5-2 Distorted Image Reconstruction Using Photorefractive Effects

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A new method of distorted image reconstruction through a turbulent medium is demonstrated using photorefractive effects. In this method, there are only one object beam and one sampling beam. The images, reconstructed with high-fidelity, are picked up.

Keywords

Image reconstruction, Distorted image, Incoherent-to-coherent conversion, Photorefractive effect, Fanning effect

1 Introduction

The holography and real-time four-wave mixing (FWM) have been used for one-way image transmission through inhomogeneous media for many years[1]~[17]. The FWM method has been more attractive because of its real-time property. In 1982, Yariv and Koch[5] proposed to transmit images through a distorting medium using FWM, then it was demonstrated by Fisher et al.[6] in a photorefractive crystal. Several other image transmission methods[11]~[17] have been also proposed. In these methods, the distorter must be a thin one, namely, it should be a phase object at the FWM material. Imaging through a thick dynamic distorter has been also demonstrated[2][9][10] using slow response materials. Another special case is the imaging through a dynamic scattering medium with a passive phase-conjugate mirror[18]. In this Letter, we demonstrated a new method to perform one-way image transmission through a thick dynamic distorter, in which no reference beam is required and besides the object beam one sampling beam is enough to obtain the reconstructed image.

In the demonstrated one-way imaging systems a FWM process is needed generally, in which two writing beams bear common phase and amplitude information about the distorter and one of them also contain the input image information. Because of the phase subtraction process of FWM, the output beam should contain the same phase and amplitude information as the input image. However, Feinberg[11] pointed out that these methods are only effective for transmitting an image through a thin phase-distorting medium. The problem of image transmission through a thick phase-distorting medium can not be solved by the subtraction process of FWM.

Often the distorter of interest is not a thin distorter, but rather a thick dynamic distorter such as the turbulent atmosphere. For the image transmission through a thick dynamic distorting medium, it was demonstrated[2][9][10] that when the fluctuation period of the distorter is enough short compared with the exposure time of the holograph or the response time of the nonlinear material, an averaging of the amplitude fluctuation at the holographic or nonlinear material allows high-fidelity image reconstruction. This method arises from an averaging of the apodization over time, that is to say, the slow response nonlinear material responds only to the time-average intensity pattern, it does not “see” the rapidly varying intensity pattern. The time-average intensity pattern can be considered as a superposition of the undistorted image and an approximate homogeneous noise background, namely, the maximum time-average intensity pattern has the spatial information of the undistorted image. The problem becomes how to pick up the undistorted image from a noise background over a time scale much longer than the fluctuation period of the dynamic distorter. From the discussion we can see that the phase subtraction process may be not necessary for a thick dynamic distorter. It is possible to image through a thick dynamic distorter without a reference beam, furthermore, without a FWM process.

According to the above principle, the nonlinear material should have a slow time response relative to the fluctuation period of the dynamic distorter and respond to the time-average intensity of the object beam over a period, and the output signal should bear the spatial information of the maximum time-average intensity pattern of the object beam. Recently we proposed a new incoherent-to-coherent converter[19][20] using the photorefractive fanning effect, in which the transmission of the coherent beam increases with the increase of the intensity of the incoherent beam. We will use this property to pick up the undistorted image from a noise background and demonstrate that one-way image transmission through a thick dynamic distorter can be carried out without a reference beam and a FWM process.

2 Experimental setup

The experimental setup was schematically plotted in Fig.1. A cw doubled Nd:YVO$_4$ laser operating at 532 nm was used as the transmitting and receiving light source. Although general natural light beam is principally available for the object beam I_O, a laser beam from the Nd:YVO$_4$ laser with an ordinary-polarization and a diameter of 6 mm was used for an I_O beam in this work. After it passed through the U.S. Air Force resolution chart RC, I_O bore the spatial information of the image of RC. The transmitting and receiving telescopes were composed of L1, L2, L3 and L4, respectively. The distance between L2 and L3 was 800 mm. Two 1200 W electronic fan-heaters placed between L2 and L3 were used to generate hot air, which acted as a dynamic distorting medium. The total length of the distorting medium along the propagating direction of the object beam was ~ 550 mm, which was much longer than the collection optics' depth of field (~ 4mm). Therefore it should be completely considered as a thick distorter. The measured turbulence fluctuation period of the hot air was round about 10 ms. The photorefractive crystal was a Ce:BaTiO$_3$, which had dimensions of 7.38 mm × 7.22 mm × 6.34 mm and with the *c*-axis along the 7.38-mm edge. In the receiving side the sampling beam I_S, which was a collimated uniform laser beam from the Nd:YVO$_4$ laser, had an extraordinary-polarization and a diameter of 6 mm. It was mutually-incoherent with I_O because the path difference between them was much longer than the coherent length of the laser. It should be noted that in fact the object beam and the sampling beam can come from two different light sources, respectively. I_S and I_O were incident upon the crystal coaxially by a beam splitter BS in order to obtain a high resolution. The external incident angle was 25°. The crystal was located at the focal plane of L4 and the U.S. Air Force resolution chart RC was imaged on the crystal by L1, L2, L3, and L4 with the same size as the original object. A polarized beam splitter was used to separate

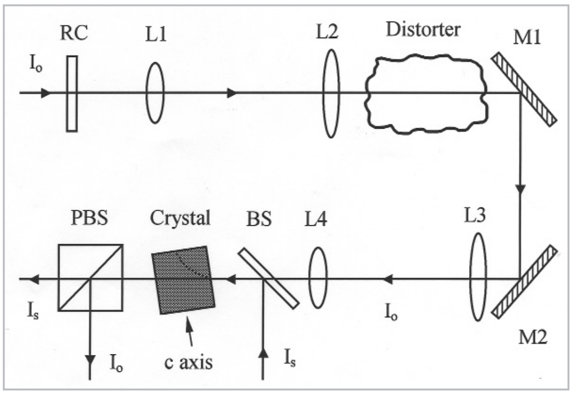

Fig.1 Schematic of the experimental setup. RC, U.S. Air Force resolution chart; L1, L4, lenses with focal length of 200 mm; L2, L3, lenses with focal length of 400 mm; M1, M2, mirrors; BS, beam splitter; PBS, polarized beam splitter.

the object beam I_O and the output sampling beam I_S. The photographs of the transmitted image and the reconstructed image were taken from a screen or a CCD camera system..

3 Experimental results

First we demonstrated the image reconstruction using the experimental setup of Fig.1. Because of the strong fanning effect of the crystal, the transmission of the sampling beam I_S was very small. When we used the object beam I_O, which bore a dynamically distorted image of the U.S. Air Force resolution chart, to erase the fanning gratings, the output intensity pattern of the sampling beam was modulated by I_O selectively. The output intensity of I_S should increase in proportion to the time-average intensity of I_O over a period, as a result, the output maximum intensity pattern of I_S bore the spatial information of the maximum time-average intensity pattern of I_O. According to the previous discussion, the maximum time-average intensity pattern in the object beam should bear the spatial information of the undistorted image. Thus the output I_S should bear the spatial information of the undistorted image. By using a CCD camera to detect the output sampling beam the reconstructed image could be recorded.

When the intensity of the object beam I_O and the sampling beam I_S were 150 mW/cm^2 and 34 mW/cm^2, respectively, the establishing and erasing time of fanning were 6.4 s and 1.3 s, respectively, which were much longer than the fluctuation period of the distorter. The transmitted images borne by the object beam on the crystal before and after the distorter was turned on were shown in Fig.2 (a) and (b), respectively. It can be seen that the original image was blurred fully by the dynamic distorter. By using the slow responding characteristic of the photorefractive crystal, the reconstructed image with a high resolution was obtained and shown in Fig.2 (c).

Then we fixed the intensity of I_O at 150 mW/cm^2 and changed the intensity of I_S to measure the resolution of the reconstructed image. It was shown in Fig.3, in which β is the intensity ratio of I_O to I_S. It can be seen that the reconstructed image had a high resolution over a large range of β. When β became small, noises and unstability increased evidently. We have also measured the response time versus the intensity of I_S at a fixed intensity ratio $\beta = 4.4$ by removing the resolution chart. The establishing and erasing response time of fanning were shown in Fig.4. When we measured the erasing time, both the object beam and the sampling beam were turned on. Although the response time changed over a large range, we found that the resolution of the reconstructed image did not change obviously versus the intensity of I_S for a fixed β (= 4.4). The reason is that the response time is still much longer that the fluctuation period of the distorter.

From the experimental results we can see

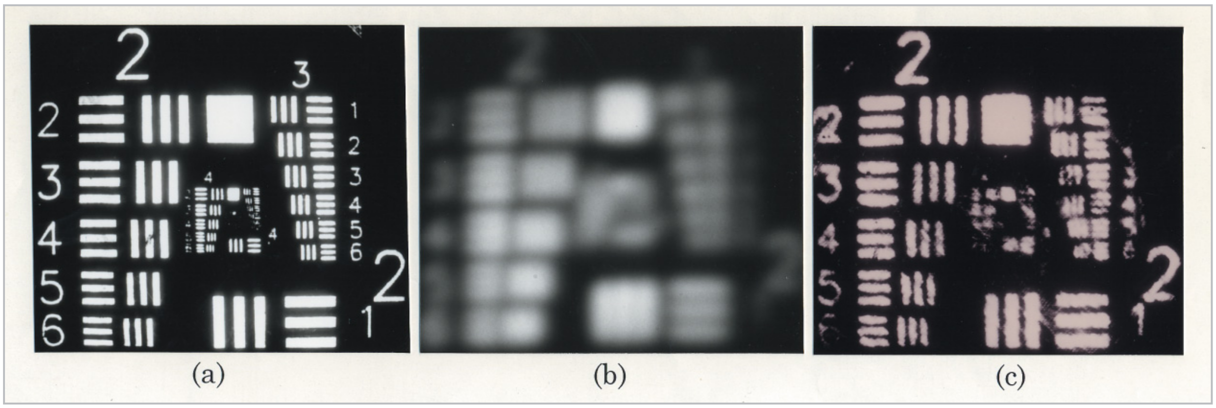

Fig.2 Photographs of the transmitted image before (a) and after (b) the distorter was turned on, as well as the reconstructed image (c)

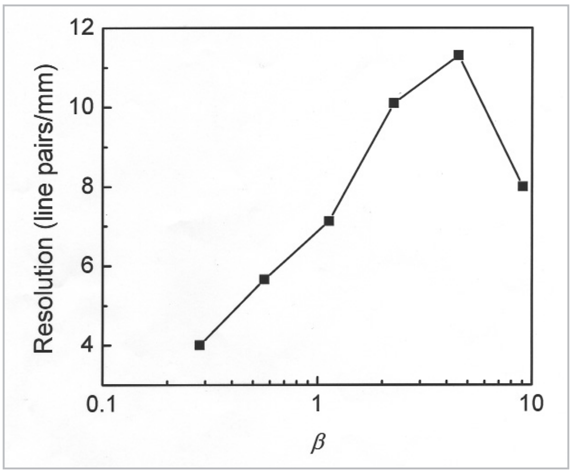

Fig.3 *Resolution of the reconstructed image versus the intensity ratio* **β** *of the object beam to the sampling beam. The solid curve is a guide for the eye.*

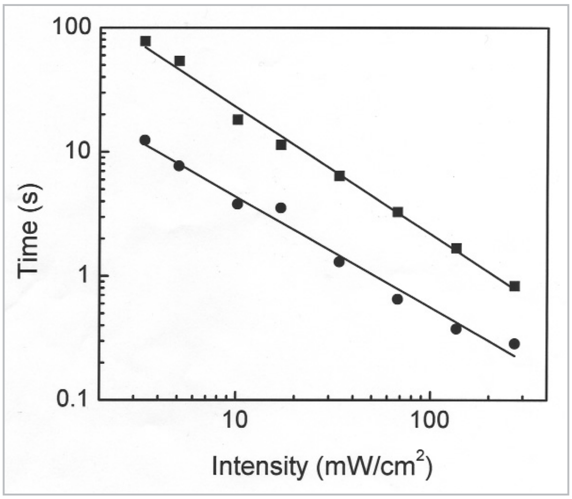

Fig.4 *The establishing (■) and erasing (●) response times of fanning versus the intensity of the sampling beam. For the erasing respond time the intensity ratio* **β** *= 4.4. The establishing and erasing response time can be fitted with* $t_{1/e}^{es} = 242.4/I^{1.0}$ *mW/cm*^{2} *and* $t_{1/e}^{er} = 30.1/I^{0.89}$ *mW/cm*^{2}*, respectively.*

that image reconstruction is demonstrated without a reference beam and a FWM process for a thick dynamic distorter. In this method the object beam worked as an erasing beam to spatially modulate the transmission of the sampling beam and the crystal responds to the time-average intensity of the object beam over a period. Thus even a white light source can be used as the transmitting light source. With this advantage this method has many potential applications. Additionally, one sampling beam and one incoherent object beam are enough to transmit an image through a thick dynamic distorter and no reference beam is required. This characteristic makes the beam alignment of the optical system more easy without considering the precise overlap of the object beam and the reference beam in a normal FWM image transmitting system and the output reconstructed image can have a high resolution. By use of the fanning effect, the object beam modulates the transmission of the sampling beam directly, as a result, the efficiency of the system is high and the output reconstructed image can have a high intensity.

4 Conclusion

In summary, we demonstrated a new method to perform one-way image transmission through a thick dynamic distorter without a reference beam and a FWM process. In this method, there are only one object beam and one sampling beam. The response time of the photorefractive crystal must be much longer than the fluctuation period of the dynamic distorter. Thus the crystal responds only the time-average intensity pattern of the quickly varying object beam. By use of the photorefractive fanning effect, the time-average intensity pattern of the object beam modulates the transmission of the sampling beam directly. As a result, the output sampling beam bears the spatial information of the undistorted image. By using this method reconstructed images with high-fidelity have been obtained.

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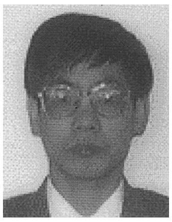

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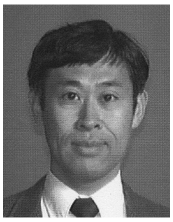

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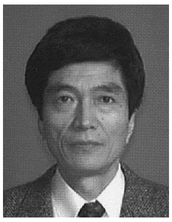

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