Passive phase conjugate mirror based on self-induced oscillation in an optical ring cavity

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A passive phase conjugate mirror based on four-wave mixing in an optical ring cavity is described. Unlike previously demonstrated passive phase conjugate mirrors it generates only one of its pumping beams by nonlinear optical interactions, the other being provided by feedback of the probe after transmission through the nonlinear medium. The results of a theory yielding phase conjugate reflectivity and oscillation thresholds are presented together with an experimental demonstration of phase conjugation in barium titanate and strontium barium niobate. The device is self-starting by four-wave mixing, and has an oscillation threshold lower than that of other previously demonstrated passive phase conjugate mirrors with similar ease of alignment. The operation of a device which generates nonconjugate oscillation beams is also reported.

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The high efficiency of four-wave mixing in several photorefractive crystals such as barium titanate[1] and strontium barium niobate[2] makes them attractive candidates for phase conjugation down to very low light power levels.[5] In addition, the recently demonstrated use of these materials in passive phase conjugate mirrors[3–6] has eliminated the necessity of using an external laser to provide high quality pumping beams coherent with the signal beam.

In the first demonstration of passive phase conjugation, the signal beam was allowed to pass through a photorefractive crystal in a linear cavity formed by two external mirrors [Fig. 1(a)]. Both pumping beams then built up in this cavity via nonlinear interactions fed by the signal beam itself. Phase conjugate reflectivities as high as 30% have been achieved so far, without techniques such as the use of antireflection coatings to reduce reflection losses. A theory of this device and its application in imaging experiments and as the end mirror of an argon ion laser have been recently reported.[3–5] Henceforth, we identify this type of passive phase conjugate mirror as the *linear mirror*. Another passive phase conjugate mirror has also been reported which contains the first device and makes use of totally internally reflecting surfaces of the crystal as feedback mirrors.[6] We identify this device as the *two interaction region* (*2IR*) *mirror*, since it uses two linked interaction regions.

In this letter we introduce a new kind of single interaction region passive phase conjugate mirror: unlike the linear and 2IR mirrors it generates only one of its pumping beams via nonlinear optical interactions. The results of a theoretical analysis of this device are shown as well as experimental verification of its action as a phase conjugate mirror.

In the basic implementation of the new device [Fig. 1(b)] the signal beam 2 passes through a photorefractive medium and returns to it as pumping beam 4 around an optical ring cavity, here represented by mirrors M_1 and M_2. It may be advantageous to use curved mirrors or intracavity lenses to minimize diffractive loss of any spatial information on the signal beam. The possibility then arises that the nonlinear optical coupling in the crystal may be such that both the second pumping beam 3 and the phase conjugate beam 1 build up as oscillation beams in the ring cavity. We now turn to a theoretical examination of this possibility. As in the case of the linear mirror[5] use of the undepleted pumps approximation is inappropriate so we use the analysis of Ref. 7, where we derived the reflectivity of a holographic phase conjugate mirror allowing for pump depletion. After some further development of the theory to take account of the boundary conditions of the new device (henceforth named the *ring mirror*), we find that buildup of oscillation in the ring is in fact possible when the spatial phase shift between the holographic refractive index grating and the light interference pattern is nonzero so that advantage is taken of unidirectional beam coupling effects typical of real time holo-

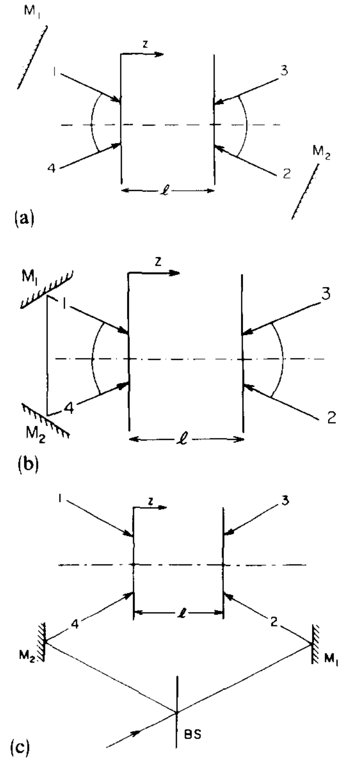

FIG. 1. (a) Geometry of the linear passive phase conjugate mirror. The probe is beam 4 and its phase conjugate is beam 3. The two pumping beams, 1 and 2, oscillate in the cavity bounded by mirrors M_1 and M_2. (b) Geometry of the ring passive phase conjugate mirror. Consistently with the convention that the intensity of beam 3 should be zero at its entrance face, the probe is designated as beam 2. Pump beam 4 is provided by reflection of the probe beam by mirrors M_1 and M_2. The second pump, beam 3 and the phase conjugate beam 1 are self-induced by the nonlinear medium. (c) Geometry of a four-wave mixing oscillator which can produce output beams which are not phase conjugates of the input beams (see text). Beams 2 and 4 are provided from an external source and beams 1 and 3 build up via four-wave mixing.

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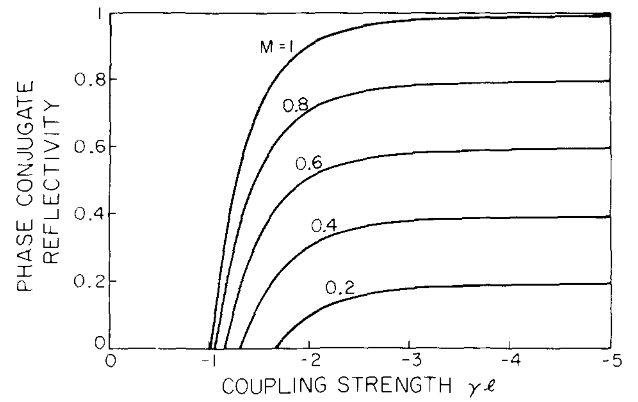

FIG. 2. Reflectivity of the ring passive phase conjugate mirror as a function of coupling strength for several values of the product M of the intensity reflectivities of the feedback mirrors M_1 and M_2.

graphy in noncentrosymmetric media such as photorefractive crystals.

Let the product of the intensity reflectivities of the feedback mirrors M_1 and M_2 be M so that the appropriate boundary conditions for this device [Fig. 1(b)] are $I_4(0)/I_2(0) = M$ and $I_1(0)/I_3(0) = M$, where I_j is the intensity of beam j. These boundary conditions are then used to find the constants of integration in the expressions derived in Ref. 7 for $A_1(z)/A_2^*(z)$ and $A_3(z)/A_4^*(z)$, where A_j is the amplitude of beam j. The reflectivity, given by $|A_1(l)/A_2^*(l)|^2$, is shown in Fig. 2 as a function of γl, a coupling constant characteristic of the medium.[8] It has been taken to be real so that it represents the $\pi/2$ phase shift characteristic of holographic recording in photorefractive crystals by diffusion of charge carriers. Curves for several values of the feedback parameter M are included.

The threshold coupling strength for $\pi/2$ phase shift is given by

$$\gamma l_t = \frac{(M+1)}{(M-1)} \ln \left(\frac{M+1}{2M} \right). \tag{1}$$

This is a self-starting threshold: when it is exceeded, oscillation beams of infinitesimal intensity experience gain. This self-starting ability is not possessed by certain previously demonstrated passive phase conjugate mirrors, namely, linear mirrors in which the reflectivity of one of the cavity mirrors, M_1 is zero,[4,5] (*semilinear mirror*) the 2IR mirror.[6] The oscillation beams of these devices experience gain only when their intensities are above a certain nonzero threshold. Starting these devices thus requires seeding of their oscillation beams. The 2IR mirror has in fact been shown to be able to start without the aid of externally provided seeding but this is believed to be dependent on effective seeding by the fanning effect[9] which is due to two-beam coupling amplification of scattered light and not to the four-wave mixing process referred to here.

Moreover, Eq. (1) shows that the threshold coupling strength for unity feedback, $M = 1$, is $\gamma l_t = -1$. In Ref. 6 the self-starting threshold for the linear mirror was shown to be $\gamma l_t = \frac{1}{2} \ln M$, where M is the product of the intensity reflectivities of the linear cavity mirrors, so that with ideal feedback ($M = 1$) the threshold coupling strength is zero. The threshold of the semilinear mirror with unity reflectivity for the surviving external mirror was found to be $\gamma l_t = -2.49$, while the threshold for the 2IR mirror with ideal feedback[6,10] was $\gamma l_t = -4.68$.

The linear mirror thus has the simultaneous advantages of having very low threshold and of self-starting by four-wave mixing. It does, however, require careful alignment. Of the remaining passive phase conjugate mirrors, all of them easily aligned, the ring mirror seems to be most attractive in that it has the lowest threshold and is self-starting. A major advantage of the 2IR mirror has been that it is completely self-contained in a single crystal, using total internal reflection at the crystal faces for feedback. In the future, of course, the ring mirror could be implemented in the same manner using crystals whose surfaces are cut at appropriate angles.

The faithfulness of phase conjugation in these devices is a separate issue; it might be expected that since the self-induced pumping beams are not plane waves a certain amount of distortion would be introduced into the phase conjugate beam. In the case of the linear mirror, physical constraints imposed by the cavity mirrors may lead to filtering of the signal information from the pumping beams, but one of the pumps in the ring mirror is simply light transmitted through the crystal fed back to it by a passive optical system containing, at least in the experiment described below, very little spatial filtering. One plausible theory is that oscillation beams building up in these devices contribute most to the four-wave mixing process and experience maximum gain when the spatial overlap of counterpropagating beams is maximum, that is, when they are phase conjugates of each other. However, this explanation is inconsistent with the behavior of another device [Fig. 1(c)] which we built with the hope that it would be a phase conjugate mirror. A signal beam was incident on a beamsplitter and the transmitted beam was directed by mirror M_1 onto a barium titanate crystal as beam 2. The reflection from the beamsplitter was directed by mirror M_2 onto the crystal as beam 4. Theory indicates that with sufficient coupling strength and $\pi/2$ phase shift between the interference fringes and refractive index fringes, oscillation beams 1 and 3 can be expected to build up via gratings written between beams 1 and 4 and beams 2 and 3. The wave vector of the bem 1–beam 4 grating must be the same as that of the beam 2–beam 3 grating so that both combine to form a single grating coupling all four beams. Thus, we require

$$\mathbf{k}_1 - \mathbf{k}_4 = \mathbf{k}_3 - \mathbf{k}_2, \tag{2}$$

where $\mathbf{k}_j$ is the wave vector of beam j. In conventional applications of four-wave mixing $\mathbf{k}_1$,$\mathbf{k}_2$, and $\mathbf{k}_4$ are fixed so that Eq. (2) gives a unique value for $\mathbf{k}_3$, the wave vector of the phase conjugate beam. Since only $\mathbf{k}_2$ and $\mathbf{k}_4$ are fixed in the device of Fig. 1(c), however, there is an extra degree of freedom manifested in the expected and observed appearance of beams 1 and 3 as cones of light with axis $\mathbf{k}_2 - \mathbf{k}_4$ and surfaces including both vectors $\mathbf{k}_2$ and $\mathbf{k}_4$. This means that self-induced oscillation by four-wave mixing does not always require that the counterpropagating beams be phase conjugates of each other.

The linear and ring mirrors also involve feedback to the crystal of the oscillation beams. In the linear mirror, beam 1 is reflected into beam 2 and vice versa by external mirrors, and in the ring mirror, beam 3 is reflected by external mir-

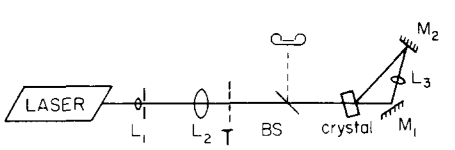

FIG. 3. Experimental arrangement used to demonstrate phase conjugation in the ring passive phase conjugate mirror. An argon ion laser was used at 488 nm in single longitudinal mode. Using a Cartesian coordinate system with the abscissa coincident with the incident beam direction, the locations of the elements measured in centimeters were 30 × objective L_1 (61,0) transparency T(30,0), beamsplitter for observing phase conjugate reflection BS (5,0), 14 cm focal length 3-cm-diam lens L_2 (41,0), barium titanate crystal (0,0), plane mirror M_1 (− 9,0), plane mirror M_2 (− 28, − 20), 15 cm focal length 3-cm-diam lens L_3 (− 18, − 10). The c axis of the crystal pointed in the direction of the vector (0.68,0.73).

rors into beam 1. It is this feedback that gives phase conjugate oscillations an advantage in gain over other kinds of oscillation. Consider for example the case of the ring mirror where $A_4 = M^{1/2}\mathbf{K}A_2$ and $A_3^* = M^{-1/2}\mathbf{K}A_1^*$ with $\mathbf{K}$ the lossless linear operator for propagation of beam 2 around the ring to beam 4. The relevant index grating is represented in the coupled wave equations[11] by a term proportional to $A_1^*A_4 + A_2A_3^*$ which equals $M^{1/2}A_1^*\mathbf{K}A_2 + M^{-1/2}A_2\mathbf{K}A_1^*$ at the crystal face ($z = 0$). Unless $\mathbf{K}$ is the identity or otherwise pathological, then both terms in the sum will add in phase at this crystal face if and only if A_1 is proportional to A_2^*.

The apparatus of Fig. 3 was used to demonstrate the phase conjugating nature of the ring mirror. The expanded and spatially filtered output of an argon ion laser in single longitudinal mode at 488 nm passed through lens L_2 and illuminated an Air Force Resolution Chart. The beam then converged on the passive phase conjugate mirror, consisting of a single poled crystal of barium titanate[12] in the $M_1 - M_2$ ring cavity. Lens L_3 was provided to decrease diffractive loss in the ring. The reflected beam was picked off by a beam splitter (BS) and photographed at the location where a phase conjugate image would be expected. The result is shown in Fig. 4(a). The phase conjugating behavior of the passive phase conjugate mirror is evident. Some lack of uniformity in the intensity of the image was apparent. This can be seen more clearly in Fig. 4(b), which is the phase conjugate reflection of the uniformly expanded expanded laser beam vignetted by the aperture of lens L_2. We believe that the dark areas in the image at six and twelve o'clock are due to losses via the fanning effect. As mentioned above, a single beam passing through a photorefractive crystal with a sufficiently large coupling constant will lose intensity via holographic two-beam coupling to a broad fan. Figures 4(c) and 4(d) show the effect of fanning on the spatial distribution of intensity in such a signal beam. Mirrors M_1 and M_2 were removed from the ring mirror and holographic gratings in the crystal were allowed to decay by dark current leakage. The uniform signal beam was then allowed to pass through the crystal and a photograph [Fig. 4(c)] of this beam after passage through the crystal was immediately taken, before fanning could build up, the time scale of hologram writing being of the order of several seconds. Figure 4(d) shows the same beam with intensity loss by fanning. A dark area developed, just as dark areas developed in the phase conjugate beam of Fig. 4(b).

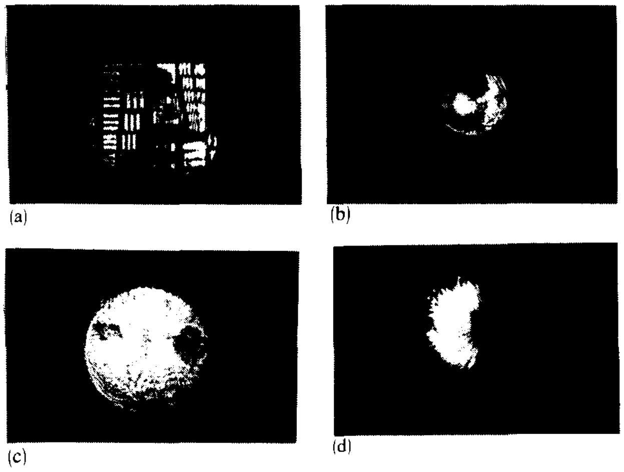

FIG. 4. Experimental results showing (a) the phase conjugate image of an Air Force Resolution Chart, (b) the phase conjugate image of uniform expanded beam vignetted by lens L_2, (c) the effect of fanning on the signal beam with apparatus as in Fig. 3, without transparency T and mirrors M_1 and M_2 (beam transmitted through crystal before buildup of fanning), and (d) beam transmitted through crystal after buildup of fanning.

Experiments similar to those reported above have also been performed using a crystal of strontium barium niobate with a coupling strength somewhat smaller than that of the barium titanate. These were facilitated by the above mentioned advantages of the ring mirror: ease of alignment and low threshold.

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[8] This coupling strength depends on parameters such as crystal orientation, electro-optic tensor, and index grating wave vector (see Ref. 11). When it is real, the phase shift between the light interference pattern and the refractive index grating is $\pi/2$. This is a behavior typical of photorefractive materials with no bias field. When γl is purely imaginary, the index grating is in phase with the light interference patten, which is the case in media which have a local response such as atomic vapors.

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[12] This crystal measured 5.1 × 4.8 × 5.1 mm and was poled into a single domain so that the c axis was parallel to the 4.8-mm side.