Optical thresholding and switching using a fiber-coupled phase-conjugate mirror

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A fiber-coupled-ring passive phase-conjugate mirror is used to achieve mutual thresholding free of bistability effects and to obtain switching among several mutually incoherent light beams.

Progress in optical computing and data processing has created a demand for all-optical switching and thresholding devices. Among the possible applications are beam steering and routing of optical signals in fiber communication networks and holographic associative-memory systems. Several thresholding configurations using photorefractive crystals have been reported. These systems are limited to one signal beam and usually exhibit hysteresis behavior (bistability).

Recently it was shown that a multimode-fiber-coupled phase-conjugate mirror (PCM) can phase conjugate any input field of limited N.A., restoring the input polarization state, in the presence of both reciprocal and nonreciprocal (e.g., magnetic and amplitude) distortions. We also demonstrated how it can be used for channeling temporal information among several mutually coherent inputs.

In this Letter we propose and demonstrate that a similar configuration can be used for an all-optical thresholding purpose, in which each of the (possibly many) input beams that are coupled to the fiber can play the role of either a signal beam or an erasure beam. The phase-conjugate signal is free of hysteresis effects, and such a device can also be used for steering (or switching) the output to different directions.

The experimental setup is shown in Fig. 1. Two mutually incoherent input beams are focused into a multimode graded-index fiber (length >40 cm); each beam has an incidence angle between 0° and 10° and a separation angle θ < 20°. The fiber N.A. is 0.3. The N.A. of each of the input beams is approximately 0.03. The input beams are either x polarized or cross (x and y) polarized, with no difference in the thresholding characteristics between the cases and with good recovery of the input polarization for the reflected phase-conjugate beam (because of the small input N.A., the fidelity of the restoration is ensured; see Ref. 7 and references therein for more details on this issue).

The reflectivity of Beam 1 alone is shown in Fig. 2. It is seen that at intensities (I₁) smaller than approximately 2 mW/mm² the reflectivity is not saturated (owing to the effect of large dark conductivity).

The threshold behavior is demonstrated in Fig. 3. The input power of Beam 1 is held fixed (P₁ = 3 mW), while the power of Beam 2 (P₂) is increased, starting from zero. We see that as long as P₂ ≪ P₁, only Beam 1 is phase conjugated. When P₂ ≫ P₁, only Beam 2 is phase conjugated. The reflected output field is a true phase conjugate of the stronger input beam, free of cross talk from the second beam. It should be emphasized that there is no a priori distinction between the two beams as far as the threshold behavior is concerned; the roles of P₁ and P₂ are interchangeable, and each of them can be regarded as either an erasure beam or a signal beam, depending on the specific application. It is therefore also possible to use this con-
Figure 2. Measured reflectivity of Beam 1 as a function of the input intensity to the crystal. Beam 2 is closed in this case ($P_2 = 0$).

Figure 3. Reflectivities of Beam 1 ($R_1$) and Beam 2 ($R_2$) as functions of $(P_2 - P_1)$. $R_1$ is normalized to 1 when $P_2 = 0$, and $R_2$ is normalized to 1 when $P_1 = 0$.

Figure 5 shows the dependence of $(P_2/P_1)_\text{th}$ (the point where the reflectivity drops to 10% of the maximum value) on $P_1$ for a greater range of input powers ($P_1$). It is seen that the threshold ratio tends to saturate to a fixed value beyond 5-mW input power to the crystal.

The experiment was repeated with three mutually incoherent beams simultaneously coupled into the fiber. When $P_1 > P_2 + P_3$, only Beam 1 was reflected back with a full recovery of its properties, while $P_2$ and $P_3$, being below threshold, were not reflected.

When one or more of the input beams carry spatial information, the thresholding acts globally on the whole spatial profile. Only if the total power exceeds the threshold value is this picture phase conjugated in its entire spatial structure. (The fidelity of reproduction is limited, however, by the input N.A.) High fidelity could be obtained by using a polarization-preserving phase conjugator after the fiber.

The basic features of the results shown above can be explained by a phenomenological model, according to which each beam serves as an erasure beam for the other. We emphasize that these properties are a direct consequence of the use of a multimode fiber, which permits the complete overlap of the different inputs while preserving the original initial conditions on reflection.

Figure 4 shows the experimental results of Beam 1 reflectivity ($R_1$) for several fixed values of input power $P_1$ as a function of the input power ratio $P_2/P_1$. These results were achieved independently of the direction of change of $P_2$ and the initial condition. We notice that for each $P_1$ there is a threshold ratio beyond which the reflectivity of Beam 1 is negligible and that $R_1$ is almost linear in most of the cases.

Figure 4. Experimental results of the reflectivity of Beam 1 as a function of the input power ratio of Beam 2 to Beam 1 for several values of Beam 1 input powers ($P_1$). The results are normalized to 1 when $P_2 = 0$.

Figure 5. Dependence of the threshold power ratio (defined in the text) as a function of Beam 1 input power ($P_1$).
We assume that Beam 2 erases the grating created by Beam 1 and reduces the effective coupling, $\gamma_{\text{eff}} = \gamma_0 / (1 + I_2 / I_1 + \sigma_d / \sigma_p)$. Here $\sigma_d$ is the dark conductivity and $\sigma_p (\propto I_1)$ is the photoconductivity induced by the signal beam. Figure 6 shows the theoretical reflectivity of a ring self-pumped PCM as a function of the coupling constant, with $M = 0.65$ and $\sigma_d / \sigma_p \rightarrow 0$.

We can fit the threshold value and functional behavior of our data, as shown in Fig. 2, to the theoretical predictions [Eqs. (1) and (2)] if $\gamma_0 l = 2.4$ and $\sigma_d / \sigma_p (I_1 = 1 \text{ mW/mm}^2) = 0.5$. Using these values, Fig. 7 shows the theoretical predictions as given by Eqs. (1)-(3) (with $I_2 \neq 0$). By comparing Fig. 4 with Fig. 7 we can see that the simple theory can approximately recover the main features of the experimental results for $P_1 < 2 \text{ mW}$. The almost linear behavior of $R_1$ is due to the small ($< 3$) value of $\gamma_0 l$, as explained before in the case of $\sigma_d = 0$ (Fig. 6). The increase of $(P_2 / P_1)_{\text{th}}$ with increasing $P_1$ is due to the nonzero contribution of $\sigma_d / \sigma_p$ to $\gamma_{\text{eff}}$ at the experimental values of $P_1$ (remember that $\sigma_p$ depends on $I_1$). However, for higher values of $P_1$ we do not reproduce the exact threshold points, as the theoretical reflectivity is decreased much faster than the experimental results. Such behavior is thought to be due to mutual scattering, because at high powers of both beams Beam 1 can also be diffracted, to some extent, from the grating created by Beam 2.

To conclude, we have shown how a simple all-optical thresholding and switching device can be obtained by using a fiber-coupled PCM. Such a device is effective for several simultaneously coupled mutually incoherent beams; it operates on the basis of input power ratios and is robust in the sense that the operation is not sensitive to any other characteristics of the input beams.

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References