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Elimination of Dynamic Instabilities in the +*c*-face Incident Photorefractive $BaTiO_3$ Mutually Pumped Phase Conjugator

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Experimental observations of the dynamic instabilities in the $+c$-face incident mutually pumped phase conjugator (MPPC) of a $BaTiO_3$ crystal are reported for the first time. Experiments show that it is possible to stabilize the phase-conjugate output by choosing a proper geometry formed from the crystal and two incident beams. By choosing the proper geometry the essential configuration of the MPPC attained is a "kite" rather than a "fish head". Data also indicate that the phase-conjugate output can reach a very steady state with a high value (∼32%) and is insensitive to angular and positional variations.

KEYWORDS: phase conjugation, mutually pumped phase conjugator, photorefractive, $BaTiO_3$, injection locking

The mutually pumped phase conjugator (MPPC) has become an attractive photorefractive device in which two mutually incoherent beams interact indirectly and emerge as the phase conjugates of one another. In the past decade, several interaction geometries[1–7] of the MPPC have been proposed. These geometries differ from one another according to the entrance face on which the incident beams (to be phase conjugated) impinge, the number of total internal reflections and the number of interaction regions. Recently, additional geometries[8–10] for the MPPC, with distinct configurations, such as the "fish head",[8] the "plate-form"[9] and the "rainbow",[10] were discovered for effective coupling of two mutually incoherent laser sources. In these configurations, the two beams were incident to the $+c$ face of the crystal. Based on the idea of how the stimulated photorefractive backscattering self-pumped phase conjugation (SPB-SPPC)[11] occurs, the difficulty in these configurations is that the SPB interactions cannot support the generation of self-pumped phase conjugation (SPPC)[12] due to this special beam/crystal geometry. With the "$+c$-face incident" geometry, one can improve the performance of the mutually pumped phase conjugation without special doping or crystal orientation cutting.

The injection locking of incoherent laser sources, achieved by the class of MPPCs,[13–17] can be regarded as a photorefractive holographic coupling between two mutually incoherent laser sources.[18] However, MPPC stability during the coupling will determine the performance of the injection locking process. MPPC dynamic instabilities were previously observed in several configurations.[19,20] In the "modified bridge" configuration, various instabilities (regular and irregular pulsations, periodic oscillations, and optical chaos) were observed by changing the incident geometric parameters. In the "bird-wing" configuration phase conjugate, dynamic instability outputs, including regular and irregular oscillations, were detected by precisely choosing the experimental geometry. Therefore, how to effectively stabilize the phase-conjugate output of the MPPC is still an open question.

In this study, we demonstrate that a better $+c$-face incident MPPC for a nominally undoped $BaTiO_3$ crystal is possible if the proper geometry formed from the crystal and incident beams is chosen. The results will demonstrate that the phase-conjugate output can reach a very steady state with a higher value when the optical path inside the crystal has the "kite" configuration (as shown in inset (a) of Fig. 1) rather than the fish-head configuration[8] (inset (b) of Fig. 1). The kite configuration also accounts for the angular and lateral positional acceptance of the incident beams from the operation of the MPPC.

A schematic of the experimental arrangement for the $+c$-face incident MPPCs is shown in Fig. 1. A single domain, 0°-cut, nominally undoped $BaTiO_3$ crystal ($a \times b \times c = 5.16\,\text{mm}\times 4.74\,\text{mm}\times 5.00\,\text{mm}$ with the c-axis along the 5.16 mm edge) was employed for producing mutually pumped phase-conjugate waves. The crystal was mounted onto a translation/rotation stage so that the angular (θ) and positional (z) dependence of the MPPC effect could be investigated. Using a variable beam splitter (VBS), an argon ion laser beam ($\lambda = 488\,\text{nm}$) was split into two beams, I_A and I_B and directed onto the $+c$ face of the $BaTiO_3$ crystal to form the kite or fish-head configurations, respectively, inside the crystal. Both beams were extraordinarily polarized with respect to the crystal by rotating a half-wave plate to make full use of the crystal's coupling strength.[21] Two beam splitters, BS_1 and BS_2, were used to couple the mutually pumped phase-conjugate outputs into the photodetectors (which were connected to an x-t chart recorder) for detection. A camera set was utilized to capture the top view of the MPPC optical paths inside the crystal. The two incidence angles, θ_A and θ_B (as measured outside the crystal), were set to be unequal or equal to one another but at Brewster's angle of the $BaTiO_3$ crystal to avoid direct reflection from the crystal face, $+c$. Two lenses, L1 and L2, whose focal lengths were 50 mm, were used to diverge the two incident beams before they entered the crystal to provide sufficiently large beam diameters to achieve significant beam fanning and subsequent beam coupling inside the crystal. The two input beams in this geometry were made to be mutually incoherent, so that very little competing photorefractive grating (such as the reflection grating) was formed. This mutual incoherence was achieved by simply removing the etalon from the cavity of the Ar^+ laser and by making the optical path different around 200 cm between the two incident beams, which was larger than the Ar^+ laser coherence length L_c (∼3 cm). A white light source with a fiber bundle was used to illuminate the crystal for about two min between consecutive measurements to erase any index gratings formed within the crystal in the previous measurement.

In the first set of experiments, we conducted the following

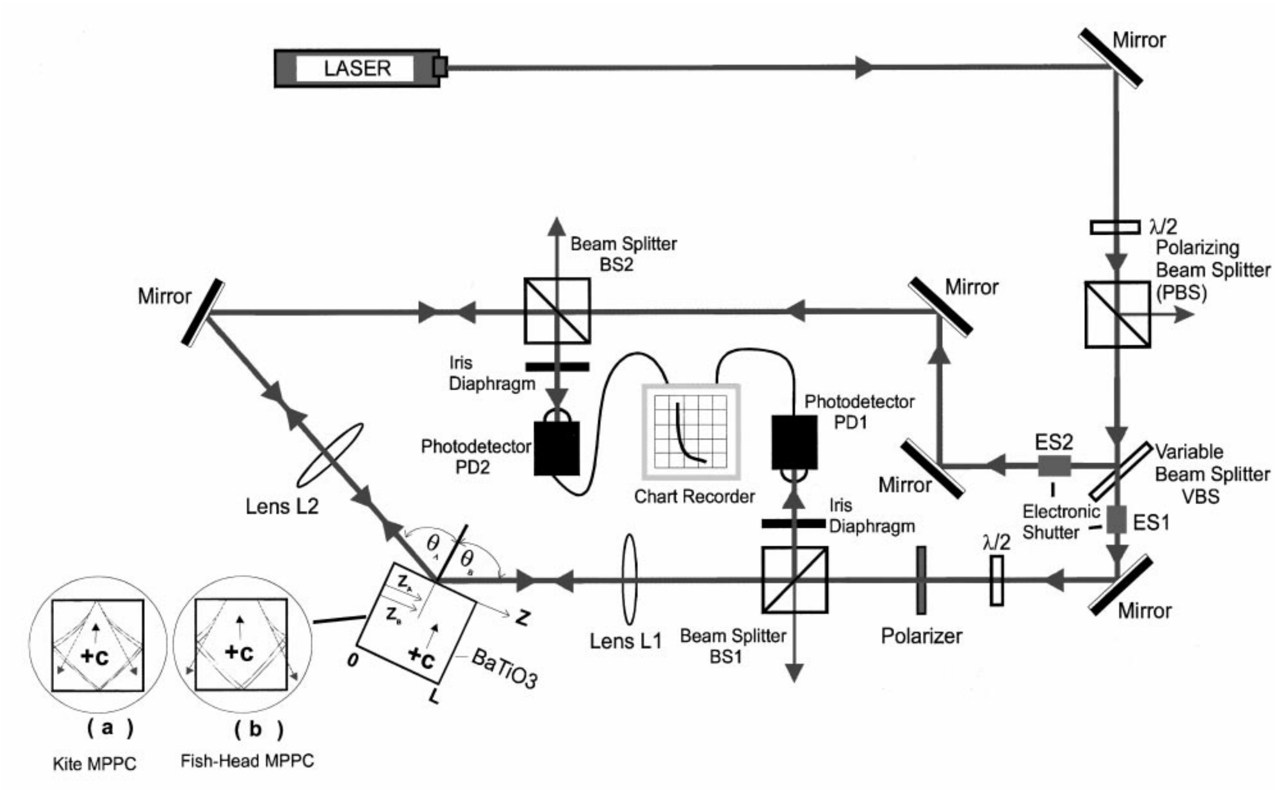
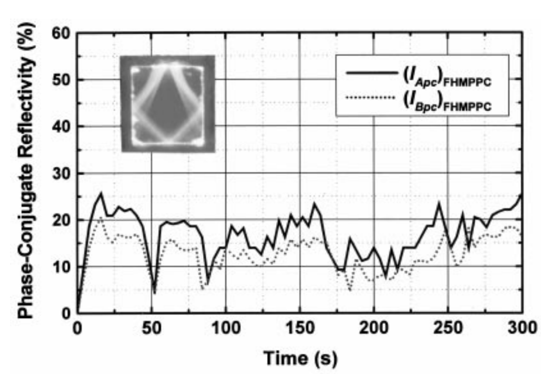


Fig. 1. Experimental arrangement for demonstrating and investigating the $+c$ face incident type of MPPCs.

tests to verify the observation of the dynamic instabilities of the $+c$-face incident MPPC, especially in the fish-head configuration (or fish-head MPPC: FHMPPC). Two unexpanded Gaussian beams, each having a power of $I_A = 17$ mW and $I_B = 20$ mW with an area of ~ 0.95 mm^2, were incident at the distance $d = z_A - z_B = 2$ mm onto the crystal's $+c$ face. The lateral positions (z_A and z_B) of the two beams were measured from the crystal corner ($z = 0$) to the center of the area of each beam incident onto the $+c$ face. When both of the two incident beams impinged upon the crystal, the two phase-conjugate light beams could be detected simultaneously while the fish-head configuration was forming inside the crystal. Both MPPC phase-conjugate outputs with the fish-head configuration were stable when the incidence angles of those two mutually incoherent beams were smaller than 55°.[8)] However, when we symmetrically increased the external angle ϕ ($= \theta_A + \theta_B$) between the two input beams to greater than 110° (i.e., $\theta_A = \theta_B > 55°$), the phase-conjugate outputs of the fish-head conjugation became unstable. Figure 2(a) shows the temporal response of both established phase-conjugate outputs, which varied irregularly and markedly at the angle between the two incident beams, 134°, i.e., the Brewster's angle ($\sim 67°$ for $BaTiO_3$ at $=488$ nm) of each beam. It was found that the fluctuation in the outputs was greater than 75% with respect to the mean value of at least five min. With the same symmetrically incident conditions mentioned above, we rotated the crystal along the axis vertical to the plane of the two input beams with angles $\Delta\theta$ and d kept constant at 2 mm. In Fig. 3(a), both phase-conjugate outputs also reveal a dynamic instability with about 80% variation as the crystal was rotated clockwise by an angle of $\Delta\theta = -10°$. To study the lateral positional response of the FHMPPC, we shifted the crystal along the z-axis. We found that both phase-conjugate out-



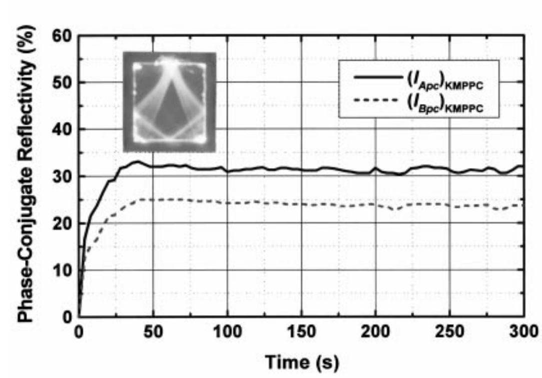
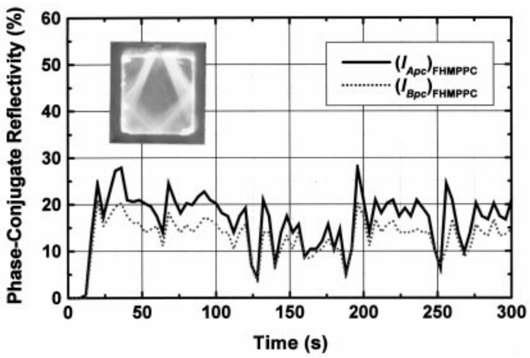
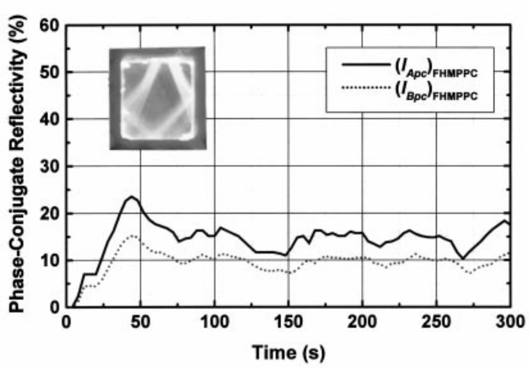


Fig. 2. Temporal evolution of the MPPC's phase-conjugate output of (a) the fish-head and (b) the kite configurations. Photographs in the figures show the optical path formed inside the crystal when the phase conjugation process is established.

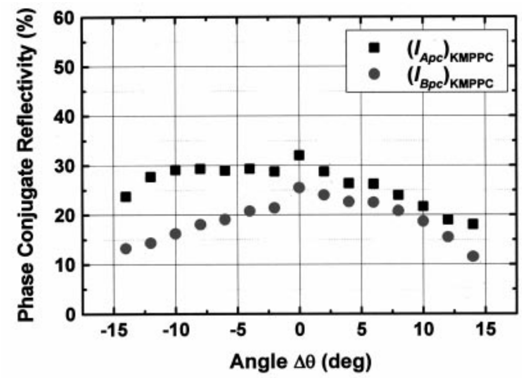


(a)

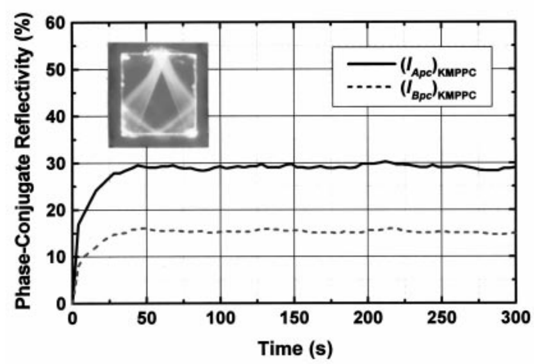


(b)

Fig. 3. Temporal evolution of the MPPC's phase-conjugate output of the fish-head configurations for (a) the crystal rotated by an angle $\Delta\theta = -10°$ and (b) the crystal shifted along the *z*-axis 1 mm away from the crystal corner ($z = 0$).



(a)



(b)

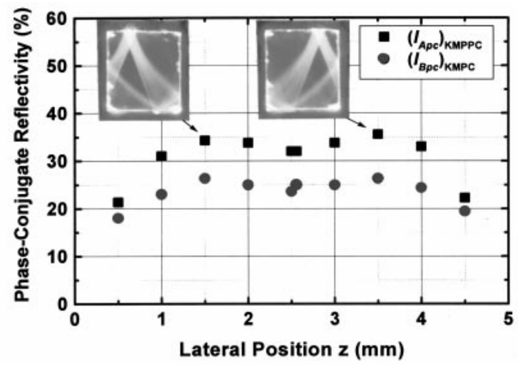
Fig. 4. (a) Plot of the KMPPC's phase-conjugate reflectivity as a function of the rotated angle $\Delta\theta$. (b) Temporal evolution of the KMPPC's output as the crystal is rotated by angle $\Delta\theta = -10°$.

puts of the FHMPPC were sensitive to positional variations at greater incidence angles with respect to the normal direction of the crystal $+c$ face as well. The dynamic instability of the MPPC phase-conjugate outputs as also observed (Fig. 3(b)) while a deformed fish-head configuration, as shown in the upper-left corner of Fig. 3(b), was forming inside the crystal.

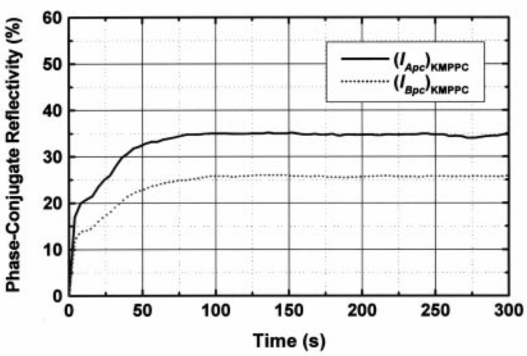
In the next set of experiments, we proposed another configuration, the kite, for the MPPC (or kite MPPC: KMPPC) with $+c$ face incident geometry to overcome the drawback mentioned above. Once the phase conjugation process was established, the MPPC with the kite configuration showed a greater stability and higher phase-conjugate output than the fish-head configuration, while the mutually incoherent beam(s) were incident at a large angle with respect to the normal direction of the $+c$ face. Figure 2(b) illustrates the temporal response of the phase conjugation in the kite configuration with large incidence angles ($\theta_A = \theta_B = 67°$). The photograph in the upper-left corner of Fig. 2(b) shows the optical beam path formed inside a $BaTiO_3$ crystal when the KMPPC is well established. Both phase-conjugate waves were generated less than five s apart. As indicated in Fig. 2(b), the output powers of the phase conjugation were strikingly stable, and the fluctuation of the outputs was within about 5% within five min. Compared to the fish-head conditions, the phase-conjugate output of the kite geometry was not only more stable but also generated higher reflectivity.

In the following experiments, we scrutinized the angular and lateral positional acceptance of the KMPPC. To measure the angular response, we rotated the crystal clockwise and/or counter clockwise along the axis vertical to the plane of the input beams. The phase-conjugate output power varied slightly with the rotated angle in an asymmetrical path (as shown in Fig. 4(a)). As indicated in Fig. 4(b), the outputs maintain a stable and fast response when the crystal has been rotated clockwise by an angle of 10°. The photograph in the upper-left corner of Fig. 4(b) shows the kite configuration with a slight deformation. To measure the lateral positional response, we shifted the crystal along the *z*-axis back and forth. Figure 5(a) shows that the phase-conjugate outputs varied symmetrically with the lateral positioning of the intersection and increased on both sides ($z_A = z_B$) at $z = 1.5$ mm & 3.5 mm. As indicated in Fig. 5(b), both phase-conjugate outputs were highly stable, and the fluctuation of the outputs was within 3%. Unlike the FHMPPC, the KMPPC can generate phase conjugation easily regardless of the lateral movement of the intersection of the input beams on either side of the $+c$ face. Neither counter nor counter clockwise movement along the axis vertical to the plane of the two input beams affected KMPPC phase conjugation generation.

In conclusion, we demonstrated another geometry, the kite configuration, of the $+c$-face incident MPPC of a $BaTiO_3$ crystal. The phase-conjugate output of the kite geometry was not only more stable but also generated higher reflectivity. As with the existing MPPCs, the performance of the KMPPC,



(a)



(b)

Fig. 5. (a) Plot of KMPPC's phase-conjugate reflectivity as a function of the lateral position of the intersection point z. (b) Temporal evolution of the KMPPC's phase-conjugate output when the crystal is shifted along the z-axis and the intersection point z is set to 1.5 mm away from the crystal corner ($z = 0$).

especially the positional and angular acceptances, makes this MPPC very promising for practical applications such as injection locking lasers and optical free space communications.

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