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Highly Efficient Mutually Pumped Phase Conjugators Using $BaTiO_3$:Ce

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High-efficiency mutually pumped phase conjugation (MPPC) has been realized in a $BaTiO_3$:Ce crystal in the bridge geometry. The laser source is a dye laser operating from 580 to 650 nm. We have observed that, with a beam ratio of 1, self-pumped phase conjugation (SPPC) appears and competes with MPPC at short wavelengths while it disappears at long wavelengths. When the beam ratio is slightly higher than 1, SPPC no longer occurs. Phase conjugate reflectivity near 500% has been obtained at a beam ratio of 70. Our experiments demonstrate that Ce-doped $BaTiO_3$ crystals, which have already been found efficient in SPPC experiments, are also efficient for the generation of MPPC.

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I. INTRODUCTION

Mutually pumped phase conjugation (MPPC) has been intensively studied due to the many potential applications such as optical communication, information storage and processing [1]. An MPPC signal could be generated with various configurations such as bridge and double phase-conjugate mirror [2,3]. However, it is well recognized that self-pumped phase conjugation (SPPC) often appears and competes with MPPC in doped photorefractive crystals. The reason is that the SPPC mechanism in doped crystals is usually stimulated photorefractive backscattering and four-wave mixing (SPB-FWM) [4-7] that is not sensitive to the beam/crystal geometry and it thus can appear even if the beam/crystal geometry is best chosen for the operation of MPPC.

$BaTiO_3$:Ce crystals have been intensively investigated during the past several years in two-beam coupling [8,9] and SPPC [7,10-12] experiments in the visible and near-infrared. High reflectivity can be easily observed in SPPC with these crystals where the SPPC mechanism is usually SPB-FWM. In comparison, very limited studies have been carried out to investigate their properties for MPPC because it is generally thought that these crystals are not suitable for operations of MPPC. In one of the studies, MPPC was realized in a plate-formed sample with a new configuration in which SPPC could not build-up [13]. The input beams are cw lights at 514.5 nm. Phase conjugate reflectivity about 72% has been obtained at a large beam ratio. In another study [14], another new MPPC configuration was used to couple two pulsed green light beams from an YAG laser where SPPC also could establish. The highest reflectivity observed is about 25% (at beam ratio = 1).

In our present study, we investigate the performances of $BaTiO_3$:Ce in MPPC with the traditional bridge configuration at different wavelengths in order to study the effect of SPPC on the operation of MPPC. We have observed that, when the beam ratio of the two inputs is 1, SPPC appears and for one of the input beams the phase conjugate signal generated from SPPC is mixed with that generated from MPPC at short wavelengths. At longer wavelengths, however, SPPC no longer exists. For the other input beam, the phase conjugate signal is only generated from MPPC. We have also observed that, at a beam ratio slightly larger than 1, SPPC does not appear even at short wavelengths.

Furthermore, at large beam ratio, we can obtain phase conjugate reflectivity as high as near 500% for the weak input beam partially due to the SPPC suppression. It is caused by the special geometry of bridge configuration in which the strong beam that enters the crystal through the +c-face cannot generate

SPPC signal while the advantage of large coupling strengths for FWM interactions in the doped crystal can be fully taken. We have tried to do MPPC experiments with many other MPPC configurations [1,2,15-17] and found that it is not easy to obtain MPPC at any beam ratio. The reason is that, when the beam ratio is 1, SPPC can build-up for both input beams and their coupling via MPPC, if realized, is usually very weak. When the beam ratio is high, on the other hand, the two mutually incoherent beams could not be coupled through MPPC at all because the strong input beam only generates SPPC on its own way.

II. MUTUALLY PUMPED PHASE CONJUGATORS WITH BRIDGE CONFIGURATION

Basic configuration for mutually pumped phase conjugation is based on the introduction of two mutually incoherent optical beams into a photorefractive crystal in various geometries including the bridge configuration which is used in this experiment. Each of the beams produces a fan, which then makes a number of reflections within the crystal, from zero to three, that depends on the MPPC geometry. Finally, the two beams and their associated fans interact in some region in the crystal. In the bridge conjugator, no internal reflections are necessary for production of the two phase-conjugate beams.

Our experimental set-up is schematically shown in Fig. 1. Two horizontally-polarized and mutually incoherent beams from an Ar-ion-laser-pumped dye laser

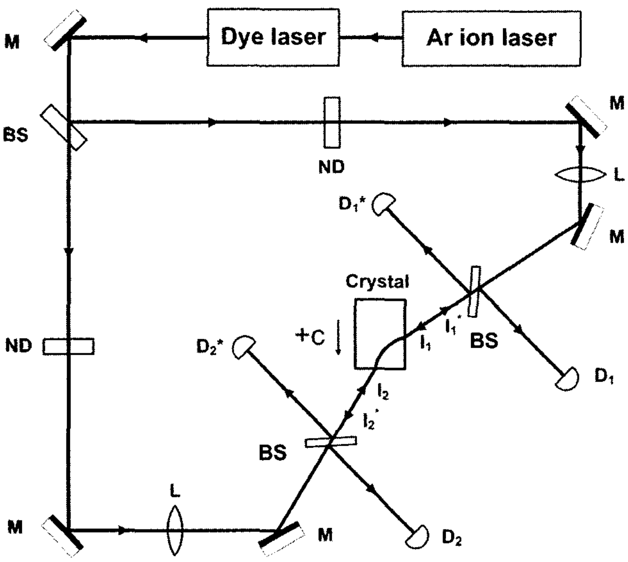

FIG. 1. A schematic drawing of the experimental setup for the bridge MPPC experiments. BS's: beam splitter; ND: neutral density filter; D's: detectors.

FIG. 2. Optical beam patterns observed in the bridge phase conjugator using $BaTiO_3$:Ce. $I_1 = I_2 = 8$ mW. $\lambda = 589$ nm

(Spectra Physics 375B) were incident on an a-face and the +c-face of a 0°-cut $BaTiO_3$:Ce crystal. The size of two laser beams is properly reduced by lens L to make best condition for beam fanning in the crystal. The conjugates return along the input beams' paths until they are separated by beam splitters and reflected onto detectors. The detector D_1 and D_2 are employed for monitoring of the incident beam, and the detector D_1* and D_2* for detection of MPPC output. The external incident angles of Beams 1 and 2 are 21° and 36°, respectively. Their incident positions are as shown in Fig. 2. The diameters of the two beams are about 1.5 mm at the surface of the crystal. The $BaTiO_3$:Ce crystal has a doping concentration of 20 ppm. It has dimensions of 6.25 mm × 5.50 mm × 5.70 mm with the 6.25-mm-edge along the c-direction.

At a fixed beam ratio of 1, we have measured the phase conjugate reflectivity of the phase conjugator at different wavelengths.

III. RESULTS AND DISCUSSION

The results are presented in Fig. 3. In the figure, the reflectivity R_1 and R_2 are defined as a ratio of the intensity of phase conjugated beam to the input beams I_1 and I_2, respectively. We have observed that, at short wavelengths, the phase conjugate signal of beam 1, I_1*, came from both beam 2 and beam 1 while that of beam 2, I_2*, came only from beam 1. That is to say, both MPPC and SPPC exist in the crystal for beam 1, and I_1* is composed of two mutually incoherent beams. SPPC appears for beam 1 because the stimulated photorefractive backscattering (SPB) process (2K grating formed by counter-propagating two beams) for the fanning beams of beam 1 in the coupling channel is strong even though the fanning beam of beam 2 in the channel tends to diminish it by erasing the 2K gratings. This SPB process will make part of the fanning beams of beam 1 go back to read the fanning gratings and

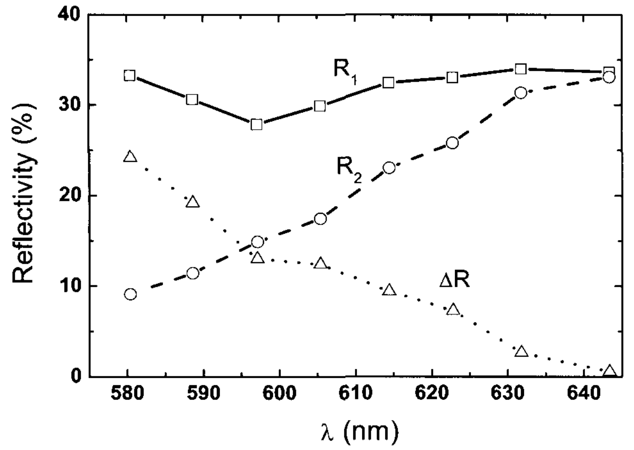

FIG. 3. The phase conjugate reflectivities and their difference for the two input beams as a function of wavelength. $R_1 = I_1^* / I_1$, $R_2 = I_2^* / I_2$, $\triangle R = R_1 - R_2$, $I_1 = I_2 = 8$ mW.

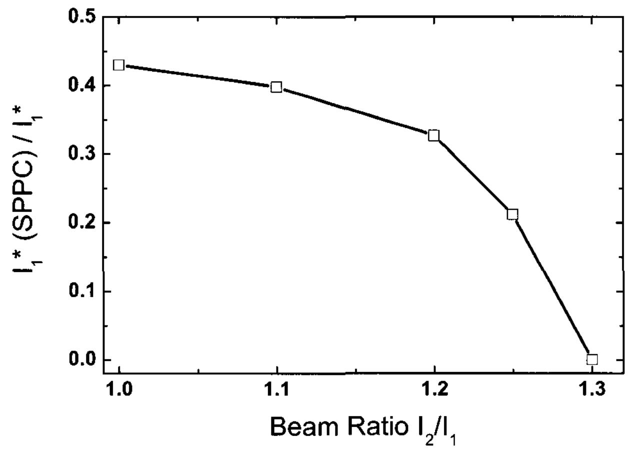

FIG. 4. The relative contribution of SPPC to I_1^*, I_1^* (SPPC) / I_1^*, as a function of the beam ratio I_2 / I_1, where I_1^* (SPPC) is that part in the total phase conjugate signal that is generated from SPPC. $I_1 = 8$ mW.

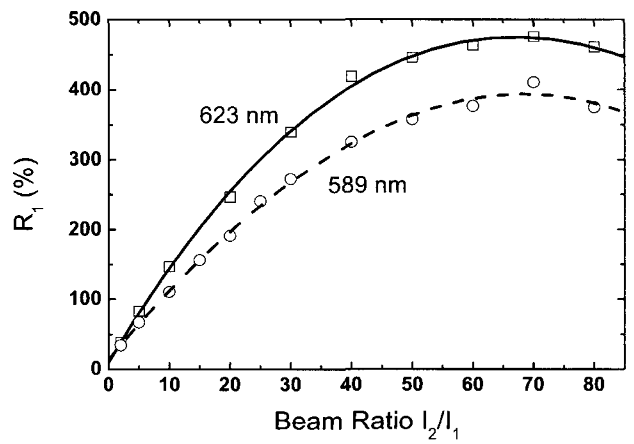

FIG. 5. R_1 measured as a function of the beam ratio I_2 / I_1 at different wavelengths. The total power of the two beams was kept at about 15 mW.

generate SPPC phase conjugate signal for beam 1. Thus the reflectivities for the two input beams are quite different as shown in Fig. 3. With the increase of wavelength, however, the SPPC becomes weaker and R_1 and R_2 become closer due to the diminution of the SPB process. Eventually SPPC no longer exists and R_1 and R_2 are approximately equal. This decrease of SPPC should result from the decrease of the contra-directional two-beam coupling coefficients of the crystal with increasing wavelength as observed before [5].

We can know the contribution of SPPC and MPPC to R_1 by temporally block beam 1 or beam 2. From the experimental results as shown in Fig. 3, we found that the contribution of SPPC to R_1 is approximately equal to 0.7 $\triangle R$=0.7(R_1-R_2) at all the wavelengths.

At a fixed wavelength, the SPB interaction in the fanning beams of beam 1 is expected to become weak if we increase I_2 and thus the erasure of the 2K gratings in the coupling channel. In order to see how SPPC change, we have measured the relative contribution of SPPC signal to the total phase conjugate signal I_1^* at different beam ratio. The results are shown in Fig. 4. Obviously, the SPPC signal will decrease when the beam ratio is increased from 1 and will disappear when the beam ratio is larger than 1.3.

IV. CONCLUSIONS

We have measured R_1 at different beam ratios at two wavelengths. Reflectivity as high as nearly 500% was obtained. The results are given in Fig. 5. It can be also seen that R1 reaches maximum at $I_2/I_1 = 70$ for both wavelengths. From the results at the two wavelengths we can easily expect that high reflectivity should be obtainable at least over the whole wavelength range from 580 to 650 nm. It is worthwhile to discuss why so high a reflectivity can be obtained, knowing that except for only a few cases of double phase conjugation [18-19], the phase conjugate reflectivity observed in all previous MPPC experiments is usually less than 100%. We believe there are several main reasons for the present high reflectivity. (a) The Ce-doped $BaTiO_3$ crystals are highly photorefractive and thus the FWM interaction strength is large, especially in the Bridge configuration; (b) The relatively strong beam, 2, cannot generate SPPC with the incident angle and position used while it has steady fanning, even when it is alone, towards the a-face through which the weak beam, 1, enters the crystal; (c) There is no internal reflection and the coupling channel is short in a bridge phase conjugator; (d) The absorption of the crystal is low in the wavelength range investigated. Another fact is that the diameters, the incident angles and positions of the two beams seemed to be optimized. We observed that the reflectivity was very sensitive to their variations.

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