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Holographic and phase conjugate interferometry with nonlinear optical media

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Abstract

The utilization of the results obtained in the course of investigations on the absorbing dyes, to develop and implement new schemes, to re lize certain practical applications involving phase conjugators with special emphasis on interferometry is reported. Techniques employing two different geometries for the realization of the real-time and time-averaged interferometries using a combination of dye-doped polymers and photorefractive crystals are discussed here. The ability of a dye–crystal composite structure to generate two independent but overlapping phase conjugate waves which can interfere to reveal the phase changes in a test object is discussed and demonstrated using specific cases

Keywords Optical phase conjugation, holographic interferometry, photorefractive effect, saturation of absorption, wave mixing, holographic storage.

1. Introduction

Phase conjugate mirrors (PCM) incorporate nonlinear optical effects to precisely reverse both the direction of propagation and the overall phase factor for each plane wave in an arbitrary beam of light incident on them. This peculiar image transmission property has given rise to a vast range of important practical applications like phase aberration compensation, pointing and tracking and interferometry. It has been demonstrated in a variety of applications that any nonuniform phase change caused by atmospheric turbulence or distortions due to optical elements can be corrected for, due to the healing property of a PCM[1]. The auto-tracking property of the phase conjugate (PC) wave and possible amplification with high-gain phase conjugators is also widely known. It is also known that in an interferometer in which the conventional mirror is replaced by a PCM carries several advantages over the conventional interferometric configurations[2].

A variety of materials have been used for the generation of PC waves. Photorefractive (PR) crystals and organic dyes in several hosts have been utilised as efficient phase conjugators. Here we present several techniques employing PR crystals and dye-doped polymer (DDP) thin films to realise real-time and time-averaged holographic and PC interferometries[3].

2. Real-time and time-averaged holographic interferometry

Holographic interferometry by two-wave mixing (TWM) utilising nonlinear optical media was achieved using a variety of mechanisms and geometries. The major problem in such holographic interferometric configurations is the necessity to provide spatial separation between the object wave and the diffracted wave in order to avoid the bright background. Many methods of separation have been proposed, *viz.*, amplification of the image[4], polarization separation of the signal[5], etc. Here we report the proposal and implementation of two interferometric schemes using PR crystals and DDP thin films in a TWM geometry. One scheme involves the ability of some media like photorefractive lithium niobate crystals or certain organic dyes to store a recorded hologram for a large amount of time. Another scheme is to use the –1 order diffracted image, which is phase conjugate of the object wave, generated by DDP films. This provides spatial separation between the diffracted and the object beams[6]. The design and implementation of both the schemes are presented here. In either case the influence of various experimental parameters on the diffraction efficiency is investigated. The factors that have to be taken into consideration for optimising each scheme are also briefly discussed.

2.1. *Holographic storage and two-wave mixing*

Both PR crystals and DDP films are now extensively used as recording media in dynamic holography through the TWM process. The formation of a hologram in these nonlinear materials is accompanied by an energy redistribution between two interfering light waves passing through the media[7]. The physical mechanism governing beam coupling is the self-diffraction of the beams by the photoinduced phase volume grating recorded in the nonlinear medium.

PR crystals are known to exhibit semipermanent photoinduced refractive index changes. These crystals are well suited for recording the interference field due to an object wave, containing spatial information of the object, and the reference beam in real-time. With a dynamic PR crystal all the steps like recording, developing and read-out of the hologram can occur simultaneously. Certain organic dyes undergo photoinduced chemical changes when exposed to laser light. This can occur either by photoisomerization or an irreversible photochemical reaction. Here we discuss the realization of interferometry through nonlinear media having a long holographic storage life. The case of iron-doped lithium niobate crystal is discussed in detail. The principle is the same for DDP films showing irreversible photochemical changes.

Generally in a PR material, the optical nonlinearity is understood to be originating from the space charge field set up by photoexcitation of free charge carriers in the material. A spatially modulated intensity pattern incident on such a PR medium gives rise to a spatially nonuniform distribution of carriers which are transported by various mechanisms[8,9] like diffusion, drift, etc. It has been shown that phase holograms can be recorded in iron-doped $LiNbO_3$ through the generation of space charge patterns that set up an electric field-induced modulation of the refractive index[10].

2.1.1. *Factors influencing beam coupling efficiency in TWM*

The TWM geometry shown in Fig. 1 is used to investigate the parameters influencing the beam coupling efficiency. The diffraction efficiency of the grating (defined as the ratio of the intensity of the diffracted beam to that of the reading beam) depends on the

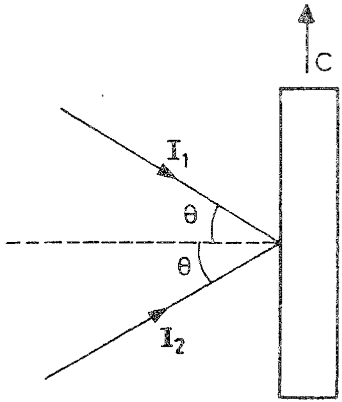

FIG. 1. Two-wave mixing geometry

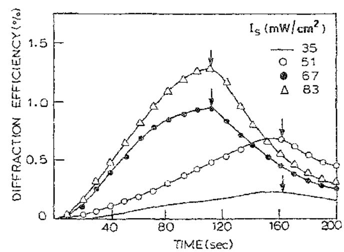

FIG. 2 The growth and decay of the diffracted intensity at different levels of overall intensity I_S. The arrow (↓) indicates the time at which one of the incident beam is blocked in order to monitor the decay.

total light intensity, the spatial frequency and the intensity ratio of the writing beams. It is observed that for this particular sample with 0.02 mol% of Fe by weight, high efficiency could be obtained even at an interaction angle (2θ) nearly equal to 60° between the incident beams. This large interaction angle allows the recording of holograms of even large size objects. This implies that higher spatial frequencies can also be faithfully reconstructed.

Figure 2 shows the time development of the diffraction efficiency at different levels of overall intensity I_S at 488 nm. For each I_S the intensities of the beams I_1 and I_2 are equal. Both beams are linearly polarized and oriented perpendicular to the plane of incidence. Care is taken to fix the path difference between the two beams to be well within the coherence length of the laser. Each curve shows the grating formation and decay at that particular I_S. In the geometry shown earlier, on the transmission side of the crystal, there are two contributions in the direction of each of the beams. The first-order diffraction of each beam overlaps with the zero-order transmission of the other beam. The diffraction efficiency during the growth of the grating was hence monitored by intermittently chopping one beam and recording the light intensity diffracted from the other beam.

The duration for which the beam is chopped is very small compared to the interval between two successive blockings, and much less than the typical grating decay times prevalent in lithium niobate crystal. Hence there is no readout erasure during the measurement of the diffraction intensity. The decay of the grating is measured by blocking one of the beams and continuously monitoring the diffracted intensity of the other beam. The time at which it is blocked is shown by an arrow mark (↓) in Fig. 2. The formation and decay rates show a considerable increase with an increase in the overall intensity I_S. Thus in an interferometric scheme an optimum intensity can be chosen so that there is a proper balance between the diffraction efficiency and the dynamic erasure at that intensity. This ensures that the life of the hologram is large compared to the rate of phase change of object wave in a real-time holographic (RH) interferometer.

The normalized diffraction efficiency for different values of the incident intensity ratio β (I_1/I_2) is shown in Fig. 3. Different values of β were obtained by introducing neutral density filters (NDF) in the path of beam I_1. The modulation index m of the electro-optic field induced in the crystal and β are related by $m = \frac{2\beta^{1/2}}{(1+\beta)}$. The theory of holographic recording in PR materials[11] predicts that the diffraction efficiency $\eta \propto m^2$. The solid curve in Fig. 3 shows the plot of m^2 for different values of β. It is clearly seen that it fits well with the experimental values of normalized diffraction efficiency. Hence in order to get a high holographic diffraction efficiency it is desirable to work with values of $\beta \geq 0.7$. This implies that even if the test object is diffusely reflecting, reasonable diffraction efficiencies can be achieved. Thus the two experimental parameters, interaction angle and incident intensity ratio impose a restriction on the type of test object that can be used for imaging.

2.1.2. *Experimental configuration and principle*

Experimental techniques similar to the one being discussed here[12] have been utilised earlier with different photorefractive crystals[13,14]. The lithium niobate crystal is oriented such that its C-axis is parallel to the plane of incidence as shown in Fig. 4. A reference wave and the object wave are allowed to be incident on the PR crystal and the hologram containing the original phase information of the object is recorded. Suppose that the test object undergoes phase changes. Now the beam I_0' contains two components as mentioned earlier. One is the diffracted reference beam I_{rd} from the recorded hologram that contains the phase information of the original object and the other the transmitted object beam I_{ot} that carries the phase information of the deformed object. These two components interfere with each other and form a fringe pattern at the image plane D. These fringes are a direct measure of the phase changes that the object has undergone.

The contrast of the fringes in the interferogram observed at the image plane in the above experiment is poor because the diffracted intensity of the reference beam is three orders of magnitude less than that of the transmitted object beam. In order to get the maximum fringe contrast, it is necessary to make the intensities of the two interfering beams nearly equal. This is achieved by introducing an appropriate NDF in the path of the original object wave which helps in two ways.

1. It increases the fringe contrast by making the intensities of the interfering beams I_{ot} and I_{rd} nearly equal.
2. It also reduces the overall incident intensity on the crystal. According to Fig. 2 low overall intensity allows the hologram to decay and grow at a very slow rate. Hence

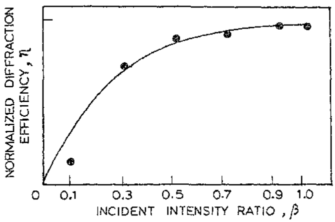

FIG. 3. Normalized diffraction efficiency in lithium niobate crystal for different values of incident intensity ratio β.

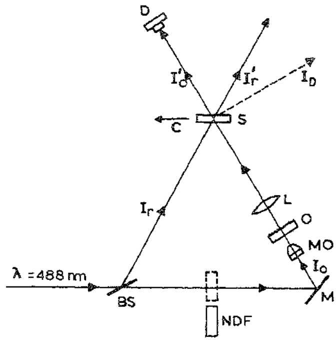

FIG 4. Schematic diagram of a real-time holographic interferometer using TWM geometry; M:Mirror, BS.Beam splitter, O:Object; L:Lens; D:Detector; MO:Microscope objective, NDF:Neutral density filter, C:Crystal axis; I_D -1 order diffraction signal.

the object deformation can be continuously studied before the dynamic erasure of the original grating takes place.

Thus the contrast of the interference pattern formed in the crystal and the contrast of the interference pattern formed at the image plane can be controlled to reduce the effect of the background intensity.

2.1.3. *Demonstration*

The experimental arrangement used to demonstrate RH interferometry in iron-doped $LiNbO_3$ is shown in Fig. 4. A transparent glass cell filled with glycerin with a heater coil inserted into it is chosen as the object. In the first step, the hologram of the unheated coil is recorded in the PR iron-doped $LiNbO_3$ crystal. The image reconstructed in the transmission direction is shown in Fig. 5(a). In the second step, the heater coil is switched on and switched off after about one minute. The diffracted reference beam, that contains a recorded image of the original object, interferes with the modified transmitted object beam continuously. The time evolution of the optical phase changes due to the thermal currents and can be recorded in the form of an interference fringe pattern.

The interferograms obtained at different times while heating the coil are shown in Fig. 5(b–d), and those after the coil is switched off are shown in Fig. 5(e–f). These photographs show that heat generated from the coil gradually diffuses into the surrounding medium which can be clearly seen from the increase in the number of fringes as time progresses. After switching off the coil the fringe movement settles down slowly as the liquid reaches the equilibrium state where the temperature becomes uniform. This can be

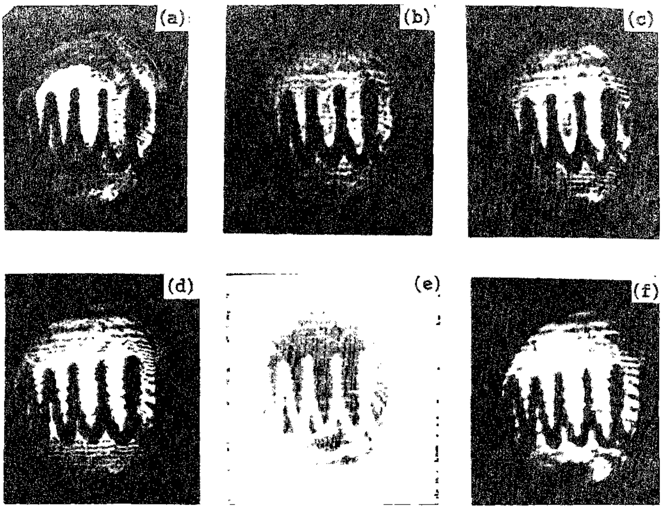

FIG. 5. Real-time holographic interferometry utilising $LiNbO_3$ crystal; (a) holographically reconstructed image of the original object, (b–d) interferograms while the coil is heated, (e–f) interoferograms after the coil is switched off.

seen from the absence of fringes in the horizontal direction. But still a vertical temperature gradient exists, as is evident from the set of vertical fringes seen in the last set, Fig. 5(e–f), of interferograms. Thus a continuous monitoring of thermally induced optical phase changes is made possible by this interferometer.

2.2. *Generation of* –1 *order diffracted beams*

The ability of the dye/polymer films to generate forward PC signals by TWM using the modulation of the saturable absorption coefficient of the medium is well known. Higher diffraction orders have been produced due to self-diffraction in the thin grating regime. The technique being described here involves the observation of the reconstructed hologram in the –1 order diffracted beam. The most essential features of this scheme are : (a) The reconstructed image is spatially well separated from the transmitted object beam hence the signal-to-noise ratio is extremely high; (b) The first diffraction (±1) orders are phase conjugates of each other; (c) The –1 order beam carries all the phase information of the object beam; (d) Any changes in the object show up in the reconstructed image with a time lag due to the finite response time of the dye medium; (e) The recording of the hologram is usually much faster than the erasure time.

2.2.1. *Experimental*

The geometric arrangement used for the observation of the −1 order diffraction is the same as shown in Fig. 4. The influence of parameters like angle of interaction, β, etc., on the first-order diffraction efficiency is studied. The first-order diffraction efficiency, η_{-1}, is measured as the ratio of the spatially separated I_D beam intensity to the intensity of I_r beam. The experiment is carried out on some of the azo-dyes like aniline yellow and methyl yellow embedded in PMMA matrix which have fast response times to optical fields. A CW argon ion laser operating at 488 nm wavelength is chosen for the investigations.

2.2.2. *Discussion*

The experimental investigations[15] give a set of criteria for optimising the configuration of an RH interferometer for operation in the −1 order diffraction regime. Since there is a total separation of the object wave from the reconstructed hologram, isolation of the diffracted and transmitted images does not require polarizers. An important parameter influencing the design and implementation of a holographic interferometer is its spatial resolution. This is determined by the spatial frequency dependence which in turn determines the maximum angle that an object can subtend at the nonlinear medium. This determines the size of the object that can be viewed with the system. It has been observed that for efficient two-beam coupling not a very wide interaction angle range is permissible in the case of dye films, as opposed to that of a PR crystal. Also the images produced using the −1 order diffracted beam are known[16] to be phase conjugate of the object beam.

The time taken for growth and decay of grating recorded in the DDP film, especially in the event of probe or object beam modulation at various pump intensities (Fig. 6) indicates that the dye has a fast response time which primarily depends on the incident intensity and the nonradiative excited singlet to triplet state transition rate. The decay of the grating sets in as soon as either of the beams is switched off and the rate is slower than the growth times. These decay times are indicative of the excited triplet to singlet ground state relaxation times.

Thus this finite interval of overlap between the growth and decay patterns can be utilized for the interferometric scheme. If an object is placed in the path of the probe beam, a −1 order diffracted image can be reconstructed using the above geometry. This image disappears if either of the recording beams is turned off. If the phase of the object wave is altered by any disturbance then a new image can be reconstructed with the new object wave. The old hologram meanwhile decays in a finite time and a period of time exists where both the old and new images overlap. Thus in a single growth–erasure cycle there will be two diffracted waves which can differ in phase during a part of the grating erasure. This results in an interference pattern and the phase difference shows up as fringes. If this erasure and recording is repetitive then a time-averaged interference pattern gets established and interferograms can be taken.

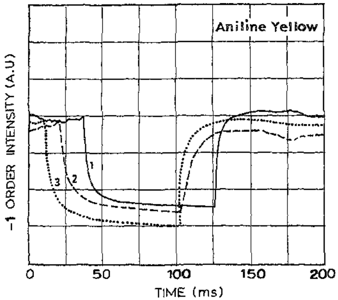

FIG. 6 Oscilloscope patterns showing growth and decay of first-order diffraction signal in DDP films when probe wave is modulated at various pump intensities (mW/cm^2); (1) 70, (2) 175, (3) 220.

This configuration is most suitable for time-averaged interferometry, a simple demonstration of which is shown in Fig. 7. The figure shows the phase changes due to heating of the air by a steady flame from a double-wick candle. The interferogram in the −1 direction was recorded with a long exposure so a fuzzy halo developed around the flame. A more useful application would be to have a repetitive phase change of the object wave as in the case of a vibrating membrane where a clear time-averaged fringe pattern can be recorded. Thus a clear first-order holographic image reconstruction and time-averaged holographic interferometry useful in vibration analysis can be realized.

3. PC interferometry with a novel composite structure

Ferroelectric photorefractive crystals were shown to be capable of having large storage times and slow response to optical fields as discussed earlier. DDP films like methyl-red/PMMA can generate PC waves by degenerate four-wave mixing with a fast response time due to the saturation of absorption of the dye medium. The comparison of the values of PC reflectivities in various media reveals that PR crystals are about two orders of magnitude more efficient than DDP thin films. But the response to optical fields of the PR effect is generally two orders of magnitude slower than the saturable absorption mechanism in the dye films. Here we report a novel approach[17] to combine the high diffraction efficiency of a PR crystal and the fast response times offered by DDP films, by preparing a composite material. We have prepared a new composite material by depositing a thin layer of an absorbing azo-DDP film on a photorefractive iron-doped $LiNbO_3$ substrate.

This composite structure can now generate two kinds of PC waves in an FWM geometry. The crystal will generate a PC signal due to the creation of a space charge field-modulated refractive index grating. The diffraction efficiency of this grating reaches a steady-state value and PC intensity saturates. The dye film can, in FWM geometry, also generate a PC wave due to saturation of absorption of the dye. The growth of the PC signal due to the dye film is almost instantaneous in comparison. The difference in the time scales of the two PC waves is made use of in PC interferometry with this composite.

FIG 7 Time-averaged interferogram obtained by the -1 order diffraction scheme using dye-doped polymer films

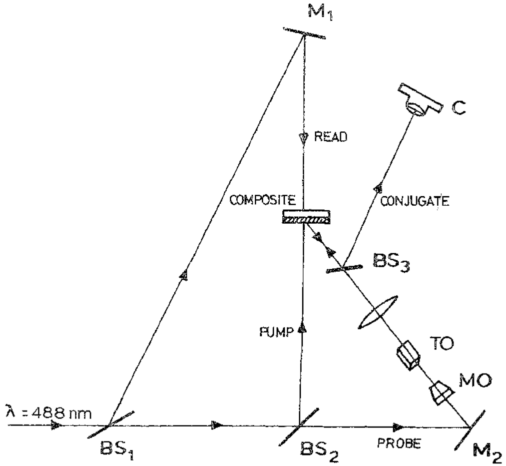

FIG 8 Schematic diagram of a phase conjugate interferometer M:Mirror, BS:Beam splitter, MO:Microscope objective, O.Object, L Lens, R:Camera; C.Composite, NDF:Neutral density filter

3.1. *Principle and demonstration*

The experimental setup used for performing PC interferometry is shown in Fig. 8. The 488-nm wavelength of a CW argon ion laser is split into three beams which are made to overlap on the composite material in a typical degenerate FWM geometry. The principle involved in the realization of PC interferometry using this composite material is illustrated with a specific case.

A test object, a transparency slide, is kept in the path of the probe beam, suitably expanded. Initially, only pump and probe beams are switched on. The hologram of the slide is recorded in the crystal in this TWM geometry. No permanent holographic storage is observed in the dye film part of the composite structure. In the next step all the three beams are switched on simultaneously. A phase change in the object wave from the transparency is introduced by way of a slight positional disturbance either in the optical elements or the test object. The dye film generates a new PC signal in this FWM geometry. Now two distinct images are formed by the read beam. One is due to diffraction from the hologram written in the first step and the other is an FWM signal with the new object wave. These two PC waves carrying the two distinct images are travelling in the same direction and overlap in space. They are slightly different in phase and this shows

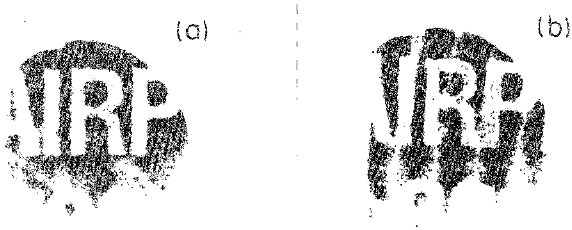

FIG. 9. Phase conjugate interferometry using a composite structure, (a) holographic reconstruction of the original transparency slide, and (b) interferogram showing fringes due to a small positional disturbance

up in the form of interference fringes as can be seen in Fig. 9. The fringe spacing is a measure of the phase changes. This is a double-exposure type of PC interferometry.

Real-time PC interferometry has also been realized using composite material to study the refractive index changes due to thermal currents in a liquid. The FWM geometry employed by us helps in obtaining a PC image of the object which is free from distortions because of its aberration compensation property. The importance of the present work lies in the fact that by preparing the nonlinear medium, as suggested, interferogram contrast of near unity can be attained at the image plane. This is possible because the phase conjugate reflectivities of the two media in the composite structure can be tailored independently by choosing appropriate experimental and medium parameters.

4. Conclusion

Various schemes have been discussed that realize holographic and phase conjugate interferometries using both FWM and TWM in nonlinear optical media like photorefractive crystals and dye-doped polymer films. The advantages of the schemes over conventional interferometry and an analysis of the influence of experimental and geometric parameters on the design of the interferometer are presented. The long holographic storage times of PR crystals and the short response times of the DDP films are made use of to realize the holographic interferometers. A novel composite material which combines the efficiency of the PR crystal and the fast response times offered by DDP films is utilized to realize a PC interferometer.

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