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High-Resolution Double Self-Pumped Phase Conjugations with $+c$-face Incident Configuration in a $BaTiO_3$ Crystal

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The geometry of creating two stable self-pumped phase-conjugate outputs in one photorefractive $BaTiO_3$ crystal is demonstrated. This novel geometry provides two phase-conjugate images with a resolution as high as 4 μm (or 114 lp/mm). The reflectivity versus the angle of the incident beam is also investigated.

KEYWORDS: photorefractive, $BaTiO_3$ crystal, self-pumped phase conjugator, phase conjugation

Self-pumped phase conjugation (SPPC) is attracting great attention because of its numerous practical applications in confocal microscopy,[1–4] optical feedback,[5] oscillator-amplifier systems,[6] and holographic data storage.[7,8] Since its discovery, SPPC of a single beam in a photorefractive crystal has been found to have three kinds of formation mechanisms. The first kind of SPPC, referred to as the "cat" configuration, relies on four-wave mixing (FWM) processes in two interaction regions in the photorefractive crystal, where an optical path loop exists because of two total internal reflections in one corner.[9,10] The second kind is a stimulated photorefractive back-scattering process.[11,12] The third kind of SPPC-first realized recently with KNT: Fe-is back-scattering and four-wave mixing (BFWM) SPPC. These last two kinds of SPPC rely on a crystal in which no optical path loops exist.[13–15] In addition to SPPC, there is a case for two or more phase-conjugate waves to be generated in a photorefractive crystal. The generation mechanism for two phase-conjugate waves is mutually pumped phase conjugation (MPPC) through one of several possible configurations[16–26] in the photorefractive crystal. In MPPC, the phase-conjugate outputs are closely related to one another through the effective holographic link between two mutually incoherent input beams. To date, it has been rarely observed that two independent SPPC waves are generated in one crystal by means of the "cat" mechanism because SPPC generation is so critical that the incident beams tend to become interacting with each other through beam coupling to generate phase-conjugate waves in a photorefractive crystal.

In this study we demonstrate, for the first time to our knowledge, two SPPCs with a $+c$-face incident configuration. We refer to this mechanism as double SPPC (DSPPC), generated in only one 0°-cut $BaTiO_3$ crystal. In this geometry, two mutually incoherent beams (input beams to be phase-conjugated) are simultaneously incident and overlapping on the $+c$ face of the crystal with acute angles to the normal of the crystal surface at a distance from the corners of the crystal (as shown in the inset of Fig. 1). When the input beams are traveling at a nonzero obtuse angle to the crystal's c-axis in the $+c$ direction, they tend to fan and bend towards the $+c$ direction within the crystal. Accordingly, each beam—by creating its own wide range of fanning gratings within the crystal—suffers energy loss to fanning noise. However, the fanning loss of one incident beam can be suppressed through the Bragg-mismatched reading of the fanning grating by the other beam. This leads to greater incident energy in each beam, which provides highly efficient SPPCs via the four-wave mixing and corner internal reflection mechanism.

A schematic of the experimental setup for the $+c$-face incident DSPPC is shown in Fig. 1. In our experiments, measurements were carried out with one nominally undoped 0°-cut $BaTiO_3$ crystal with the dimensions $a \times b \times c = 5.16\,\mathrm{mm} \times 4.74\,\mathrm{mm} \times 5.00\,\mathrm{mm}$. An Ar^+ laser (Coherent Inova 90) operating with multilongitudinal modes ($\lambda = 488$ nm) was used. The laser output was split, using a variable beam splitter (VBS), into two incident beams, I_1 and I_2, with different or similar intensities, and it was extraordinarily polarized to ensure the maximum two-beam coupling strength between the incident beam and its own scattered beam.[9] These beams, reflected and transmitted using beam splitters BS_1 and BS_2, each had a strength of ~40 mW. These beams were directed and overlapped onto the $+c$ face of the crystal to form a DSPPC configuration inside the crystal (as shown in Fig. 1). BS_1 and BS_2 were also used to monitor the self-pumped phase-conjugate outputs, I_{1pc} and I_{2pc}, respectively. The two beams, with incident angles θ_1 and θ_2, were set to acute angles with respect to the normal $+c$ face of the crystal. The degree of coherence between the two input beams was controlled by making the optical path lengths between the laser and the crystal much longer than the coherence length (~5 cm) of the argon ion laser. Accordingly, the photorefractive grating, the transmission grating formed by the two incident beams, did not form. The electronic shutters, ES_1 and ES_2, switched the two input beams on and off. It was necessary to use two lenses, L_1 and L_2, both with a focal length of $f = 140$ mm and diameter of 50 mm, to image the input patterns (resolution chart) into the crystal for the investigation of phase-conjugate imaging.

The phase conjugation technique was used in the following tests to ensure that the geometry of the two beams was indeed DSPPC. Two unexpanded Gaussian beams, I_1 and I_2, having powers of 41 mW and 35 mW, respectively, and the area of ~0.818 mm^2 were incident in a symmetrical geometry: $z_1 = z_2 = 2.58$ mm, and $\theta_1 = \theta_2 = 35°$ (i.e. $\phi = 70°$) to the normal of the crystal $+c$ face as defined in the inset of Fig. 1. When both inputs were simultaneously turned on, the phase-conjugate outputs were not detected concurrently. Figure 2 shows how each phase-conjugate power develops with time. They rise over about 20 and 25 s to reach their final magnitudes, which are very stable in time to ±7.0% and

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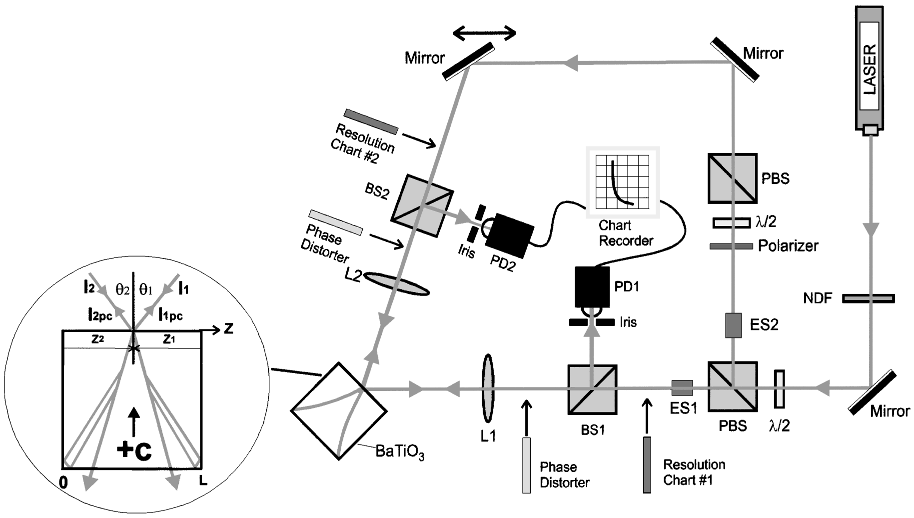

Fig. 1. Experimental arrangement for measuring DSPPC output. The inset shows a schematic of the top view of the light path in the $BaTiO_3$ crystal.

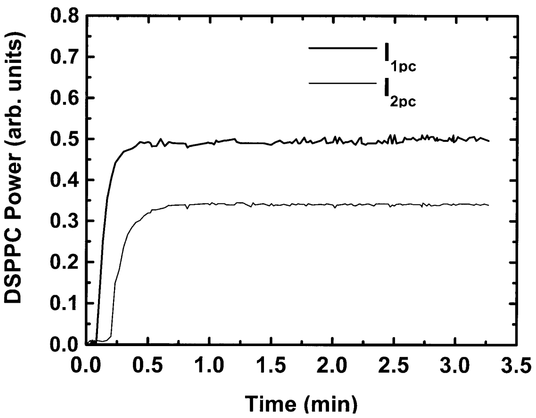

Fig. 2. Time evolution of the phase-conjugate output of the proposed DSPPC at the angle $\phi = 70°$ between I_1 and I_2.

±6.6% over 5 min, respectively. There are two curving loops sustained separately inside the crystal, as shown in Fig. 3(a). We can detect an unstable SPPC output in one beam while blocking off the second beam (as shown in Figs. 4(a) and 4(b)). The self-pumped phase-conjugate reflection of each incident beam can be generated in this configuration, as shown in Figs. 3(b) and 3(c). We postulated that, unlike the case with only one input beam incident at a small angle, the Bragg-mismatched reading could erase the noise grating accompanying one of the two incident beams in the overlapping area. More energy is directed to the crystal's corner. After two totally internal reflections at the crystal's corner, each beam can form a "cat" loop and generate a stable self-pumped phase conjugation output.

To investigate the angular dependence of this phase-conjugate reflectivity, we carried out measurements with the input beams symmetrically incident on the crystal, i.e., $\theta_1 = \theta_2$ (defined in Fig. 1). We varied the incident angle ϕ while keeping z_1 and z_2 constant (=2.58 mm), and controlled the power of each beam at ∼25 mW. Figure 5 shows the experimental result of the phase-conjugate reflectivity of the input beams as a function of the incident angle, ϕ. The DSPPC behavior was found to exist at an angular range of at least $\phi = 50°$ to 100°.

Finally, we investigated the phase-conjugate fidelity of the DSPPC. Two USAF resolution charts were inserted into each beam path. One resolution chart was rotated 90° with respect to the other. They were imaged into the crystal with the two lenses, L_1 and L_2. Before imaging into the crystal, each image passed through a phase aberrator. Figures 6(a) and 6(b) show these two thoroughly distorted images. The phase-conjugate images were recorded by projecting the im-

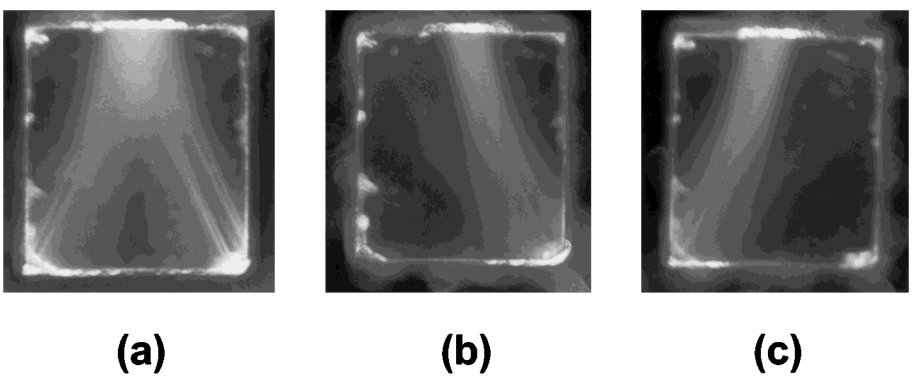

Fig. 3. Experimental photos of the optical beam paths inside the crystal in three different cases: (a) switch on I_1 and I_2, (b) switch on I_1 (I_2 OFF), and (c) switch on I_2 (I_1 OFF).

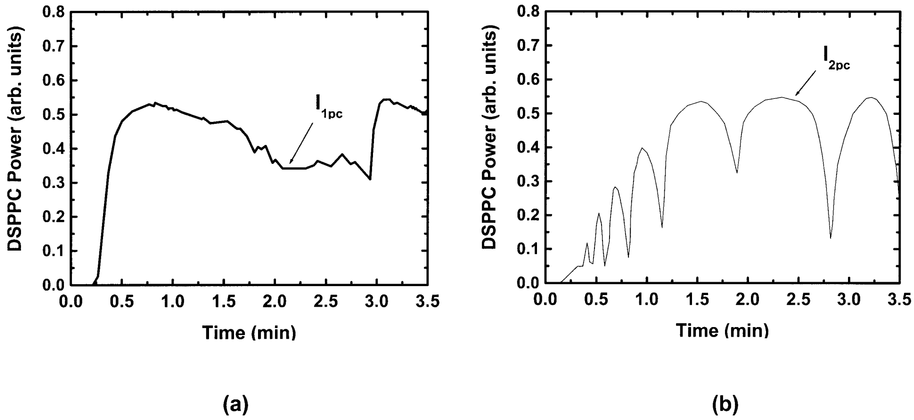

Fig. 4. Time evolution of the phase-conjugate output of the proposed DSPPC at the incident angle $\theta_1 = 35°$ of I_1 (I_2 OFF), and that of $\theta_2 = 35°$ of I_2 (I_1 OFF).

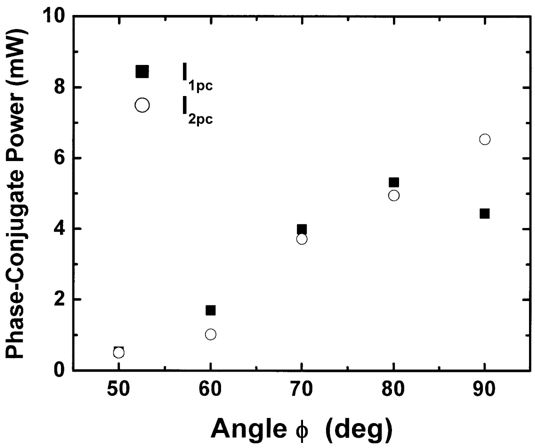

Fig. 5. Plot of the DSPPC phase-conjugate power as a function of the external interaction angle ϕ on the $+c$ face.

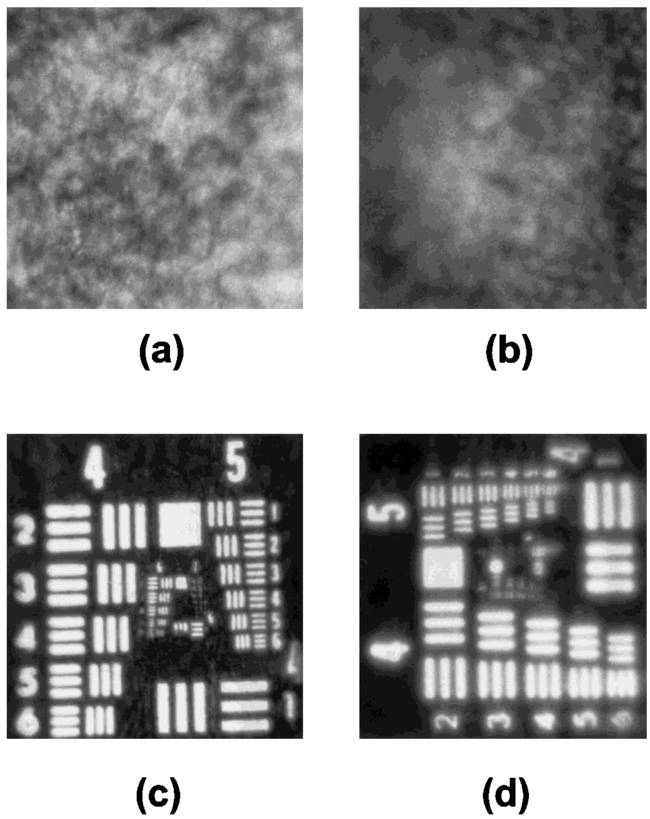

Fig. 6. Distorted images of a resolution chart carried by (a) beam I_1 and (b) beam I_2. Phase-conjugate images reflected by the DSPPC. (c) beam I_1 and (d) beam I_2.

age onto the film of a camera. Figures 6(c) and 6(d) show the two resulting DSPPC images, which demonstrate that there is no image crosstalk in the two phase-conjugate images. Though a resolution of ∼114 line pairs/mm (4 μm) per phase-conjugate DSPPC image was obtained for each of the two beams, there is a minor difference in resolution between the two images that may be caused by the nonuniformity of the illumination beams. The resolution is about one third of the cutoff frequency of our imaging system which is $f_{\mathrm{cutoff}} = D/(2\lambda f) \approx 360$ line pairs/mm (lp/mm), where $D = 50$ mm is the diameter of the lens, $f = 140$ mm is the focal length of the imaging lens, and $\lambda = 488$ nm is the laser wavelength. However, it was unexpected that the resolution of the present DSPPC images was higher than those of the SPPCs of 0°-cut $BaTiO_3$: Co[12] (∼5.7 lp/mm), 16°-cut KNSBN: Cu[26] (∼23 lp/mm), and pentagon-shaped $BaTiO_3$[27] (∼16 lp/mm).

One possible explanation for this high degree of image resolution is that, in our setup, the inputs are imaged and converged into the crystal. Typically, when generating a “cat” configuration SPPC with *a*-face incidence,[9] measures must be taken to strengthen the fanning effect within the crystal. This is accomplished either by focusing the incident beam to a point outside the crystal so that it is diverging as it enters, or by using a beam that is incident to the normal of the *a* face at a relatively large angle. In either case, much of the higher spatial-frequency components of the resolution chart of the incident beam are lost during the competition of multiple gratings,[28] formed in the crystal, which seriously limits the resolution of the phase conjugation. In DSPPC with $+c$-face incidence, on the other hand, the strong tendency of the beams to fan towards the $+c$ axis eliminates the need for either of these measures. The beams are incident at a small acute angle with the normal to the $+c$-face and are focused within the crystal, thereby minimizing energy loss and preserving the higher frequencies of the input image.

In conclusion, double SPPC using a $+c$-face incident configuration was proposed. In this novel configuration, two

SPPCs with high resolution can be created in a crystal. This technique can be applied to holographic data storage for robust systems and memory refreshment.[7,8)]

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