Extraordinary-polarized light does not always yield the highest reflectivity in self-pumped $BaTiO_3$

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For certain input geometries it is possible to double the phase-conjugate reflectivity of the self-pumped (cat) phase conjugator in $BaTiO_3$ by the inclusion of an ordinary-polarized component in the input beam. It is also shown that it is possible to control the power in the phase-conjugate output with an overall gain. The observed enhancement is attributed to erasure of competing parasitic gratings by the ordinary-polarized component.

The cat mirror self-pumped phase conjugator (SPPC) has continued to stimulate further research since its discovery in 1982.[1] The exact mechanism or mechanisms responsible for the effect are still under discussion, and techniques such as surgical erasure of photorefractive gratings within the SPPC geometry have been used in attempts to locate the principal interaction regions[2,3] and also to control the magnitude and temporal characteristics of the phase-conjugate (PC) output.[4]

The SPPC has been shown to possess a well-defined threshold of the gain–interaction length product.[1] In $BaTiO_3$ the largest electro-optic coefficient, r_{42}, and hence the largest gain, is accessed by using an extraordinary- ($\hat{e}$) polarized input beam. As the plane of polarization of the input beam is rotated, only the $\hat{e}$ component will contribute to the PC output, as the ordinary ($\hat{o}$) component is not phase matched to the gratings written by the $\hat{e}$-polarized component and sees insufficient gain. The $\hat{e}$ component of the input beam, $I_{\hat{e}}$, and hence the expected behavior of the PC output, would therefore be of the form

$$I_{\hat{e}}(\theta) = I_{\text{inc}} \cos^2(\theta), \tag{1}$$

$$I^*(\theta) = R_{\text{PC}} I_{\text{inc}} \cos^2(\theta), \tag{2}$$

where I_{inc} is the input power, $I^*(\theta)$ is the PC output power, R_{PC} is the PC reflectivity, and θ is the angle of the plane of polarization with respect to the $\hat{e}$-polarization direction. Equation (2) would be expected to represent the upper limit on the PC output, as the copropagating (and virtually collinear) $\hat{o}$ component might be expected to erase the SPPC gratings, thereby reducing the PC output.

In this Letter, however, we show that for certain input geometries it is possible to increase the PC reflectivity (by as much as a factor of roughly 2) through the inclusion of an $\hat{o}$-polarized component and that by controlling the $\hat{o}$-polarized input, it is possible to achieve optical gain in the PC output.

This method of using a copropagating $\hat{o}$-polarized beam of the same frequency as the signal to control the PC output is related to, but experimentally distinct from, that of Ref. 4, where the erasing beam is of a different frequency to the signal beam and is incident from a different direction (i.e., from below the crystal).

The experimental arrangements are shown in Fig. 1. The output from the Kr^+-ion laser, operating at its strongest line at 647 nm, was directed toward the 6 mm × 6 mm × 6 mm crystal of $BaTiO_3$. The plane of polarization of the input beam could be rotated by means of the half-wave plate, with the total input power kept constant at 15 mW, or, in the second experiment (with the additional components shown in the dashed box), the $\hat{e}$-polarized input power was kept constant and the $\hat{o}$ input, arranged to be copropagating with the $\hat{e}$ input by means of the polarizing beam splitter (PBS), could be controlled by the variable neutral-density filter (ND). The PC output was monitored off beam splitter BS1 by a calibrated photodiode (pd) connected to a computer.

Figure 2 shows the PC reflectivity, here defined as $I^*/(I_{\hat{e}} + I_{\hat{o}})$, where I^* is the PC output and $I_{\hat{e}}$ and $I_{\hat{o}}$ are the intensities of the $\hat{e}$ and $\hat{o}$ components of the input beam (i.e., defined as the ratio of the PC output to the *total* input power, I_{inc}) obtained at four angles of incidence ϕ as the plane of polarization θ was rotated. The reflectivities are normalized to that obtained when the input is totally $\hat{e}$ polarized ($\theta = 0$). The graph shows that for $\phi = 10°, 25°$, and $50°$ the output initially follows the $\cos^2(\theta)$ curve, with the range of angles over which the output approximates to $\cos^2(\theta)$

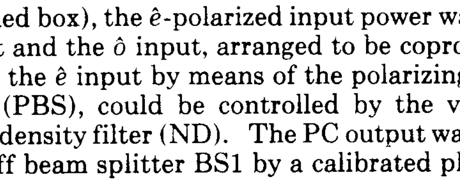

Fig. 1. Schematic diagram of the experimental configurations. The components and beam paths inside the dashed lines represent the additional components required for the second experiment.

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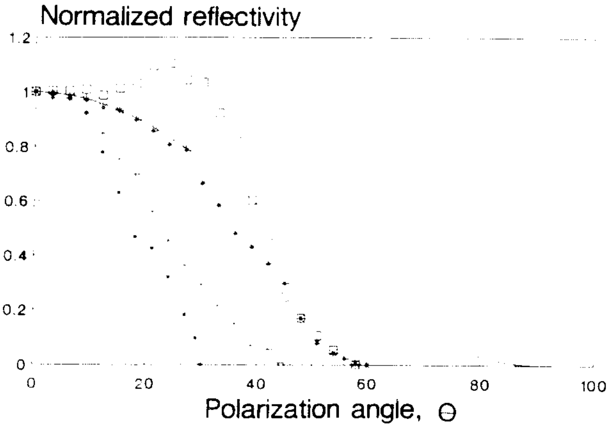

Fig. 2. Normalized PC reflectivities as a function of the plane of polarization θ of the input beam for four different angles of incidence: $\phi = 10°$ (■), 25° (+), 50° (✱), and 58° (□). The expected $\cos^2(\theta)$ dependence is shown by the solid curve.

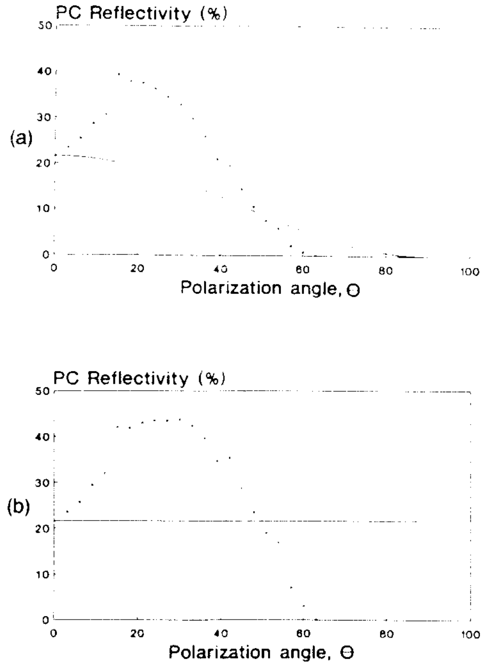

Fig. 3. PC reflectivity as a function of plane of polarization θ of the input beam for an angle of incidence $\phi = 58°$. In (a) the PC reflectivity is defined as $I^*/(I_{\hat{o}} + I_{\hat{e}})$, with the solid curve representing the expected $\cos^2(\theta)$ dependence, while in (b) the PC reflectivity is redefined as $I^*/I_{\hat{e}}$, with the expected constant value of reflectivity represented by the solid line. These data are not corrected for Fresnel reflections.

increasing with increasing ϕ, before the erasure of SPPC gratings by the $\hat{o}$-polarized component causes the output to fall away sharply. At $\phi = 58°$, however, we see that the output exceeds the limiting $\cos^2(\theta)$ value out to $\theta \approx 40°$ and shows an enhancement of $\approx$15% for $\theta = 27°$.

By optimizing the position of incidence of the input beam on the crystal face for $\phi = 58°$, it was possible to obtain the result shown in Fig. 3(a), where we see an enhancement of $\approx$75% in the PC reflectivity at $\theta = 15°$ and that the output exceeds the expected $\cos^2(\theta)$ dependence at all angles out to 45°. It is informative to redefine the PC reflectivity here as $I^*/I_{\hat{e}}$ since as θ is varied we change the $\hat{e}$ input according to the $\cos^2(\theta)$ dependence of Eq. (1). Replotting the data with this definition of reflectivity, shown in Fig. 3(b), we see that the reflectivity is in fact doubled and remains at this value from $\theta = 15°$ to $\theta = 36°$. The solid line represents the expected constant value of reflectivity.

The key to understanding this behavior lies in the time dynamics of the SPPC process for these geometries, which, for the data set of Fig. 3, is shown in Fig. 4. Here we see that when the input beam is totally $\hat{e}$ polarized there is an initial exponential increase in PC output followed by a decay to a steady-state value. As the $\hat{o}$ component is increased, by rotation of the input plane of polarization, the amplitude of the subsequent decay is gradually reduced before being eliminated completely.

This leads to the conclusion that the onset of SPPC output, for this geometry, is accompanied by a secondary parasitic process, of a longer time constant, which effectively extracts power from the SPPC process. The presence of an $\hat{o}$ component in the input results in the erasure of these competing gratings, which reduces the deleterious effect of the parasitic process in a similar way to that noted in Ref. 4.

In the previous experiment the useful $\hat{e}$ component of the input beam was decreased for increasing θ. Alternative data sets have also been recorded keeping the $\hat{e}$ component of the input constant at 10 mW, with the $\hat{o}$ component being introduced off the polarizing

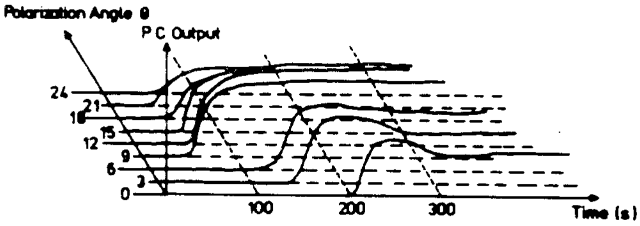

Fig. 4. Time dependence of the PC output for the data set of Fig. 3.

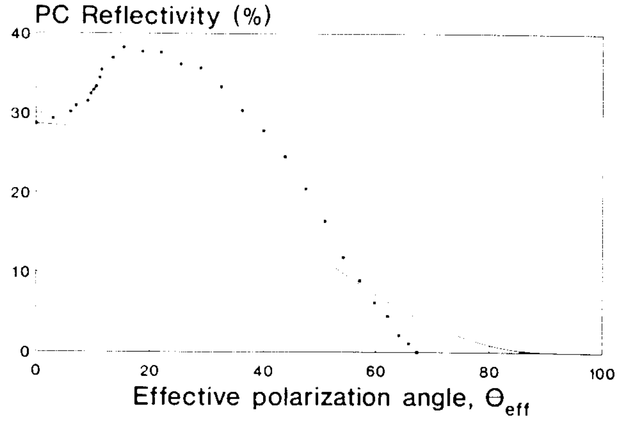

Fig. 5. PC reflectivity as a function of the effective polarization angle for the second experiment where the $\hat{o}$ input is controlled by the variable neutral-density filter. The angle of incidence $\phi = 57°$. These data are not corrected for Fresnel reflections.

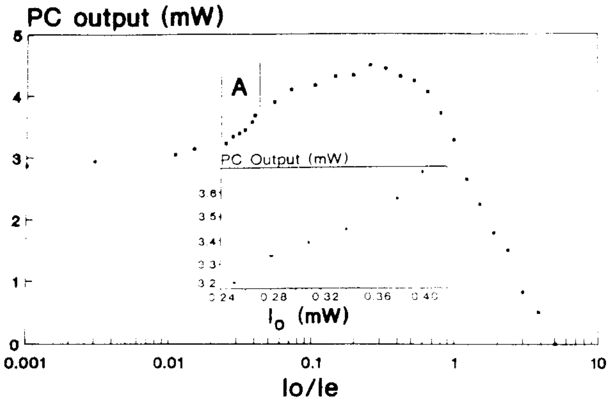

Fig. 6. PC output as function of the ratio of $\hat{o}$ input to $\hat{e}$ input ($I_{\hat{o}}/I_{\hat{e}}$). The inset shows region A expanded and plotted as PC output versus $I_{\hat{o}}$. Note that the gradient of the graph shows a net gain of 2.8.

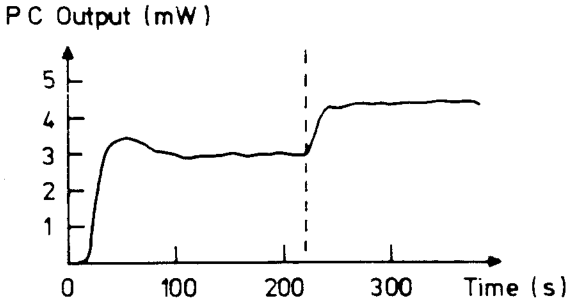

Fig. 7. Time dynamics of the switching process.

beam splitter shown in Fig. 1 and controllable by the variable neutral-density filter.

In order to facilitate comparison of this method of controlling the PC output with that previously described, we have considered the input polarization to be linear, with the effective polarization angle θ_{eff} defined as

$$\theta_{\text{eff}} = \tan^{-1}\left(\frac{I_{\hat{o}}}{I_{\hat{e}}}\right)^{1/2}. \tag{3}$$

In Fig. 5 the PC reflectivity [defined as $I^*/(I_{\hat{e}} + I_{\hat{o}})$] is plotted against θ_{eff}. Comparison of Figs. 3(a) and 5 shows that there is effectively no difference between these two methods of controlling the PC output.

More constructive information can be extracted from the data of Fig. 5 by plotting the PC output against the ratio $I_{\hat{o}}/I_{\hat{e}}$, as is shown in Fig. 6. Region A, expanded and plotted as the PC output versus $I_{\hat{o}}$ in the inset, shows a significant result. The gradient of this graph is 2.8, and hence it is possible to control the power in the PC output by using the copropagating $\hat{o}$-polarized input while achieving net gain. We believe that by optimization of the angle and position of incidence and the diameter of the input beam it should be possible to increase the value of gain seen here.

A typical trace of the PC output during a switching run is shown in Fig. 7. The PC output was allowed to settle to its steady-state value of 2.95 mW. At $t = 220$ s a 2.6-mW $\hat{o}$-polarized beam was introduced, and the PC output immediately began to grow, reaching its new value of 4.37 mW after 30 s.

In summary, we have observed that, for certain input geometries, extraordinary polarization is not necessarily the optimum input polarization for SPPC in $BaTiO_3$. We have shown that the introduction of an ordinary-polarized component can as much as double the PC reflectivity. The time dynamics of the process have led us to propose erasure of parasitic gratings by the $\hat{o}$ component as being responsible for this enhancement. We have also shown that it is possible to switch the power in the PC output, by using the $\hat{o}$ component, with net gain. Further research is under way to try to optimize the observed gain.

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