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$BaTiO_3$ waveguide self-pumped phase conjugator

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For the first time to our knowledge, self-pumped phase conjugation is reported in a planar waveguide structure in a $BaTiO_3$ single crystal. The waveguide was fabricated by the technique of ion implantation, with 1.5-MeV H^+ ions at a dose of 10^{16} ions/cm^2. Phase-conjugate reflectivities >20% have been measured for waveguide self-pumped phase conjugation, and, for a given input power, an order-of-magnitude reduction in the response time is observed in the waveguide compared with the bulk. The fidelity of phase conjugation in the guide is also discussed.

In recent years, several self-aligning phase-conjugate mirror configurations have been demonstrated in high-gain photorefractive materials. In particular, the self-pumped phase conjugator,[1] which produces a high-fidelity phase-conjugate (PC) output from a single beam incident upon the crystal, continues to stimulate further research. Although many potential applications for such a device may be envisaged, a significant limitation to its performance is the slow growth of the PC output in materials such as $BaTiO_3$. The response time of $BaTiO_3$ may be reduced by, for example, material manipulation,[2] use at elevated temperatures,[3] and increased intensity. The intensity may be increased by simply turning up the laser output, focusing the input beam, or confining the beam within a waveguide geometry.

Self-pumped phase conjugation (SPPC) relies on beam fanning for its initiation, the magnitude of which depends on the number of scattering centers encountered by the input beam and the interaction length of the two-beam coupling between the input beam and the scattered light. The use of a spherical lens to focus the signal tightly decreases the fanning response time by increasing the intensity but reduces the magnitude of the beam fanning by decreasing both the number of scattering centers accessed and the two-beam coupling interaction length. Use of a cylindrical lens to produce a line focus parallel to the extraordinary polarization direction increases both the number of scattering centers accessed in the high-gain direction and the interaction length and results in an order-of-magnitude decrease in the SPPC response time.[4] Performing SPPC in a waveguide with a cylindrical lens to launch the input should permit an improvement on this result, because the optical confinement of the signal ensures that a high intensity is maintained over the length of the crystal and is not restricted by the depth of focus of the cylindrical lens, which will be an important limitation in practice.

Techniques previously used to fabricate waveguides and thin films of $BaTiO_3$ include He^+-ion implantation,[5] pulsed laser deposition,[6] molecular beam epitaxy,[7] and the sol-gel process,[8] but, to our knowledge, there was no report of photorefractive properties of these structures. Slab waveguides (70–100 μm) have also been prepared in $BaTiO_3$,[9] in which intermode coupling effects were observed.

In this Letter we report the observation for what is to our knowledge the first time of SPPC in a waveguide geometry. The waveguide was fabricated by the technique of H^+-ion implantation. A flat polished face of a single crystal of $BaTiO_3$ was implanted with 1.5 MeV H^+ ions at a dose of 10^{16} ions/cm^2. The ion beam was directed perpendicular to the plane containing the crystal *c* axis. Within the crystal, the ions initially lose energy through electronic interaction with lattice atoms, which, in general, does not result in displacement damage but can produce color-center defects that may contribute to propagation losses.

Once the ions' energy has been sufficiently reduced, they undergo nuclear collisions, displacing lattice atoms and distorting the crystal lattice, creating a sharply defined layer of reduced refractive index. Light may then be confined between the polished top surface and the low-index damage barrier. Dark-mode analysis indicated a guide depth of ≈15 μm and predicted a waveguide capable of supporting ≈20 modes.[10] Waveguide losses, measured by means of end launching, were estimated at 14 dB/cm, corrected for Fresnel reflections and assuming a launch efficiency of 80%.

Figure 1 is a schematic diagram of the crystal. The unusual crystal geometry was chosen to facilitate previous two-beam coupling measurements,[10] which revealed a reduction of the response time by >2 orders of magnitude for a given input power in the waveguide compared with the bulk and that the ion implantation process had reversed the gain direction in the waveguide region. The SPPC experiments discussed here were conducted with the output from an Ar^+-ion laser at 488 nm, with the crystal oriented so that the gain direction was appropriate for SPPC.

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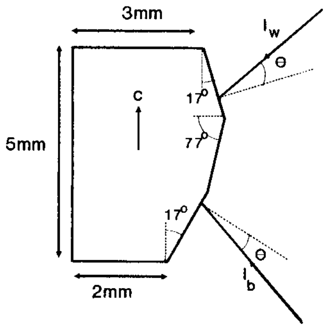

Fig. 1. Schematic diagram of the implanted crystal of BaTiO$_3$. The input beams, I$_w$ and I$_b$, indicate the input geometry required for SPPC in the waveguide and the bulk, respectively, resulting from the reversal of the gain direction in the waveguide compared with the bulk, which was induced by the implantation process.

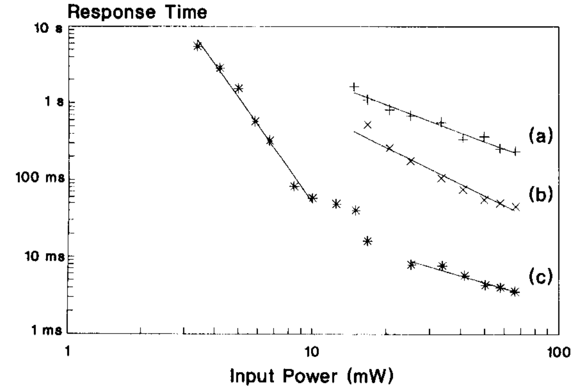

Fig. 2. Response time (time required for the SPPC output to reach $1/e$ of maximum) as a function of the incident power for (a) an unfocused beam in the bulk (+), (b) a line focus in the bulk (×), and (c) the waveguide (∗). Estimated irradiances at the crystal face with 30-mW incident power are (a) 1 W/cm^2 and (b), (c) 300 W/cm^2.

SPPC did not occur in the waveguide region when the light is launched with a 4× microscope objective, which produced a beam waist of 4 μm at the crystal face, possibly a result of the reduced beam fanning that takes place for small spot sizes. With a cylindrical lens, which produced a line focus of 1.5 mm × 7 μm, SPPC occurred readily. All results reported here were obtained for an angle of incidence of 30° on the crystal face, as shown in Fig. 1.

Figure 2 shows a comparison of the response times, defined as the time taken for the PC output to reach $(1/e)$ of its maximum, as a function of the incident power, for the three cases of (a) an unfocused beam in the bulk, (b) a beam focused by cylindrical optics into the bulk, and (c) a beam in the waveguide. At the higher input powers, the graphs reveal an order-of-magnitude decrease in the response time with the cylindrical lens in the bulk compared with the unfocused case, whereas in the waveguide the response time is reduced by 2 orders of magnitude compared with that shown in (a).

The bulk crystal displayed a threshold of ≈10 mW, below which it would not self-pump, whereas in the waveguide this threshold was significantly reduced to <1 mW. The intensity dependence of the waveguide SPPC response time is seen to change from $\tau \propto I^{-0.9}$ to $\tau \propto I^{-4.5}$ at the bulk SPPC threshold power. In Fig. 3(a) the intensity dependence of the SPPC response time and of the PC reflectivity are compared, showing a correlation between the change in the response-time dependence and a decrease in PC reflectivity as the SPPC geometry approaches threshold. This behavior was also observed in the bulk crystal, at an angle of incidence of 45°, as shown in Fig. 3(b). The dark decay time of gratings was observed to be ≈1 s, implying that the crystal has high dark conductivity and is hence a type B crystal.[11] Thus rapid thermal erasure of gratings may explain the high threshold for SPPC in the bulk. In a previous report, the observed reversal of the two-beam coupling gain direction in the waveguide compared with that in the bulk was attributed to a change in the dominant charge carrier.[10] The reduction of the SPPC threshold power in the waveguide may result from a combination of the optical confinement within the waveguide and a change in the dark conductivity in the waveguide region induced through the implantation. This behavior is the subject of further investigation.

The maximum PC reflectivity observed in the waveguide was ≈20% (uncorrected for Fresnel reflections and launch efficiency), and this result leads to interesting conclusions as to the location of the gratings responsible for SPPC in this waveguide. If the traditional two-interaction region model[12] is to hold, then the beam makes a double pass through the crystal, resulting in a loss in the guide of ≈14 dB, and hence an absolute maximum reflectivity of 4%

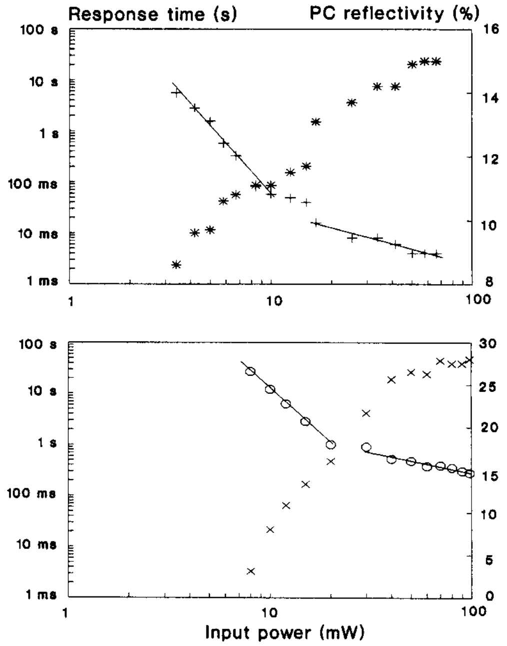

Fig. 3. (a) SPPC response time (∗) and PC reflectivity (+) as a function of input power in the waveguide. (b) SPPC response time (○) and PC reflectivity (×) as a function of input power in the bulk crystal. The intensity dependence of the response times may be approximated by two straight lines of different gradients, as indicated, corresponding to regions of saturated and decreasing reflectivity.

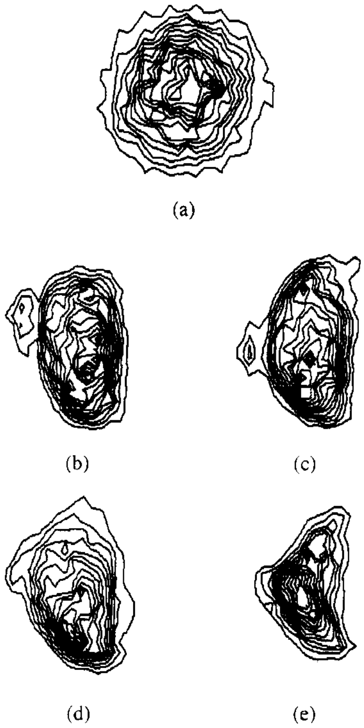

Fig. 4. Contour plots of (a) the input beam and the PC output from the waveguide at (b) 5°, (c) 10°, (d) 25°, and (e) 45° angles of incidence.

would be achievable. A simple calculation reveals that, assuming that the gratings are 100% efficient, the maximum effective distance that the gratings could extend into the crystal would be 2.5 mm. Thus it appears that the cat geometry may not be in operation here but that a different mechanism, possibly stimulated photorefractive scattering, is responsible. Note, however, that for SPPC to occur in the guide, the corner of the crystal providing the feedback of the fanned light in the cat geometry had to be carefully edge polished, leading to the conclusion that such feedback is necessary to initiate SPPC but is not required to sustain it. This behavior is consistent with previous reports of seeded stimulated photorefractive scattering.[13]

An issue that has to be addressed in waveguide SPPC is the fidelity of the PC output. In a planar waveguide configuration, one dimension has been lost for the transmission of spatial information, as in the plane normal to the plane of the waveguide the propagating beam is constrained to be a mode, or superposition of modes, of the waveguide. Information would also be lost by exciting radiation modes and through evanescent coupling into the substrate.[14] The major limitation on fidelity in this crystal results from the current crystal geometry, which requires that, for SPPC to operate, the input launch not be normal to the crystal face, with the result that the launch efficiency will vary across the beam. Figure 4 shows a comparison of contour plots of the intensities of the input beam and the output beams for angles of incidence 5°, 10°, 25°, and 45°. The fidelity is clearly seen to be input-angle dependent. The output profiles suggest a nonuniform launch efficiency, which could be corrected by choice of a near-0° launch.

In conclusion, the observation of SPPC in a planar waveguide of $BaTiO_3$ fabricated by ion-beam implantation has been reported. At a given input power, a reduction of a factor of 100 has been measured in the SPPC response time in the waveguide compared with the bulk, and PC reflectivities of 20% have been observed. Further research is in progress on crystals with optimized waveguide parameters.

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