Fidelity Analysis Of Phase Conjugated One-Way Transmitted Images Through A
Thin Distortion Medium Using Moire Technique

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ABSTRACT—In this paper we analyze the fidelity aspect of the one-way transmitted images through a thin distorctor using Moiré technique with self-imaging of a grating. With this technique, we experimentally demonstrate that the fidelity of the one-way transmitted images is very high only when the distortion is focused on to the same plane as that of the object transparency.

1. Introduction

In applications like image transmission through optical fiber and phase-distorting media like atmosphere, the transmitted image gets distorted and if the distortions are too severe, it becomes obscure. In order to have an effective communication link it is always desirable that this distortion in the transmitted image be as minimum as possible or completely removed. A number of methods for imaging through distorted media based on holography have appeared [1–3]. Phase conjugation is one of the newer methods by means of which one can effectively cancel out the phase distortions of an image bearing beam on its passage through the distortion medium twice [4, 5]. However, such techniques for distortion correction 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 distortion medium. In order to overcome this difficulty, schemes for one-way optical field imaging through a distortion medium were proposed by Fischer et al. [6], Feinberg [7] and Joby Joseph et al. [8]. Feinberg has demonstrated a one-way imaging scheme through a distortion medium with a self-pumped phase conjugator configuration. Here it has been demonstrated that though it is possible for a phase conjugator and a lens to transmit the amplitude of an image through a thin aberrator, it fails in the case of a thick aberrator. It has also been theoretically shown that when the imaging lens images both the object and the thin distorctor in the same plane, the one-way transmitted image represents the object information more closely [6, 7].

In this paper, using Talbot interferometry with moiré phenomenon we analyze the fidelity of the one-way transmitted images through a thin aberrator and demonstrate that the fidelity is very high only when the distortion and the object transparency are focused on to the same plane.

2. Theory

The schematic of experimental set up is shown Fig. 1. Here the object transparency T is read by the signal beam itself instead of pump beam, which is the case with earlier methods [6, 7]. For
simplicity the analysis is confined to one dimension. In the case, an extension to two dimensions is straightforward.

Fig. 1. Scheme for working out the theory of one-way image transmission. D: Distortion plate, T: Object transparency, L: Focusing lens and C: BaTiO₃ crystal.

The complex field at any point \( x'' \), to the right of the distortion medium (D) is given by

\[
A_1(x'') = A_e \exp \left[i \theta(x_1)\right]
\]  

(1)

Where \( A_e \) is the field of the wave impinging on the distortion medium from the left and \( \theta(x_1) \) is the phase retardation at the point \( x_1 \) due to the distortion medium; where distortion D is kept at \( x_1y_1 \) plane.

The complex field at a corresponding point \( x''' \), to the right of object transparency is given by

\[
A_3(x''') = A_3 Q(x') \exp \left[i \theta(x_3)\right]
\]  

(2)

Where \( Q(x) \) is the amplitude transmittance function of the object transparency at the point \( x_3 \). The propagation of fields from plane \( (x_1, y_1) \) to plane \( (x_3, y_3) \) can be carried out using Fresnel-Kirchhoff diffraction theory. This aspect, however, has not been included in this analysis. This complex field is then focused on to the crystal, say, at the midplane C. In the field distribution at the focal plane, there will be a point \( x \) corresponding to the point \( x''' \) in the complex object field. Then we can write

\[
A_4(x) = A_3 Q(x') \exp \left[i \theta(x_3)\right]
\]  

(3)

The nonlinear mixing of this complex field with the other two fields \( A_1, A_3 \) due to the pump beams, in the crystal gives rise to a polarization [6] given by

\[
P(x) = A_1 A_3 Q(x') \exp \left[-i \theta(x_1)\right]
\]  

(4)

Here the sign reversal of \( \theta(x_1) \) is due to phase conjugation. Also it should be noted that the pump beams are derived from the incident signal beam. The complex field distribution of these
length with a coherence length of 15 cm. The gratings used are dual-field linear gratings [9] and is as shown in the Fig. 3. In these gratings, the grating lines in the two fields are oriented in opposite directions and make a small angle with Y-axis. The grating \( G_x \) is the mirror image of the grating \( G_y \) (reverse copy). Frequency of these gratings is 5 lines/mm. The nonlinear crystal used is a 5 x 5 x 5 mm\(^2\) BaTiO\(_3\) crystal (Lockheed Sanders Inc., U.S.A.) operating in the diffusion region, i.e., without applying an external electric field. A glass microscopic slide etched with Hydrofluoric acid is used as the phase-distorting medium.

A laser beam, which is horizontally polarized inside the crystal, to exploit the \( r_{42} \) electro-optic coefficient, is expanded, spatially filtered and then collimated with the help of a microscope objective-spatial filter (SF)—lens \( (L_3) \) combination. The phase of this collimated beam is randomly modulated while passing through the distortion plate \( (D) \) kept in its path. This randomly phase modulated beam then reads the object information before being focused on to the crystal by means of an achromatic lens \( (L_4) \). Since the object transparency kept is an amplitude object, it modulates the amplitude of the phase distorted beam. The object transparency in the present case is a dual-field linear grating \( (G_y) \).

The crystal is oriented for optimum self-pumped phase conjugation. The phase conjugated signal while retracing its path passes through the object transparency and the distortion medium again and in the process is cured of all the phase distortions as discussed in the theory. But the signal is still left with the amplitude modulation which is the object information to be transmitted.

The phase conjugated distortion corrected signal contains self-images of \( G_x \) which are equally spaced. If \( G_x \) is placed in one of the self-imaging planes of \( G_y \), a moiré pattern of maximum contrast is obtained. This moiré pattern is grabbed with the help of a CCD camera coupled to a video monitor. The moiré pattern is as shown in the Fig. 4(a). With the positions of the gratings fixed, the distortion medium is introduced in the path of the beam such that the distortion plate is very close to \( G_y \). In this case the distortion is focused on to the same plane as that of the object transparency inside the crystal. This temporarily disrupts the conjugation process. After allowing enough time for the conjugate beam to grow a second frame is grabbed [Fig. 4(b)]. Keeping the positions of two gratings fixed, the distortion plate is moved away from the object transparency in steps of 5 mm and corresponding moiré patterns are grabbed [Figs. 4(c)–4(f)]. When the distortion plate is moved away from the object transparency the image plane of the distortion plate gets displaced. Therefore distortion and the object transparency are focused on to different planes inside the crystal.

4. RESULTS AND DISCUSSION

The moiré patterns obtained from the conjugate beams in the absence and in the presence of the distortion medium [Fig. 4(a) and Figs. 4(b)–4(f)] are recorded under the same experimental conditions. If the distortion correction process is complete these moiré patterns should be identical. If the distortion correction is partial, this distortion will show itself as displacement or distortion in the moiré fringes. Comparing the moiré patterns [Figs. 4(b)–4(f)] obtained with distortion to that of the moiré pattern in Fig. 4(a), it can be seen that, the fidelity of the one-way transmitted image is high when both the distortion plate and the object transparency are in the same plane [Fig. 4(b)], and the fidelity falls down rapidly as the distance between the object transparency and the distorter is increased [Figs. 4(c)–4(f)].
Fig. 4. (a) Moiré pattern obtained in the absence of the distortion medium.

Fig. 4. (b) Moiré pattern obtained in the presence of the distortion medium. The distortion plate is kept very close to the object transparency.

4. (c)

4. (d)

4. (e)

4. (f)

Fig. 4. (c-f) Moiré patterns obtained when the distortion plate is displaced in steps of 5mm away from the object transparency.
The aberrations introduced by the imaging lens get compensated when the wavefront retraces its path through the lens again. When the lens \( L_x \) used for imaging suffers from spherical aberration, the image at the image plane is not restricted to a single plane. However, due to the ability of the conjugator to compensate for aberrations, the imaging condition of the conjugated beam (imaging in the reverse direction) is not disturbed. Hence the presence of spherical aberration of the lens \( L_x \) has no effect on the fidelity of the one-way transmitted signals.

5. Conclusion

In conclusion, we have demonstrated with the help of a Moiré technique that the fidelity of the one-way transmitted images through a thin aberrator is high only when the distortion is focused onto the same plane as that of the object transparency and begins to fail as one departs from this condition.

The requirement that the distortion plate and the object transparency should lie in one plane restricts the use of this technique. In applications like photolithography, while using transparent masks which have the desired object information, it is necessary that the mask itself does not introduce any phase distortions. This stringent requirement can be overcome by using the present experimental set-up.

References
