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Intensity-dependent thresholding and switching in the photorefractive bridge mutually pumped phase conjugator

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Beam-intensity-ratio-dependent effects have previously been observed in several photorefractive mixing configurations. Here we report the observation of *total* input-intensity-dependent effects in the bridge mutually pumped phase conjugator, which results in optical thresholding and switching behavior. The cause of these effects is attributed to competition between bridge conjugation and self-pumped phase conjugation that results from different exponents in their measured intensity-dependent response times (10–90%), namely, $\tau_{\mathrm{bridge}} \propto I^{-0.79}$ and $\tau_{\mathrm{SPPC}} \propto I^{-0.38}$.

Phase conjugation in photorefractive materials has been extensively researched with a range of configurations, such as externally pumped degenerate four-wave mixing[1] and a variety of self-pumped phase conjugators[2] (SPPC's). More recently a novel class of phase conjugator, the mutually pumped phase conjugator (MPPC), has been observed in which two simultaneous phase-conjugate (PC) outputs are produced by the interaction of two mutually incoherent beams within a photorefractive crystal. Several generic MPPC configurations have been reported, which differ more in terms of their exact beam geometry than in the physical mechanism responsible for the effect. These geometries include the double phase-conjugate mirror[3] (DPCM), the mutually incoherent beam coupler,[4] the bird-wing phase conjugator,[5] and, more recently, the bridge conjugator.[6,7] Both the DPCM and the mutually incoherent beam coupler have been shown to have reflectivities and thresholds dependent on the input-beam intensity ratio, and these properties have been utilized in the DPCM for image-processing applications such as image thresholding and edge enhancement.[8]

The MPPC used here is the modified bridge conjugator of Refs. 6 and 7, which is shown in Fig. 1. The input beams are incident upon adjacent faces of the crystal, and both suffer beam fanning, beam 1 toward the $+c$ face and beam 2 toward the face upon which beam 1 is incident. These fanning gratings were observed to collapse into the characteristic bridge coupling channel, and PC outputs grew simultaneously. The two input beams, of 2-mm diameter, which were extraordinarily polarized, were derived from the output of an argon-ion laser that operated multilongitudinal mode at 514.5 nm and were directed toward the 6 mm × 6 mm × 6 mm single-domain crystal of $BaTiO_3$. The path difference between the two beams at the crystal was 15 times the coherence length of the laser (≈5 cm) to ensure that the beams were mutually incoherent. The input-beam intensity ratio was kept constant, and the total input power I_{tot} could be varied either by rotation of a variable neutral-density filter wheel or by direct control of the output power from the laser.

The precise form of the effects observed could be modified by alteration of the input beam parameters defined in Fig. 1, which were θ_1 = 60–70°, θ_2 = 10–40°, and x_1 and x_2 between 2 and 4 mm, with the beam intensity ratio fixed at $r = I_2/I_1 = 0.93$.

All the effects observed, and reported here, involve variation of the *total* input intensity rather than the more usual experimentally observed and theoretically predicted consequences of variation of the beam intensity ratio. Such results have not to our knowledge been reported for MPPC geometries and allow us to study and report effects such as thresholding, bistable and hysteretic switching, and optical flip-flop-type behavior within an MPPC configuration.

An example of thresholding of the PC outputs from both the beams is shown in Fig. 2, which shows the PC reflectivities obtained for upward and downward cycles of the input power for the two geometries detailed in the figure caption. For one case (the crosses and filled squares) the reflectivities are constant at the higher powers but fall off at $I_{\mathrm{tot}} \approx 30$ mW and show a threshold at 12 mW, below which no PC output was obtained. Optical thresholding of this sort could be

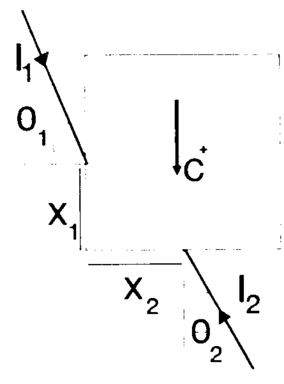

Fig. 1. Schematic diagram of the bridge MPPC.

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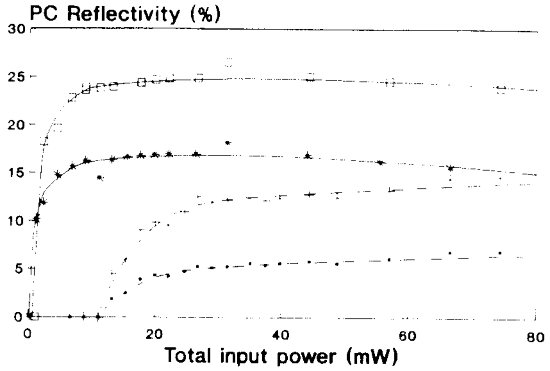

Fig. 2. PC reflectivity R obtained from the bridge MPPC as a function of the total input power for two input-beam geometries: (i) $\theta_1 = 70°$, $\theta_2 = 10°$, $x_1 = 4$ mm, $x_2 = 2$ mm, and R_1 (■) or R_2 (+), and (ii) $\theta_1 = 70°$, $\theta_2 = 40°$, $x_1 = 3.5$ mm, $x_2 = 3$ mm, and R_1 (✱) or R_2 (□). The beam intensity ratio was $r = I_2/I_1 = 0.93$ for both geometries. The curves indicate the trend only. Note the threshold at 12 mW for geometry (i), below which no PC output is obtained. Alteration of the input geometry to that of case (ii) resulted in a decrease in the threshold to 0.2 mW. No hysteresis was observed between upward and downward cycling of the total input power in either case.

useful in schemes that involve, for example, correlation effects, weighting procedures, and associative memory configurations. It proved possible, by suitable adjustment of the input parameters, to either increase or decrease this threshold, an example of which is shown in the second case of Fig. 2 (the asterisks and open squares), where the threshold has fallen to $I_{tot} = 0.2$ mW.

Further changes in the geometry permitted a systematic study of several associated effects to be carried out. It was possible to set up configurations in which regular oscillations were observed in the PC output, and other configurations that showed a different type of thresholding, in which the bridge conjugator gave way to a SPPC output from one of the beams, which formed a coherence switch and even resettable flip-flop-type behavior.

The bistable/hysteretic switching is illustrated in Fig. 3, which shows the situation in which, on the downward cycle, a threshold of 18 mW was reached, below which the bridge conjugator was destroyed by the onset of a SPPC output from beam 1. On the upward cycle the SPPC output persisted until I_{tot} reached 42 mW before the initial bridge configuration was restored, with its reflectivity being the same as that obtained on the downward cycle. Thus we have a device that permits the switching of the PC output of beam 2 in a bistable/hysteretic fashion and also, perhaps more interestingly, a way of changing the source of the light for the PC output of beam 1, from beam 2 in the bridge configuration (option 1) to beam 1 itself in the SPPC interaction (option 2). Owing to the difference in the pump beam path lengths for these two options, this provides a coherence switch arrangement for subsequent wave mixing processes involving the PC output of beam 1.

Figure 4 illustrates the flip-flop behavior. On the downward cycle the quashing of the bridge interaction by the switching on of the SPPC from beam 1 is again observed. However, in this case, on the upward cycle the SPPC does not give way to the bridge conjugator, and the PC output of beam 2 can only be switched back on by resetting the whole system, i.e., erasing the SPPC gratings and starting over, which is analogous to the behavior of electronic flip-flops.

It is likely that these effects are caused by competition between the bridge MPPC and the SPPC, possi-

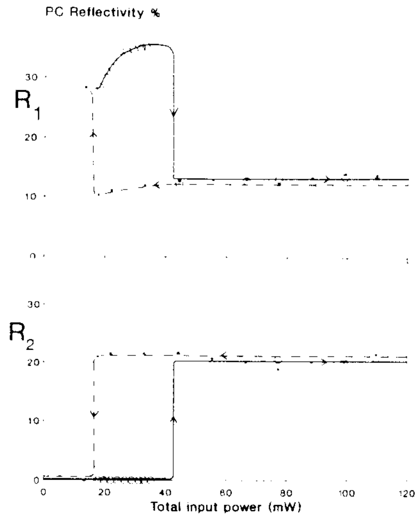

Fig. 3. PC reflectivity R obtained from the bridge MPPC versus total input power, with $\theta_1 = 60°$, $\theta_2 = 20°$, $x_1 = 4$ mm, $x_2 = 4$ mm, and $r = 0.93$. Squares, downward cycle; circles, upward cycle. On the downward cycle, at a total input power of 18 mW, the output from the bridge conjugator configuration is quashed by the onset of a SPPC output from beam 1. Note the hysteretic loop in both figures as the SPPC output from beam 1 persists on the upward cycle until total input power reaches 42 mW. (The traces are displaced for clarity.)

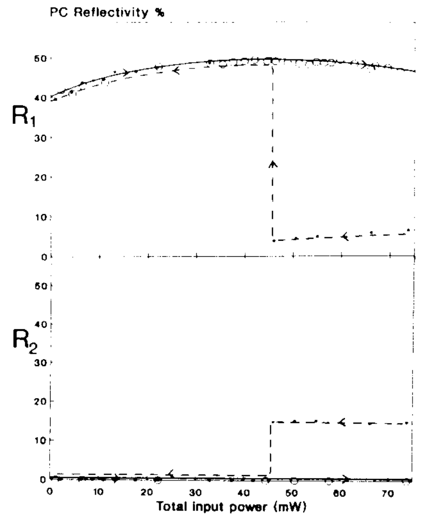

Fig. 4. PC reflectivity R obtained from the bridge MPPC against total input power, with $\theta_1 = 65°$, $\theta_2 = 15°$, $x_1 = 4$ mm, $x_2 = 2$ mm, and $r = 0.93$. Squares, downward cycle; circles, upward cycle. The bridge conjugator output is quashed on the downward cycle by the onset of SPPC from beam 1. To restore the output from beam 2 the system has to be reset. (The traces are displaced for clarity.)

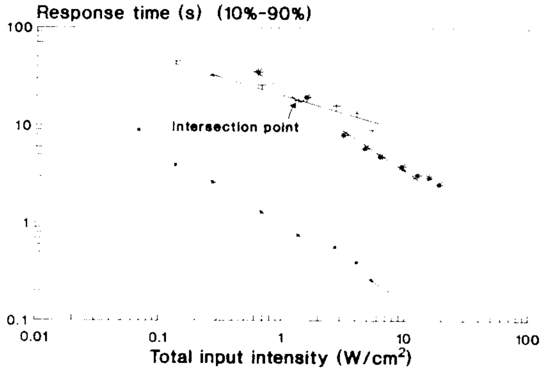

Fig. 5. Response times (10–90%) of beam fanning (■), SPPC (+), and the bridge MPPC (∗) as a function of total input intensity.

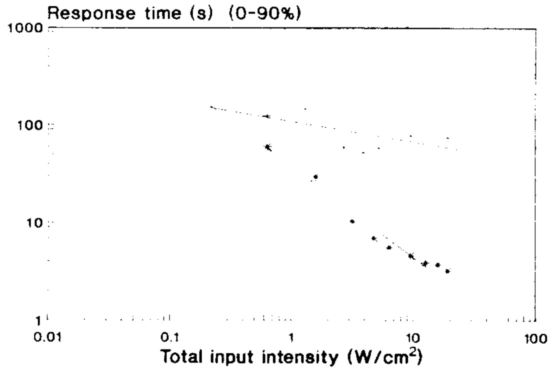

Fig. 6. Response times (0–90%) of the SPPC (+) and the bridge MPPC (∗) as a function of total input intensity.

bly owing to the different response times of these two processes. With this in mind the response times, here defined as the time taken to rise from 10% to 90% of the maximum, of the three processes—beam fanning, the SPPC, and the bridge conjugator—were measured as a function of total input-beam intensity. The SPPC and fanning data were acquired with an input angle θ_1 of 60°, while for the bridge the experimental parameters were $\theta_1 = 60°$, $\theta_2 = 40°$, $x_1 = 3$ mm, $x_2 = 2$ mm, and $r = 1.4$, with this set of parameters chosen to prevent the occurrence of the behavior illustrated in Figs. 3 and 4. The results of these measurements are shown in Fig. 5, in which the curves for fanning and bridge conjugation can be seen to have a similar form, $\tau_{\mathrm{fanning}} \propto I^{-0.75}$ and $\tau_{\mathrm{bridge}} \propto I^{-0.79}$, whereas for SPPC $\tau_{\mathrm{SPPC}} \propto I^{-0.38}$. Sharp *et al.*[7] reported a similar ratio of ≈ 2 between the bridge and SPPC intensity exponents for cerium-doped SBN:60. It may be that the initiation time, i.e., the buildup from noise, for these conjugators has a significant effect on the competition between the processes, and therefore we have included the 0–90% rise times, as shown in Fig. 6, in which we again observe a comparable intersection point.

A significant feature of the curves for the bridge and the SPPC is that they have an intersection point. On the high-intensity side of this point the bridge will form fastest and might be expected to dominate, possibly preventing the SPPC from forming, whereas on the low-intensity side the SPPC grows first, similarly preventing the bridge conjugator from building. In the vicinity of the intersection point one might expect competition that could lead to the experimentally observed fluctuations in the PC outputs mentioned above. Note that, while this graph shows an intersection point, no thresholding was observed during the response time measurements for the bridge conjugator. This can be explained by pointing out that the SPPC response time measurements were made in the absence of a second input beam, which would have had the effect of slowing down the SPPC formation by erasing the gratings, causing a decrease in the intensity at which the curves intersect.

In summary, we have observed, for the first time to our knowledge, total input-intensity-dependent thresholding and switching within a photorefractive MPPC. A qualitative argument based on competition between the SPPC and the bridge conjugator that results from a difference in the forms of the response times of the two processes, $\tau_{\mathrm{bridge}} \propto I^{-0.79}$ and $\tau_{\mathrm{SPPC}} \propto I^{-0.38}$, has been presented to account for these effects. The range of effects observed includes bistability, hysteresis, flip-flop action, and a novel coherence switching behavior that permits selection of the coherence characteristics of the PC output. Further research is currently in progress to see whether these effects are universal within other MPPC geometries.

References

1. J. Feinberg and R. W. Hellwarth, Opt. Lett. **5**, 519 (1980).
2. J. Feinberg and K. R. MacDonald, in *Photorefractive Materials and Their Applications II*, P. Gunter and J. P. Huignard, eds. (Springer-Verlag, Berlin, 1989), Chap. 5.
3. S. Sternklar, S. Weiss, M. Segev, and B. Fischer, Opt. Lett. **11**, 528 (1986).
4. R. W. Eason and A. M. C. Smout, Opt. Lett. **12**, 51 (1987).
5. M. D. Ewbank, Opt. Lett. **13**, 47 (1988).
6. D. Wang, Z. Zhang, Y. Zhu, S. Zhang, and P. Ye, Opt. Commun. **73**, 495 (1989).
7. E. J. Sharp, W. W. Clarke III, M. J. Miller, G. L. Wood, B. Monson, G. J. Salamo, and R. R. Neurgaonkar, Appl. Opt. **29**, 743 (1990).
8. S. Sternklar, S. Weiss, and B. Fischer, Opt. Eng. **26**, 423 (1987).
9. A. M. C. Smout and R. W. Eason, Opt. Lett. **12**, 498 (1987).