Holographic interferometry using anisotropic self-diffraction in \( \text{Bi}_{12}\text{SiO}_{20} \)

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Anisotropic self-diffraction in photorefractive \( \text{Bi}_{12}\text{SiO}_{20} \) crystals is applied to the investigation of dynamic holographic recording through the diffraction process. Specific attention is paid to optimization of experimental parameters for real-time holographic interferometry. The resultant interferometer is applied to obtain both time-average and double-exposure interferograms of vibrating and displaced structures.

The photorefractive effect has undergone intensive investigation since its discovery in 1966. However, practical application of the effect to real problems has been slow to materialize. Holographic interferometry of diffusely reflecting objects seems to be one of the more promising examples of a practical application for photorefractive crystals.\(^1,2\) A variety of different optical geometries have been proposed based on four-wave mixing\(^2,3\) and two-beam coupling\(^4,5\) processes. From a practical point of view the geometry proposed by Petrov \(^{et \ al.}\)\(^6\) appears to be the most suitable.

This geometry utilizes the phenomenon of anisotropic self-diffraction\(^7\) in cubic paraelectric crystals, such as those of the sillenite family: \( \text{Bi}_2\text{SiO}_3 \) (BSO), \( \text{Bi}_2\text{TiO}_3 \) (BTO), and \( \text{Bi}_2\text{GeO}_3 \). Anisotropic self-diffraction produces a rotation in linear polarization of the diffracted reference beam with respect to the transmitted signal polarization. Referring to Fig. 1, the amplitude of the phase grating produced inside the crystal is a maximum for light linearly polarized along and perpendicular to an axis bisecting the \( [001] \) and \( [110] \) crystal axes (i.e., at 45° to the grating vector \( K \)).\(^8\) This is due to the electrically induced birefringence of the crystal under the influence of an internal diffusion field. The shifted phase gratings produced from these polarizations are of opposite signs so that for writing-beam polarizations perpendicular to the plane of incidence, ignoring optical activity, the crystal acts on the readout beam as a half-wave plate. This means that the self-diffracted beam from such a phase grating will have its linear polarization rotated with respect to the transmitted beam. In considering the case in which there is optical activity, a maximum polarization separation of 90° between self-diffracted and transmitted polarizations is obtained when the reference–readout beam polarization is parallel to the \( [001] \) axis at the center of the crystal.\(^9\) Thus the transmitted beam can be canceled completely, which isolates the self-diffracted beam and thereby increases the image contrast.

Until now most investigations of a practical nature have been conducted with BTO crystals at He–Ne laser wavelengths (\( \lambda = 633 \) nm) by Kamshilin \( ^{et \ al.}\)\(^10,11\). The purpose of this Letter is to report the use of BSO crystals in a geometry similar to that used by Kamshilin. In comparison with BTO, BSO has lower diffraction efficiency because of its lower electro-optic coefficient and its higher optical activity. However, BSO is readily available in relatively large sizes of good optical quality and, in addition, has a higher sensitivity than BTO, especially in the blue–green region of the spectrum. This makes its operation possible with both argon-ion lasers and the more recently available frequency-doubled, diode-pumped Nd:YAG lasers.

The experiments were performed with a 10 mm \( \times \) 10 mm \( \times \) 2.25 mm crystal of \( (110) \)-cut BSO. The crystal was sandwiched between two polarizers (P’s) as shown in Fig. 1. The optimum output polarization separation is obtained when the readout beam has \( s \) polarization at the center of the crystal. By taking the natural optical activity of the crystal into account (measured as \( \rho \approx 38.7° \) mm\(^{-1}\) for \( \lambda = 514 \) nm), a rotation of the input polarization of \( \delta \approx 43.6° \) was necessary, and it was achieved by using the polarizer on the input face to select the required polarization. The transmitted signal- and reference-beam polarizations are shown in Fig. 1. Both beams were subject to optical activity, but the diffracted beams were also subject to a polarization rotation of \( \approx 90° \) with respect to the transmitted beams. The diffracted reference beam was isolated by cancellation of the transmitted signal beam using the polarizer on the output face.

Crystal characterization, for optimization of an interferometric arrangement, was performed by using...
the system in Fig. 1. Intensity measurements of the input signal, the input reference, and the diffracted reference were made with variations of writing-beam angle $2\theta$ and writing-beam intensity ratio $\beta_0$. Measurements of the residual transmitted signal intensity, after cancellation, were also made to give an indication of the polarization noise of the crystal. Such noise depends on scattering within the volume of the crystal probably due to stress-induced local variations of birefringence.

Figure 2 shows the variation of diffraction efficiency $\eta$ of the phase grating with respect to the grating wave number $K$. The characteristic material grating wave number was found to be $K_0 = 12.6 \, \mu m^{-1}$, equivalent to a writing-beam angle of $2\theta \approx 62^\circ$. The corresponding maximum diffraction efficiency was $\eta_m \approx 0.55 \times 10^{-3}$. This is of the same order as the reflectivities observed in classic four-wave mixing for diffusion alone.\textsuperscript{12} Although efficiency is low, it is adequate for imaging purposes, as is shown below. From the point of view of optimization for use in interferometry, it is clear from Fig. 2 that large writing-beam angles are required in order to obtain sufficient diffracted intensity at sensible laser output powers for imaging diffusely reflecting objects.

Figure 3 shows the variation of diffraction efficiency with respect to the writing-beam intensity ratio $\beta_0$ at a grating spacing of $\Lambda = 0.515 \, \mu m$. As one would expect, the graph indicates a crystal behavior similar to that observed in photographic plate holography with maximum diffraction efficiency at the maximum phase-grating modulation (i.e., $\beta_0 = 1$). From the point of view of an interferometric arrangement this would appear to be a disadvantage, since it implies that a substantial reduction in the reference-beam intensity is required for high diffraction efficiency when one is imaging a diffusely reflecting object. However, the magnitude of the diffracted reference intensity $I_{Rd}$ relative to the residual transmitted intensity $I_{Sr}$ must also be considered. Figure 4 shows the variation of the image-to-background-intensity ratio (IBR) with respect to $\beta_0$. The IBR is simply the ratio of $I_{Rd}$ to $I_{Sr}$.

The graph confirms what one would intuitively expect. As the incident signal-beam intensity increases from zero, the diffracted signal beam increases (as shown in Fig. 3) more rapidly than the increase in background scattered light until a maximum IBR is reached; for a further increase in the incident signal beam, the scattered background increases more rapidly than the diffracted signal beam. From Fig. 4 it can be seen that at its maximum the diffracted intensity is 75 times the background and occurs at a writing-beam intensity ratio of $\beta_0 \approx 0.12$. At $\beta_0 = 1$ the image intensity is only 33 times the background. From these considerations it is clear that a compromise between high diffraction efficiency and high IBR is required for optimization of interferometric imaging.

With the parameters of the system optimized as described above, real-time interferograms were obtained. Both time-average and displacement interferometry were performed using an argon-ion laser to produce spatially filtered collimated light of wavelength $\lambda = 514$ nm. Time-average interferograms were made of a 40-mm-diameter speaker, placed 240 mm from the BSO crystal. The intensity of the dif-
fuse, unfocused light incident upon the crystal was \( I_S \approx 40 \, \mu W \, cm^{-2} \). After cancellation of the transmitted signal the diffracted image was focused onto a charge-coupled-device camera, which was connected, through a computer equipped with a frame grabber, to a television monitor. In this way it was possible to view the interferograms in real time and to obtain still photographs of the fringe patterns. The typical time response for formation of an image was observed to be \( \approx 2 \, sec \), and the vibration frequency range over which time-average fringes were visible was found to be from 100 Hz to 50 kHz, the upper and lower frequency limits of the speaker. An example of the quality of the interferograms produced is given in Fig. 5(a), where the speaker was vibrating at 12 kHz. This picture was obtained from a single frame grab, and there was no postmanipulation of the image, i.e., contrast enhancement. The detail of the fringe patterns is good, of a quality equivalent to holographic plate interferometry. It was also possible to obtain double-exposure interferograms, using the same parameters as above, by rapid displacement of an object. Figure 5(b) shows a typical displacement interferogram of a white card that was tilted vertically. The fringes in this case have high contrast, and the fringe resolution is good.

In conclusion, it is clear that the use of BSO with anisotropic self-diffraction has the potential to produce high-quality interferograms of similar contrast and fringe resolution to that obtained in conventional holographic interferometry, but in real time. Also there are distinct advantages of this method of real-time interferometry in comparison with standard four-wave mixing and two-beam coupling methods: small writing-beam angles are not required, permitting objects to be placed relatively close to the crystal, which effectively reduces the laser output powers needed to perform interferometry. The method is also simple, requiring no applied electric field or frequency shifting of the writing beams.

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References