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Photorefractive Arch of Mutually Pumped Phase Conjugators in a $BaTiO_3$ Crystal

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ABSTRACT

A novel mutually pumped phase conjugation geometry, which induces an arch configuration, in photorefractive barium titanate crystals is experimentally demonstrated. Both of the mutually incoherent beams incident on opposite *a* faces of a $BaTiO_3$ crystal make obtuse angles to the crystal +C axis, respectively. This leads to effective mutual interaction as two fans emanating from the input beams have a large region of overlap and do not suffer from Fresnel losses due to internal reflection. We refer to this phase conjugator as the "arch of mutually pumped phase conjugator (Arch-MPPC)". This novel MPPC exhibits phase conjugation with zero internal reflection. We also show good concordance of spatial beam behaviour between the experimental results and the recent theoretical predictions proposed by A. A. Zozulya. The temporal response, the positional and angular acceptance, and the variations of the phase-conjugate reflectivity with the input beam intensity ratio have also been determined. Finally, a possible physical model is proposed.

Key Words: photorefractive, $BaTiO_3$, phase conjugation, mutually pumped phase conjugator, arch configuration

I. Introduction

The idea of a mutually pumped phase conjugator (MPPC) was originally developed for phase-locking of two mutually incoherent, even independent, laser sources with nominally identical (Sternklar *et al.*, 1986) or totally different (Kaczmarek *et al.*, 1994a, 1994b) wavelengths. The MPPC consists of a photorefractive crystal where two mutually incoherent beams indirectly interact and emerge as phase conjugates of each other (i.e., the beams exchange lateral spatial amplitudes and invert their own lateral spatial phase profiles). When the two input beams are incident, the input beams fan out and at the same time scatter from each other's fanning gratings. This process proceeds efficiently if the beams diffract with automatic Bragg-matching everywhere throughout the entire volume from a set of shared gratings, which is possible only if the beams are phase conjugates of each other throughout the entire volume (Segev and Yariv, 1991), which permits exchange of spatial information without crosstalk. Beam coupling using the class of MPPCs can be regarded as an effective photorefractive holographic link between two mutually incoherent laser sources. Several configurations (Weiss *et al.*, 1987; Ewbank, 1988; Wang *et al.*, 1989; Sharp *et al.*, 1990; Smount and Eason, 1987; Ewbank *et al.*, 1990; Chang and Selviah, 1995; Zhang *et al.*, 1995) of MPPCs in conjunction with their applications have been reported in recent years. The major applications of MPPCs are in optical processing (Weiss *et al.*, 1987; Sternklar *et al.*, 1987; Caulfield *et al.*, 1987; Anderson *et al.*, 1993), coupling of two incoherent laser beams (Segev *et al.*, 1987; Shimura *et al.*, 1993; Wright and McInerney, 1994), photorefractive spatial mode converters (Chiou *et al.*, 1995), and optical neural networks (Dunning *et al.*, 1987, 1991) for pattern recognition. Recently, theoretical modelling has been carried out by several research groups for the purpose of unifying the concepts and optimising the phase conjugation efficiency, response time, and fidelity in existing MPPC configurations (Fisher *et al.*, 1989; Bogodaev *et al.*, 1992; Orlov *et al.*, 1994; Engin *et al.*, 1994; Korneev and Sochava, 1995). Recently, a 2-D model was proposed by Zozulya *et al.* (1994, 1995) using a numerical approach to investigate light propagation and formation of complex structures of light in photorefractive crystals.

Performance optimization of MPPCs is required for practical applications. MPPCs depend in their operation on two self-generated effects (He, 1989; Yeh, 1989a) inside the photorefractive crystal. One is the effect of asymmetric light induced scattering of a laser beam, i.e., beam fanning, and the other is self-pumped four-wave mixing (SPFWM). In order to obtain a high-performance MPPC, the following aspects of the chosen geometry of the MPPC should be considered: (1) there should be large diffraction efficiency for the SPFWM, which requires a large coupling constant and an extensive two-dimensional interaction region, which in turn requires a wide angular range of beam fanning; (2) the light loss should be small, which includes the absorption and scattering loss in the crystal, and the specular reflection loss on the entrance and exit surfaces of the crystal; (3) high efficiency will contribute to stable operation of an MPPC which possesses large lateral positional and angular acceptance. Eight geometries for MPPCs have already been discovered and used in photorefractive materials to effectively couple two mutually incoherent laser sources. The various configurations reported to date can be categorised according to the number of internal reflections that the beams experience: no reflections in the double phase conjugator (DPC) (Weiss *et al.*, 1987), bridge (Sharp *et al.*, 1990), and modified-bridge (Smount and Eason, 1987) configurations; one reflection in the bird-wing (Ewbank, 1988) and plate-formed (Zhang *et al.*, 1995) configurations; two in the mutually incoherent beam coupling (MIBC) (Weiss *et al.*, 1987) configuration; and three in the frog-legs (Ewbank *et al.*, 1990) and fish-head (Chang and Selviah, 1995) configurations. Several mechanisms (Weiss *et al.*, 1987; Ewbank, 1988; Wang *et al.*, 1989; Sharp *et al.*, 1990; Smount and Eason, 1987; Ewbank *et al.*, 1990; Chang and Selviah, 1995; Zhang *et al.*, 1995; Feinberg, 1982; MacDonald and Feinberg, 1983) have been proposed, including the one-common grating model for the "DPC" configuration, two-common grating model for "MIBC", "bird-wing", "frog-legs", "bridge", "modified-bridge" and "plate-formed" configurations, and four-common grating model for the "fish-head" configuration, in which common gratings governing the establishment of the MPPC are enhanced and non-overlapping gratings are suppressed. Eventually, if the coupling strength Γ (average coupling coefficient, γ, multiplied by the effective interaction length, l_{eff}) is large enough, the SPFWM self-reinforce interaction stabilized in an MPPC allows a self-aligning interconnection to form between

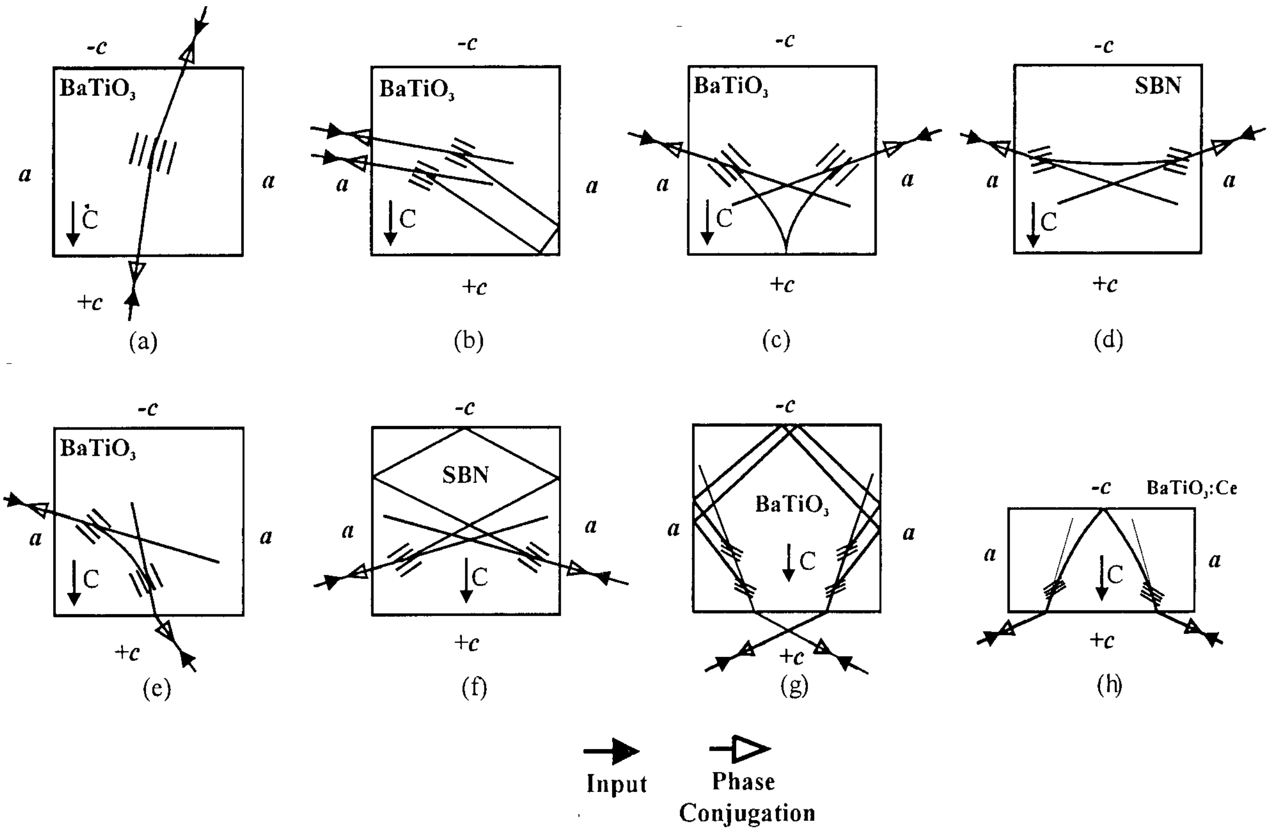


Fig. 1. Schematics of existing geometries for MPPCs. (a) double phase conjugator (DPC), (b) mutually incoherent beam coupler (MIPC), (c) the bird-wings phase conjugator, (d) the bridge phase conjugator, (e) the modified-bridge phase conjugator, (f) the frog-legs phase conjugator, (g) the fish-head phase conjugator, and (h) the plate-formed phase conjugator.

two mutually incoherent laser sources.

In this paper, we will describe our experimental research on the formation of a high-performance MPPC with a novel configuration in a $BaTiO_3$ crystal. We will start by reviewing several existing configurations (Weiss *et al.*, 1987; Ewbank, 1988; Wang *et al.*, 1989; Sharp *et al.*, 1990; Smount and Eason, 1987; Ewbank *et al.*, 1990; Chang and Selviah, 1995; Zhang *et al.*, 1995) for MPPCs discovered in the last decade and then go on to describe in detail our configuration. We have experimentally demonstrated our "arch" configuration and will show that our results are in good agreement with those of the numerical simulations carried out by Zozulya *et al.* (1994, 1995). We will also show the positional and angular acceptance, and the variations of the phase-conjugate reflectivity with the input beam intensity ratio, and compare our configuration with that of the "bird-wing" configuration. Finally, we will give an explanation for the formation of the "arch" configuration.

II. Configuration Interpretation for MPPCs

We will first briefly recall the geometry of earlier configurations in order to highlight the distinctive features of the "arch" arrangement. In the DPC configuration, both beams are incident on opposite surfaces, labelled +*c* and -*c* in Fig. 1(a), and once inside the crystal, one beam travels at an acute (non-zero) angle to the +C direction and the other at an acute (non-zero) angle to the -C direction. In the MIBC configuration, both beams enter the crystal at the same surface, labelled *a* in Fig. 1(b). In the "bird-wings", "bridge", and "frog-legs" configurations, the beams are incident on opposite surfaces (labelled *a* in Fig. 1), and once inside the crystal, travel at an acute (non-zero) angle to the c axis in the +C direction in the case of the "bird-wing" (shown in Fig. 1(c)) and "bridge" (Fig. 1(d)) configurations, or at an obtuse (non-zero) angle to the +C direction in the case of the "frog-legs" (Fig. 1(f)) configuration. In the "modified bridge" (shown in Fig. 1(e)) configuration, both beams are incident on adjacent surfaces +*c*, and either of the surfaces is labelled *a*; once within the crystal, one beam travels at a non-zero acute angle to the +C direction and the other at a non-zero acute angle to the -C direction. In the "fish-head" (Fig. 1(g)) and "plate-formed" (Fig. 1(h)) configurations, both beams are incident on surface +*c*, and once within the crystal, each beam travels at a non-zero obtuse angle to the +C direction. In our configuration, two input beams (i.e. input beams to be phase-conjugated), I_{1p} and I_{2p}, are incident on opposite crystal faces (labelled *a*) (defined in Fig. 2(a)) with acute angles of θ_1 and θ_2 to the normal of the *a* faces at distances y_1 and y_2 from the crystal corners. The incident beams both initially travel at an non-zero obtuse angle to the crystal's c-axis in the +C direction within the $BaTiO_3$ crystal. Once the phase-conjugation process has been established (Fig. 2(b)), the illuminated beam path inside the crystal resembles the structure of an arch. We follow the existing convention (Sharp *et al.*, 1990; Zhang *et al.*, 1995) based on different architectural forms and refer to this as the "arch" configuration. Notice that in this configuration, when the input beams are traveling at an obtuse angle to the +C direction, they tend to bend towards the +C direction. As a result, they create a wide range of gratings in the fans with a large interacting area.

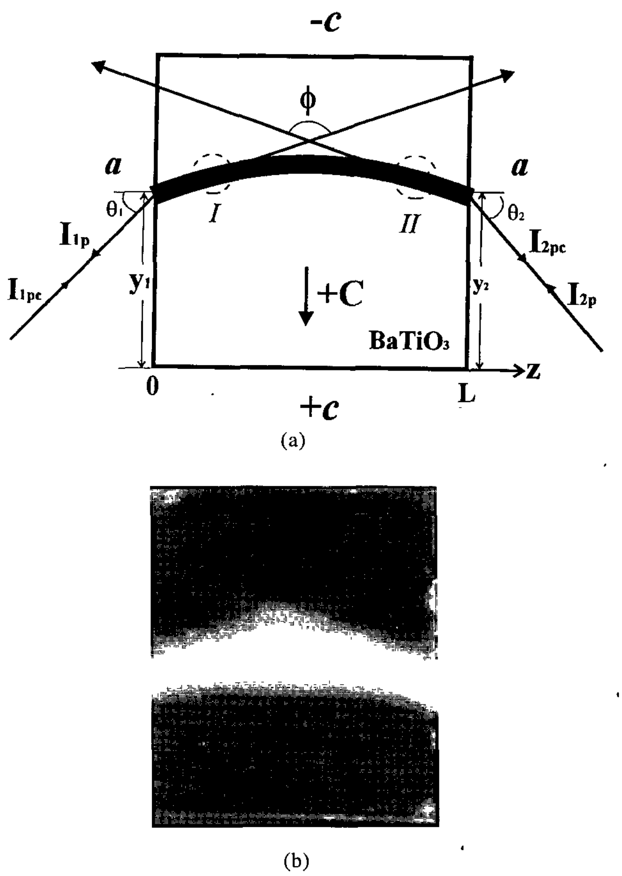


Fig. 2. (a) Schematics and (b) experimental photographs of the new MPPC geometry "arch" phase conjugator, respectively.

III. Experimental Details

The experimental arrangement for the Arch-MPPC is shown in Fig. 3. In these experiments, we used an Ar^+ laser operating with multi-longitudinal modes at a wavelength of 488 nm. The crystal was polished on six surfaces with single domain at 0°-cut undoped

$BaTiO_3$ crystal with dimensions of $a \times b \times c$= 5.16 mm × 4.74 mm × 5.00 mm, and 5.00 mm × 5.00 mm × 5.00 mm. The crystal was mounted on a computer controlled translational and rotational stage which allows rotation (± 0.001 deg) and lateral displacement (± 1μm), so that the effect of the incident beam input position (y) and angle (θ) (as shown in Fig. 2(a)) could be determined. The laser output was divided by a variable beamsplitter, VBS, into two pump (input) beams with different or similar intensities. These beams, I_{1p} and I_{2p}, were reflected and transmitted by BS_1 and BS_2, resulting in beams of several milliwatts each, and were incident upon two opposite faces (labelled a) of the $BaTiO_3$ crystal, forming an "arch" configuration. The beamsplitters BS_1 and BS_2 were used to monitor the simultaneous phase-conjugate outputs, I_{1pc} and I_{2pc}. The electronic shutters, ES_1 and ES_2, switched the two incident beams on and off. The two incident angles, θ_1 and θ_2, were set to be the identical (measured outside the crystal), and both incident beams were extraordinarily polarised to ensure maximum coupling strength. It was necessary to use lenses, L_1 and L_2, with a focal length of f = 125 mm to diverge the two incident beams before they shone on the crystal to provide sufficiently large beam diameters to achieve significant beam fanning and subsequent beam overlap inside the crystal. The degree of coherence between the two pump beams in this configuration was controlled so that competing photorefractive gratings, such as a reflection grating formed by the two pumped beams, did not form. This mutual incoherence was achieved by simply removing the étalon from the Ar^+ laser and by making the optical path lengths between the laser and the photorefractive crystal, for the two incident beams, differ by more than the Ar^+ laser coherence length (~3 cm). In this experiment, we arranged the setup so as to achieve incoherent pump beams: the path length between the two beams, I_{1p} and I_{2p}, was arranged to be ≅ 45 cm (9 times the coherence length of the laser without the étalon) at a wavelength of 488 nm.

In the first set of experiments, we carried out the following tests to ensure that our geometry was indeed an MPPC; in other words, this MPPC met the following conditions: (1) no phase-conjugate reflection of each incident beam could be generated by itself in this configuration; (2) the phase-conjugate beams I_{2pc} resulted from the beam I_{2p}, and I_{1pc} resulted from beam I_{1p}, in which one of the two incident beams was blocked (e.g. when I_{1p} was blocked off), beam I_{2pc} disappeared suddenly, and I_{1pc} decayed gradually because the holograms formed between the two beams were erased by I_{2p} gradually and vice verse if I_{2p} was blocked; and (3) there was no image cross-talk in the phase-conjugate imaging when both incident beams contained image information.

In the second set of experiments, the Arch-MPPC

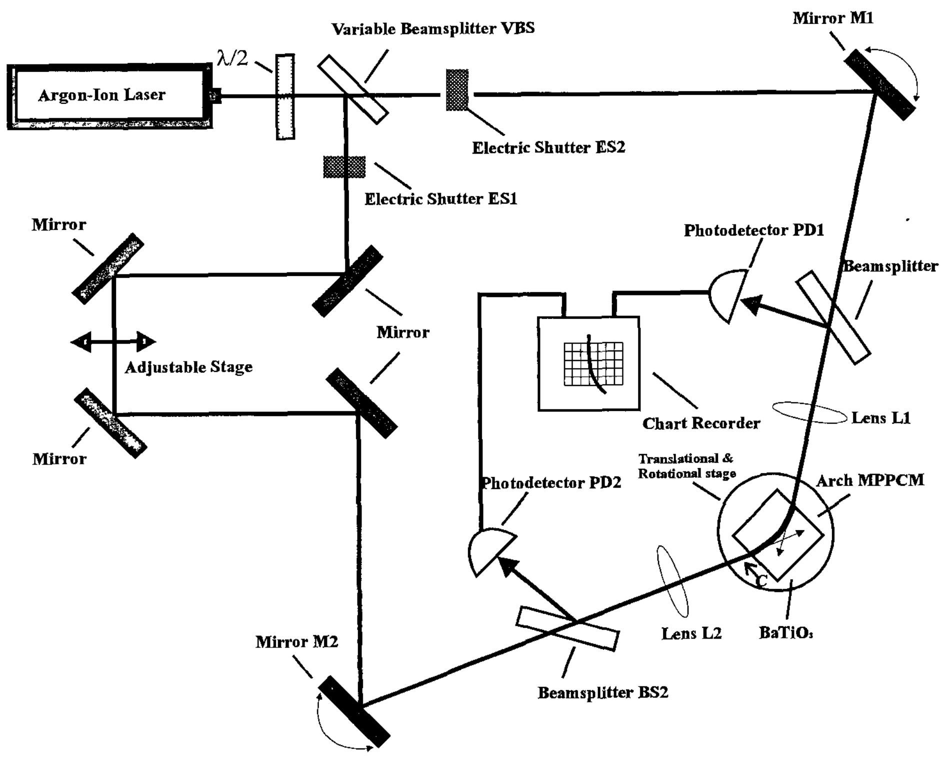


Fig. 3. Experimental arrangement used to demonstrate and investigate the Arch-MPPC.

formation process was studied. As shown in Fig. 4(a), only one input beam (I_{1p}=25 mW) with an area of ~0.8mm^2 was incident on the *a* face of the crystal at an angle of 60°, and it initially propagated straight inside the crystal as shown but with strong beam fanning because the incident beam diverged inside the

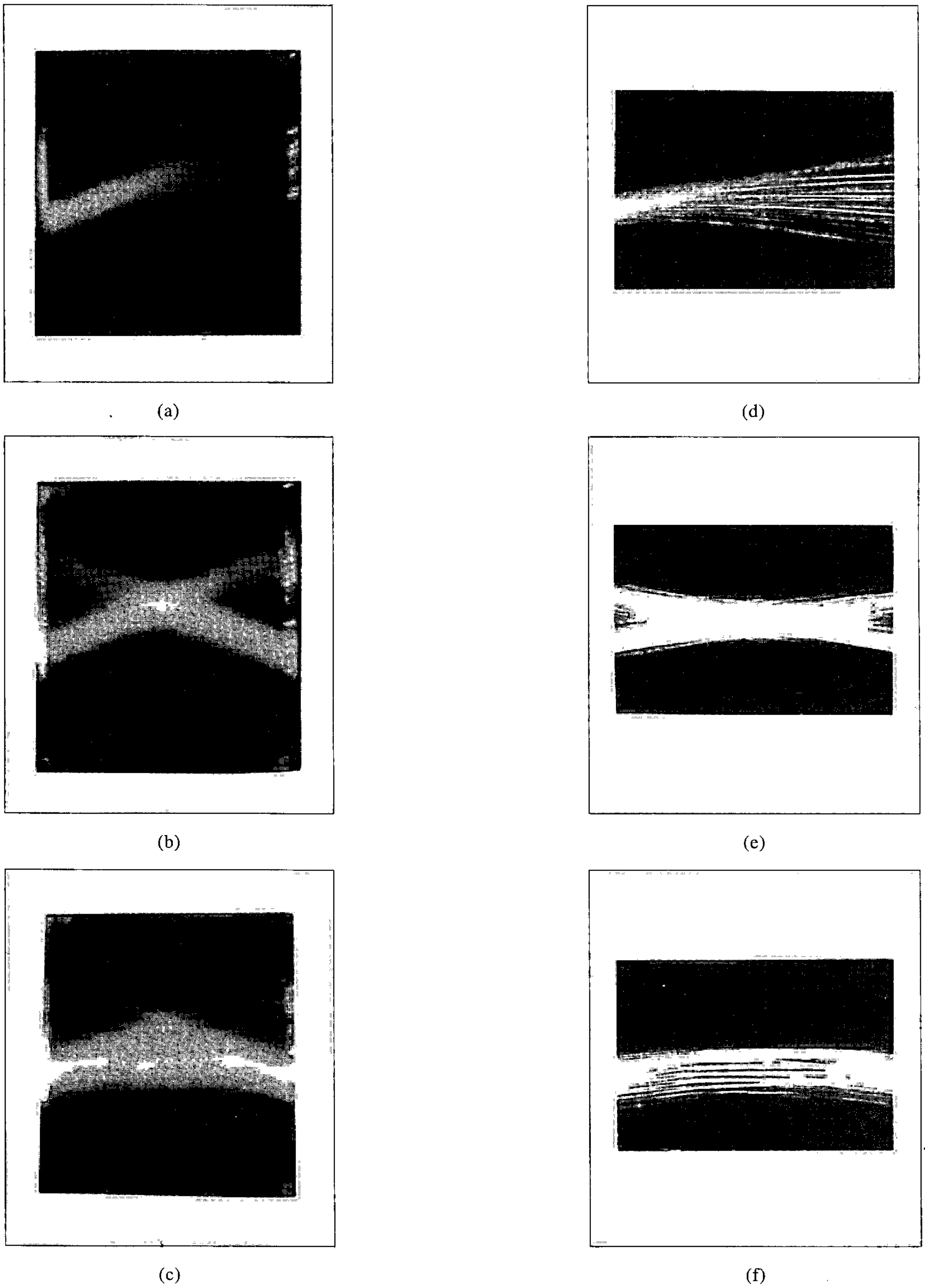


Fig. 4. A set of photographs illustrating the formation of the Arch-MPPC, taken from above the $BaTiO_3$ crystal with (a) one input beam incident on the crystal for t=0.5 s, and (b) and (c) two beams simultaneously incident with $\theta_1=\theta_2$=60° for t=0.5 and 1.5 s, respectively. (d)-(f) show simulation results from Zozulya *et al.* (1994) for comparison.

crystal. Figure 4(b) is a photomicrograph taken when two incident beams (I_{1p}=I_{2p}=25 mW; θ_1=θ_2=60°) shone together from the opposite faces (labelled *a*) of the crystal for 0.5 second. It can be seen that the two straight incident beams had begun to branch out and bend toward the +C direction, and that the arch structure had begun to form. When the two beams had been on for 1.5 seconds, more energy was seen to have been transferred to the arch from the two incident beams to give an final steady state arch (as shown in Fig. 4(c)) with 25% phase-conjugate reflectivity. Figure 5 shows how the phase-conjugate reflectivity of both input beams developed with time. They rose in ~1.5 s (after the beams were switched on) to reach a final magnitude. Comparing our experimental results with those of the simulations carried out by means of numerical modeling (Zozulya *et al.*, 1994, 1995), the agreement found to be is good.

The performance of the Arch-MPPC, especially in terms of the positional and angular acceptances, is not only important for coupling of two incoherent laser sources, but also for practical systems, such as laser phase locking applications. Therefore, in the third set of experiments, we examined the positional acceptance of the Arch-MPPC by measuring the phase-conjugate reflectivity of I_{2p} for three different input lateral positions on the *a* faces of the pair of beams. The crystal was shifted along the ±C direction between the posi-

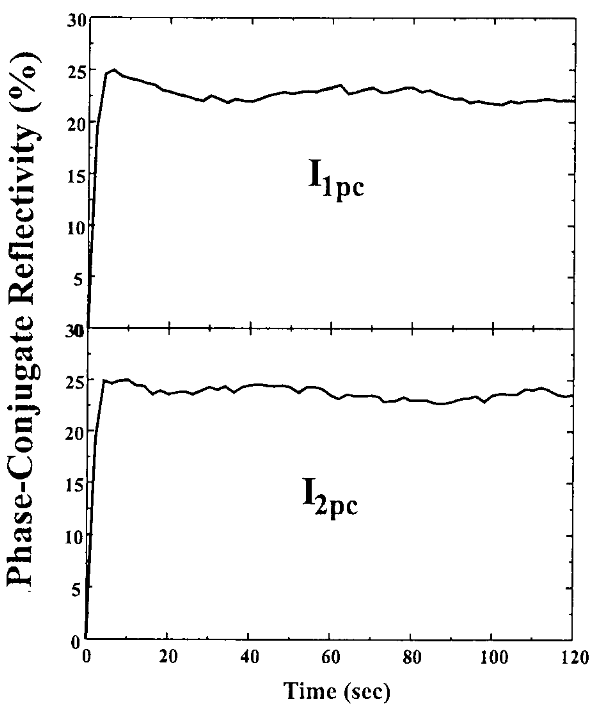


Fig. 5. Plot of the phase-conjugate reflectivities verse time for the Arch-MPPC.

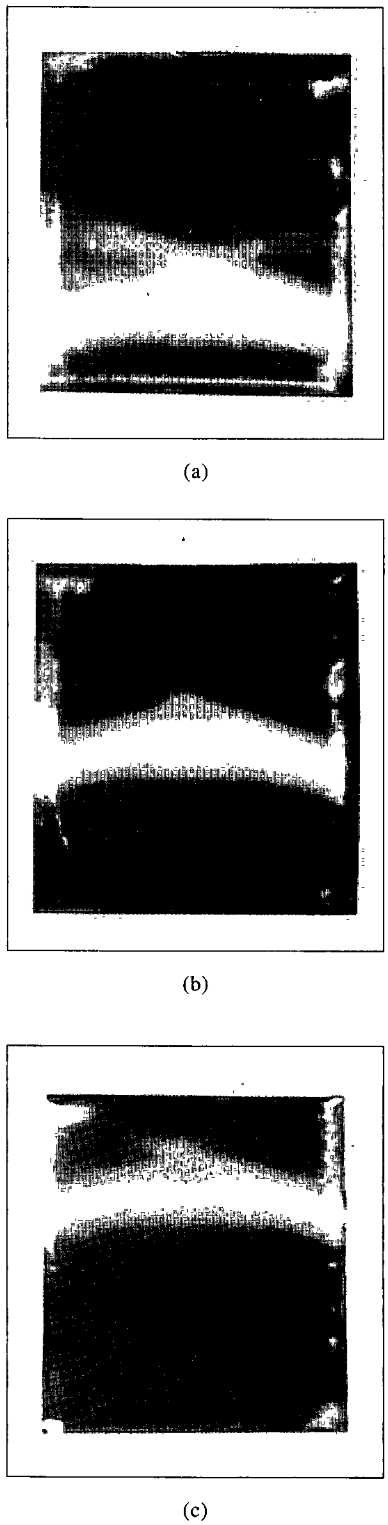
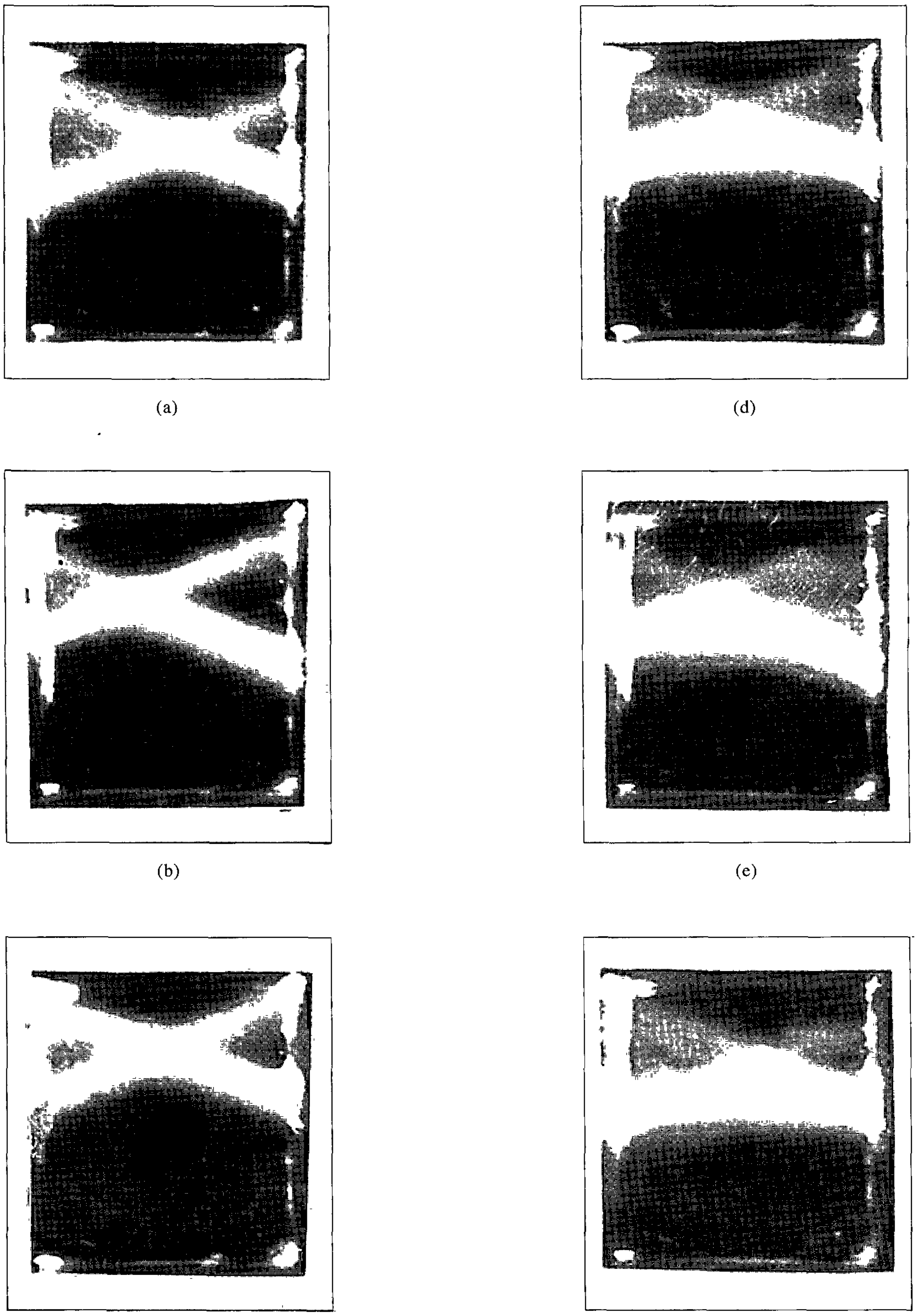


Fig. 6. A set of photographs illustrating the beam paths in the Arch-MPPC, taken from above the $BaTiO_3$ crystal with the two beams simultaneously incident on the crystal for 1.5 s at lateral position (a) y_1=y_2=1 84 mm, and (b) y_1=y_2=2.58 mm, and (c) y_1=y_2=4.30 mm. The phase conjugation efficiency measured in the three cases was 23%, 25% and 22%, respectively.



(a) (d)

(b) (e)

(c) (f)

Fig. 7. A set of photographs illustrating the beam paths in the crystal in the Arch MPPCM, taken from above the $BaTiO_3$ crystal after the two beams were simultaneously incident on the crystal for t=0.5 s (a) without rotating the crystal (y_1=y_2=1.84 mm and θ_1=θ_2=60°), (b) after rotating the crystal in the clockwise direction by 10° (y_1=2.32 mm and y_2=2.68 mm), and (c) after rotating the crystal in the counterclockwise direction by 10° (y_1=2.68 mm and y_2=2.32 mm). (d), (e), and (f) show the steady state arch in the orientation of (a), (b), and (c), respectively after t=1.5s.

tions, but the beams remained symmetrical, i.e., $y_1=y_2$ and $\theta_1=\theta_2=60°$ (defined in Fig. 2(a)). As shown in Fig. 6, the mutual phase conjugation behaviour was established with slightly differing phase conjugation efficiency with two 25 mW input beams after 1.5 seconds as can be seen in Fig. 6(a)-(c). In the next experiment, we also measured the range of angles over which the Arch-MPPC could be demonstrated. We measured the phase-conjugate reflectivity in three different input cases in which the input positions of two beams were altered by rotating the crystal in clockwise and counterclockwise directions as shown in Fig. 7. Figure 7(a) shows that two input beams were symmetrically incident on the $BaTiO_3$ crystal at $y_1=y_2$ and $\theta_1=\theta_2=60°$ (without any rotation of the crystal) before phase conjugation, and Fig. 7(d) shows that optical paths were established after 1.5 seconds, giving a phase-conjugate reflectivity of 23% of the input beam I_{2p}. Figure 7(b) and (e) show the phase-conjugate behaviour before and after phase conjugation (with 20% reflectivity), respectively, when the crystal was rotated in a clockwise direction by 10 degrees. This rotation affected not only the incident angles of the two input beams, but also the lateral positions on the entrance faces, which changed asymmetrically. Figure 7(c) and (f) show the phase-conjugate behaviour before and after phase conjugation, respectively (with 17% reflectivity), of a crystal rotated in the counterclockwise direction by 10 degrees. From these experiments, it can be seen that the MPPC with the "arch" configuration not only exhibited very wide angular and positional tolerance, but also had fairly acceptable phase-conjugate efficiencies.

The relative phase-conjugate power as a function of the input beam intensity ratio is shown in Fig. 8. The data do not take into account either Fresnel and absorption losses. It can be seen that the phase-conjugate energy was transferred during the phase conjugation process in the Arch-MPPC. Finally, to compare the performance of our Arch and that of the well-known Bird-wing MPPCs, we arranged geometries as shown in Fig. 9. The crystal's c-axis in both MPPCs was directed from top to bottom on the figure. Similar incident conditions were used, $I_{1p}=I_{2p}$=25 mW, $y_1=y_2$ =2.58 mm, except that the angles of the two input beams entering the crystal were different between the "arch" and "bird-wing" configurations. Once the phase conjugation reached a steady state, we measured the phase-conjugate reflectivity of both configurations. It must be mentioned that photorefractive conical scatterings occurred in the "arch" configuration because phase-matching diffraction could alleviate the phase conjugation efficiency of the Arch-MPPC. Although the phase-conjugate reflectivity of the Bird-wing MPPC was higher than that of the Arch-MPPC, grating competition which occurs in the Bird-wing MPPC commonly results in slow response time and temporal instability (Hussian *et al.*, 1990).

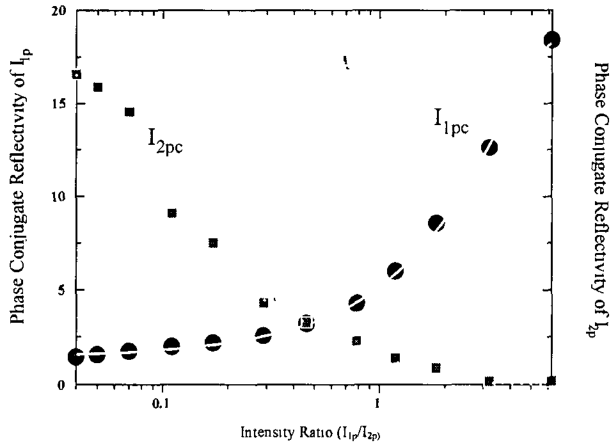
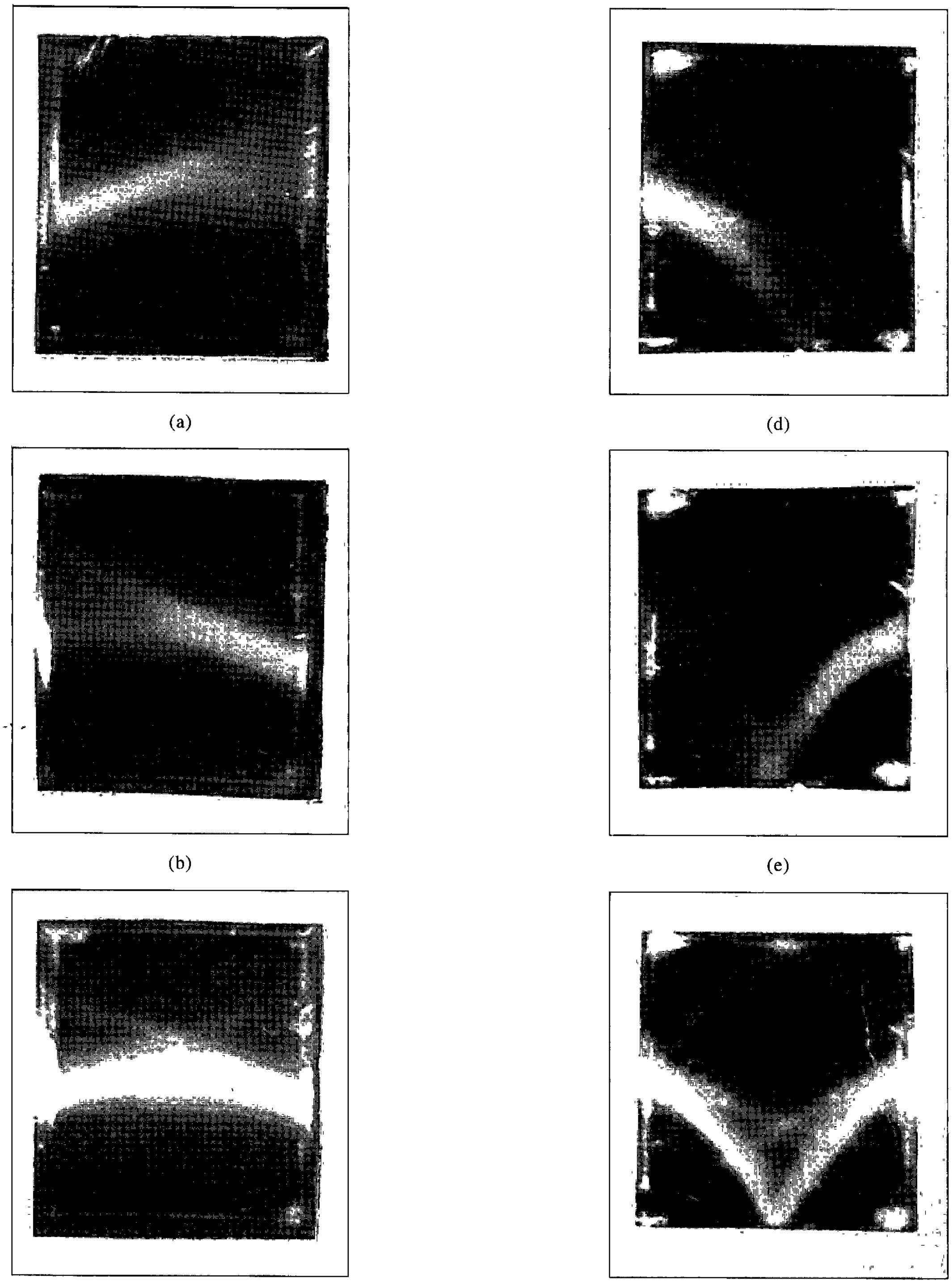


Fig. 8. Graph of the Arch-MPPC phase conjugation output powers as a function of the input beam intensity ratio.

IV. Discussion

We suggest a tentative mechanism that may be the reason for the Arch-MPPC results. When two mutually incoherent incident beams (to be phase conjugated) enter the crystal from the two opposite faces (labelled *a*) of the $BaTiO_3$ crystal, the input beams are traveling at an obtuse angle to the +C direction (as shown in Fig. 2(a)). Therefore, each incident beam interferes with its own scattered light coming from some scattering centres inside the crystal and creates a wide range of gratings in the fans and a large interacting area which generates a strong photorefractive beam that fans in the +C direction. A set of identical gratings, occurring in both fans, is reinforced by two-wave mixing (TWM) (Yeh, 1989b). The fanned light resulting from one beam can Bragg diffract from the gratings formed by the beams in the other fan, resulting in phase conjugation via SPFWM. As a result, the fans couple and bend into each other, forming an arch, hence, the "arch" phase-conjugator (as shown in Fig. 2(b)). Figure 10 schematically shows the Arch-MPPC operating in steady state. The strong volume gratings shared by both beams are written throughout the crystal, but two representatives are shown in Fig. 10 for interaction regions *I* and *II* only. The insert in Fig. 10 shows the grating details in region *I*. In region *I*, the fanned beam, I_{2fan}, reads the transmission grating, written by an input beam I_{1p}, and a fanned beam I_{1fan}. From the theory of four-wave mixing (FWM) (Cronin-Golomb *et al.*, 1984), the readout beam creates a phase-conjugate replica of the incident beam I_{1p}, i.e., I_{1pc}. The energy from beam I_{2p} is transferred to the phase-conjugate beam, I_{1pc}, by reading the transmission grating with I_{2fan}. A resemblance applies for an interaction region *II*, so in all two phase-conjugate beams are produced at the same time, i.e., I_{1pc} and I_{2pc} with magnitudes that depend on I_{2p} and I_{1p}, respectively. In reality, regions



(c) (f)

Fig. 9. Two sets of photographs illustrating the build-up process of the arch and bird-wing MPPCs, respectively. (a)-(b) two input beams individually incident on the crystal with $\theta_1=\theta_2=60°$ in the "arch" configuration, and (d)-(e) two beams individually incident on the crystal with $\theta_1=\theta_2=\pi/2+60°$ in the "bird-wing" configuration before phase conjugation. (c) and (f) show the optical path of the input beams after phase conjugation in the "arch" and "bird-wing" configurations, with reflectivities of 25% and 30%, respectively.

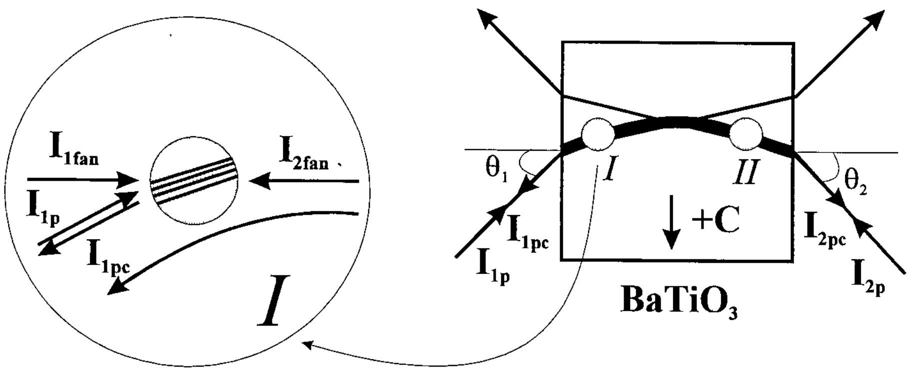


Fig. 10. Schematics showing the physics and grating in the geometry of the Arch-MPPC. The insert shows the gratings in interaction region *I*.

I and *II* are a continuum of points and correspond to gratings throughout the crystal, which gradually bend the light between *I* and *II* and form the arch.

V. Conclusions

In conclusion, we had demonstrated a new geometry, the "arch" configuration, which generates phase-conjugate waves from the interaction of mutually incoherent laser sources in shared photorefractive fan gratings. Our novel MPPC consists of two mutually incoherent beams incident on opposite *a* faces of a $BaTiO_3$ crystal which make obtuse angles to the +C direction of the crystal's axis, respectively. As a result, they create a wide range of gratings in the fans and a large interacting area. This leads to effective mutual interaction as two fans emanating from the input beams have a large region of overlap, thus reinforcing SPFWM in each interaction area and providing effective coupling between two laser sources. The "arch" configuration not only results in a broad interacting area for phase conjugation of two mutually incoherent laser beams coupling inside a photorefractive crystal without internal reflections (avoiding Fresnel losses), but also provides phase locking of one laser with another.

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在鈦酸鋇晶體中光折變弓狀互泵式相位共軛器

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摘　要

本文我們在實驗上提出一互泵式相位共軛的新幾何架構，“弓狀”，於光折變鈦酸鋇晶體中。在此互泵式相位共軛器中兩相互非同調光分別與晶體+C軸方向夾鈍角，並分別從晶體的*a*面相對入射至晶體。此時在晶體內由入射光所產生的扇形光擁有較大的重疊區而導致較有效的相互作用的形成，同時亦無因內反射所造成的Fresnel損失。我們稱此相位共軛器爲弓狀互泵式相位共軛器，簡稱Arch-MPPC。從實驗結果得知，在弓狀互泵式相位共軛器中入射光的空間動態行爲與Zozulya等人在最近所提出的理論預測結果相吻合。文中亦探討本相位共軛器之角度的與位移的容忍度，以及兩入射光間的強度比對相位共軛光的反射率的影響。最後，我們針對本互泵式相位共軛器提出可能的物理模式。