between neurons, thus increasing the association capability of the network without decreasing the processing speed of the machine and maintaining the error tolerance of the original design. Oita et al. [1990] reported a novel type of quantized learning rule with unipolar binary weights that is useful for the implementation of neural networks. Experimental demonstration of the recognition of 26 characters of the alphabet by using the single set of an optoelectronic three-layered network is performed using this learning rule.

Neural network techniques offers a different approach in that the network memorizes the experience gained by the training; eventhough the training is done, the inversion can be performed instantly. This inverse technique can be used to determine particle-size distributions by training a layered perception neural network with optical backscattering measurements at three wavelengths. An advantage of this approach is that, eventhough the training takes a long time, once the neural network is trained the inverse problem of obtaining size distribution can be solved speedily and efficiently.

4.4 Imaging through phase distortions

The time reversal like nature of the OPC has been an important responsible factor behind the wide ranging applications of phase conjugation [Fisher 1983, Giuliano 1981, 1983, Pepper 1986]. Phase aberrations can be compensated by letting the wavefront retrace its path through the aberrating medium, following the wavefront reversal via a PC mirror (PCM). A pictorial description of the distortion correction property of OPC is shown in Fig. 16. A uniform plane wave getting distorted after its passage through a phase distorting medium such as atmosphere or a severely strained optical element, is incident on a PCM. The PCM gives rise to an output wave that is as severely aberrated as the input wave but with phase reversed. When the output passes back through the aberrator, it

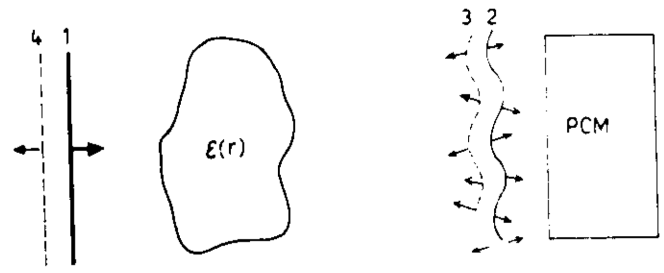


Fig. 16. Distrotion correction property of optical phase conjugation

will emerge completely free of distortion. Replacement of the PCM with an ordinary mirror leads to a distortion which gets doubled after its second passage.

One immediate application of this distortion correction property of PCM is in imaging through phase distortions [AuYeung and Yariv 1979, O'Meara 1982, Giuliano 1983, Zel'dovich et al. 1985]. An optical set up for imaging through phase distortion is shown in Fig. 17. Phase distortion is removed by allowing the time reversed wavefront to travel back through the aberrating

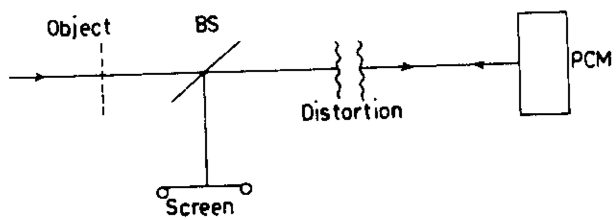


Fig. 17. Imaging through phase distortion (two-way scheme)

medium. However, since the wavefront passes through the distorter twice in order to be restored and therefore ends up on the same side of the distorter from which it began, this scheme has not been useful for transmitting an undistorted optical image from one side of a distorter to the other. This is necessary in large number of practical situations where the pictorial information is to be transmitted in a single direction only, for example, for image transmission through optical multimode fibers.

The idea of three-dimensional pictorial transmission through optical fibers was first proposed by Yariv [1976]. Here, the smeared output due to modal noise of an optical fiber is forward phase conjugated using nonlinear mixing. The PC output is sent through an identical fiber to recover the original picture at the output end of the second fiber. However, this idea never materialized because of the practical impossibility of having two fibers of exactly identical characteristics [Chang and Sato 1987, 1988]. Dunning and Lind [1982] experimentally demonstrated the fact that PC can compensate for modal distortions introduced by a fiber. They used the same fiber for forward as well as backward propagation, i.e. a two-way imaging scheme. Phase conjugation was realized using DFWM in a $BaTiO_3$ crystal.

Yariv and Koch [1982] proposed a scheme for one-way imaging through phase distorting medium using field multiplication by FWM. Theoretically they showed that it is possible to propagate a pictorial information in a pump wave through a phase distorter in the probe, without any distortion for the pictorial information. Fischer et al. [1982] experimentally demonstrated this one-way imaging scheme via a real-time PC window [Fisher and Peri 1985].

Because of the far reaching applications of distortion free imaging, two-way and one-way imaging schemes have been investigated by many [Mittra and Habashy 1984, Fisher and Sternklar 1985, McMichael et al. 1987, Chang and Sato 1988, Peri 1988, MacDonald et al. 1988, Shamir et al. 1988]. Ikeda et al. [1983a, b, 1984] made a detailed analysis and experimental demonstration of one-way image transmission through a turbulent medium using a point reflector and FWM. For high fidelity image transmission, polarization preserving PC is very important [Beckwith et al. 1987, McMichael et al. 1987], use of partially coherent light for one-way PC has been analysed by Cunha and Leith [1988, 1989].

4.4.1 Phase conjugate one-way scheme for imaging through phase distortion

Optical phase conjugation can effectively cancel out the distortions of an image bearing beam due to its passage through a phase distorting medium [Bloom and Bjorkland 1977, Huignard et al. 1979]. However, such techniques for imaging through distortions have the disadvantage that the image information passes twice through the distortion, so that the original object as well as the corrected image are obtained on the same side of the distorting medium [Dunning and Lind 1982, Ikeda et al. 1983, 1984].

Applications like image transmission through optical fiber and other phase distorting media like atmosphere require the object and the corrected image to be on opposite sides of the distortion [Lebow and Ackerman 1989]. As briefly discussed in the first chapter, one-way imaging through distorting media using FWM has been proposed by Yariv and Koch [1982] and demonstrated by Fisher et al. [1982, 1985]. In this phase conjugate window scheme, a plane beam is sent from the receiving end and passes through the distortion considered to be a thin one. The field at the distortion is imaged into a nonlinear medium. At the nonlinear medium we have two more beams, one a plane beam which is coherent to the input beam and the other a beam containing the image information to be transmitted. Through the four-wave mixing, this image information is transferred to the generated phase conjugate beam which traverses back through the distortion, cancels out the phase distortion, and transfers the image information from one end of the distortion to the other end. The use of this phase conjugate window for real-time three dimensional imaging through fiber bundles was experimentally demonstrated by Fischer and Peri [1985].

In such phase conjugate window schemes, the pump beams were derived from the input of the distorting medium, i.e., the input and the output ends are not isolated. In practical applications, it may not always be possible to have a coherent reference beam at the nonlinear mixing end. In other words, for effective one-way imaging through distorting media, the reference beam should be derived from the distorted beam. Recently Wang and Zhang [1988] described a phase conjugate scheme in which a single mode fiber was used to generate the reference waves. We have proposed and demonstrated a phase conjugate one-way scheme [Joseph et al. 1990a] for imaging through phase distortions. A spatial filtering technique is used to derive the reference beam from the distorted beam [MacDonald et al. 1988]. In the present phase conjugate scheme, the input and output ends are perfectly isolated. Hence, at least in principle the scheme is capable of transmitting images through phase distorting media like atmosphere and optical fibers of any length.

The distortion correction property of PC has been employed very effectively by many researchers for image transmission through phase distortions. However, a disadvantage of most of these schemes using FWM is that there is always an effective phase mismatch between the two pump waves since the image bearing wave is used as one of the pump waves. This phase mismatch aspect is an important factor to be taken into account for the implementation of one-way complex field imaging schemes as pointed out by Li and Zhang [1991]. Alley et al. [1990] performed FWM in a slowly responding medium for single pass imaging through a thick dynamic distorter, in which the pump as well as the image bearing beams are simultaneously propagated through the distorter and the distortion correction takes place at the FWM end.

Using the nonlinear material as a time averaging filter, Oldekop and Siahmakoun [1991] investigated a one-pass distortion correction scheme with a $BaTiO_3$ SPPC. The system works in real-time for a time-varying distorter with the information passage only once through the distortion. Kramer et al. [1991] used a real-time holographic technique employing an optically addressed spatial light modulator to correct an incoherently illuminated image that had made a single pass through an aberrator. By using polarization preserving PC in a PR crystal and correcting holograms, Volyar et al. [1991] realized image transmission through a 2 m long multimode fiber. Various methods of imaging through inhomogeneous media which include PC techniques and also incoherent light illumination methods have been reviewed by Leith et al. [1991]. They noticed that the enormous redundancy of incoherent light leads to noise immunity and very high SNR in an imaging system. Pan et al. [1991] presented a general method employing PC mirror to generate high-fidelity PC from holograms, for its application to image transmission through multimode fibers, high quality image production and parallel data communication through short multimode fibers etc.

4.5 Image amplification

A coherent image amplifier is needed for the realization of optical operational amplifiers, optical feedback systems and projection microscopes etc. The use of laser gain media in amplifying systems [Akins and Lee 1984] make it noisy and to get the input signal well above the noise, high illumination intensities are needed. TWM and FWM in electro-optic crystals provide a means of amplification with very low power input intensities [Laeri et al. 1983, Tschudi et al. 1986, Beckwith and Christian 1989, Rajbenbach et al. 1991]. Due to relative ease of operation and the possibility of very large gain, two-beam coupling in PR materials is the best choice for image amplification.

Due to their small Pockel's coefficients, two-beam coupling gains obtained with BSO and BGO without an applied field are quite small. While the coupling strength of BSO and BGO can be increased by applying a uniform dc electric field, the resulting non-90° phase shift between the refractive index variation and the light intensity interference fringes is not the optimum condition for maximum coupling [Huignard and Marrakchi 1981a, b]. However, by using an applied electric field and introducing a frequency offset between the writing beams, the phase shift can be set at the value which maximizes the amplification of the signal. The frequency offset introduces a movement of fringes inside the crystal [Stepanov et al. 1982, Valley 1984, Refregier et al. 1985]. High beam coupling efficiencies are available in photorefractive BSO and BGO when recording is done with a high electric field and moving the fringes at the optimum velocity [Valley 1984]. The gain of the amplifier is strongly dependent on the grating spatial frequency. Also, the gain reaches saturation at high beam intensity ratios [Rajbenbach 1983].

For two-beam coupling in $BaTiO_3$, the magnitude of direction of coupling depend both on material properties (e.g. electro-optic tensor and concentration of traps) and on externally controlled parameters (e.g. the angle between incident beams inside the crystal, the angle between the grating vector and the crystal optical axis, and the incident beam intensity ratio). Experimental observations by many researchers towards the optimization of coherent image amplification by two-beam coupling in $BaTiO_3$ led to the following conclusions:

Gains of the order of thousands can be easily achieved [Laeri et al. 1983]. Saturation of gain occurs for incident beam intensity ratios more than 10^4 [Rak et al. 1984]. Maximum gain occurs for grating spatial frequencies $\Lambda_0^{-1} \approx 830$ mm^{-1}. Gray level imaging obtained a dynamic range greater than 100 [Fainman et al. 1986a, b]. Imaging resolution of 250 l/mm were achieved. Extensive theoretical analysis showed that for maximum gain the angle between the beams inside the crystal should be between 4° to 10° with the crystal c-axis deviation w.r.t. the grating vector being equal to 45°. With the crystal cuts normally available, satisfying these conditions for these angles is difficult. Hence, as proposed by Fainman et al. [1986a] a specially cut crystal could be used, which allows normal incidence of larger diameter pump and signal beams at the crystal face without sacrificing high gain.

Hong et al. [1990] have analysed the image amplification by TWM when a multitude of probe beams are used. The gain experienced by the probe image was approximately uniform across the image. By the use of $BaTiO_3$

photoelectret, Pillai et al. [1990] obtained persistent gain even after the removal of applied electric field and a maximum gain obtained was over 24,000. The obtained gain values were dependent on beam mixing geometries, poling conditions and beam intensity ratio etc.

Signal beam amplification via two-beam coupling is the simplest of the beam coupling operations and it is an essential component of the PR image processing system. Because of its high beam-coupling efficiencies and the possibility of low intensity level operation, photorefractive $BaTiO_3$ is the material of choice for studies in the optimization of coupling process and for the development of novel devices using the beam coupling process. Its slow response could be a disadvantage from the application point of view, but this allows one to make temporal observations rather accurately and with ease. Image amplification by two-beam coupling in PR $BaTiO_3$ crystals has been studied by several researchers, achieving very high gains [Rak et al. 1984, Khoury et al. 1989], sometimes of the order of several thousands [Laeri et al. 1983, Tschudi et al. 1986, Yeh et al. 1989].

For the case of signal beam amplification via two beam coupling in a $BaTiO_3$ crystal, the main source of noise in the amplified signal comes from the phenomenon of beam fanning [Feinberg 1982a, Moore and Walters 1988]. The presence of this amplified scattered light reduces the signal-to-noise ratio in the amplified signal [Yakimovich 1980, Vachss and Yeh 1989, Rajbenbach et al. 1989b].

With the aim of attaining a high-gain low-noise image amplifier, coherent image amplification by two beam coupling in $BaTiO_3$ has been studied in detail by many researchers considering different parameters such as incident beam ratio, spatial frequency, pump beam intensity and c-axis orientation etc. [Rak et al. 1984, Fainman et al. 1986]. While maximizing the signal beam gain, it can be found that the amplified signal always lies within the angular spread of fanned beam [Rajbenbach et al. 1989b]. This gives rise to very poor SNR in the amplified signal which could degrade the quality of image in coherent image amplification experiments. A detailed quantitative study [Joseph et al. 1991a] showed that the crystal orientations for maximum gain and minimum SNR nearly coincide with each other. For high signal-to-noise ratios it is seen that this has to be done at the cost of a reduction in gain. Hence, a compromise has to be made between these two, depending on the application requirements.

Two-beam coupling via PR effect forms the underlying process for both beam fanning and signal beam amplification in two-wave mixing [Tobin and Ross 1988, Valley 1987]. In beam fanning, the amplification of the scattered light by two-beam coupling with the incident beam gets optimized by itself [Voronov et al. 1980, Yakimovich 1980]. Hence the maximum beam fanning direction could be a pointer to the direction for optimum two-beam coupling for that particular crystal orientation with respect to the incident pump beam. We have made investigations into the aspect whether beam fanning can be taken as a guideline for easy optimization of signal beam gain in terms of crystal orientation and angle between the beams. Since the underlying processes are the same behind both signal beam amplification and beam fanning, the maximum of noise power is expected to be in the direction of maximum signal beam gain. However, the experimental results show that the direction is not the same for maxima of beam fanning and the signal beam amplification.

For a PR material like $BaTiO_3$, because of its very large two-beam coupling efficiency, there is a considerable depletion of pump energy into the amplified signal as well as the amplified scattered light i.e. beam fanning. There have been studies, both experimental and theoretical, on the effect of pump depletion into the amplified signal on two-beam coupling characteristics [Voronov et al. 1980, Vachss and Yeh 1989]. An experimental investigation [Joseph et al. 1992a] has been made on the consequences of strong pump depletion into beam fanning for optimal signal beam amplification via two-wave mixing. Studies on fanning in the presence and in the absence of signal reveal that there is an appreciable coupling between beam fanning and signal.

As pointed out by Yao et al. [1990], for a PR material like $BaTiO_3$, because of its long dark-storage time, light induced changes caused by successive pulses are accumulated in the crystal. Studies have been made [Joseph et al. 1991b] on the cumulative nature of two-wave mixing through observations on signal beam amplification with continuous wave exposure and periodic pulse exposure. A comparison of the two shows the presence of a noncumulative component in the signal beam gain. This noncumulative component comes out to be prominent when the crystal c-axis is oriented away from its maximum signal beam gain position. Dependence of this noncumulative factor or crystal c-axis orientation has also been studied.

The large values of two-beam coupling coefficient as well as four-wave mixing reflectivity observed in $BaTiO_3$ make it a useful tool for many optical processing applications. In a photorefractive $BaTiO_3$ crystal it is possible to achieve gains of the order of thousands in image amplification via two-beam coupling [Laeri et al. 1983, Pillai et al. 1990]. This high beam coupling coefficient in $BaTiO_3$ makes the amplified image noisy because of the presence of beam fanning [Moore and Walters 1988]. Beam fanning is characteristically responsible for the phenomenon of self-pumped phase conjugation [Feinberg 1982, White et al. 1982], and has applications like optical limiter [Bialkowski 1989], one-way optical devices and bistable optical devices [Feinberg 1982]. However, in image amplification by two-beam coupling [Vachss and Yeh 1989], the beam fanning is always a noise in the amplified image [Tschudi 1986, Rajbenbach et al. 1989b].

In the standard configuration for image amplification by two-beam coupling, the use of extraordinary beam and the selection of signal beam direction with respect to the pump beam and the c-axis, drive a large amount of amplified scattered light into the amplified image. This gives rise to very low signal-to-noise ratio in the amplified image for a weak signal. The use of ordinary rays instead of extraordinary rays for the two beams can remove the beam fanning [Feinberg 1982]. However, this reduces the two-beam coupling efficiency also, because in this case the largest electro-optic coefficient r_{42} of the $BaTiO_3$ crystal is not utilized for the two-beam coupling.

Recently, Rajbenbach et al. [1989] proposed and demonstrated a technique for noise suppression in PR amplifiers by performing two-wave mixing in a slowly rotating crystal resulting in a washout of the noise gratings. We have proposed a pulse read-out technique and experimentally demonstrated its use for high quality noise-free image amplification. This pulse read-out scheme [Joseph et al. 1991c] removes the beam fanning, to obtain high-gain and low-noise signal beam amplification. The principle makes use of the large time constant for beam fanning in the $BaTiO_3$ crystal which makes the beam fanning insensitive to a short pulse. High gain of ~ 11,000 and high-SNR of ~ 1,300 have been obtained using the pulse read out scheme [Joseph et al. 1992 b].

4.5.1 *Anisotropic conical scattering in photorefractive $BaTiO_3$*

When a photorefractive $BaTiO_3$ crystal is illuminated with an extraordinary polarized laser beam, the output from the far face of the crystal contains not just the directly transmitted beam, but also the results of the phenomena called beam fanning [Feinberg 1982a, Moore and Walters 1988a, b, Tobin and Ross 1988, Clark III et al. 1990] and anisotropic conical scattering [Odoulov et al. 1985, Temple and Warde 1986]. Beam fanning results from the selective amplification of light scattered from various imperfections and crystal surface irregularities through strong two-beam coupling between the incident beam and the scattered light. On the opposite side of the beam fanning a cone of light appears which is polarized orthogonal to the incident beam. This cone of light called anisotropic conical diffraction results from the diffraction of the incident beam off the PR gratings formed during the beam fanning [Ewbank et al. 1986].

The existence of non-zero off-diagonal electro-optic tensor element in the photorefractive $BaTiO_3$ allows the anisotropic scattering of extraordinary polarized incident beam off the beam fanning gratings into ordinary polarized light by satisfying the Bragg phase matching condition. Since the fanning-grating vectors cover a wide solid angle, the phase matching condition is satisfied for a ring of wave vectors, to produce a cone of orthogonally polarized light.

Anisotropic conical diffraction in photorefractive $BaTiO_3$ crystal has been studied in detail by many researchers both experimentally and theoretically. These investigations include a standard PR analysis predicting the cone angle, polarization and the location of discontinuities in these rings [Temple and Warde 1986], phase matching conditions predicting the angular position of the light in the exit plane [Ewbank et al. 1986], observation of dark rings from conical diffraction [Chang and Yeh 1987], isotropic conical scattering [Zhang et al. 1988], a new kind of anisotropic conical scattering via wave mixing [Hu et al. 1989] and a nonlinear scattering induced by two orthogonally polarized wave [Odoulov et al. 1991b] etc.

Some experimental studies have been made on the phenomenon of anisotropic conical scattering (ACS). The simultaneous presence of beam fanning and ACS hinders the exact measurements on anisotropic conical diffraction. A method based on giving an instantaneous tilt to the crystal has been performed [Joseph et al. 1991c] for the measurement of diffraction efficiency of the gratings responsible for anisotropic conical diffraction. Such measurement is not hindered by the simultaneous presence of the strong beam fanning. Dependence of the diffraction efficiency on incident beam angle and the build up processes of beam fanning and anisotropic scattering have also been studied.

4.6 Image processing

Modification of the Fourier spectrum of a pattern allows one to perform a wide variety of complex filtering procedures that are used in optical information processing. The interest in real-time image processing is ever increasing with more and more new and improved processing schemes being developed and investigated.

Using TWM in a $BaTiO_3$ crystal, Weiss and Siahmakoun [1991] constructed a coherent optical processor which is capable of performing autocorrelation of an input image in two successive steps. A real-time optical correlator based on PR GaAs and liquid crystal TV has been demonstrated by Liu et al. [1990] with fastness as high as 1000 frames/sec. For pattern recognition, Kamemaru and Yano [1990] proposed a multiplexed matched spatial filter theory. On the basis of this theory, autocorrelation of an object is composed of its individual component signals. The phase modulating capabilities of a liquid crystal TV have been analyzed by Kirsch et al. [1990] for its application to light efficient joint transform optical correlator. Thoma et al. [1991] used purpie membrane films containing bacteriorhodopsin as light-controlled spatial light modulators for spatial filtering operations.

Much attention which the two-beam coupling in a PR material has received is because it can amplify an image optically. The input signal beam is optically amplified in parallel, and its gain is also controlled optically in two-beam coupling. Light amplification is a necessary function of optical information processing, of measurement, and especially of optical computing. The goal of attaining high gain in two-beam coupling with low noise has inspired many to develop different novel/improved techniques for image amplification. Kawata et al. [1991] demonstrated gain enhancement in two-beam coupling with a BSO crystal via signal beam chopping and polarization rotation methods. The gain enhancement here is obtained due to transient effect during the grating formation. Rajbenbach et al. [1991] proposed and demonstrated an experimental technique for suppressing the optical noise of PR amplifiers. In this technique, the entrance face of the crystal is tilted with respect to the pump beam direction. Gu and Yeh [1991] made a theoretical investigation on the scattering due to noisy gratings produced by randomly distributed charge particles in electro-optic crystals. Rabinovich et al. [1991] showed that by employing achromatic grating technique, it is possible to suppress beam fanning while still allowing two-beam coupling to occur.

The linear birefringence of PR BSO crystal in the presence of a photoinduced electric field is exploited by Pinzon et al. [1991] for real-time spatial selective filtering. The filtering is provided by incoherent imaging on the crystal of a given transparency which modifies the induced birefringence of the crystal. By this technique it is possible to attenuate selectively, the different spatial frequencies at the Fourier plane.

Another strong contender for image processing using PR materials is the technique using achromatic gratings to produce white light fringes. Rabinovich and Feldman [1991] demonstrated two-beam coupling in $BaTiO_3$ using white light. The use of achromatic grating techniques [Rabinovich et al. 1991] to form volume holograms in nonlinear materials with broad-band, spatially incoherent sources of light has obvious advantages. Laser diode arrays, for instance, are efficient, robust sources but have limited monochromaticity and coherence. The sun is another attractive source for space-based applications. Since an achromatic grating forms only under special and sensitive conditions, scattering off imperfections in crystal may not form competing gratings, thus reducing noise effects such as beam fanning [Rabinovich et al. 1991].

Image processing by spatial filtering relies on manipulation of spatial frequencies at the Fourier plane [Goodman 1968, Lee 1981, Honer 1987, Hall 1989]. In the well-established conventional scheme of spatial filtering, this manipulation is done by keeping an appropriate mask at the back focal plane of a lens [Casasent 1978]. By inserting masks, stops or slits, appropriate spatial frequency components are filtered out at the Fourier transform plane of an optical imaging system to perform operations such as edge enhancement, feature extraction, pattern recognition and image correlation etc [Lee 1981]. For example, when a mask of zero spatial frequency stop is used there is high pass filtering and the processed image shows edge enhancement.

This conventional technique of masking selected spatial frequencies at the Fourier transform (FT) plane has the limitations [Ma et al. 1989, Chang et al. 1990] of non-real-time nature, energy inefficiency and the inability for cascaded operation.

PR materials as real-time recording media have gained considerable importance because of their applications in image processing, interferometry and wave front correction etc [Huignard and Herriau 1978, Markov et al. 1979, Petrov et al. 1979, Feinberg 1980, Yeh and Chiou 1987b, Wooder and Dainty 1987, Gheen and Cheng 1987, Ikeda et al. 1987, Chang et al. 1988, Vainos and Eason 1988, Stepanov 1991, Rajbenbach and Huignard 1991]. Recently, several real-time image processing techniques have been performed using two- and four-wave mixings in PR materials. Huignard and Herriau [1978] and Khoury et al. [1989] used the spatial filtering characteristics of four-wave and two-wave mixing processes in PR materials for the success of their techniques [Feinberg 1980, Fischer et al. 1987]. Erasure of selected spatial frequencies at the Fourier transform plane of the image is another way of performing spatial filtering. Pugliese and Morris [1988, 1989] used a slide projector bulb as a source for erasure beam in a four-wave mixing geometry. Ma et al. [1989]

derived a third beam for erasure in two-beam coupling to perform real-time spatial filtering. Chang et al. [1990] demonstrated a spatial amplification technique for selective amplification of spatial frequencies. These real-time image processing techniques developed so far using photorefractives are capable of performing only edge-enhancement and band-pass filtering operations. McCall and Petts [1985] used a modifying beam, in a four-wave mixing image correlator, as a 'weighting' in favour of certain spatial frequencies. More recently, Khoury et al. [1991] presented an optical signal processing technique for additive noise reduction that uses the noisy signal and a Gaussian reference beam. They used a signal beam that is more intense than the reference beam so that the signal passes through without loss while the less intense Fourier components of noise will lose intensity exponentially.

We have proposed and demonstrated a spatial amplification technique [Joseph et al. 1991d, 1992c] by selective erasure at the Fourier spectrum in a two-beam coupling geometry using a photorefractive $BaTiO_3$ crystal (Fig. 18). The main difference of our work with that of Ma et al. [1989] is the use of

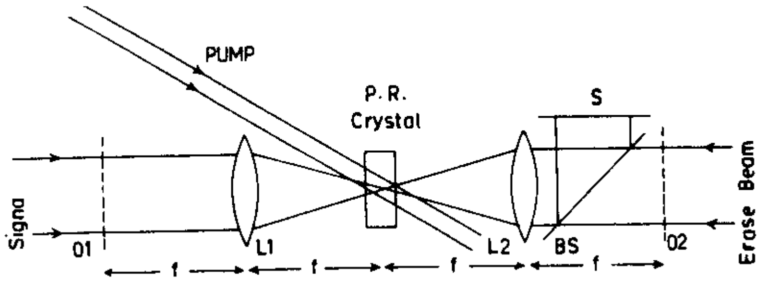
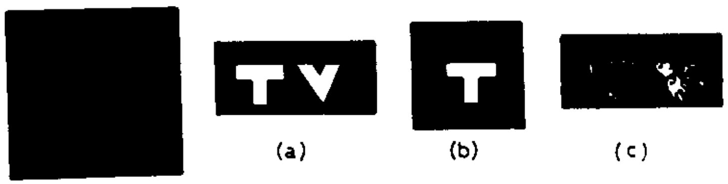


Fig. 18. Schematic arrangement for spatial amplification using selective spatial frequency erasure (After Joseph et al. 1991 d)

Fourier transform of the erasure beam. This makes technique more versatile than all the above mentioned real-time image processing techniques. Fig. 19 shows the results of edge-enhancement and character recognition operations using the spatial amplification technique. Besides these operations, the present technique is capable of performing the most important image processing operation i.e., the pattern recognition. The potentiality of the technique has been



(i) Result of edge enhancement (ii) Result of character recognition
Fig. 19 (a) Input objects (b) Object to be recognized (c) Recognized object

demonstrated by performing edge-enhancement, band-pass filtering and character recognition operations.

4.7 Image convolution and correlation

Real-time implementation of image correlation and convolution can be achieved by TWM or FWM of optical fields in PR crystals. The use of TWM configuration for correlation and convolution has been demonstrated by Pichon and Huignard [1981]. The interference pattern recorded in the Fourier plane of a lens is read-out by an auxiliary low power laser. Positioning the read-out beam at the correct Bragg angle for the maximum intensity obtains cross-correlation peak in the diffracted beam. The mutiltiplicative property of DFWM combined with the Fourier transforming properties of lenses can be used to obtain a spatial convolution and correlation system as proposed by Pepper et al. [1978b]. Experimental demonstration of this has been performed by White and Yariv [1980] to obtain the correlation and convolution of two image bearing beams using a photorefractive BSO. Dynamic implementation of joint transform correlators are possible by incorporating PR materials [Yu et al. 1990, Liu et al. 1990].

In both TWM and FWM systems, an auxiliary beam incident on the PR crystal may also be used to modify the output of the processor in real-time, thus providing a means of weighting the correlation product in favour of specified spatial frequencies. The use of a fourth beam as a means of weighting the correlation product in favour of specified spatial frequencies in a photorefractive FWM system has been investigated by McCall and Petts [1985]. Foote et al. [1986] developed a high speed two input real-time optical correlator using photorefractive BSO and Cooper et al. [1986] used PR material for a dynamic frequency plane correlator. An optical cross-correlation and auto-convolution method via photorefractive FWM as described by Chiou and Yeh [1990] is useful in selective enhancement of image components with specific symmetry. These parallel processors are very attractive for application to pattern recognition and optical computing.

4.8 Nonlinear optical image subtraction and addition

The dynamic implementation of optically subtracting one image from another to detect the differences between the two objects can be done by using wave mixing in PR crystals. Compared to the electronic part of the digital processing, optical techniques are inherently capable of parallel processing over the entire image and hence are much faster. Real-time coherent subtraction and addition can be achieved with a Mach-Zehnder or Michelson interferometer [Chiou and Yeh 1986, Chiou et al. 1988]. On the image planes, where images of two objects overlap, image subtraction (addition) takes place by destructive (constructive) interference, provided the phases of the two wavefronts are 180° out of phase (in phase) throughout the whole overlapping region. In a PC Michelson interferometer (PCMI) the two mirrors of the conventional Michelson interferometer are replaced by PC mirrors. The advantages of PCMI over the conventional interferometer are that the PCMI is self-aligned and is immune to phase fluctuations in arms. The phase shift required for the addition or subtraction operation can be obtained by grating or polarization encoding scheme as discussed by Liu and Chao [1986]. Real-time optical image subtraction using a PCMI that incorporates self-pumped $BaTiO_3$ crystal as PCM has been demonstrated by Chiou et al. [1988].

Another scheme of image subtraction (or partial image erasing) consists of superimposing a complementary refractive index modulation on the refractive index modulation of the stored hologram [Huignard et al. 1976]. Selective erasure of a page of information (complete, partial or single bit) is achieved by the use of a $\pi/2$ phase shifted reference beam during a second recording of the object to be erased. The superposition of these two holograms in the crystal volume reconstructs the image difference. Image subtraction and addition processes are useful for the implementation of logic operation between two-dimensional data planes. For example, the binary image subtraction corresponds to the logic Boolean operation "Exclusive OR". The use of DFWM in BSO crystals for performing real-time image subtraction and differentiation has been discussed by Ja [1985]. A holographic interference method for real-time amplitude subtraction of two images has been described by Yeh et al. [1988b].

4.9 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 [Soffer et al. 1986]. It is experimentally implemented as follows. A set of images is stored in a holographic medium, each image with its own angularly encoded reference beam. 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 [Owechko et al. 1987, Owechko 1989].

An analogue optical associative memory system was demonstrated by White et al. [1988] in which a multiplexed hologram acted as the memory element. A PC mirror acted as an iteration and thresholding device. A desired memory element can be reconstructed from the multiplexed FT hologram when only part of that memory is presented at the input. Learning can be incorporated into such a system by using the real-time recording capabilities of PR materials in place of the hologram.

The combination of holographic memory and phase conjugation for associative memory has been performed by Yariv et al. [1986]. Different object informations can be superimposed in the holographic memory by angular coding method. An associative memory system in which a hologram placed in a cavity formed by two PC mirrors has also been performed. This system favours highest degree of correlation with the input image and forces the system to converge to a stable state. Recently Xu et al. [1990] demonstrated a real-time holographic associative memory system using photorefractive KNSBN:Co crystal and liquid crystal electrooptic switches. They also proposed an associative memory with dynamic thresholding device made of bistable interference filter and a feedback control network where the object is recalled from several stored objects. Associative memory systems using PR, constitute an important part towards the development of optical neural networks (Fig. 20) [Psaltis et al. 1989]. Another architecture which employs liquid crystal light value (LCLV) (Fig. 21) to simulate the neural plane (Fig. 22) has been demonstrated

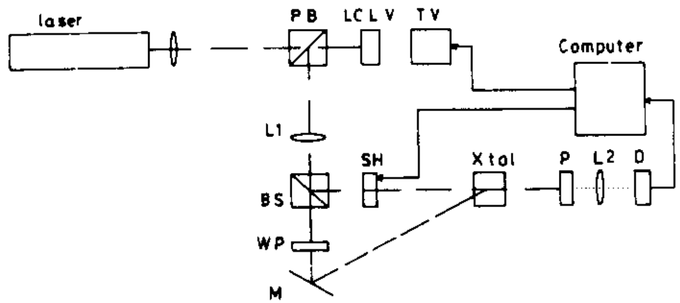


Fig. 20. Optical implementation of perceptron algorithm (After Psaltis et al. 1989, p. 272)

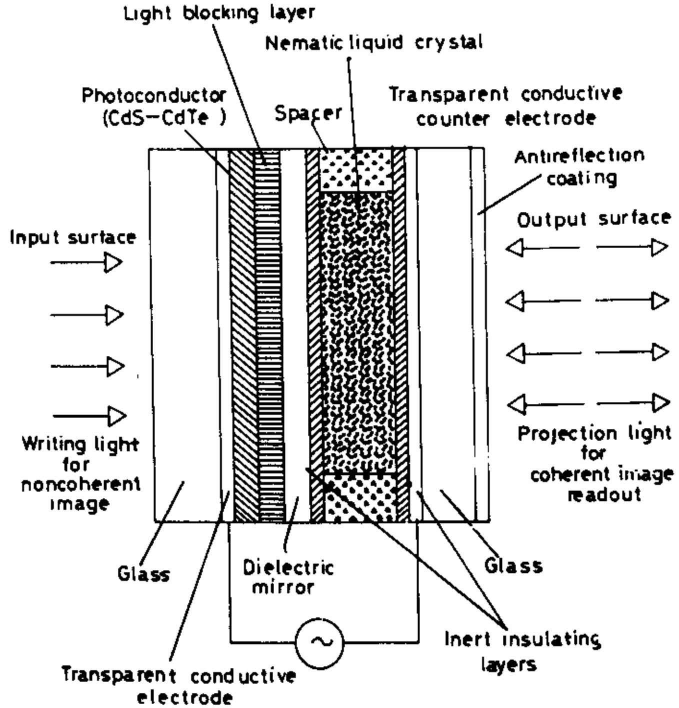


Fig. 21. Side view of a liquid crystal light valve (LCLV) and its operation (After W.P. Bleha et al, *Opt. Engng.* 17 [1978] 371)

[Paek and Psaltis 1987]. Recent proposals for optical associative memory systems by Belov and Manykin [1991] and Wang et al. [1991] are based on photon-echo effect and orthogonalized hologram respectively.

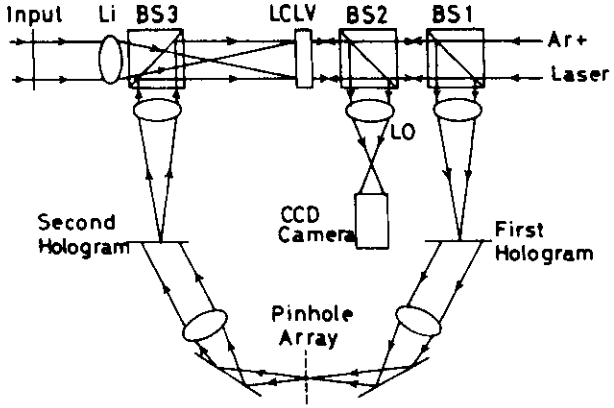


Fig. 22. Optical auto associative loop. (After Paek and Psaltis 1987)

4.10 Other applications of PR materials in brief

Real-time holography and interferometry

As compared to photographic plates, the PR materials have the advantage of not needing any processing of the recording medium and replacement, for the application in interferometry. Using a TWM geometry with an applied field and moving grating, Huignard and Marrakchi [1981] demonstrated the mode pattern visualization of a vibrating structure. If the time constant of space-charge field build-up in the crystal is longer compared to vibrational period of the object, there is spatial modulation of energy transfer corresponding to the mode pattern of the vibrating object. Improved contrast and high SNR can be obtained by polarization filtering in a suitable wave-mixing geometry [Herriau et al. 1985]. Dynamic interferometric techniques based on PC, anisotropic diffraction etc. have also been developed [Chang et al. 1988, Frejlich et al. 1989, Troth and Dainty 1991, Troth et al. 1991, Yang et al. 1991, Rossomakhin and Stepanov 1991].

Photolithography

The use of phase conjugation for high resolution photolithography has been suggested by Levenson [1980, 1981]. The phase conjugate method avoids the use of well corrected and expensive lens system for imaging. Correction of any optical aberration through PC gives full spatial resolution over a large image field in the projection process [Huignard et al. 1980b]. The use of SPPC mirrors can make the projection system self-contained.

Novelty filter

The function of a novelty filter is to display the time dependent features of a scene by exploiting the finite response time of a PC mirror. In a novelty filter configuration, PC mirror is incorporated in an interferometric set-up, which functions as a dynamic filter to perform temporal differentiation [Anderson and Erie 1987, Wherret and Tooley 1988, Günter and Huignard 1989]. An optical tracking novelty filter allows one to see only those components of the input information which change with time and it filters all of the steady state components. Cudney et al. [1988] described a transient detection microscope that preferentially displays moving objects. This device which operates in real-time using nonlinear coupling of optical beams inside a PR $BaTiO_3$ crystal, requires only milliwatts of laser power and can detect objects moving at velocities of a few μm/sec. A single beam interferometer that effectively subtracts an exponentially weighted history of the input from the current value, which functions as a novelty filter, has been demonstrated by Ford et al. [1988]. This single beam interferometer uses signal depletion due to noise amplification (fanout) in a specially cut crystal of $BaTiO_3$.

Multiple image storage

PR materials are potentially useful for parallel information storage and retrieval. Multiple data planes can be recorded and selectively retrieved using the Bragg angle selectivity of volume holograms [Amodei et al. 1972, Agranat and Yacobi 1988]. Ford et al. [1989] used a Ce:SBN:60 crystal as the material for superimposing holograms. Recently Mok et al. [1991] recorded by angular multiplexing, as many as 500 high resolution uniformly diffracting holograms in a single $LiNbO_3$: Fe crystal. Multiple holographic storage is useful in many areas including template matching, optical neural networks and optical inter-connects.

Phase locking of lasers

PC offers the possibility of coupling together several lasers to produce a diffraction limited output beam which combines the output power of the individual lasers [Cronin-Golomb et al. 1986, Feinberg and Bacher 1986]. In a phase locking configuration using FWM in a PR nonlinear (NL) medium, a 'master' laser provides pump beams in the medium. This NL medium is the output mirror of a 'slave' laser. The scattered light from the crystal initiates an oscillation and lasing starts between the NL medium and the remaining mirror of the slave laser. The role of the PC mirror is to direct a portion of the pump beams into the slave laser cavity while automatically choosing the spatial and spectral modes which optimize the gain of the system. Also, the phase distortions in the cavity and changes in the cavity lengths etc. are automatically compensated. Sternkler et al. [1986] studied the beam combining capability of DPCM and multipumped semilinear passive PCM using two Ar+ lasers with a $BaTiO_3$ as nonlinear medium. Cronin-Golomb et al. [1986] demonstrated the locking of GaAlAs lasers using PR SPPC. White and Valley [1988] have measured the locking range and energy scaling behaviour of a system of four pulsed dye oscillators coherently coupled through a common PC end mirror.

For the ultimate application of phase locking of lasers, an array of semiconductor diode lasers can be phase locked coherently into a single intense laser beam.

The ability to lock remotely placed two lasers would permit the coherent processing by NL optical techniques of images transmitted through an optical fiber.

Optical oscillators

Nonlinear optical oscillator employing PC via FWM is one of the potentially useful applications of wave mixing. It exploits almost all features of the conjugation process simultaneously to advantage (viz. spatial aspects such as wavefront inversion, frequency characteristics and temporal characteristics etc.). Using the PR materials, PC resonators are constructed which do not require intracavity laser gain medium [Cronin-Golomb et al. 1982, 1983, White et al. 1982, Fischer et al. 1986, 1989]. As is true for nearly all oscillators, two conditions must be satisfied for the self-excitation of a DFWM oscillator: (1) the energy input must compensate for the output and internal losses; and (2) the phase profile of the oscillating wave must be reproduced after one round trip in the cavity [Odoulov et al. 1991a].

Under steady state conditions the oscillating wave in an FWM oscillator is generated by diffraction from the photoinduced gratings and, at the same time, by interfering with the pump wave, sustains the grating efficiency at the required level. This is the main feature of dynamic grating lasers. The FWM type mirrors allow the development of cavities whose high-quality modes represent light fields carrying a large amount of optical information. Both pulsed and *cw* phase conjugate lasers have been constructed [Rockwell 1988, Feinberg and Bacher 1986, Jain and Sterensen 1984]. Erbschloe and Solymar [1988] demonstrated a linear resonator in a BSO crystal employing two pump beams which are frequency detuned. Detailed theoretical studies describing propagation of electromagnetic radiation in PC oscillators have been done by Lee et al. [1990, 1991].

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