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On the two-wave mixing in $BaTiO_3$ with a self-bent pump beam

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Abstract. We report the operation of a two-wave mixing (TWM) photorefractive amplifier wherein fanning of both pump and signal beams has been simultaneously suppressed to an acceptable limit. This is achieved by the use of an input signal with mixed polarisation in conjuction with a self-bent pump beam. The possibility of obtaining a good-quality, strong amplified signal maintaining a high value of the TWM gain makes this method particularly suitable for laser beam clean-up applications.

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Image amplification and beam clean-up are the two important areas where a two-wave mixing (TWM) photorefractive amplifier finds application ([1] and refs therein). Even though many photorefractive crystals exhibit a large small-signal gain coefficient, significant amplification of the signal almost invariably calls for the use of thick crystals. However, a thick crystal poses a serious problem as it gives rise to significant beam fanning. The fanning increases with the thickness of the crystal and limits both the quality of the amplified signal and the overall TWM gain.

In the last few years there have been several reports of work aimed at suppressing the fanning effect in photorefractive amplifiers [2–6]. In a slowly rotating crystal, Rajenbach et al. [2] demonstrated complete wash-out of the noise photoinduced gratings. Splitting of the pump beam into a low-power pump for writing the image and a short pulse for reading it [3], as well as use of multiple wavelengths [4], have also been shown to keep fanning at a low level. He and Yeh [5] have successfully employed a pump beam with a mixed polarization state in order to suppress fanning. Recently Brignon et al. [6] reported the use of a pump beam that undergoes self-bending in a very thick (7.4 mm) $BaTiO_3$ crystal, a novel geometry allowing to obtain very high TWM gain with greatly reduced fanning. This method is very attractive for practical applications because of its simplicity, but its applicability and performance with thinner crystals remained to be clarified.

Controlling the fanning of the pump beam alone would suffice in an application involving image amplification for which the signal is low and does not produce fanning. However, in laser beam clean-up applications, the fanning of the strong signal beam poses problems and needs to be controlled. In a very recent publication where the work aimed at generating a clean beam from a high-current semiconductor amplifier, MacCormack et al. [7] reduced the fanning of the amplified signal beam by letting it travel exactly along the *c*-axis of the crystal. Such a solution, however, is at the expense of the photorefractive TWM gain.

In this paper, we report on the simultaneous control of fanning of both the pump and the signal, retaining the high gain of the TWM amplifier. By utilizing the self-bent pump beam geometry of Brignon et al. with a $BaTiO_3$ crystal of somewhat lesser thickness (5.5 mm, compared with 7.4 mm in [6]), we report a narrow region of parameter values wherein a good amplification is obtained along with reduced pump-fanning, and the competing processes are avoided. We discover, however, that at high levels the signal develops strong fanning which, in addition to reducing the TWM gain, leads to a total frustration of the self-bending of the pump through self-pumped phase conjugation (SPPC). We show that employing an input signal with mixed polarization extends the region of operation of the amplifier to the strong-signal limit, making it suitable for beam clean-up applications.

1 Experimental method and results

In our experiment, the pump and the signal were derived from an argon-ion laser operating at 488 nm by splitting the laser beam into two equal parts. The signal beam was then passed through a variable attenuator. The power density of the pump beam was kept at $1\ W/cm^2$ in a spot radius of 0.8 mm. An undoped, $7 \times 5.5 \times 5\ mm^3$ $BaTiO_3$ crystal with the longest side parallel to its *c*-axis was used. The introduction of the pump beam and the signal, which was in a manner similar to the work of Brignon et al., is illustrated in Fig. 1. In this configuration, when the angle of incidence (ϕ) of the pump beam (P_{in}) exceeds some positive value, there is a strong rotation of

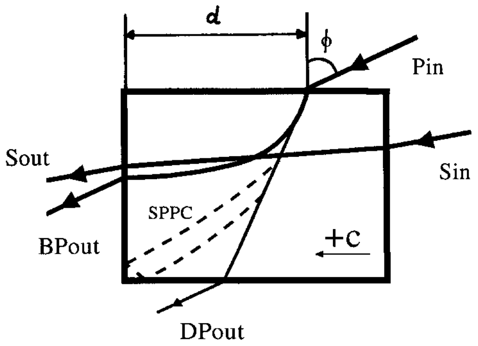

Fig. 1. Schematic illustration of the TWM with self-bent pump beam geometry. P_{in} is the input pump beam, S_{in} is the input signal beam, DP_{out} is the pump out without bending, BP_{out} is the self-bent beam out, S_{out} is the amplified signal beam, and SPPC is the self-pumped phase conjugation trajectory

its initial propagation direction in the crystal, so that it finally leaves the crystal through the face perpendicular to the *c*-axis (BP_{out}). The signal (S_{in}) is introduced at a small angle to the *c*-axis and does not exhibit bending.

The available experimental data [6] and the theoretical treatment [8] describing the beam trajectory in this regime do not present details of self-bending behavior in the presence of competing processes, for example SPPC. Nevertheless SPPC can in fact be the dominant process for the considered geometry if the crystal used in the experiment is not very thick. To clarify this point, we first studied the selfbending effect in the absence of a signal as a function of the angle of incidence of the pump beam and the distance (d) between the entering point of the pump beam and the crystal corner (see Fig. 1).

We found that, for $\phi < 32°$, the main beam almost invariably exhibited SPPC, undergoing total internal reflection near the corner [9], as shown in Fig. 1 with dashed line. We found that the same trend persisted for all chosen values of d. This result differs from that reported in [6], where the authors observed SPPC only for $\phi < 10°$, in very good agreement with the formula for the bent-beam trajectory given in [8]. In our case, in the absence of SPPC, the beam bending is also well described by the same formula. We found, however, that SPPC often takes place even if there is a possible self-bending trajectory ending far higher than the crystal corner.

With increasing ϕ, we found the probability of SPPC reduced and became extinct at large angles of incidence ($\phi > 60°$). We chose to operate near to the Brewster angle (66°) as then a maximum fraction of the incident radiation is coupled inside the crystal. Here, within a very brief period of time (~ 1 s), the main beam transfers practically all of its energy (if $d > 3.5$ mm) into the self-bending beam. The latter exhibits growing fanning, which reaches steady state in 5–10 s. We found that maximum energy is coupled into the self-bending beam for $d = 4.5$ mm. For larger values of d, we observed greatly increased directional fanning, which was verified to originate from the feedback provided to the fanned beam by the Fresnel reflections on the side crystal faces.

Based on the above observations, we set ϕ and d to 66° and 4.5 mm, respectively, and then introduced the signal. The incident angle of the signal was chosen to give an efficient overlapping of the signal and the self-bent pump beam, as well as to keep its cross-talk with the fanned wave at minimum. We found out that making the signal incident at about 7 ± 1 ° yielded the most optimized performance. At this point we experimentally measured the direct TWM gain, defined as the ratio of the intensity of the amplified signal after the crystal to the intensity of the input signal before the crystal. The gain was experimentally measured as a function of the ratio of the intensity of the input pump beam to that of the input signal beam (β_0) and is presented in Fig. 2.

The performance in the small signal regime was found to be satisfactory. The gain, when estimated following the convention of [6], followed closely the values reported there. However, when we gradually increased the intensity of the input signal, the amplified signal beam visibly started creating its own fanning and decreased in intensity. The situation can be better seen by referring to Fig. 3, where the output signal is represented by "□" signs as a function of the input signal. The point from where the output starts dropping with increasing input indicates the onset of signal fanning. For ease of reference, we will henceforth call this the "runaway" point. When the input signal was increased about eight times with respect to the runaway point, the bent beam was so depleted that with a time constant of about 1 minute it was completely disappearing and SPPC was taking over. This switching to SPPC was very well reproducible and was taking place only with a signal than a well defined value.

As has already been mentioned, the fanning can be significantly reduced by using a pump beam with mixed polarization state [5, 10]. This cannot be done, however, in the case of a self-bent pump beam, since the ordinary polarized component would not be bent and would thus be spatially separated from the *e*-polarized component inside the crystal. So we tried to suppress the fanning of the signal beam by using an input signal with mixed polarization states (50% $e-$ and 50% $o-$polarized). In this case, the presence of the *o*-polarized component in the signal beam was visually observed to greatly reduce the fanning. The output versus the input signal in this mode of operation is indicated by the "+" signs in Fig. 3.

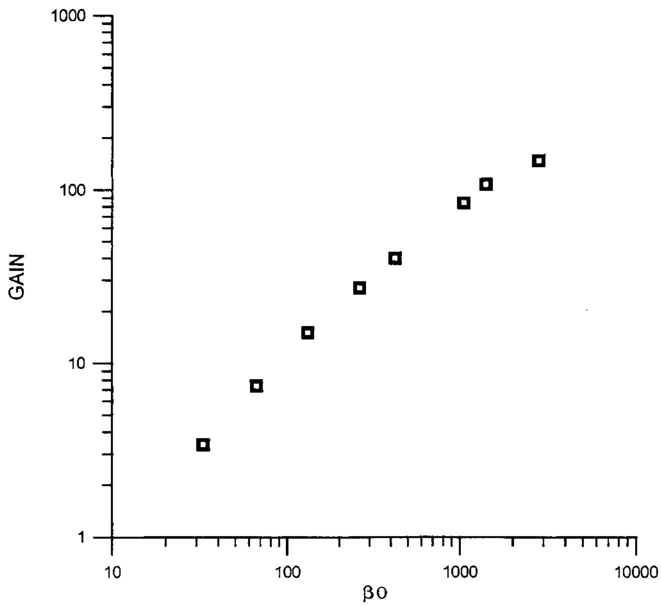

Fig. 2. Direct TWM gain as a function of the ratio of input pump to input signal (β_0)

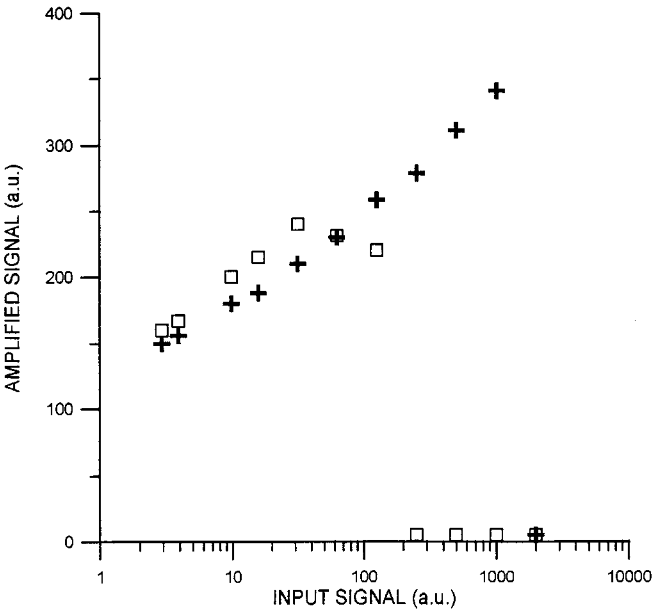

Fig. 3. Dependence of the amplified signal on the input signal: "□" represents a 100% *e*-polarized input signal; and "+" represents a 50% *e*- and 50% *o*-polarized input signal. The first point of this figure corresponds to $\beta_0 = 1000$

The decided advantage of using a signal with mixed polarization states with regard to performance in the high-signal regime is quite obvious. It can be seen that the mixed polarization allows operation at up to 16 times higher input-signal level without switching to SPPC. In order to understand qualitatively why, in the strong-signal regime, the mixed polarization influences also the pump beam, let us refer to the model proposed in [5] for describing the incoherent erasure of fanning. It is clear there that, to a good approximation, the pump and the signal can be considered to create a common fanning wave and the energy exchange between them is well described by a system of three coupled equations. The introduction of the *o*-component of the signal decreases the growth of the fanning wave and therefore decreases the losses of both the signal and the pump beam. This in turn prevents the switching of the pump to SPPC.

It is also seen from Fig. 3 that when the input signal is small, the amplified signals in the two cases are not very different. This result may seem intriguing as the effective input signal in the mixed polarization case can be considered to be nearly half of the case with *e*-polarization due to the poor two-wave coupling of the *o*-polarized light in $BaTiO_3$. On closer inspection it will be seen, however, that twice a smaller signal means twice a higher β_0, and the gain will also be higher according to Fig. 2.

In Fig. 4, we present the output signal corresponding to the runaway point of our TWM amplifier as a function of the percentage of extraordinary light in the total input signal. An input signal containing about 38% *e*-polarisation appears to give best performance in this respect.

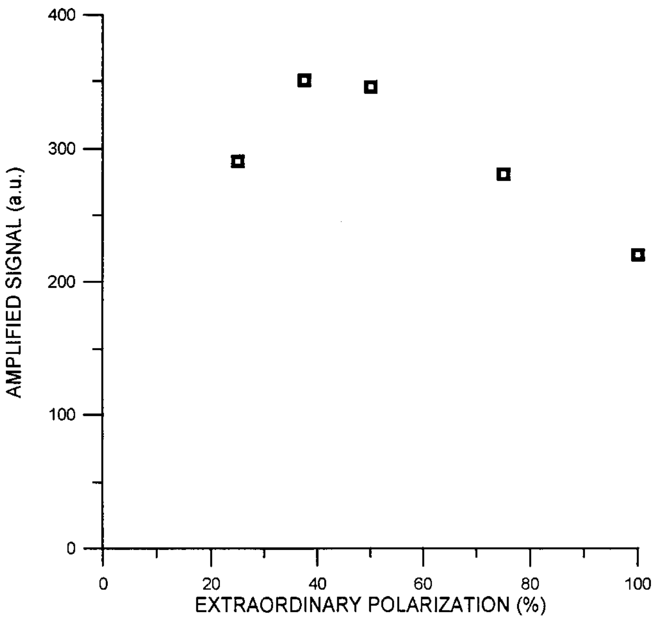

Fig. 4. Dependence of the maximum amplified signal on the percentage of the *e*-polarized light in the total input signal

2 Conclusions

In conclusion, we have presented experimental data on the performance of a TWM amplification scheme using a self-bent pump beam. We report that in a not-very-thick (5.5 mm) undoped $BaTiO_3$ crystal, such a scheme can be successfully used. We have found that even in the optimized geometry, the pump-bending process can be totally suppressed by the appearance of SPPC at high signal levels. Such switching of the main beam from a well defined self-bending trajectory to SPPC has not been (to our knowledge) reported in the literature so far and may deserve further study.

We further demonstrate that if a signal with mixed polarization states is used at high signal levels, the performance of the scheme is greatly improved, making feasible the applications requiring higher absolute values of the amplified signal, for instance laser beam clean up.

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