J. Indian Inst. Sci., Mar.–Apr. 1996, 76, 257–262.

Phase conjugation by two-beam coupling in iron-doped lithium niobate

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Received on October 18, 1994.

Abstract

A novel technique using two-beam coupling in photorefractive iron-doped lithium niobate crystal to produce phase conjugate waves has been demonstrated. The phase conjugate of a probe wave is generated by exploiting a second-order change in the susceptibility of the nonlinear medium instead of a change in the third-order susceptibility as in four-wave mixing. The phase conjugate of the probe beam is formed in the direction of transmission due to the diffraction of the pump wave from a 180° rotated volume grating that is formed in the crystal.

Keywords: Photorefractive materials and phase conjugation.

1. Introduction

The photorefractive effect in certain nonlinear crystals was noticed as a nuisance in attempts of generating second harmonic waves[1,2]. The incident laser pulse was found to cause a local, semipermanent refractive index change. This change, caused by light-induced electrostatic field of the order of 10^5V/m, is termed as optical damage. Photorefractive effect may be explained as follows: (i) Light induces separation and migration of charges that originate from impurity (intrinsic) levels or by dopants (extrinsic) in the crystal. (ii) The separation of the charges results in a strong electrostatic field. (iii) The electrostatic field causes a change in the refractive index of the crystal by the Pockel's (linear electro-optic) effect. Photorefractive index change is independent of the total intensity of the beams but depends on their relative intensity. However, the speed of formation of photorefractive effect increases with increase in total intensity.

Chen and coworkers[3] used optical damage to their advantage when they demonstrated that the light-induced refractive index change could be used to store high-quality holographic images in photorefractive $LiNbO_3$ and $LiTaO_3$. Holography is the process of recording and retrieval of three-dimensional images. The phase information of the object is stored as an interference pattern in a photographic emulsion. Small changes of the object position can be studied by the holographic double-exposure process. Here a holographic exposure of an object in its equilibrium state and a reference wave is simultaneously recorded on a photographic plate. The second exposure is made on the same plate after the object is displaced. This plate after being developed and on illumination with the reference wave would contain the virtual image of the object and the interference fringes which is the measure of displacement of the object. Double-exposure holography is chiefly used for permanent storage and is extremely useful for the study of transient events. In real-time holographic technique the first step of the double-exposure holography is incorporated. After the development *in situ* of the photographic plate the object and the reference waves illuminate the hologram. Changes in the position of the object cause relative phase changes in the object wave and can be seen as a shift in the fringe location. The information content of holograms can be sufficiently high to permit the recording and reconstruction of fine details of a complicated wave with great fidelity. An exhaustive holographic interferometric analysis and applications may be seen elsewhere[4–6].

The property of real-time holography as a tool for the generation of PC waves was demonstrated[7] by the four-wave mixing (FWM) geometry. Figure 1 shows the FWM geometry. The FWM scheme consists of two counterpropagating pump waves of equal but high intensities and a probe wave of low intensity interfering in a nonlinear medium. Owing to nonlinear interactions in the medium a fourth wave is generated which counterpropagates to the probe wave and is observed to be the PC replica of the probe wave. The formation of the PC wave may be visualized as follows. One of the pump waves (I_{REF}) and the probe wave (I_{OBJ}) interference in the nonlinear medium to form a grating is shown in Fig. 2a. This grating is read by the counterpropagating pump wave ($I_{REF'}$.) The diffracted read (I_{READ}) is the new wave generated and has its phase conjugated with respect to the probe wave. Figure 2b shows the I_{READ} diffracted by the grating to form the PC wave, I^*_{OBJ}. Such a PC wave is called 'time-reversed' wave since it counterpropagates to the direction of the probe wave. The incident laser power level required to cause a change in the second-order susceptibility is at least two orders less in magnitude than that to produce a third-order susceptibility change in any nonlinear medium. Several nonlinear optical materials have been used to generate PC waves by the degenerate FWM geometry through the dependence of third-order nonlinearity[8]. Ferroelectric photorefractive crystals are suitable media for FWM of low-power CW

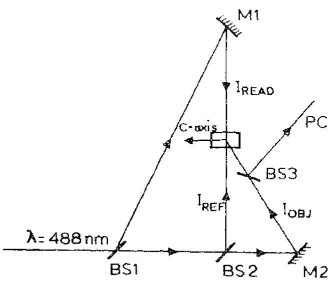

FIG. 1. Experimental FWM scheme to generate phase conjugate waves.

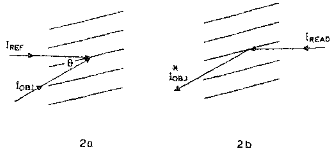

FIG. 2. Schematic representation of four-wave mixing as lapsed-time holographic process.

light beams permitting their amplification, phase conjugation and optical oscillation. Photorefractive materials have also been extensively studied in a similar geometry and self-pumping mechanism to obtain PC replica of an input wave. Continuous wave generation of complex conjugate wavefront *via* FWM in $LiNbO_3$ and $LiTaO_3$ with diffusion nonlinearity was studied by Kukhtarev and Odoulov[9]. Higher order nonlinear effects were seen in $LiNbO_3$:Fe in producing phase conjugate waves[10,11].

Phase grating in ferroelectric photorefractive materials with diffusion nonlinearity is $\pi/2$ shifted with respect to the interference pattern and the shift direction depends on the polar axis orientation. The interesting feature is that the FWM process in ferroelectric crystals is not invariant to the polar axis inversion[9]. The calculation of sensitivity of the FWM to misalignment depends also on the crystal axis orientation and is more strict for a situation in which the intensity of the third wave decreases. Due to the diffusion nature of nonlinearity, the efficiency of the FWM depends on the angle of beam intersection. The divergence of the laser beam at the point of interaction affects the sensitivity of FWM.

We report a novel technique of generating PC waves using photorefractive iron-doped lithium niobate. Two waves of equal intensity from an argon laser is made to interfere in the crystal. The interference results in the formation of a semipermanent phase grating. It has been observed that in $LiNbO_3$:Fe a phase grating formation time is of a few seconds while that of its decay time is much longer. The formation and the decay times are however dependent on the intensity of the input waves. After the formation of the phase grating due to the interference of I_{REF} and I_{OBJ} , the crystal is rotated by 180° (π-rotation) about an axis perpendicular to the optical table. π-rotation of the crystal amounts to rotation of the grating vector by 180° about an axis perpendicular to the table. The π-rotated grating is similar to that observed in a typical FWM geometry (Fig. 2b), where I_{REF} reads the grating instead of I_{READ} . Therefore, it has been observed that I_{REF} diffracted from the π-rotated grating in the direction of transmission is the forward phase conjugate (FPC) wave. The FPC wave has its complex amplitude conjugated in comparison with the probe wave. However, unlike, 'time-reversed' PC wave, the FPC wave propagates in the direction of I_{OBJ} (probe wave).

2. Experimental

The two-beam coupling (TBC) experiment was carried out in iron-doped (0.02% wt) $LiNbO_3$ ($5 \times 5 \times 2$ mm). The input beams with an overall power of 10 mW and of equal intensities were derived from an argon laser, $\lambda = 488$ nm. The beams were polarized normal to the c-axis of the crystal, the c-axis being in the plane of incidence (Fig. 3). The initial phase grating formation is observed by blocking one of the two input waves. The other input wave gets diffracted from the grating in the direction of the first. The detector, UDT-S380, United Detector Technology, USA, was used to measure the diffracted signal. The intensity ratio of the diffracted wave with this input wave is the diffraction efficiency. The diffraction efficiency increases and reaches a saturation on the formation of the phase grating. After the formation of the phase grating due to I_{REF} and I_{OBJ} the crystal is π-rotated about an axis perpendicular to the optical table. I_{REF} is now diffracted from the π-rotated grating in the direction of I_{OBJ} . With the object wave

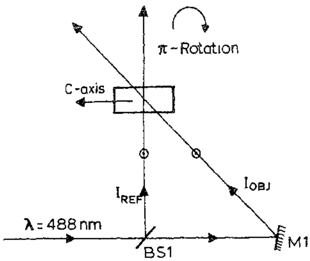

FIG. 3. Two-beam coupling scheme to generate forward phase conjugate wave. The input waves are polarized normal to c-axis.

I_{OBJ} cut off, the diffracted I_{REF} is the FPC wave (I^*_{OBJ}). The FPC wave propagates in the direction of I_{OBJ} and also has its complex amplitude conjugated in comparison with I_{OBJ}.

The time taken for rotating the crystal by 180° is far smaller than the time taken for the complete erasure of the phase grating. The phase distortion correction for PC wave of the input Gaussian beam has been studied. An oil-smeared transparency at a distance 2 cm from the crystal was inserted in the object beam. The new phase distorted object wave was made to interfere with I_{REF}. The crystal was π-rotated as mentioned above. The reference beam I_{REF} diffracted from the grating in the crystal, with I_{OBJ} cut off, gave rise to the generation of the FPC wave of the distorter. The transparency is also π-rotated and is now placed in the front-focal plane of the crystal at a distance of 2 cm. The generated FPC wave which when passed through the same region of the transparency in the transmission direction got its phase distortion corrected for. Figure 4 shows the original, the distorter and the corrected beam. These experiments were performed in the transmission geometry. Similar observations could be seen in the case of reflection geometry in which I_{REF} and I_{OBJ} interfere from either side of the crystal.

The TBC experiment for the phase distortion correction has the initial hologram of the object stored but, unlike conventional holography, the hologram is reconstructed by

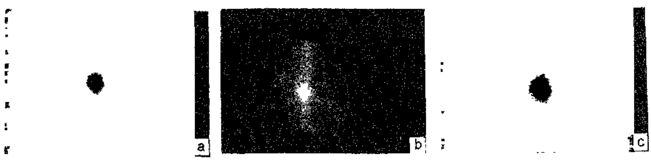

FIG. 4. Distortion correction properties of the FPC waves generated by TBC scheme. a) the input wave, b) the distorted wave, and c) the reconstructed wave.

the conjugate reference wave. The TBC setup could be used for real-time holography. In real-time holography the initial hologram of the object is stored. A π-rotation of the crystal generates an FPC wave by the diffraction of I_{REF} on the grating. The object in consideration is subject to a displacement, stress or vibration. The far-field pattern of this object wave interferes with the FPC object wave. The far-field pattern is a set of dark and bright fringes which is a measure of the change in the object. PC interferometers are doubly sensitive in comparison with the conventional ones[4].

3. Conclusions

In the TBC experimental setup an object wave was made to interfere with an equally intense reference beam in the volume of $LiNbO_3$:Fe ($5 \times 5 \times 2$ mm). After the formation of the phase grating due to the interference of these two beams, the crystal is rotated by an angle of 180° about an axis perpendicular to the optical table and with the object wave cut off. The reference wave diffracted from the 180° rotated grating is the FPC replica of the object wave. Phase distortion correction property of the generated FPC wave was studied. The technique incorporated the interference of only two waves to generate PC waves unlike FWM scheme that requires three input waves. It was also pointed out that such a technique required low laser power levels to bring about a second-order susceptibility change in $LiNbO_3$:Fe to necessitate the generation of PC waves. The technique could be used in several real-time applications as well as in PC interferometry. A comparison of an interferometer using the TBC technique with the conventional phase conjugate interferometer was mentioned.

Acknowledgement

Thanks are due to Prof. Vikram Kumar, Director, Solid State Physics Laboratory, New Delhi, for providing the iron-doped lithium niobate crystal. Our grateful thanks are due to late Prof. P. S. Narayanan, Department of Physics, Indian Institute of Science, for inspiration and guidance. Financial support from the Defence Research and Development Organization, Ministry of Defence, is gratefully acknowledged.

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