Image transmission and interferometry with multimode fibers using self-pumped phase conjugation

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A double-pass image transmission through a single multimode fiber is demonstrated, using a passive phase conjugate mirror. An application to interferometry based on phase sensing is demonstrated, by implementing the multimode fiber and the passive phase conjugate mirror as one arm of a Michelson interferometer. Due to the unique properties of the self-pumped conjugator, nonuniform distortions caused by modal dispersion in the fiber and other aberrations are cancelled out, while uniform phase changes are detected.

Modal dispersion in multimode optical fibers is the main cause for the distortion of an optical field that is transmitted through the fiber. Thus, imaging and any detection scheme requiring phase sensing, such as interferometry, are difficult to achieve in multimode fibers.

An elegant technique based on phase conjugation for transmitting images through multimode fibers in real time was suggested by Yariv[1]: phase conjugate the output from the fiber and retransmit it through an identical fiber link. The phase distortions of each mode are cancelled, thus producing the original pictorial field. A partial demonstration of this method was reported,[2] in which an information-bearing distorted wave, after propagating through an optical fiber, was incident upon a photorefractive $BaTiO_3$ crystal. After standard four-wave mixing in the crystal, its phase conjugate form was generated and propagated back through the same link, emerging at the transmitting end as the original undistorted image.

In this letter we demonstrate (a) two-pass pictorial imaging through a multimode fiber using a passive (self-pumped) phase conjugate mirror (PPCM), and (b) the operation of a Michelson interferometer utiizing a multimode fiber plus a PPCM as one arm of the interferometer; it allows interferometry with multimode fibers that is based on phase modulation, rather than amplitude modulation. In both cases we employ this self-pumped four-wave mixing technique in the photorefractive $BaTiO_3$ crystal.

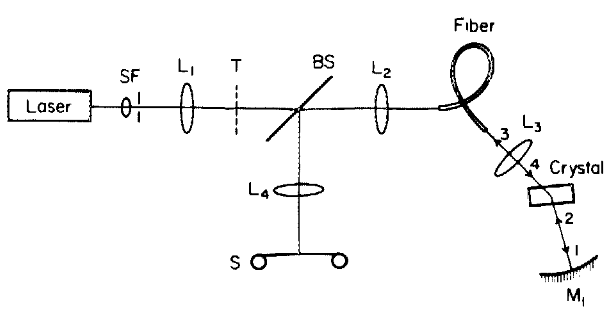

FIG. 1. Two-way image transmission through a multimode fiber using a passive phase conjugate mirror (PPCM). Extraordinarily polarized light (in the plane of the paper) from an argon ion laser, after spatial filtering by SF and collimation by lens L_1, picks up pictorial information from transparency T, and is focused by lens L_2 into the multimode fiber. The distorted output A_4 is focused inot the $BaTiO_3$ crystal which is optimally oriented to make use of the large electro-optic coefficient r_{42}. Pump beams A_1 and A_2 build up and oscillate between the crystal and spherical mirror M_1. This causes $A_3(\propto A_4^*)$ to be generated and is focused by lens L_3 into the back fiber face. It emerges from the front fiber face carrying the undistorted pictorial image and is projected by beam splitter BS onto the screen S.

The experimental arrangement for the two-pass image transmission is shown in Fig. 1. The 488-nm line of an argon ion laser carries the information of the slide T which is then coupled into the multimode fiber (step idex, 1000-μm diameter, 75 cm long). The output of the fiber, A_4, is focused into a single $BaTiO_3$ crystal. Self-oscillation of the pump beams A_1 and A_2 starts between the crystal and the spherical mirror M_1; a second mirror required in former works[3,4] is not needed here. This is probably due to the strong seed of scattered light provided by the fanning effect.[5] In the four-wave mixing process in the $BaTiO_3$ crystal the grating that is written by the information-bearing probe beam 4 and the oscillating pump beam 1 is added constructively to the grating written by the phase conjugated signal beam 3 and pump beam 2. Thus the two pump beams and phase conjugated signal beam build up in the PPCM. In this manner, signal beam $A_3(\propto A_4^*)$ is generated. It retraces the fiber link and emerges as the original undistorted image which is then projected onto the screen S. A typical transmitted image is shown in Fig. 2. We have achieved good quality images both with and without polishing the fiber faces; however, diffused background light reflected from the unpolished fiber face tended to obscure the image somewhat.

Previously [2] the need for mutual coherence between the probe and pump beams in writing the volume hologram imposed an upper limit on the fiber length, especially in slowly responding materials such as $BaTiO_3$. In our case, the use of an internally generated pump assures coherence between the pump and probe for any length of fiber.

The fiber plus the PPCM can be implemented as one

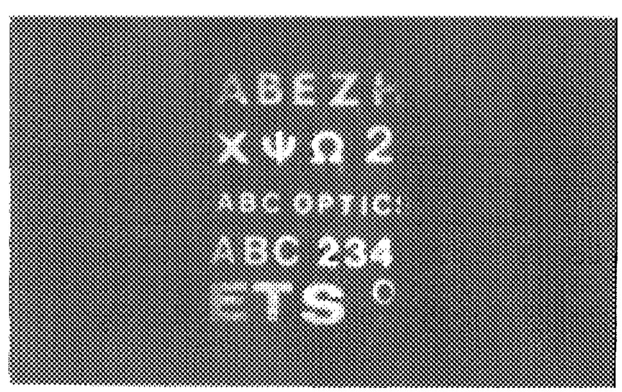

FIG. 2. Resulting image on screen S after fiber transmission and phase conjugation by the PPCM.

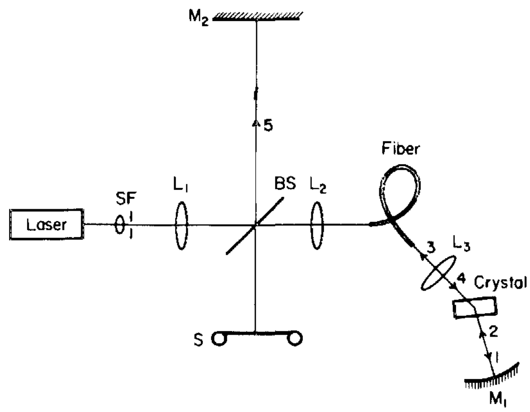

FIG. 3. Michelson interferometer with multimode fiber and PPCM in place of a conventional interferometer arm. Extraordinarily polarized light from the argon ion laser, after spatial filtering and collimation by SF and lens L_1, is split via two beam splitter BS. One beam continues into the fiber-PPCM arm and is processed in the exact manner described earlier. The other beam, A_5, is diverted to mirror M_2 and is reflected. The two returning beams are combined by BS and are projected onto the screen S, resulting in an interference pattern.

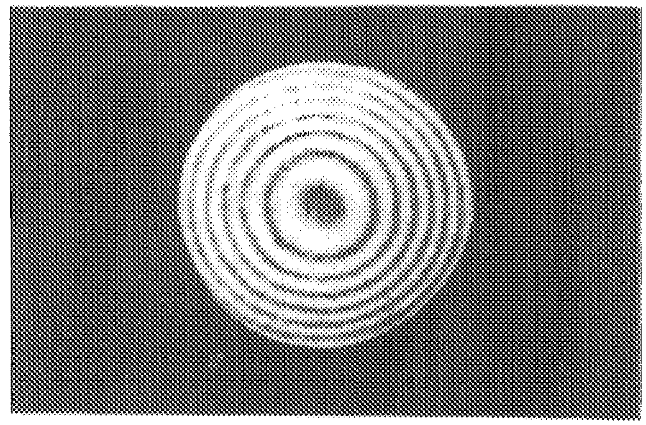

FIG. 4. Interference fringe pattern observed on the screen S from the multimode fiber-PPCM interferometer.

arm of a Michelson interferometer, due to the unique properties of the PPCM.[6] It was noticed[3] that a laser resonator employing a PPCM at one end possesses normal longitudinal modes, as opposed to a resonator with a regular phase conjugate mirror (PCM),[7] yet is capable of correcting nonuniform phase distortions in the cavity. Thus unlike the regular PCM, the PPCM is a partial phase conjugator of the nonuniform phase of the field. Since the pump beam is internally generated in the PPCM, it carries the same uniform phase as the information-bearing probe beam. This can be understood by realizing that the coupled wave equations which describe the four-wave mixing[8] are unchanged when the same uniform phase φ_0 is added to each beam. The equations describing the interacting beam are[8,9]

$$\frac{dA_1}{dz} = -g A_4,$$

$$\frac{dA_2^*}{dz} = -g A_3^*,$$

$$\frac{dA_3}{dz} = g A_2,$$

$$\frac{dA_4^*}{dz} = g A_1^*,$$

where

$$g = (\gamma/I_0)(A_1 A_4^* + A_2^* A_3),$$

γ is the strength of the interaction that depends on the geometry and the crystal parameters, and I_0 is the total light intensity of the beams. These equations and the volume grating structure given by g are invariant under the transformation $A_j \rightarrow A_j \exp(i\varphi_0)$. Thus, in the PPCM configuration a change of the probe beam's uniform phase component is followed by the same phase change of each of the other three beams generated in the process. Therefore, the reflected phase conjugate beam A_3 retains that uniform phase as an ordinary mirror would. On the other hand, nonuniform phase arising from modal dispersion in fibers or other distortions is conjugated. This situation[4] optimizes the buildup of the grating written by the two couples $[A_1, A_4]$ and $[A_2, A_3]$ and enables oscillation and buildup of three of the beams. This was the basis of the recent new interferometer demonstrated by Feinberg.[6]

Here we implement this idea for the multimode fiber interferometer shown in Fig. 3. The output of an argon ion laser after spatial filtering is split via beam splitter BS. One beam is coupled into the multimode fiber, the output of which is processed by the PPCM and generates signal beam $A_3(\propto A_4^*)$ which retraces the fiber link as explained above. The other beam A_5 is directed to the conventional mirror M_2 and is reflected. The fiber output and A_5 are combined on screen S and form the interference pattern shown in Fig. 4. The fringe pattern here is similar to Feinberg's.[6]

With this technique it is possible to achieve interferometry with the enormous flexibility and ease of alignment of multimode fibers, while at the same time retaining the high sensitivity inherent in phase modulating systems. In addition, the PPCM interferometer is blind to random distortion due to environmental or optical effects, which can be quite detrimental in an interferometric measuring scheme.[10]

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