Highly efficient self-pumped phase conjugation at near-infrared wavelengths by using nominally undoped $BaTiO_3$

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Using a nominally undoped crystal of photorefractive $BaTiO_3$, we have examined self-pumped phase conjugation at near-infrared wavelengths. We report reflectivities as high as 74% between 720 and 800 nm. As expected, the crystal response time increases significantly at longer wavelengths. We believe that this value of reflectivity in the self-pumped geometry is the highest reported to date for this range of wavelengths with the use of a nominally undoped crystal.

Phase conjugation by using photorefractive crystals has found many applications in areas such as optical processing and distortion correction at mostly visible wavelengths. Several geometries exist for generating the conjugate signal, however, the CAT[1] (or total internal reflection) geometry remains the simplest and most elegant configuration that allows phase conjugation without the need for additional optics. The highest reflectivity reported so far to our knowledge (73%) was obtained[2] at 514 nm by using photorefractive $BaTiO_3$, cut in a 45° orientation, in the CAT arrangement. (Note, however, that this represented a Fresnel-corrected value compared with their actual reported reflectivity of 62%. In our case reported here, no Fresnel correction was necessary for reflection at the crystal entrance face owing to incidence at Brewster's angle.) Reflectivities of as much as 70% have also been achieved by the use of an additional erase beam.[3] More recently, efforts have turned toward obtaining efficient phase conjugation at infrared wavelengths, compatible with AlGaAs diode-laser sources, and this has stimulated research into dopants for $BaTiO_3$ (such as cobalt[4]) in an attempt to improve and extend the crystal response at these longer wavelengths. Comparison with undoped crystals is clearly important in assessing the effect of the dopants, and in a recent study of nominally undoped $BaTiO_3$, Zhang *et al.*[5] reported phase-conjugate reflectivities of $\sim$55% at 761 nm. In this Letter we also investigate the behavior of a sample of $BaTiO_3$ in the near infrared and report what we believe to be the highest phase-conjugate reflectivity to date at these wavelengths using a nominally undoped crystal. The crystal used in our experiment was a polished 6 mm × 6 mm × 6 mm cube of $BaTiO_3$. Its absorption coefficient was measured with a Perkin-Elmer spectrophotometer and found to be 0.1 cm^{-1} at 800 nm.

Our experimental arrangement for observing phase conjugation is shown in Fig. 1. A Ti:sapphire laser (pumped using a 5-W argon laser) provided a tunable infrared source that was first calibrated with an Anritsu optical spectrum analyzer. The crystal was mounted (in air) on a combined rotation–translation stage and placed 25 cm downstream from a 50-cm focal-length lens (L). The crystal was placed at Brewster's angle with respect to the incident beam by minimizing the light reflected from the entrance face. The input-beam diameter was $\sim$1 mm. A polarizing beam splitter (PBS) ensured that the light incident upon the crystal was *e* polarized. The beam splitter (WBS), used to monitor the incident and phase-conjugate signals, was wedged (1° wedge) in order to avoid interference effects. In Fig. 1, I_o (I_o') is the intensity of the Ti:sapphire beam incident upon (reflected from) the WBS, and I_{in} is the intensity of the beam transmitted through the WBS and incident upon the crystal. I_{pc} (I_{pc}') is the intensity of the phase-conjugate signal incident upon (reflected from) WBS. The phase-conjugate reflectivity of the crystal was determined from the incident and phase-conjugate signals reflected from the beam splitter (I_o' and I_{pc}', respectively). Great care was taken to calculate correctly the slight difference in reflectivity between the beam splitter faces (owing to the 1° wedge), and the computed correction factor that this implied was used to determine the actual reflectivity. It is worth noting here that it is possible to position the wedged beam split-

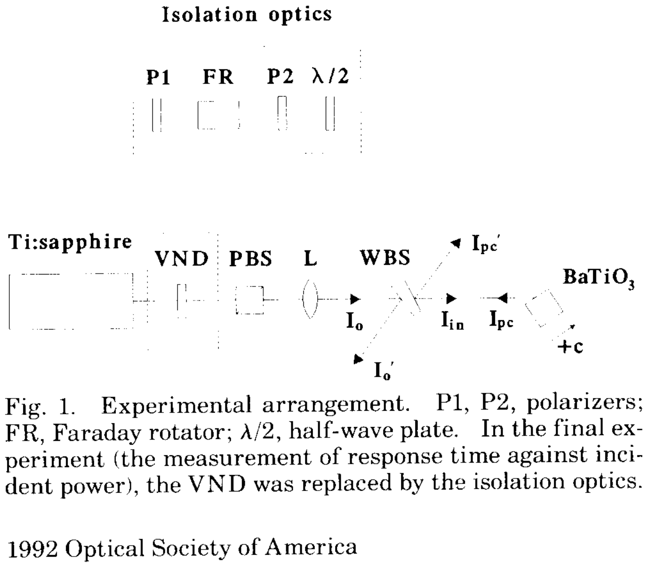

Fig. 1. Experimental arrangement. P1, P2, polarizers; FR, Faraday rotator; λ/2, half-wave plate. In the final experiment (the measurement of response time against incident power), the VND was replaced by the isolation optics.

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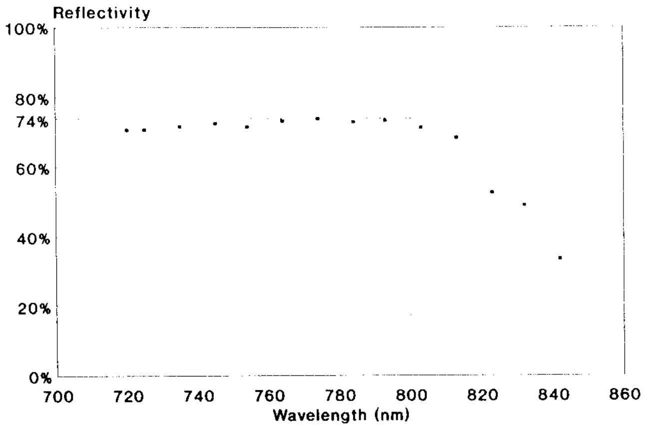

Fig. 2. Graph of phase-conjugate reflectivity against wavelength.

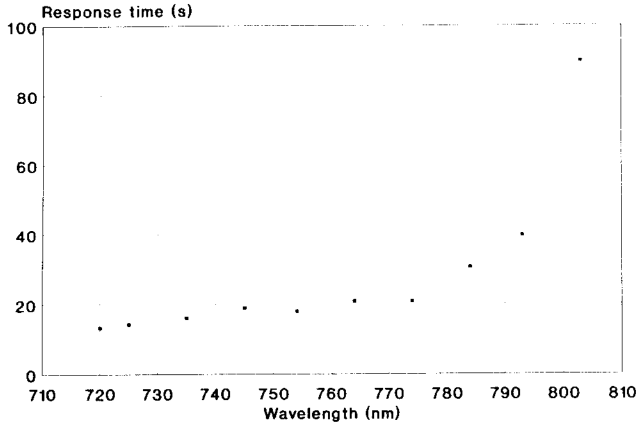

Fig. 3. Graph of response time against wavelength. The response time is defined as the time taken for the phase-conjugate signal to rise from 10% to 90% of its saturated value. The saturated value was >71% for all wavelengths in this range.

ter such that the ratio I_{pc}'/I_o' gives the phase-conjugate reflectivity directly without correction. I_o' and I_{pc}' were detected by using two calibrated Newport power meters in order to monitor the growth of the phase-conjugate signal and also to measure any effects of feedback into the Ti:sapphire laser. A variable neutral-density filter (VND) served to reduce, but not eliminate, these feedback effects. Once the phase-conjugate signal was established, I_o' and I_{pc}' were measured by using the same detector in order to avoid any cross-calibration problems. The phase-conjugate reflectivity (in terms of percentage) is plotted against wavelength in Fig. 2, in which the lower end of the wavelength range was limited by the Ti:sapphire tuning. Measurements from 720 to 803 nm were made without adjusting the crystal, and it can be seen that, over this range, the reflectivity remains fairly constant (from 71% to 74%). For wavelengths of 813 nm and beyond, slight adjustment of the crystal was necessary to obtain optimum reflectivity. This may have been due to slight changes of the position and size of the incident spot on the entrance face caused by tuning. At the shorter wavelengths, a narrow loop of light was observed inside the crystal extending diagonally from the total-internal-reflection corner to the opposite corner.

The range of wavelengths over which the reflectivity remained uniform was investigated further by examining crystal response time against wavelength (Fig. 3). We define response time as the time taken for the phase-conjugate signal to rise from 10% to 90% of its saturated value. The initial incident Ti:sapphire power was 65 mW for the wavelengths examined; however, this power was observed to rise by ~10% owing to feedback as the phase-conjugate signal developed. Despite the feedback, however, the response time can be seen to increase significantly beyond 800 nm—a characteristic also observed by Zhang *et al.*[5]

A wavelength near the center of this range was then selected for further investigation of response time and incident power. For this experiment, the Ti:sapphire laser was tuned to 760 nm and isolated by replacing the VND with the additional optics shown in Fig. 1. The incident intensity was then varied by rotating its polarization by using the half-wave plate (and rejecting the *o*-polarized component at the PBS). Figure 4 (note the logarithmic scales) shows the temporal response of the crystal, and the straight-line fit would suggest that the response time is proportional to I^{-x}, where I is the incident intensity and $x = 0.8$ from the graph. This relationship appears to be sublinear and may perhaps indicate a shallow-trap mechanism.[6]

In conclusion, we have obtained efficient phase conjugation at near-infrared wavelengths using a nominally undoped crystal of $BaTiO_3$ mounted in air using the CAT configuration. The response time was also studied as a function of wavelength and incident power.

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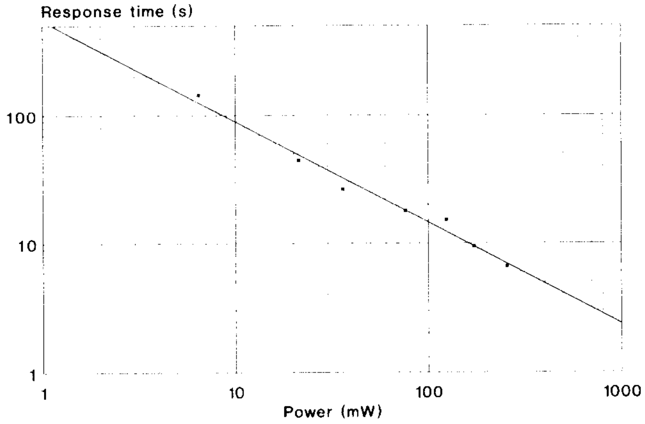

Fig. 4. Graph of response time against incident power at 760 nm. The straight-line fit indicates an I^{-x} power law, with $x = 0.8$. Note that 100-mW incident power corresponds to ~2.3 Wcm^{-2}.

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