Double phase-conjugate mirror with sixfold gain in photorefractive $BaTiO_3$ at near-infrared wavelengths

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We describe incoherent beam coupling using the double phase-conjugate mirror arrangement between a laser diode and a Ti:sapphire laser at the near-infrared wavelengths of ~800 nm using a nominally undoped sample of $BaTiO_3$. We report phase-conjugate reflectivities of greater than 6 times, which we believe to be the highest reported to date at these wavelengths. We also examine the fidelity of the phase-conjugate beam and the wavelength response of the double-color-pumped oscillator.

Beam coupling using the class of mutually pumped phase conjugators in photorefractive materials has recently become a subject of great interest as a method of forming a holographic link between two mutually incoherent, even independent, laser sources. The beam-coupling interaction within the photorefractive crystal may be explained by the sharing of fanning gratings, with automatic Bragg matching allowing a self-reinforcing self-aligning interconnect to form between the two sources. In this way, phase conjugates of both beams are generated simultaneously: diffracted light from source 1 forms the phase conjugate of beam 2 (hence the source of photons for the phase conjugate of beam 2 is beam 1, and vice versa), which permits the exchange of spatial information without cross talk.[1] Several geometries exist for incoherent beam coupling,[2-6] however, an interesting feature of the double phase-conjugate mirror (DPCM) geometry[2] is the possibility of gain as previously demonstrated at 488 nm by Fischer *et al.*[7] In this Letter we examine gain using the DPCM at near-infrared wavelengths and utilize the wavelength tolerance of the DPCM geometry [the double-color-pumped oscillator[8] (DCPO)] to aid coupling between two separate lasers.

In our experiment, a laser diode and a Ti:sapphire laser were used to provide the mutually incoherent beams. The laser diode was a Sharp LTO17 AlGaAs device operating single longitudinal mode at approximately 808 nm with an output power of ~30 mW after collimation. The laser-diode beam was incident upon the $+c$ face of the photorefractive crystal (Fig. 1), and light from the Ti:sapphire laser (tuned to approximately the same nominal wavelength as the laser diode) was incident upon the $-c$ face of the crystal; the external beam angles ($\theta_1 = 68°$ and $\theta_2 = 52°$) are indicated in the figure. The crystal used in our experiment was a 6 mm × 6 mm × 6 mm cube of nominally undoped $BaTiO_3$, which has been shown previously to exhibit favorable response[9] at near-infrared wavelengths. Although the crystal absorption was found to be low, ~0.1 cm^{-1} at 808 nm, the infrared photorefractive behavior of this particular crystal is good up to wavelengths of ~830 nm.

The laser-diode beam, with its characteristic elliptical spatial profile, was adjusted in order to increase the beam overlap with the Ti:sapphire beam in the horizontal plane inside the crystal. The laser diode (LD) was mounted such that the major axis of the ellipse was horizontal, and a half-wave plate ($\lambda/2$) was then inserted into the diode beam path in order to rotate the polarization into the same plane, ensuring that both incident beams were e polarized (see Fig. 2). Lens L1 ($f = 20$ cm), placed 15 cm from the crystal, was used to focus loosely the Ti:sapphire beam to a diameter of ~0.5 mm, and the diode collimating lens L2 ($f = 6.5$ mm) brought the laser-diode beam diameter (major axis) to ~1 mm at the crystal, although a more favorable overlap may have been achievable using an anamorphic prism arrangement. A neutral-density filter (ND = 0.6) reduced the diode power incident upon the crystal to ~5.8 mW and also reduced any feedback that was due to the phase-conjugation process. A variable neutral-density filter (VND) placed in the path of the Ti:sapphire beam allowed the incident power ratio of the Ti:sapphire laser to the laser diode at the crystal ($r = P_{Ti}/P_{LD}$) to be adjusted. The reflectivity of each beam splitter was carefully deduced by monitoring the reflected power and the corresponding transmitted power with a calibrated power meter. During the experiment, the power of both incident beams was monitored after reflection from beam splitters BS1 and BS2 (at positions A and B, respectively, in Fig. 2). The phase-conjugated

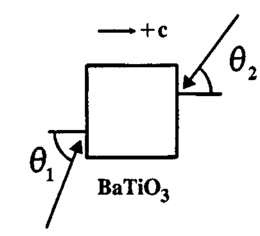

Fig. 1. DPCM configuration used in our experiments. $\theta_1 = 68°$ and $\theta_2 = 52°$.

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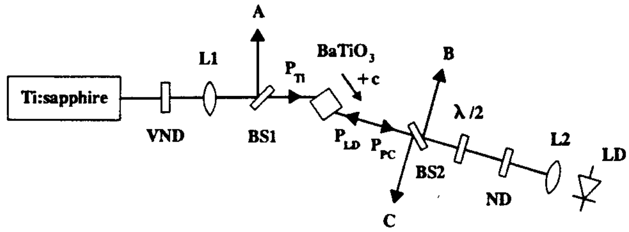

Fig. 2. Experimental arrangement. Position A, location of power meter; position B, location of power meter/optical spectrum analyzer; position C, location of power meter/beam profiler.

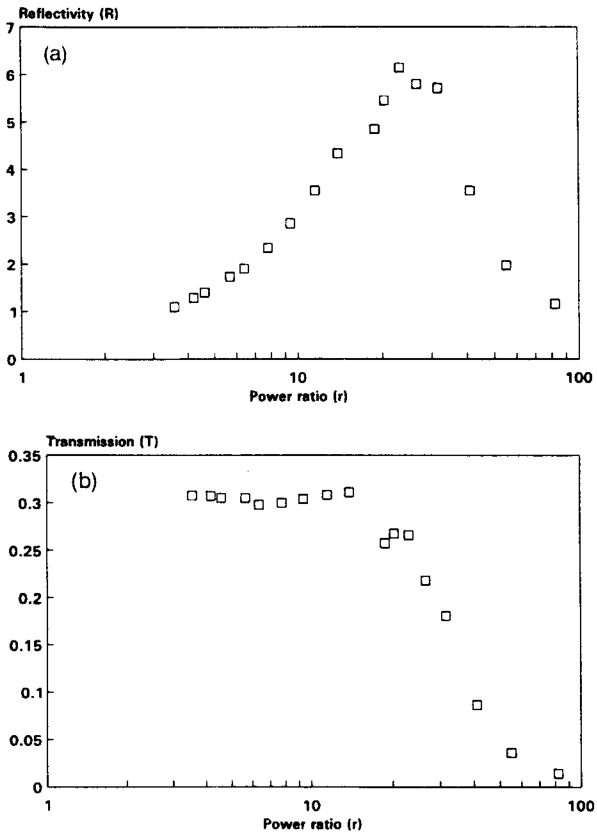

Fig. 3. (a) Laser-diode reflectivity R versus power ratio r, (b) Ti:sapphire transmission T versus power ratio r.

diode signal power also was monitored after reflection from BS2, at position C, using an identical power meter. Figure 3(a) shows the effective laser-diode reflectivity ($R = P_{PC}/P_{LD}$) of the crystal for different incident power ratios (r) measured by using the same detector to avoid cross-calibration problems. Each measurement of steady-state reflectivity was made after 100 s from any adjustment of r, in order to avoid transient effects, and it was confirmed that the phase-conjugated diode beam was formed by light from the Ti:sapphire laser. Figure 3 represents the unmodified measurement of incident and reflected powers uncorrected for Fresnel losses (an incident angle of 52° at the crystal entrance face implies a 5% reflection). It can be seen from Fig. 3(a) that $R > 1$ for the range $\sim 3.5 < r < \sim 82$, and the curve exhibits the characteristic shape predicted theoretically and observed experimentally by Fischer *et al.*[7] in their DPCM experiments. The maximum reflectivity of ≥ 6, which to our knowledge is the highest reported to date at near-infrared wavelengths, occurs with an incident power ratio of $r \sim 23$. Figure 3(b) shows the fraction of Ti:sapphire light channeled into the phase-conjugate diode beam ($T = P_{PC}/P_{Ti}$), which can be seen to fall from its maximum value of ~ 0.3 toward zero as r increases. When R is at its maximum value of 6, $T \sim 0.27$.

Throughout the experiment, the incident beam powers were monitored for changes caused by possible feedback. This could be particularly significant in the case of the laser diode; however, no effects were observed owing to the presence of the ND filter and, perhaps, an incident wavelength mismatch between the diode and the Ti:sapphire, which led to a consequent lateral shift of the diffracted light at the laser-diode facet. The beam profile of the diffracted Ti:sapphire light was examined by replacing the power meter at position C with a beam profiler. Figure 4(a) shows a plot of the intensity of the phase-conjugate beam from the diode-laser input. This shows that, in fact, the laser-diode conjugate beam consists of a bright peak with smaller sidelobes that appear to lie on the arc of an ellipse. This is consistent with the observations of Statman and Liby,[10] who predicted that a range of angles satisfying the Bragg-matching requirement of the gratings in the crystal would diffract light into a cone that is observed as an ellipse on a screen. Imprecise or degraded phase conjugation may also be accounted for by incomplete beam overlap in the crystal as is likely with the elliptical Gaussian beams used here. However, it can be seen that most of the power is concentrated in the central peak. Figure 4(b) shows

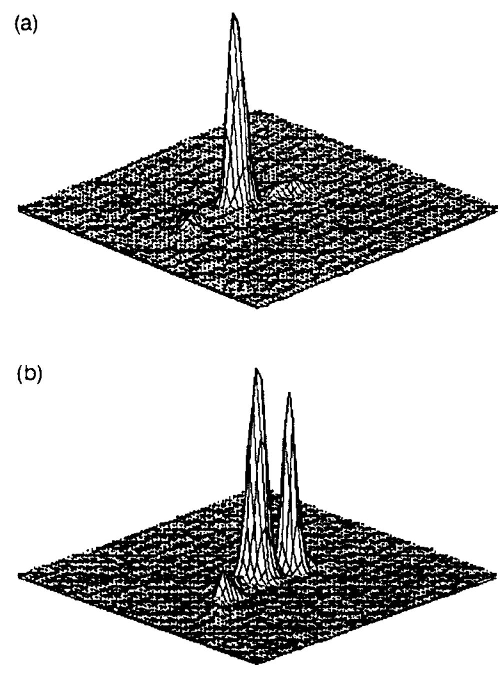

Fig. 4. Intensity profiles of the phase-conjugated diode beam (diffracted Ti:sapphire beam) observed at position C in Fig. 2: (a) steady-state profile, (b) transient image as gratings form.

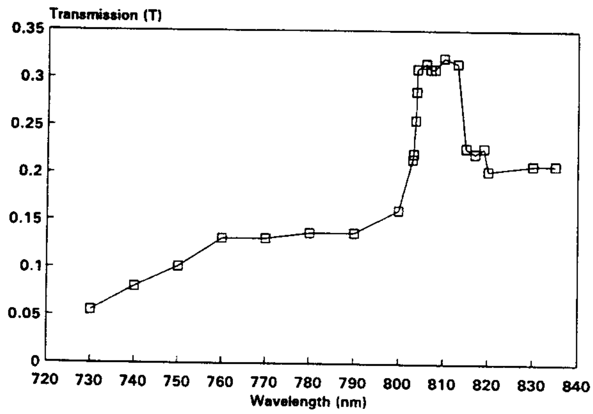

Fig. 5. Ti:sapphire transmission T versus wavelength.

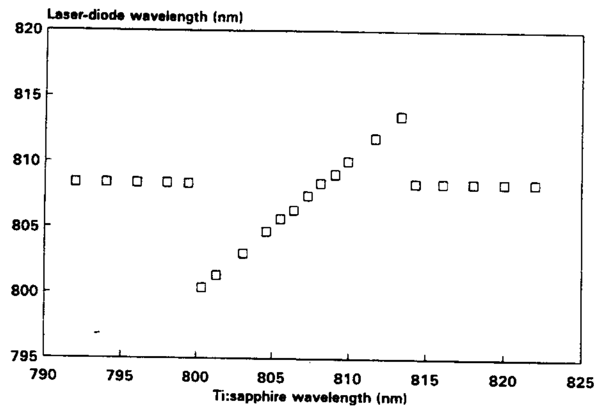

Fig. 6. Laser-diode wavelength (measured at position B in Fig. 2) versus Ti:sapphire wavelength.

the effect of deliberately misaligning the Ti:sapphire beam in the vertical plane without allowing time for the crystal to readjust to the change—the sidelobes increase in power and the arc becomes enhanced, indicating inefficient conjugation. It has been suggested[8] that the fidelity of the phase-conjugate beam may, however, be improved when structure is imposed on the beams (rather than using simple Gaussian beams as we have here), which would give rise to more complex gratings and, therefore, more constrained Bragg-matching requirements.

The wavelength of the DCPO configuration was then examined by measuring the transmission (T) as a function of Ti:sapphire wavelength. The results (Fig. 5) demonstrate that transmission is greatest (~0.3) for a range of wavelengths spanning ~15 nm around the nominal diode wavelength. This maximum transmission would intuitively occur when both sources are of the same wavelength (allowing precise Bragg matching) and imply that perhaps the wavelengths of the two sources are matched over this region. This would in turn imply that light channeled from the Ti:sapphire laser into the laser-diode facet by the DCPO influences the lasing characteristics of the laser diode by forcing it to lase at the Ti:sapphire wavelength. To confirm this, an Anritsu optical spectrum analyzer was placed at position B in Fig. 2, and the laser-diode wavelength was measured as a function of the Ti:sapphire wavelength. In the range 800 to 814 nm, it was found that when the injected Ti:sapphire wavelength corresponded to a longitudinal mode of the laser diode, the diode lased single mode at the injected Ti:sapphire wavelength, and the diode mode spacing was confirmed to be 0.33 nm. Figure 6 shows the diode lasing wavelength for a selection of such injected Ti:sapphire wavelengths. At intermediate wavelengths, not corresponding to longitudinal modes, the laser diode appeared unstable, flipping between the injected wavelength and the nominal lasing wavelength of 808.4 nm. At wavelengths outside the range 800 to 814 nm, the laser diode was unaffected by the Ti:sapphire laser. Thus the region in which the laser-diode wavelength follows closely that of the Ti:sapphire laser corresponds to the region of maximum ~0.3 transmission in Fig. 5. It would seem that the main factor influencing the width of this peak is the laser-diode gain bandwidth: outside this region, the laser diode cannot support the lasing wavelength imposed by the Ti:sapphire laser and instead relaxes to its nominal wavelength, at which point the fraction of Ti:sapphire signal injected into the diode facet is reduced by the angular offset due to the DCPO Bragg selection. Figure 5 shows that the DCPO transmission drops to approximately half its maximum value when there is a wavelength mismatch between the sources.

In conclusion, we have demonstrated mutually incoherent beam coupling in the near infrared between a laser diode and a Ti:sapphire laser using a nominally undoped sample of $BaTiO_3$. Phase-conjugate reflectivites of ≥6 were observed, fidelity was examined, and the wavelength response of the DCPO investigated.

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