Laser crystal with nonreciprocal feedback as a parametric mirror which performs passive optical phase conjugation

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Parametric passive phase conjugation of light beams has been achieved in a Nd:YAG crystal with a population inversion. Parametric generation arises in the field of orthogonally polarized, mutually incoherent light waves. These waves consist of a wave incident on the laser crystal and a wave which has traversed a feedback loop. Achieving passive phase conjugation of a light beam in a laser crystal requires that the feedback be nonreciprocal in terms of phases and amplitudes.

The amplification of light beams in resonant media with a population inversion may be accompanied by nonlinear-optics effects which cause changes in the wavefronts of the beams. One such effect, the wavefront inversion (phase conjugation) of a light beam, has been realized previously in resonant media with a population inversion in the course of four-wave mixing in the field of mutually conjugate pump beams.[1,2] In recent years, there has been a discussion of yet another possible setting for generating a phase-conjugate light beam: a resonator with a "holographic mirror" which is excited by virtue of gain saturation of the laser crystal in the interference field of beams incident on and transmitted through the resonator. [3,4] If this effect is to be realized, however, the pump beams must be mutually coherent.

This letter is the first report of a study of passive phase conjugation of a light beam in a laser crystal with a population inversion and nonreciprocal feedback. Parametric passive phase conjugation, which was originally seen in media with striction[5] and photorefractive[6] nonlinearities, can be summarized as follows: As the incident light beam and the beam which has traversed a feedback loop intersect in a nonlinear medium (in general, these waves are mutually incoherent), they participate in a joint stimulated scattering. As a result of this scattering, waves with phases which are the conjugates of the pump phases are generated. The possibility of parametric generation in a resonant medium with a population inversion (for light pulses whose length is far longer than the transverse relaxation time of the laser working transition) stems from an excitation of population gratings which are induced by the interference fields of the pump wave, $E_0^{\pm}$, and the luminescence wave, $E_1^{\pm}$, and the joint scattering of the pump beams by these gratings. However, the analogy between the processes of parametric generation in a resonant medium with a population inversion and stimulated scattering in a medium with refractive-index nonlinearities is not complete. The reason is that minima of the population difference form at maxima of the interference of the light waves in a resonant

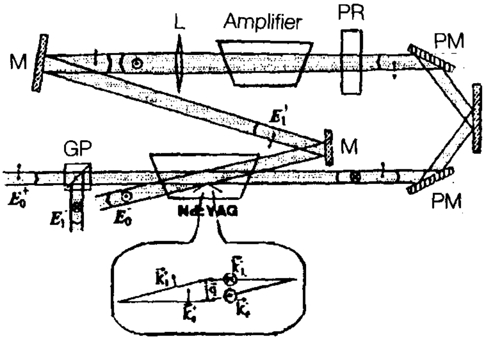


FIG. 1. Experimental layout and diagram of the wave vectors and polarizations of the pump waves, $\mathbf{E}_0^+$ and $\mathbf{E}_0^-$, and the generated waves, $\mathbf{E}_1^+$ and $\mathbf{E}_1^-$. GP—Glan prism; Nd:YAG—rod; PM—polarization mirrors; M—aluminum-coated mirrors; PR—polarization rotator; L—lens.

medium with a population inversion. The luminescence wave, which is correlated with maxima of the light interference, is thus amplified to a lesser extent as it propagates than the waves which are not correlated with the interference field. In other words, a negative feedback is set up between the excitation of the population gratings and the growth of the luminescence waves during scattering of the pump waves by these gratings. Parametric generation during the joint scattering of incoherent beams is not possible. Nevertheless, there is the possibility of establishing a positive feedback between the growth of the luminescence waves, E_1^+ (and E_1^-), and the scattering of the pump waves, E_0^+ (and E_0^-), by the population gratings δn^- (and δn^+) which are induced by the interference field of another pair of light waves in a resonant medium with a population inversion: $\delta n^- \sim E_0^{-*}E_1^-$ (and $\delta n^+ \sim E_0^{+*}E_1^+$). As we will show below, this possibility is realized in a laser crystal with a nonreciprocal feedback.

Let us consider a two-level medium with a population inversion in which plane pump waves E_0^+ and E_0^- (these are the incident wave and the wave which has been transmitted through the feedback loop), with orthogonal polarizations, intersect at a small angle $\theta \ll 1$. Let us examine the conditions for growth of the luminescence waves E_1^+ and E_1^-, which are propagating opposite the pump waves E_0^- and E_0^+, respectively, and which have polarizations identical to those of the copropagating pump waves (Fig. 1). We assume that the length of the light pulse (τ_p) is much greater than the longitudinal (T_1) and transverse (T_2) relaxation times of the two-level medium ($\tau_p \gg T_2$ and $\tau_p > T_1$). At the threshold for parametric generation ($|E_0^{\pm}| \gg |E_1^{\mp}|$) the system of Maxwell–Bloch equations can then be written

$$\begin{cases} \pm 2\dfrac{\partial E_1^{\pm}}{\partial z} = \dfrac{\alpha E_1^{\pm} I_s}{|E_0^+|^2 + |E_0^-|^2} + \alpha n E_0^{\pm}, \\ \pm 2\dfrac{\partial E_0^{\pm}}{\partial z} = \dfrac{\alpha E_0^{\pm} I_s}{|E_0^+|^2 + |E_0^-|^2}, \\ T_1 \dfrac{\partial n}{\partial t} + n = -\dfrac{E_0^{+*}E_1^+ + E_0^{-*}E_1^-}{I_s + |E_0^+|^2 + |E_0^-|^2} - n\,\dfrac{|E_0^+|^2 + |E_0^-|^2}{I_s}, \end{cases} \tag{1}$$

where α is the logarithmic small-signal gain of the medium with the population inver-

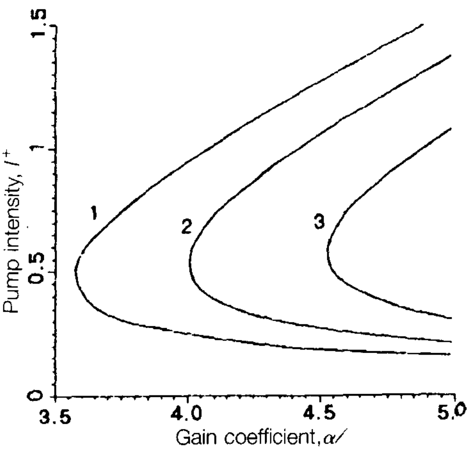


FIG. 2. Threshold intensity of the pump wave versus the logarithmic gain coefficient of a "nonlinear rod," $\alpha\ell$, for various values of the gain in the feedback loop. 1—$R_1=30$, $R_0=1.1$; 2—$R_1=25$, $R_0=0.9$; 3—$R_1=21$, $R_0=0.75$.

sion, I_s is the saturation intensity, and n is the complex amplitude of the population-difference grating, normalized to the steady-state population difference.

The conditions at the $z=\ell$ boundary of the resonant medium couple the amplitudes of the waves which have left the rod and which have traversed the feedback loop:

$$E_0^-(z=\ell)=E_0^+(z=\ell)r_0\exp(i\varphi_0),$$
$$E_1^-(z=\ell)=E_1^+(z=\ell)r_1\exp(i\varphi_1). \quad (2)$$

We also assume that there is a weak (seed) wave at the entrance to the medium and that there is initially no population-difference grating:

$$E_1^+(z=0)\ll 1, \quad n(t=0)=0. \quad (3)$$

Solving Eqs. (1) under conditions (2) and (3) in the approximation of given intensities of the pump waves, $|E_0^+|^2/I_s=\text{const}=I^+$ and $|E_0^-|^2/I_s=\text{const}=I^-=R_0I^+$ $(R_0=r_0^2)$, we find the growth of the luminescence wave (near the threshold for parametric generation) at the exit, $E_1^-(z=0)$, with a growth rate

$$M(t)=\left(\frac{\alpha\ell I^+(1-R_0)}{1+I^+(1+R_0)}\text{Re}\left[\ln^{-1}\left(\frac{r_0r_1\exp(i(\varphi_1-\varphi_0))+R_0}{r_0r_1\exp(i(\varphi_1-\varphi_0))+1}\right)\right]\right.$$
$$\left.-1-I^+(1+R_0)\right)\frac{t}{T_1}. \quad (4)$$

Expression (4) can be positive if the amplification of the luminescence wave in the feedback loop is far greater than the amplification of the pump wave ($r_1\gg r_0$), and if the difference between the phase shifts of the pump and luminescence waves, $\varphi_1-\varphi_0$, is greater than $\pi/2$ (the greatest growth rate is possible in the case $\varphi_1-\varphi_0=\pi$). At fixed values of the gain in the resonant medium and in the feedback loop, there then exists an interval of pump-wave intensities I^+, within which parametric generation is possible (Fig. 2). At pump intensities I^+ above the lower boundary of the threshold curve, the population-difference (δn) grating grows more rapidly as a result of the light interference field than it decays because of transverse relaxation, with a time T_1. The upper boundary of the threshold pump intensity, on the other hand, is set by gain saturation of all waves and by an increase in the relaxation rate of the population-difference grating in the course of induced emission in the strong average light field. Note that these processes give rise to a threshold value of the gain coefficient $\alpha\ell$ of the inverted medium; below this value, generation does not arise at any intensities.

Realizing parametric generation in a resonant medium with a population inversion thus requires that the feedback loop be nonreciprocal in terms of phases and amplitudes. The phase nonreciprocity $\varphi_1 - \varphi_0 = \pi$ leads to a spatial shift of the gratings of the interference of the pump and luminescence waves, $E_0^{+*}E_1^+$ and $E_0^{-*}E_1^-$, with respect to each other, by half a period. This spatial shift of the gratings, in turn, has the consequence that the pump wave E_0^-, scattered by the population-difference grating $\delta n^+ = E_0^{+*}E_1^+$, amplifies the conjugate wave E_1^-, which is correlated with minima of the $E_0^{+*}E_1^+$ interference field. By removing the excess population inversion at the maxima of the population-difference grating δn^+, the wave E_1^- has an advantage over other luminescence waves in terms of amplification.

The amplification of the light waves in the feedback loop leads to a difference between their interference fields: under the condition $r_0 r_1 > 1$, amplitude of the grating of the waves traveling toward the exit, $E_0^{-*}E_1^-$, is greater than the amplitude of the grating of waves traveling in the opposite direction, $E_0^{+*}E_1^+$. The difference between the amplitudes of the optical interference fields which are out of phase with each other prevents a mutual quenching of the population-difference gratings δn^+ and δn^- induced by these fields. A difference between the gain values for the generation and pump waves in the feedback loop, $r_1 \gg r_0$ (an amplitude nonreciprocity), on the other hand, prevents rapid relaxation of the $\delta n^{\pm}$ gratings due to induced transitions in the strong average field of the oppositely directed pump wave E_0^-.

In our experiments, the phase and amplitude nonreciprocities of the feedback loop are realized with the help of a polarization rotator (PR in Fig. 1), which is a quartz plate, and polarization mirrors (PM). The light waves which are propagating from opposite ends through the quartz plate, with active rotation of the polarization plane, and which have identical polarization unit vectors before the passage, have oppositely directed polarization unit vectors after the passage through the rotator. These directions are orthogonal to the original directions. Accordingly, the pump and generation waves, which have identical polarizations $\mathbf{E}_0^+ \uparrow\uparrow \mathbf{E}_1^+$ at the exit from the "nonlinear" Nd:YAG rod, have oppositely directed polarization unit vectors, $\mathbf{E}_0^- \uparrow\downarrow \mathbf{E}_1^-$, at the entrance to the same rod after they have passed through the feedback loop in opposite directions. The opposite directions of the polarization unit vectors correspond to a difference between the phase shifts of the waves in the loop: $\varphi_1 - \varphi_0 = \pi$.

Since there are polarization mirrors along with a polarization rotator in the experimental layout, there is also a difference between the transmission coefficients for the waves propagating in opposite directions through the feedback loop. The pump wave which is polarized in the plane of incidence on the polarization mirrors is reflected weakly by these mirrors (the resultant reflection coefficient of the two polarization mirrors for the pump wave is 0.005–0.01). The generation wave which is propagating through the feedback loop in the opposite direction, and which is polarized in the same way as the pump wave at the entrance to the Nd:YAG rod, has a polarization after passage through the rotator which is perpendicular to the plane of incidence on the polarization mirror. The system of mirrors ($\sim 0.95-0.97$) thus has a high reflection coefficient for this wave.

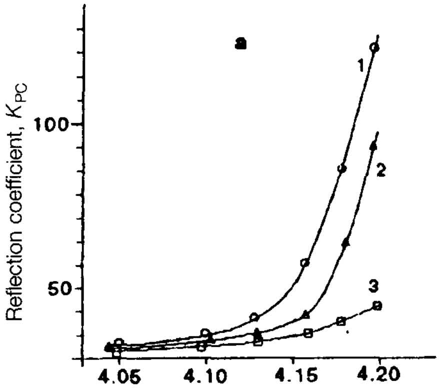
The presence of an amplifier in the layout (two optically pumped Nd:YAG rods with a resultant power gain coefficient of 700–1500), which amplify light of all polarizations identically, makes it possible to compensate for the losses in the layout and to maintain the transmission coefficients of the loop for the generation wave, $R_1' \sim 2-7$, and the pump wave, $R_0' \sim 0.1-0.2$. (When the amplification of the waves over half the length of the conjugating Nd:YAG rod is taken into account, the transmission coefficients R_1 and R_0 corresponding to the theory have the values $R_1 \simeq 10-120$ and $R_0 \simeq 0.5-6.0$.)

In the experiments, the pulse from the Nd:YAG oscillator, formed with the help of a mechanical chopper from the cw beam, has a length of 0.6–1.0 ms. The output beam from this laser passes through a polarization isolator consisting of a permanent-magnet Faraday rotator and two Glan prisms. This beam is sent to a Nd:YAG rod, which is pumped by gas-discharge tubes. The beam leaving the laser crystal, after passage through the feedback loop, is again sent to the nonlinear rod, at an angle $\theta \simeq 0.01$ from the exactly backward direction. The optical pumps of the nonlinear rod and the loop amplifier are synchronized in time by means of the laser pulse.

The power and energy of the beams reflected backward are measured. The spatial structures of these beams in various polarizations are studied with the help of an image converter and a polarization wedge. When the input power level of the Gaussian light beam and the gain coefficients of the nonlinear rod and the amplifier in the feedback loop exceed certain threshold levels, we observe generation of the conjugate beam with the polarization orthogonal to the polarization of the input wave. The threshold level of the logarithmic gain coefficient of the nonlinear rod in terms of power is 4.1–4.3, depending on the gain in the loop and the power of the conjugate beam (Fig. 3a). The threshold power of the input wave in turn depends on the gain coefficients of all the amplifiers; it has values of 0.02–0.1 W (Fig. 3b). These values correspond to pump intensities $I_0^+ \simeq 20-100$ W/cm^2 in the nonlinear-interaction region. The reflection coefficient for the conjugate wave, measured within 1.2–1.5 diffraction angles of the original beam, reaches $K_{PC} \simeq 3000-4000$ at the peak power, or 500–1000 in terms of energy.

For values of the gain coefficient of the loop amplifiers which are not too large, the spatial structure of the generation wave remains approximately the same as that of the conjugate Gaussian beam. The level of the unconjugated background is $\sim 0.001-0.01$ of the intensity of the conjugate wave. However, in the case of self-excitation of the scheme, which is characteristic of large values of the amount by which the loop gain exceeds the threshold for parametric generation ($R_1 \geqslant 100$), the background light intensifies by a factor of 10–100 near the conjugate beam.

In the experiments we also checked the possibility of compensating for the phase distortions introduced in the input wave with the help of a phase aberrator. If the aberrator is not too strong, and it increases the divergence of the pump by a factor of 3–4, it is possible to achieve generation of a conjugate wave which compensates for the distortions



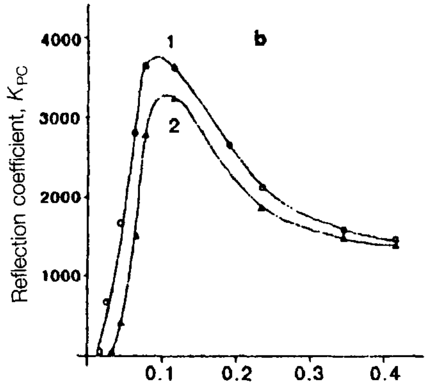


FIG. 3. Reflection coefficient for the conjugate beam versus the logarithmic gain coefficient (a) for $R_1 \simeq 35$, $R_0 \simeq 0.3$; for input power levels 0.23 W (1), 0.34 W (2), and 0.46 W (3); and the input power (b) for $\alpha \ell \simeq 4.5$ and $R_1 \simeq 110$, $R_0 \simeq 1$ (1) and $R_1 \simeq 80$, $R_0 \simeq 0.7$ (2).

introduced on the return path, in the former layout of the optical system of the feedback loop.

In summary, our study has shown that it is possible to realize passive phase conjugation of light beams in laser rods with a population inversion and feedback loops with phase and amplitude nonreciprocities. A conjugator based on laser crystals with a population inversion has a low threshold power and a large reflection coefficient, and it holds promise for quasi-cw light with a high average power.

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