Mutual phase conjugation of incoherent light beams in a photorefractive crystal

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A new arrangement for the phase conjugation of mutually incoherent light beams is proposed. This arrangement has been implemented experimentally. A theoretical description has been derived, and the results are compared with experiment.

Phase conjugation of low-intensity beams for cw lasers, with simultaneous amplification, is a problem of importance for practical applications. One way to solve it is to develop arrangements for a mutual conjugation[1–3] on the basis of photorefractive crystals. These arrangements make it possible to cause a simultaneous phase conjugation of two mutually incoherent laser beams, one weak and one strong, with an energy transfer from the strong beam to the weak one. It is also possible to synchronize the beams from two or several lasers.[4,5]

In this letter we are reporting a new phase-conjugation arrangement, in a generation regime with a feedback configuration fundamentally different from those which have been reported previously. The geometry can be summarized as follows: Two laser beams, I_1 and I_2, are incident on a photorefractive crystal (Fig. 1). After they have passed through the crystal, the beams are rotated by a system of mirrors and sent back to the crystal, with the result that each of the beams which are passed through the crystal intersects the other beam. As the result of an absolute instability (generation), scattered light arises and propagates opposite the original signal beams. The scattered light which is propagating opposite beam I_1 has a temporal coherence which is determined by beam I_2, and vice versa. In each of the intersection regions, the configuration of the wave vectors of the interacting waves permits the existence of four gratings of a nonlinear increment in the refractive index. Under typical experimental conditions,

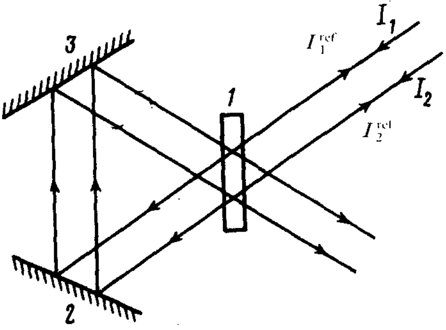

FIG. 1. Arrangement for mutual phase conjugation. 1—Photorefractive crystal; 2,3—rotatable mirrors.

the coherence times of wave I_1 and I_2 are substantially shorter than the response time of the photorefractive medium. The only grating which is effectively excited is that which is written by the coherent pairs of signal and scattered waves. Readout of this grating by signal beams closes the feedback loops which lead to the generation of the scattered light.

In the theoretical analysis of this arrangement, we use a system of simplified coupled equations to describe the four-wave mixing in each of the beam intersection regions. After an averaging over times longer than the coherence time of each of beams I_1 and I_2 this system of equations becomes the standard system describing a four-wave mixing in which a single grating is written. We supplement the equations with boundary conditions corresponding to a conversion of the beams as they pass from one intersection region to another along the optical system. To determine the transverse structure of the scattered light, we take the approach of Ref. 6, examining a three-dimensional model which makes it possible to find the modes of this generator and their excitation thresholds. It turns out that the selection of the conjugate beam can be carried out through a change in the scale of the cross sections of beams I_1 and I_2 during the first and second passages through the crystal. Specifically, conjugation requires satisfaction of the relation $\alpha_1\alpha_2 < 1$, where α_j $(j = 1.2)$ is the ratio of the diameter of beam I_j during its second passage through the crystal to its diameter during the first passage.

To calculate the energy characteristics of the arrangement we use a nonlinear one-dimensional model. We find that the range of intensity ratios of the incident beams in which generation occurs can be described by

$$T^{-1}\exp(-2\gamma l) \leqslant I_2/I_1 \leqslant T\exp(2\gamma l),$$

where T is the transmission coefficient (in terms of intensity) of the optical system, and γl is a nonlinearity coefficient. This relation is satisfied at $T\exp(2\gamma l) \gg 1$. Over the entire generation range, the relation $I_1^{\text{ref}}/I_2^{\text{ref}} = I_2/I_1$ holds. At a given intensity ratio $\rho = I_2/I_1$ generation is possible if $\gamma l > (\gamma l)_{\text{th}}$. At $T = 1$, for example, we would have $(\gamma l)_{\text{th}} = 1/2\ (1+\rho)(\rho - 1)^{-1}\ln\rho$. At a point sufficiently far above the generation threshold we would have $I_1^{\text{ref}} \to (I_1^{\text{ref}})_{\max} = TI_2$, $I_2^{\text{ref}} \to (I_2^{\text{ref}})_{\max} = TI_1$, corresponding to a complete pumping of the energy from each of the beams into the light which is the conjugate of the other beam (the transmission of the optical system has been taken into account here).

In the experiments, we used the beams from two helium-neon lasers, an LG52-1 and an LG52-2 ($\lambda = 0.63\ \mu$m), with a power ≈ 2 mW, as the two mutually incoherent light beams. These beams were directed to a crystal of cerium-doped strontium-barium niobate (SBN).[7] The optical axis of the crystal and the polarization vectors of the beams were in the plane of incidence of the beam. The angle at which the beams intersected in air was $\approx 40°$; the beam diameters at the crystal were ≈ 2 mm; the distance between the beams was ≈ 6 mm; and the crystal thickness was ≈ 3 mm. The transmission coefficient T of the external optical system (in terms of intensity) was $T \approx 1/3$, where we are taking into account the reflection coefficients of the mirrors and the Fresnel reflection at the faces of the crystal. That a conjugation occurred for each of the beams was verified by the standard procedure,[8] in which we placed a phase plate

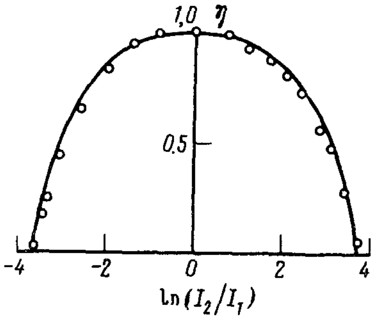

FIG. 2. Normalized sum of the intensities of the waves reflected backward, $\eta = (I_1^{\text{ref}} + I_2^{\text{ref}})/(I_1^{\text{ref}} + I_2^{\text{ref}})_{\max}$, as a function of the ratio of the intensities of the incident beams, I_1/I_2, at fixed sum of these intensities. Points—experimental; line—theoretical.

either in front of the crystal or in the optical system. The fraction of light which was conjugated was $\approx 80\%$.

In the experiments we tested the condition $\alpha_1\alpha_2 < 1$. If it was violated, the divergence of the light reflected backward, in the direction perpendicular to the beam intersection plane, increased substantially, in accordance with the theory. For the crystal which we used the range of the intensity ratio of the incident beams in which the generation occurred was $1/40 \leqslant I_2/I_1 \leqslant 40$. Over this entire range, the experimental ratio of the intensities of the beams reflected backward can be described as a function of the intensity ratio of the incident beams quite well by a theoretical dependence $I_1^{\text{ref}}/I_2^{\text{ref}} = I_2/I_1$. The points in Fig. 2 show the experimental results on the normalized sum of the intensities of the beams reflected backward, $\eta = (I_1^{\text{ref}} + I_2^{\text{ref}})/(I_1^{\text{ref}} + I_2^{\text{ref}})_{\max}$ as a function of I_2/I_1 at a constant sum $I_1 + I_2 = \text{const}$. The total reflection coefficient of the arrangement, $R = (I_1^{\text{ref}} + I_2^{\text{ref}})/(I_1 + I_2)$, is found to be $\approx 25\%$ at the maximum of the curve $(I_1 = I_2)$, when we correct for the Fresnel reflection of the light from the front face of the crystal. The solid line in Fig. 2 is the theoretical dependence of η on I_2/I_1 which follows from the nonlinear one-dimensional model. The theoretical value of the maximum reflection coefficient is $\approx 28\%$.

In summary, we have proposed a new arrangement for the phase conjugation of mutually incoherent light beams in a generation regime. The threshold for this arrangement is low; precise focusing of the beams is not necessary; and the range of the ratio of beam intensities in which the mutual conjugation occurs is wider than those of Refs. 1–3. We have derived a theory for the method, including the development of a three-dimensional threshold model for determining the structure of the wavefront of the scattered light and the conditions for selecting the conjugate component. We have also derived a nonlinear one-dimensional model for determining the energy characteristics of the arrangement. This method has been implemented experimentally, and the results have been compared with the theory.

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