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Optical phase conjugate interferometry with a photorefractive crystal

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Abstract

Photorefractive iron-doped lithium niobate crystal is made use of to generate phase conjugate waves in various experimental configurations. These configurations are extended to interferometers to measure phase changes of an object wave displacement. The interferometers that involve the generation of phase conjugate waves are shown to be highly sensitive to phase changes. The Michelsons interferometer with a photorefractive iron-doped lithium niobate as the beam splitter is proposed for the measurement of angular tilts.

Keywords: Phase conjugation, photorefractive crystals and interferometry

1. Introduction

In the absence of transient phenomena occurring in nonlinear media, the four-wave mixing (FWM) scheme to generate phase conjugate (PC) waves is considered to be analogous to real-time holography. The FWM scheme (Fig. 1) consists of two counterpropagating plane waves (pump waves) and a probe wave of an arbitrary wavefront 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 as a real-time holographic process may be visualized as follows: (i) the probe wave and one of the pump waves (write wave) form an interference pattern in the medium; (ii) the other pump wave (read wave) is diffracted by the standing interference pattern, and (iii) the resultant diffracted wave is the desired PC wave.

Several nonlinear materials have been used to generate PC waves[1,2]. Photorefractive (PR) materials form a distinct class of nonlinear media because of their large and saturable nonlinearities. Lithium niobate, barium titanate, bismuth silicon oxide, and bismuth germanium oxide are a few examples of the PR crystals which have been extensively studied to generate PC waves[3]. We have made investigations in iron-doped lithium niobate (IDLN) to generate PC waves. In this paper, we have summarized two new methods of generating PC waves in IDLN crystal, subsequently utilizing it in interferometric applications. These methods have been described in two separate subdivisions, namely, Parts I, and II. We have also evaluated the Michelsons interferometer after replacing the beam splitter with the nonlinear IDLN crystal. This has been briefly described in Part III.

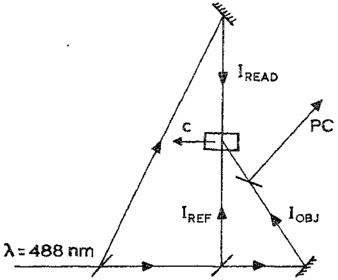

FIG. 1. The four-wave mixing geometry to generate phase conjugate waves with $LiNbO_3$:Fe crystal. The direction of the c-axis of the crystal is indicated.

2. Experimental

Part 1

We had reported a novel technique of generating PC waves in PR iron-doped lithium niobate[4]. Two waves of equal intensity from an argon laser are made to interfere in the crystal. The interference results in the formation of a semipermanent phase grating. 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. The π-rotation of the crystal amounts to rotation of the grating vector by 180° about an axis perpendicular to the plane containing I_{REF} and I_{OBJ}. The π-rotated grating is similar to that observed in a typical FWM geometry (Fig. 1) 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).

The π-rotation of the crystal to generate PC waves had been successfully incorporated in an interferometric scheme[5]. Here I_{REF} is a plane wave and I_{OBJ} is obtained from a beam passing through a positive transparency. Figure 2 shows I_{OBJ} imaged into the crystal by a biconvex lens. After the formation of the spatially varying interference pattern of I_{REF} and I_{OBJ} the crystal is rotated by 180° about an axis perpendicular to the plane of incidence. With the object wave I_{OBJ} cut off, the reference wave I_{REF} gets diffracted in the forward direction. The forward diffracted wave is observed to be the FPC replica of the input object wave I_{OBJ}. Figure 3 shows the FPC replica of I_{OBJ}. This figure is equivalent to the backward propagating PC wave in the conventional FWM geometry.

The π-rotation scheme has the FPC wave co-propagating with the probe wave and can be used in realising sensitive holographic interferometers[5]. Interferometers that incorporate conjugate waves are known to be more sensitive than the conventional interferometers[6].

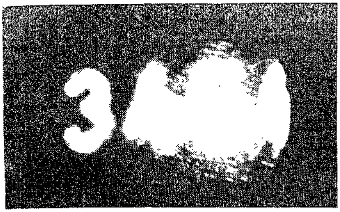

FIG. 2. The image of the positive transparency used as the object wave in the π-rotation scheme.

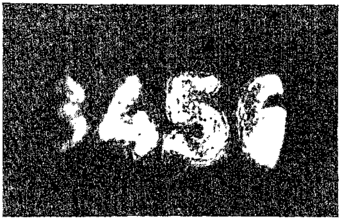

FIG. 3. Photograph of the forward phase conjugate of the object wave generated by the π-rotation scheme.

The $LiNbO_3$:Fe crystal was used because of its dynamic write, read, and erasure properties. The PC interferometer using a PR crystal is shown to be doubly sensitive in comparison to the conventional interferometer.

Part II

The schematic representation of generating PC waves by amplitude division is shown in Fig. 4. An input wave is amplitude divided into two waves at the beam splitter BS2. These two waves are made to interfere at the back surface of the IDLN crystal such that the normal to the crystal surface is the angular bisector. The back surface of the crystal promotes the growth of the diffracted signal on the reflection side[7]. It is known from holography[8] that two plane waves can be considered as conjugates of each other if their angular bisector is the normal to the holographic emulsion. In the proposed experimental scheme a phase grating in the IDLN crystal is formed by the interference of a wave and its conjugate. Due to self-diffraction each of these waves gets diffracted from the phase grating in the direction of the other, both on the transmission and the reflection sides. Thus on the reflection side, owing to self-diffraction, each wave may be considered as generating its own PC wave[9]. The experimental scheme is extended to an interferometer to measure small phase changes in the transmission side[10]. The interference of the object wave on passing through a positive transparency at equilibrium is first stored in the IDLN crystal. An interference pattern due to the displacement of the transparency is subsequently stored. These two holograms are reconstructed simultaneously by the displaced object wave. The far-field pattern formed is a contour of dark and bright fringes that gives a measure of the displacement. Such an interferometer is seen to be doubly sensitive[6] as mentioned earlier.

A similar experimental scheme of self-pumped phase conjugation by wavefront division was carried out[11]. The advantages and the drawbacks of such a scheme were highlighted.

Part III

Recently we had set up the Michelsons interferometer with the PR iron-doped lithium niobate crystal as its beam splitter. The nonlinear beam splitter has a two-fold operation.

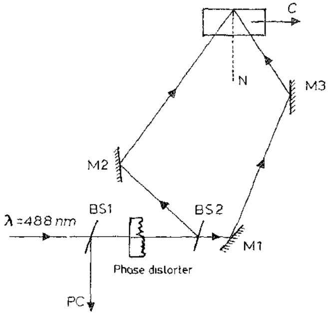

FIG. 4. Schematic representation of generating phase conjugate waves by amplitude division. The amplitude division of the object wave occurs at the beam splitter BS2. The phase distorter is an oil-smeared transparency.

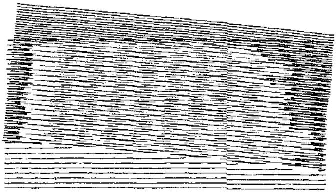

FIG. 5. A typical Moire pattern (simulated) that is a measure of a tilt caused at the input of the Michelsons interferometer. The Michelsons interferometer has a nonlinear holographic beam splitter.

(i) With the front surface coated with anti-reflection substrate, the back surface of the crystal serves as the beam splitter. (ii) Due to PR effect the crystal acts as a hologram to store information. The crystal therefore serves as a beam splitter and as a hologram storage device. An argon laser was used as the source to obtain the Michelsons interference fringes on a screen and simultaneously record the hologram formed due to the interference of the beams from the two arms of the interferometer. The hologram is continually written and read by the input beam. The hologram on being read by the input beam forms a distinct pattern different from the Michelsons fringes on the screen and is governed by Bragg's diffraction law. A glass wedge is inserted to cause an angular shift in the incident laser beam. This would cause twice the angular shift of the Michelsons set of fringes and an angular shift of the holographic pattern on the screen. A resultant Moire interference pattern which is attributed to the phase shift caused by such a tilt is seen in the region of overlap of these interference fringes. Figure 5 shows the Moire pattern (computer generated) that is typical of such tilts.

3. Theory

Let the sinusoidally varying input wave be given as

$$E_{\mathrm{OBJ}}(\boldsymbol{r},t) = A(\boldsymbol{r})\exp\left\{i\left[\omega t - \boldsymbol{k}.\boldsymbol{r} - \phi(\boldsymbol{r})\right]\right\}. \tag{1a}$$

The phase conjugate wave of equation (1a) is

$$E_{\mathrm{PCOBJ}}(\boldsymbol{r},t) = A^{*}(\boldsymbol{r})\exp\left\{i\left[\omega t + \boldsymbol{k}.\boldsymbol{r} + \phi(\boldsymbol{r})\right]\right\}. \tag{1b}$$

The FPC wave of eqn (1a) is

$$E_{\mathrm{FPCOBJ}}(r,t) = A^*(r)\exp\{i\,[\omega t - k.r - \phi(r)]\}. \tag{1c}$$

The FPC wave described by eqn (1c) has been used in the π-rotation interferometric scheme. Experimental details of such a scheme have been mentioned in Section 2 (Parts I and II). Here the theoretical analysis of the π-rotation scheme is briefly mentioned. We now consider the complex amplitude of an object wave (plane wave), I_{OBJ}, passing through a phase object as given by

$$\boldsymbol{E}_{\mathrm{OBJ}} = \boldsymbol{E}_{\mathrm{OBJ}}\,\exp(-i\phi). \tag{2}$$

A deformation or displacement of the object affects $\boldsymbol{E}_{\mathrm{OBJ}}$ and is given by

$$\boldsymbol{E}_{\mathrm{DIS}} = \boldsymbol{E}_{\mathrm{DIS}}\,\exp(-i(\phi + \delta\phi). \tag{3}$$

If the holographic recording medium is exposed first to the interference between $\boldsymbol{E}_{\mathrm{OBJ}}$ and $\boldsymbol{E}_{\mathrm{REF}}$ then a hologram of the object is stored. When this hologram is illuminated by the reference wave $\boldsymbol{E}_{\mathrm{REF}}$ the object wave is reconstructed. If the object was to undergo phase change given by $\boldsymbol{E}_{\mathrm{DIS}}$ then a simultaneous illumination with the reference wave $\boldsymbol{E}_{\mathrm{REF}}$ causes the interference between $\boldsymbol{E}_{\mathrm{DIS}}$ and $\boldsymbol{E}_{\mathrm{OBJ}}$ and the reconstructed $\boldsymbol{E}_{\mathrm{OBJ}}$ wave and is given by

$$I_1 = \left|\boldsymbol{E}_{\mathrm{OBJ}} + \boldsymbol{E}_{\mathrm{DIS}}\right|^2 \approx \cos(\delta\phi). \tag{4}$$

Equation (4) represents the irradiance of the object modulated by $\cos(\delta\phi)$. Small phase shifts of $\delta\phi$ can be detected by this holographic technique and are revealed as dark and bright contours of constant values of $\delta\phi$. These dark and bright fringes are formed at odd and even integer multiples of π respectively.

Let two input waves $\boldsymbol{E}_{\mathrm{REF}}$ and $\boldsymbol{E}_{\mathrm{OBJ}}$ record the hologram. $\boldsymbol{E}_{\mathrm{OBJ}}$ which is the phase conjugate of the original object wave can be obtained on illuminating the hologram by $\boldsymbol{E}'_{\mathrm{REF}}.\boldsymbol{E}_{\mathrm{OBJ}}$ and the transmitted $\boldsymbol{E}_{\mathrm{DIS}}$ can be made to interfere to form fringes that enhance the phase sensitivity as indicated by

$$I_2 = \left|\boldsymbol{E}'_{\mathrm{OBJ}} + \boldsymbol{E}'_{\mathrm{DIS}}\right|^2 \approx \cos(2\phi + \delta\phi). \tag{5}$$

In the π-rotated PC interferometer the interference of the object wave with its FPC wave is seen as

$$I_3 = \left|\boldsymbol{E}_{\mathrm{DIS}} + \boldsymbol{E}'_{\mathrm{DIS}}\right|^2 \approx \cos(2\phi + 2\delta\phi). \tag{6}$$

Thus the interference between the displaced object beam and its conjugate gives rise to doubling of the phase sensitivity in comparison with the conventional holographic interferometer as described by eqn (4). In general, it is evident that a PC replica of the object wave when used in an interferometer enhances the sensitivity as compared to conventional interferometers.

4. Conclusion

Various experimental schemes to generate PC conjugate waves with iron-doped lithium niobate crystal were carried out. These schemes were realised as interferometers to measure small displacement of the object wave. The Michelsons interferometer with the IDLN crystal as the beam splitter was used to measure the input tilt.

Acknowledgement

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