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We implement a feedback loop oscillator, using a $BaTiO_3$ crystal that provides stable high-quality phase conjugation for nanosecond pulses, with an efficiency close to the theoretical maximum.

Thermal lenses in optical amplifiers, such as YAG rods, introduce phase distortions in laser beams and thus degrade their transverse mode quality. As these thermal lenses depend on parameters such as the pumping energy and the repetition rate, the distortions vary with operating conditions. One can dynamically correct these distortions with a double pass in the amplifier and a phase-conjugate mirror[1] (PCM). The good-quality laser beam, coming from an oscillator, passes through the amplifier and becomes phase aberrated. Then it is reflected by the PCM and passes back through the amplifier, where the distortions are now compensated for in the process. Such a demonstration has been made with stimulated Brillouin scattering to produce the phase-conjugate beam.[2] Another solution is to use the four-wave mixing technique in a photorefractive material. A self-pumped photorefractive PCM geometry has been demonstrated in the pulsed regime,[3] but there is no quantitative information available about the phase-conjugation quality. The purpose of this Letter is to show that it is possible to correct thermal lenses with a good fidelity.

Among all the different self-pumped photorefractive PCM arrangements, we consider the feedback loop oscillator[4,5] (FLO). In this geometry the signal beam, beam 1, enters the photorefractive crystal, and its transmitted part, beam 2, is sent back in the crystal via a Sagnac loop. Beam 2 is the first pump beam. The second pump beam, beam 3, is generated from scattered light amplified by photorefractive two-beam coupling, so-called beam fanning. The transmitted part of beam 3 is also sent back in the crystal and forms beam 4, which is the phase conjugate of beam 1. The FLO has the following qualities. First, in the loop configuration the two counterpropagating light pulses experience the same optical path; thus they always interfere in the crystal, whatever their coherence length and pulse duration.[3] There is a threshold defined by the product of Γ, the photorefractive gain, and l, the interaction length of the beams in the crystal. Neglecting absorption and other optical losses, the threshold[4] for the FLO is $\Gamma l = 2$ only. Therefore the FLO compares well with other self-pumped photorefractive PCM's. Finally, as demonstrated in Ref. 6, a transformation of the beam characteristics in the loop by modification of the diameters or rotation of the beam cross sections by 90° forces the oscillation of the phase-conjugate beam only. All these qualities make the FLO the best self-pumped photorefractive PCM for nanosecond pulse operation.

We implement the FLO with a cobalt-doped $BaTiO_3$ crystal.[7] This crystal is cut along the directions $[01\bar{1}]$, $[011]$, and $[100]$, and its dimensions are 2.1 mm × 3.7 mm × 5.5 mm. The beam entrance and exit faces, $(01\bar{1})$ and $(0\bar{1}1)$, are antireflection coated to avoid self-oscillation and reflection losses. We first characterized this crystal by two-beam coupling experiments with a cw laser at 532 nm and ordinary polarization. We determined an effective photorefractive trap density of 5.6×10^{16} cm^{-3}. Finally, the absorption is 3 cm^{-1}, and the crystal has a memory effect of two days in the dark.

We study the FLO operation with 10-ns pulses at 532 nm. These pulses are generated by a frequency-doubled Nd:YAG oscillator with a repetition rate of 10 Hz. Both laser cavity mirrors have Gaussian reflectivity profiles to ensure the transverse coherence of the beams. We limit the diameter with a 1.5-mm aperture located 1 m before the sample. Barry and Damzen[8] show and explain that there is a diminution and an inversion of the photorefractive gain with the increase of the intensity. Our crystal has the same behavior with an inversion of the photorefractive gain at an intensity of 1.1 MW/cm^2 (average power over

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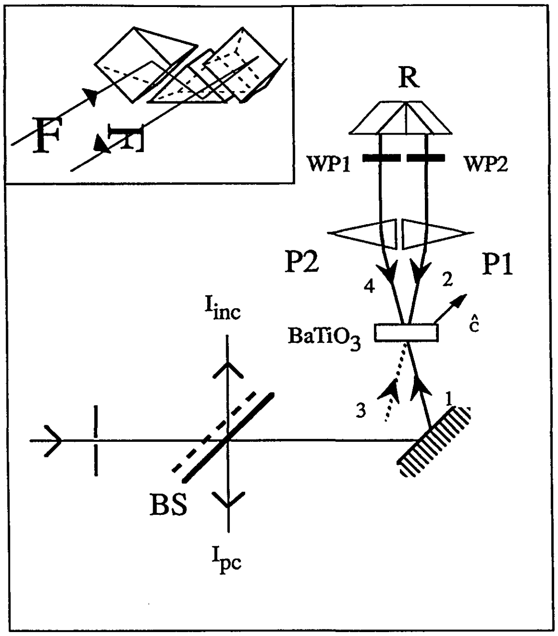

Fig. 1. Experimental setup. The inset shows a detail of prism system R.

one pulse). For this reason, we limit the power range at 50 to 100 kW/cm^2, where the photorefractive gain is constant.

Part of the incident beam is reflected by beam splitter BS, and the transmitted part is sent into the FLO (Fig. 1). The main element of the loop is the three-prism system, R, which achieves 90° beam cross section rotation for selection of the phase-conjugate beam. We have chosen to rotate the beam cross section rather than to modify the beam diameters because this method is possible without the use of lenses and thus without the focusing that may be problematical with high energy peaks. In the FLO the role of the two half-wave plates, WP1 and WP2, is to adapt the polarizations in the loop. Indeed, at the crystal level, the polarizations must be in the incident plane, which also contains the $\hat{c}$ axis, and they have to be oriented at 45° with respect to this plane at entrance R to fit the prism system eigenpolarizations. Prisms P1 and P2 deflect the beams in the cavity such that they enter R at normal incidence and enter the crystal with a ±10° incident angle. These symmetrical incidence angles permit a good overlap of the beams in the crystal, which is a sensitive parameter with respect to the phase-conjugate quality and efficiency. In this angular configuration the photorefractive gain value is 56 cm^{-1} and the interaction length is 0.23 cm. With this high gain the beam fanning is strong enough to destroy the phase-conjugation quality. We reduce the photorefractive gain and therefore the beam fanning by illuminating the crystal with incoherent white light,[9] adjusting its intensity to obtain high-quality phase conjugation. Note that this adjustment is not critical relative to the white-light intensity.

The photorefractive grating providing phase conjugation cannot be fully constructed with one pulse in the intensity range that we use. But because the crystal has a memory effect it is possible to construct the photorefractive grating by accumulation. In our case the steady state is obtained for approximately 2000 pulses. Because the photorefractive effect is sensitive to accumulated energy, this pulse number can be reduce by increasing the pulse intensity.

The phase-conjugate reflectivity is calculated with the ratio $I_{pc}/(1 - r)I_{inc}$, where I_{pc} and I_{inc} are the intensities of the incident and phase-conjugate beams reflected by the beam splitter, which has a reflectivity r. The crystal absorption induces 75% of energy loss, and the optical elements of the cavity induce 24%. Consequently the maximum phase-conjugate reflectivity is limited to 19%. We measure a 16% phase-conjugate reflectivity, which corresponds to 84% of the accessible maximum and thus shows a good efficiency.

To determine the FLO ability to correct thermal lenses, we measure the quality of the phase-conjugate beam as lenses are introduced in the beam path between beam splitter and the crystal. Because the incident beam profile is not Gaussian but has the characteristics of a diffraction pattern, it is impossible to rely on quantities such as the beam divergence. But if the beam reflected by the FLO is perfectly phase conjugated with the incident one, they both must have the same intensity profile at the same distance D from the crystal, even if a lens is introduced in the incident beam. However, there is an inherent limitation for the phase-conjugate beam fidelity. Indeed, there is a large distance D between the FLO and the position at which the incident beam profile is measured. Thus, because of diffraction, the highest-frequency components of this profile fall outside the crystal and cannot be phase conjugated. We measure the phase-conjugation quality by taking the incident and the phase-conjugate beam intensity profiles with a CCD camera (512 × 512 pixels). To compute the correlation factor between the images, we reduce the image pixel number to 63 × 63 pixels, each pixel value on this new image being the average value of the corresponding 8 × 8 pixel square on the original image. We define as $a_{i,j}$ and $b_{i,j}$ the pixel values of the two images and as $c_{i,j}$ the valves of the correlation pattern. The relation between these quantities is given by

$$c_{i,j} = \frac{\sum a_{k,l} b_{k-i,l-j}}{\sqrt{\sum a_{k,l}{}^2}\sqrt{\sum b_{k,l}{}^2}}. \tag{1}$$

The maximum of this correlation is our numerical criterion for phase-conjugation quality. The closer $c_{i,j}$ is to 1, the better the phase-conjugation quality. With a beam profile showing high spatial frequencies the maximum of correlation is always lower than 1. However, if there is no variation of the correlation maximum for the different lenses introduced, this shows that the lenses are corrected and that the FLO is actually a good PCM.

We study the fidelity of the phase conjugation for two cavity lengths: cavity A, which is 90 cm long, and cavity B, which is 40 cm long. For cavity A the lenses are located 30 cm before the crystal, and for

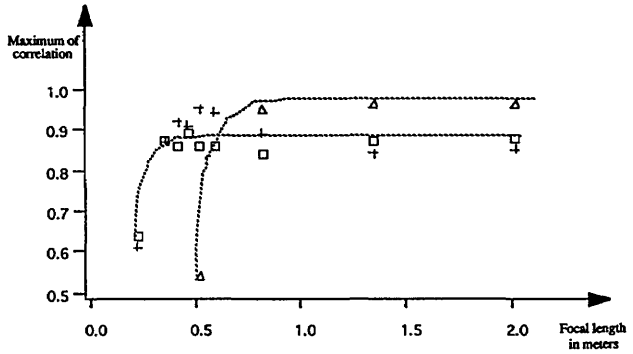

Fig. 2. Variation of the maximum of correlation with the focal length of the lenses. Triangles, cavity A with lenses located 30 cm before the crystal; squares, cavity B with lenses located 30 cm before the crystal; crosses, cavity B with lenses located 6 cm before the crystal. The dashed curves are visual aids only.

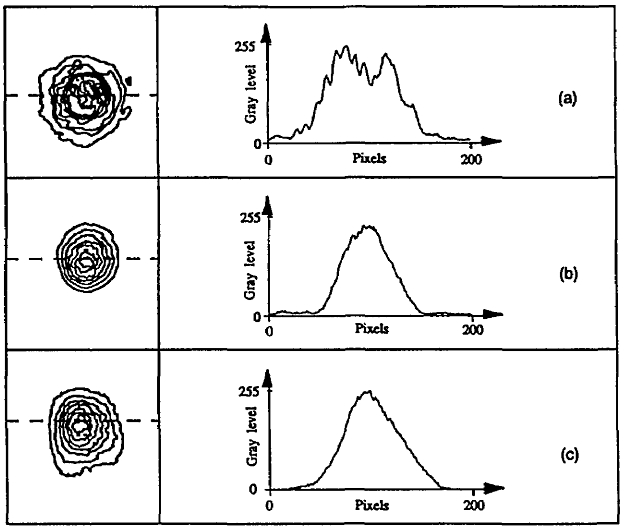

Fig. 3. Beam intensity profiles: left, beam intensity profiles; right, section of the profile containing the maximum of intensity. (a) Incident beam, (b) phase-conjugate beam without a lens, (c) phase-conjugate beam with a lens of 57-cm focal length. We observe that the highest spatial frequencies have been filtered and that there is no change for the phase-conjugate beam with or without lens.

cavity B they are located at 30 cm before the crystal for the first lens set and at 6 cm for the second set. The results of these measurements and calculations are shown in Fig. 2. One sees that the maximum of correlation is almost constant and above 0.9 for lenses of focal lengths longer than 60 cm for cavity A and above 0.85 until a focal length of 30 cm for cavity B. For shorter focal lengths we observe a strong degradation of the phase-conjugate quality and efficiency. This degradation comes from the strong divergence of the beams that makes the diameters very different at the crystal position. So the overlap is no longer good enough to achieve phase conjugation of good quality. With a shorter cavity length, a shorter focal-length lens can be corrected. This limitation of the FLO may be suppressed by imaging the crystal on itself with an optical system inside the loop. So we always keep the same beam diameters in the crystal whatever the incident beam divergence. As discussed above, the maximum of correlation is never reached, even when there is no lens on the incident beam, because of spatial filtering at the crystal entrance face. Figure 3 shows the intensity profile of an incident beam and its phase conjugate with and without a lens. One sees that the highest spatial frequencies are indeed removed, whereas the global shape of the conjugate beam is unchanged compared with that of the incident one. These results demonstrate that the FLO permits efficient compensation of lenses, and they are obtained with a good stability over time. Indeed, no modification of the phase-conjugate beam cross section is observed over a few hours of laser operation. In particular, we do not see any degradation as a result of beam fanning, as observed in Ref. 10, because we use an additional incoherent illumination. Such stability is important for the realization of a double-pass amplifier with a PCM.

In summary, we demonstrate a photorefractive self-pumped phase-conjugate mirror working in the nanosecond regime that has good and stable phase-conjugation quality. This research will be pursued for longer wavelengths and higher repetition rates. Indeed, in the cw regime a FLO has already been demonstrated at 1.06 μm with a $BaTiO_3$ crystal.[11] Furthermore, efficient $BaTiO_3$ crystals exist now for the near infrared.[12] Consequently, we expect a strong phase-conjugate reflectivity in the pulsed regime with the same quality of correction as the one presented here.

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