Phase conjugation during second-harmonic generation in few mode fibers

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Quadratic-polarizability holograms in optical fibers have been studied experimentally during their writing by picosecond pulses from a neodymium laser and its second harmonic. Phase conjugation of a green signal was achieved during readout of the hologram by oppositely propagating IR light.

Osterberg and Margulis[1–3] (see also Refs. 4–6) have observed the generation of the second harmonic of the light from a picosecond-pulse neodymium laser in an optical fiber. Stolen and Tom[4,5] and also Baranova and Zel'dovich[6] have suggested that the interference of the ω and 2ω fields leads to a nonzero time-average cubic field product $E_1^{*2}E_2\exp(i\Delta kz)$ + c.c., which is written in the medium as a granting of the quadratic polarizability $\delta\chi^{(2)}(\mathbf{r},z)$:

$$\delta\chi^{(2)}(\mathbf{r},z)\sim E_1^2(\mathbf{r},z)E_2^*(\mathbf{r},z)e^{-i\Delta kz}+E_1^{*2}(\mathbf{r},z)E_2(\mathbf{r},z)e^{+i\Delta kz}, \qquad (1)$$

where $\Delta k = k_{-2} - 2k_1$.

In the present study, we have demonstrated that phase conjugation can be achieved at quadratic-polarizability gratings in fibers which support several transverse modes of both the second harmonic and the fundamental frequency. Information about the wavefronts of the interfering IR and second-harmonic fields is written. In other words, a hologram is formed. The fields $E_1(\mathbf{r},z)$ and $E_2(\mathbf{r},z)$ in (1) are superpositions of several transverse modes, whose beats generally create a speckle in the fiber. If the IR readout wave is coupled into the fiber from the end opposite that used for the writing, the readout of the hologram produces a polarization

$$P_{2\omega}(\mathbf{r},z)\sim E_1^2(\mathbf{r},z)E_2^*(\mathbf{r},z)B_1^2(\mathbf{r},z)e^{-ik_2z}. \qquad (2)$$

If the wave $B_1(\mathbf{r},z)$ during the readout is the conjugate of the wave $E_1(\mathbf{r},z)$ during the writing, i.e. if $B_1(\mathbf{r},z)\sim E_1^*(\mathbf{r},z)$, then the polarization $P_{2\omega}\sim|E_1|^4E_2^*(\mathbf{r},z)\times\exp(-ik_2z)$ effectively excites the conjugate signal $E_2^*(\mathbf{r},z)$. If $B_1(\mathbf{r},z)$ and $E_1(\mathbf{r},z)$ are not exactly coincident, only the projection of B_1 onto E_1^* operates.

The experimental layout is shown in Fig. 1. In the experiments we used a picosecond-pulse neodymium laser with a repetition frequency $f = 4000$ Hz, a pulse length of 100 ps, and 30 pulses per packet. In the writing regime, the laser beam (1) was partially converted into the second harmonic in a KTP crystal (2). The mixture of ω and 2ω was then split by prisms (3,4) into two parallel beams, which were coupled by a microscope objective (5) with a focal length of 9 mm into the fiber (6) in such a way that the beam at the frequency ω propagated along the center of the objective, while

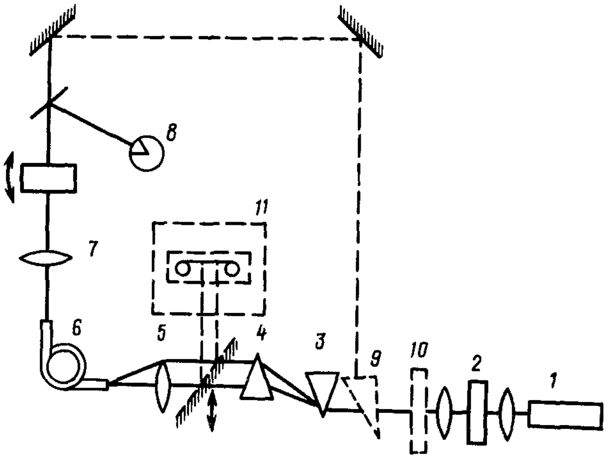

FIG. 1. Experimental layout for observing phase conjugation. *1*—laser; *2*—KTP crystal; *3,4*—prisms for separating beams; *5,7*—microscope objectives; *6*—optical fiber; *8*—photodiode; *9*—prism; *10*—IR glass filter; *11*—plane-parallel plate; *12*—movable mirror.

the beam at the frequency of 2ω was displaced from the center and thus entered the fiber at an angle. The fiber axis coincided with the direction of the IR light. The light was coupled out of the fiber through a similar objective (7). The power of the IR light which was transmitted through the fiber was detected by a photodiode (8) and was found to be 0.2 W. The power of the transmitted second harmonic was 0.005 W. During the readout of the hologram, a prism (9) and a filter (10), which cut out the second harmonic, were inserted in the beam. Light was coupled through a system of mirrors and a plane-parallel plate (11), 40 mm thick, by a microscope objective (7) into the fiber (6) from the opposite end. In this situation we observed the generation of the second harmonic, which was coupled out of the fiber through objective *5* and movable mirror *12* and recorded on KN-4 film. The IR readout light was recorded on the same film. On this film we observed a clear spatial resolution of the ω and 2ω beams. The 2ω beam was deflected from the ω beam in the direction corresponding to the conjugate wave.

Figure 2 shows the typical pattern and the relative positions of the beams. The grating was written for an angle of 4° between ω and 2ω beams. The 2ω distribution is shown in the photograph at the top, and the ω distribution at the bottom. The horizontal displacement of the 2ω beam from the ω beam corresponds to the displacement observed experimentally. As a scale for a rough estimate of the magnitude of the deflection we can use the angular size of the central 2ω mode: $\Delta\theta(LP_{01},2\omega,FWe^{-1}M) = 3.9°$. We see that the horizontal distance between the centers of the upper and lower distributions is roughly equal to the diameter of the bright spot at the frequency 2ω: 4°. For a more precise estimate of the deflection angle, we subsequently placed a wire 350 μm in diameter in the path of the light to be recorded. The distances between the centers of the diffraction fringes produced the scale on the photograph. We measured the on-center distance between the ω and 2ω beams as a function of the writing angle. Figure 3 shows a plot of the angle at which the second harmonic was emitted during the readout, α^*, versus the angle at which the

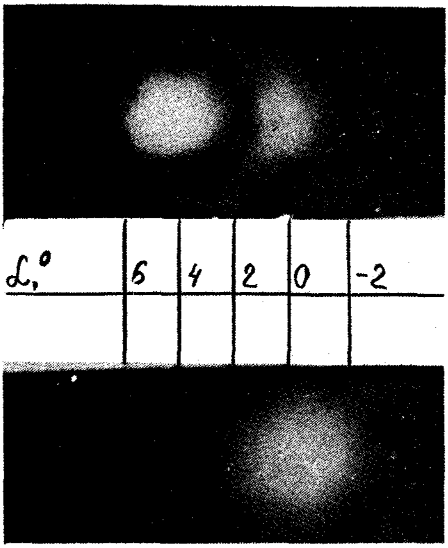

FIG. 2. Typical pattern of the relative positions of the IR readout light (lower photograph) and the conjugate second harmonic (upper photograph) along the horizontal axis. The second harmonic entered at an angle of 4° during the writing. The angular size of the main second-harmonic mode is 4°.

second harmonic entered during the writing, α. We see that the second-harmonic wave during the readout can be regarded as the conjugate wave. The reason for the deviation from linearity at large angles is that the fiber conjugates only that set of writing-signal angles which satisfies the conditions for propagation in the fiber. Further evidence for phase conjugation comes from the fact that as the entrance angle of the readout light is varied, through a rotation of plane-parallel plate *11*, the position and shape of 2ω distribution which is read out do not change. The only change is in the brightness of this light.

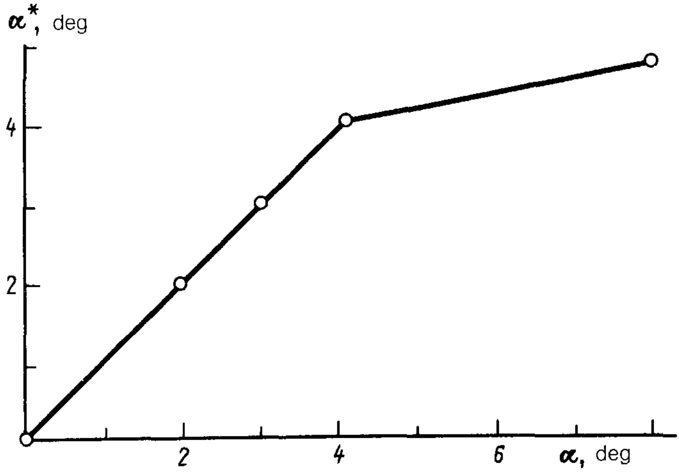

FIG. 3. The angle (α^*) between $E^*(\omega)$ and $E^*(2\omega)$ during the readout of the hologram versus the angle (α) between $E(\omega)$ and $E(2\omega)$ during the writing.

The holograms written in this experiment were far from saturation. As saturation is approached, those second-harmonic components which overlap relatively well with the IR field are written relatively strongly. If the writing is continued long enough, the original information about the signal wave is lost, and the second-harmonic distribution acquires an axisymmetric structure.

In summary, we have shown experimentally that during the writing of $\chi^{(2)}$ holograms in few-mode fibers through a joint exposure at the wavelengths 1.06 μm and 0.53 μm information about the transverse structure of each of the waves is written. We have demonstrated phase conjugation of 0.53-μm light in a $(\omega + \omega - 2\omega) + \omega + \omega = 2\omega$ process which might be called a "six-photon process" or "six-wave mixing."

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