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Thermally-Induced Optical Bistability with Two Holding Beams

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Abstract. Thermally-induced optical bistability with two holding beams has been experimentally investigated in a metal-dielectric-metal interference mirror. Steady-state responses different from the usual S-shaped curve and with potential interest for composite logic operations are reported.

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The nonlinear phenomena included under the name of optical bistability are observed in optical systems with a feedback mechanism in their response to an external light beam. Such phenomena permit the control of one light beam by another through common effects on the feedback loop and may be of potential interest for all-optical signal processing and computing [1].

The usual operation of a bistable device involves two or more light beams: one beam which holds the system at a given bias point and the signal beams, usually pulsed, which influence the response to the holding beam. In such a way the typical S-haped curve in the input/output characteristic of a bistable device under one-beam illumination has been used to demonstrate all-optical operations as optical switching, logic gating, differential gain and power limiting [1, 2]. On the other hand, it has been theoretically shown [3, 4] that the characteristics of an optical bistable device subjected to more than one incident beam significantly depart from the S-shaped curve and a wealth of possible responses can be obtained through the nonlinear coupling between the light beams. Marquis et al. [3] studied the mode-coupling effects in the case of a bidirectional ring cavity, showing the appearance of slaved bistability and cross-coupled bistability as well as the occurrence of positive-slope instabilities leading to self-pulsing. Golaire et al. [4] numerically investigated the steady two-beam operation of a nonlinear Fabry-Perot cavity with light beams of distinct angle of incidence.

In this paper we present an experimental analysis of a bistable interferometer illuminated by two holding beams of different angle of incidence. The experimental results are compared with theoretical calculations within the plane-wave approximation and the two-beam operation features are interpreted by means of a graphical solution. The analysis deals with a particular scheme of thermally induced optical bistability, but the main conclusions apply to the two-beam operation of any bistable system of interferometric nature.

Analysis

The optical bistability scheme here considered was recently introduced on the basis of two-beam interferometer configurations [5–7]. In the present work we deal with the system of Fig. 1, which consists of a transparent layer with temperature-dependent optical thickness sandwiched between a high-reflectivity mirror and an absorbing thin film with the following property: it introduces phase shifts on transmission and reflection such that the absorption losses vary

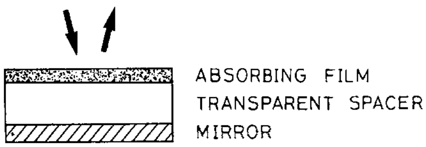

Fig. 1. Selective mirror by interference absorption

strongly with the interference state. Thus, the film absorption is affected by a feedback mechanism involving the thermooptic or thermal expansion effects of the intracavity spacer and the light interference within the thin film.

The reflectivity of such an interference mirror is periodically selective with respect to the wavelength λ_j and incident angle θ_j and is given by [7]

$$\mathscr{R}_j = R + TR_M T_F + 2\sqrt{RTR_M T_F}\cos(\Psi_j + \theta_F + \phi) \tag{1}$$

with

$$T_F = \frac{T}{(1-\sqrt{R_M R'})^2}\,\frac{1}{1+F\sin^2(\Psi_j/2)}, \tag{2}$$

$$F = 4\sqrt{R_M R'}/(1-\sqrt{R_M R'})^2, \tag{3}$$

$$\theta_F = \tan^{-1}\frac{\sqrt{R_M R'}\sin\Psi_j}{1-\sqrt{R_M R'}\cos\Psi_j}, \tag{4}$$

$$\phi = 2\delta_T - \delta_R - \delta_{R'}, \tag{5}$$

$$\Psi_j = 4\pi n_j d\cos\theta'_j/\lambda_j, \tag{6}$$

$$\theta'_j = \sin^{-1}(\sin\theta_j/n_j), \tag{7}$$

where the external and internal film reflectivities are denoted by R and R', the transmission by T and the respective phase changes by δ_R, $\delta_{R'}$, and δ_T; R_M is the rear mirror reflectivity ($T_M=0$ is assumed, for simplicity), n_j and d are the refractive index and thickness of the transparent layer.

In the detuning Ψ_j, (6), a constant due to reflection phase changes has been neglected and the angle θ'_j describes the light beam inclination within the device. To include the thermal effects on the optical thickness we writte

$$\Psi_j = \Psi_j^0\,[1+(\gamma+\alpha)\Delta T] = \Psi_j^0 + \beta_j P_A \tag{8}$$

with

$$\beta_j = \Psi_j^0\,(\gamma+\alpha)C, \tag{9}$$

where Ψ_j^0 is the initial detuning without laser heating, α is the linear thermal expansion coefficient, $\gamma = n^{-1}(dn/dT)$ and C is a constant relating the average temperature rise ΔT with the absorbed power P_A and which depends on the thermal boundary conditions of the active volume [7]. The parameter β_j characterizes the thermal refractive nonlinearity of the intracavity spacer. The absorbed power has to be derived by energy conservation considerations and, in the case of only one input beam, it is given by

$$P_A = P_0^j - P_R^j = (1-\mathscr{R}_j)\,P_0^j = \mathscr{A}_j P_0^j, \tag{10}$$

where P_0^j and P_R^j denote the power of the incident and reflected beams, respectively. As will be shown bellow, the nonlinear response of the system is related to the semireflecting film's ability to change its absorption with Ψ_j through the interference phenomenon. The parametric analysis of (1) reveals that the interference contrast in $\mathscr{R}_j$ and, therefore, in $\mathscr{A}_j$ maximizes as ϕ approaches to 0.

Let us now consider the nonlinear mirror illuminated by two or more light beams of different wavelength, angle of incidence or polarization state ($P_0^j, \lambda_j, \theta_j, n_j; j=1,2,\ldots m$). In the case of a single laser beam with two polarization modes, a birefringent intracavity medium is supposed in order to introduce different detuning for both modes. For simplicity, R, R', T, ϕ, γ and R_M are assumed to be the same for all the input beams.

The reflectivity $\mathscr{R}_j$ for each input beam is even given by (1) with the light beam exclusively characterized by the respective initial detuning Ψ_j^0. It is convenient to introduce the relative detuning $\Delta\Psi_j^0 = \Psi_j^0 - \Psi_1^0$ and write (8) as follows

$$\Psi_j = (\Psi_1^0 + \Delta\Psi_j^0) + (1 + \Delta\Psi_j^0/\Psi_1^0)\,\beta_1 P_A, \tag{11}$$

where β_1 has been also taken as a reference parameter. Usually $\Delta\Psi_j^0 \ll \Psi_1^0$ and then $\beta_j \simeq \beta_1$.

The absorbed power now arises from various light beams whose effects add incoherently because they do not interfere. If we assume that the input power variations affect simultaneously all the holding beams, then the total absorption may be expressed as follows

$$P_A = \sum_{j=1}^{m}(P_0^j - P_R^j) = \mathscr{A} P_0 \tag{12}$$

with

$$\mathscr{A} = \sum_{j=1}^{m} f_j(1-\mathscr{R}_j) = \sum_{j=1}^{m} f_j \mathscr{A}_j \tag{13}$$

where P_0 is the total input power, $f_j = P_0^j/P_0$ and $\mathscr{R}_j$ is given by (1).

The input/output characteristics of the nonlinear mirror may be numerically obtained from the following equations

$$\beta_1 P_0 = \frac{1}{\mathscr{A}(\beta_1 P_A)}\,\beta_1 P_A, \tag{14a}$$

$$\beta_1 P_R^j = \frac{f_j \mathscr{R}_j(\beta_1 P_A)}{\mathscr{A}(\beta_1 P_A)}\,\beta_1 P_A,\ j=1,2,\ldots m, \tag{14b}$$

by using $\beta_1 P_A$ as a dummy variable. The feedback parameter β_1 appears only as a light power scale factor.

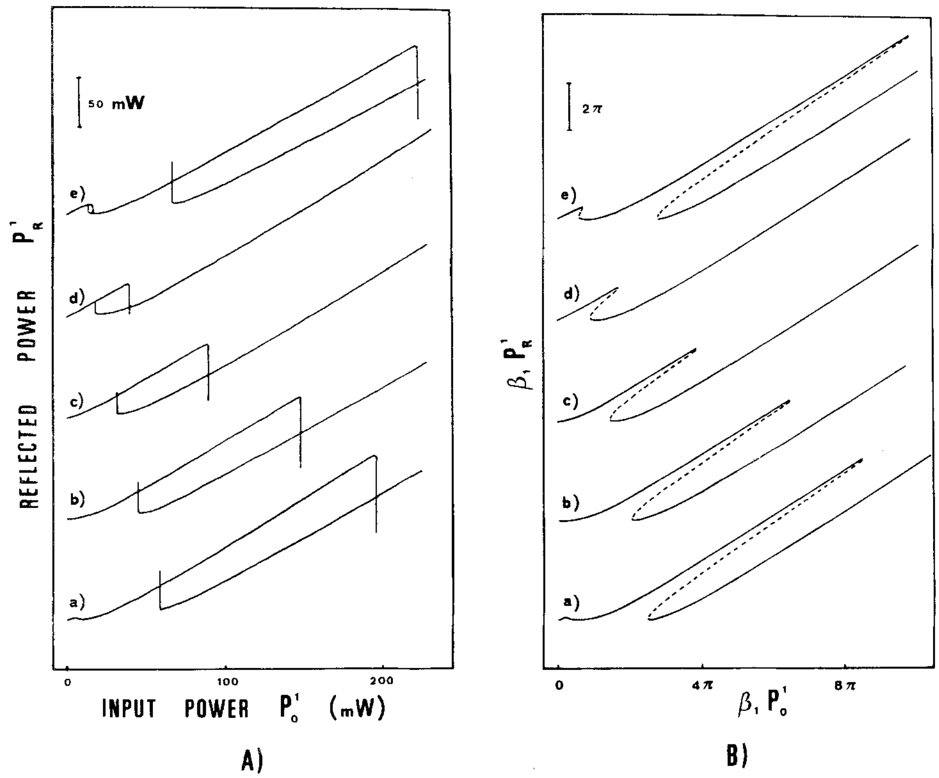

Fig. 2. (A) Experimental input/output characteristics for one-beam operation and different angles of incidence. (B) Calculated input/output characteristics for $R=0.14$, $R'=0.08$, $T=0.46$, $\phi=0.3\pi$, $R_M=0.81$ and $\Psi_1^0=0.05\pi$ (*a*), 0.49 π (*b*), 1.03 π (*c*), 1.5 π (*d*), 1.77 π (*e*)

In addition to this scale factor, it is clear from (14a) that the nonlinear response is determined by the dependence of $\mathscr{A}$ on $\beta_1 P_A$ through the interference phenomenon. For various input beams, such a dependence results strongly affected by the superposition of interference effects in accordance with the relative detuning and intensity of the different light beams.

Results

Experimental demonstrations were performed with a bistable mirror consisting of a 150-μm-thick crown glass plate with a thick layer of aluminium on one side ($R_M=0.81$, $T_M \simeq 0$) and a thin film of nichrome (Ni:Cr, 80:20) on the other side ($R=0.14$, $R'=0.08$, $T=0.46$, $\phi=0.3\pi$). The beam from an argon-ion laser operating on the 514.5 nm line was focused with a $f=50$ cm lens onto the nichrome surface to a spot of about 0.3 mm diameter. Figure 2A shows a set of input/output characteristics for the one-beam operation at different angles of incidence. The corresponding calculated curves (Fig. 2B) point out that, for the case of one input beam, the plane-wave theory describes very well the steady-state response of the bistable device. From the experimental curves of Fig. 2A it is seen that the phase changes associated with the switching jumps and the respective absorbed power jumps are $\delta\Psi_1 \sim 3\pi/2$ and $\delta P_A \sim 36$ mW, respectively, so that the feedback parameter is estimated to be $\beta_1 = \delta\Psi_1/\delta P_A \sim 0.13$ rad mW^{-1} and the switch temperature changes are

$$\delta T = \frac{\lambda}{4\pi n d(\gamma+\alpha)}\,\delta\Psi_1 \sim 72\ \mathrm{K}\,,$$

where $n=1.52$, $\gamma=2\times10^{-6}\,K^{-1}$ and $\alpha=9.3\times10^{-6}\,K^{-1}$ are standard crown-glass parameters.

The two-beam operation was analysed with light beams of distinct incident angle, derived from the same laser beam and with the power varying simultaneously. Each beam was focused with a $f=50$ cm lens to a spot of ~ 0.3 mm diameter. Here, we describe the peculiar case $\Delta\Psi_2^0 \sim \pi$ in which the holding beams suffer opposite interference effects. Figure 3A shows the reflected power of each separate beam as a function of the total input power for $f_2/f_1=0.85$ and with the incident beams forming an angle of 2.3° that corresponds to $\Delta\Psi_2^0=-1.2\,\pi$. Notice the complementary behaviour of both characteristics and the presence of successive hysteresis loops of opposite logic. Figure 3A also shows the behaviour of the total output power which, as in the one-beam operation, always exhibits negative logic loops. The corresponding theoretical curves obtained from (14) are depicted in Fig. 3B. The agreement between experimental and theoretical curves is not so excellent as in the one-beam operation and, as will be shown bellow, this may be related to a defective superposition of the two light spots.

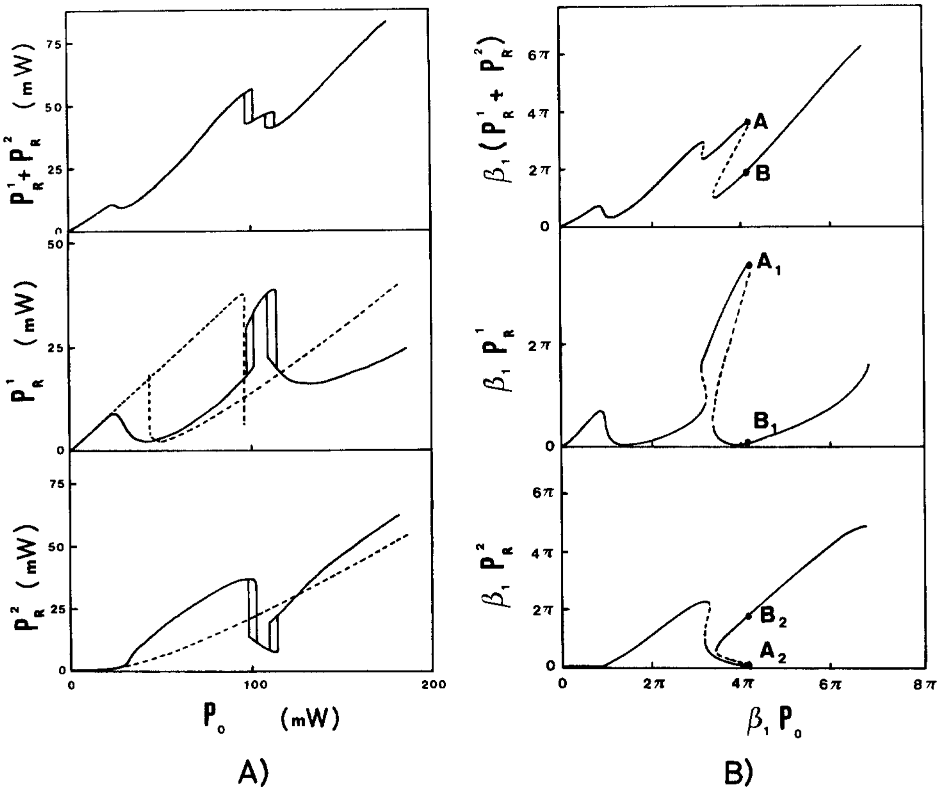

Fig. 3(A). Reflected light powers P_R^1, P_R^2, and $P_R^1 + P_R^2$ as a function of the total input power for the two-beam operation with $\Psi_1^0 = 1.44\,\pi$, $\Delta\Psi_2^0 = -1.2\,\pi$ and $f_2/f_1 = 0.85$. The dashed line describes the reflected power of each beam with the other one screened. (B). Calculated curves corresponding to the experimental results of (A)

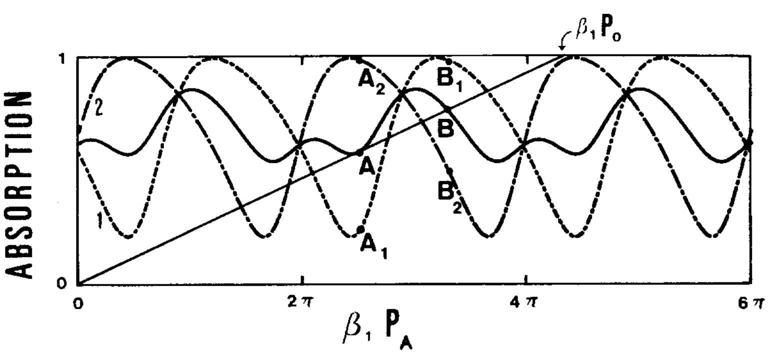

Fig. 4. Graphical solution for the two-beam operation of Fig. 3B pointing out the switch at $\beta_1 P_0 \cong 4.2\,\pi$

In the case of Fig. 3A the switching times occurred on a time-scale of tenths of second, while in the one-beam operation the switch was about ten times faster. The reduction of speed from the one- to the two-beam operation arises from the complementary behaviour of both holding beams in the considered case.

The two-beam operation may be easily understood by means of the graphical solution shown in Fig. 4, which corresponds to the situation of Fig. 3B. For a given input power the steady solutions are determined by the intersections of the straight line with the continuous curve, which respectively represent the two relations between $\mathscr{A}$ and $\beta_1 P_A$ derived from (14a and 13). By changing the slope of the straight line the intersection point gives P_A as a function of P_0. The absorption of each holding beam is obtained from the dashed curves describing the functions $\mathscr{A}_j(\beta_1 P_A)$. For instance, the straight line in Fig. 4 points out the switch at $\beta_1 P_0 = 4.2\,\pi$ in which $\mathscr{A}$ jumps from A to B and $\mathscr{A}_j$ from A_j to B_j, $j = 1, 2$.

Figure 5 shows a set of input/output characteristics of one holding beam for succesively increasing f_2/f_1 ratios and fixed $\Delta\Psi_2^0$ value. It is seen that the second beam originates a gradual shift of the hysteresis cycles towards lower input powers and the appearance of an opposite logic cycle which becomes dominant for $f_2/f_1 > 1$. Such an evolution may be easily interpreted on the basis of the graphical method shown in Fig. 4.

The light spot superposition constitutes a critical point in the two-beam operation with separated beams. Differences in size and shape and any relative displacement between the two light spots cause noticeable effects on the input/output characteristics. As shown in Fig. 6, the gradual diminution of cross coupling between the holding beams leads to an evolution towards the one-beam operation. The results

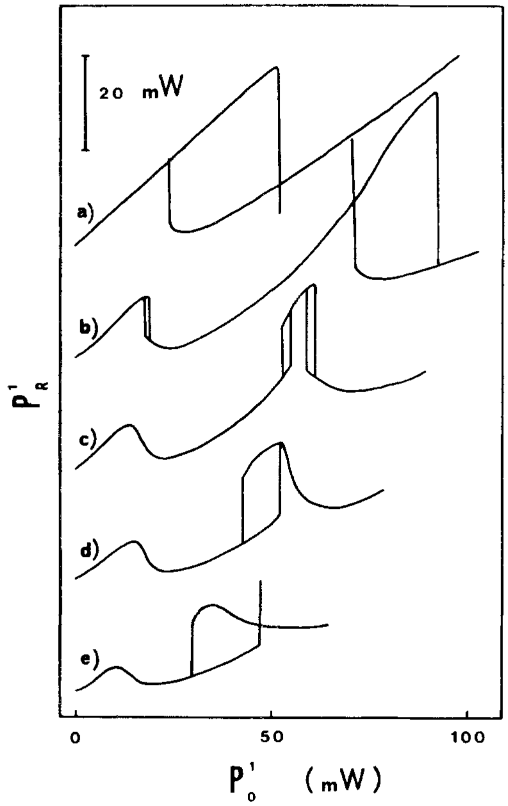

Fig. 5. Experimental characteristics of one holding beam for $\beta_1 = 1.44\,\pi$, $\Delta\Psi_2^0 = -1.2\,\pi$ and $f_2/f_1 = 0$ (*a*), 0.45 (*b*), 0.85 (*c*), 1.04 (*d*) and 1.56 (*e*)

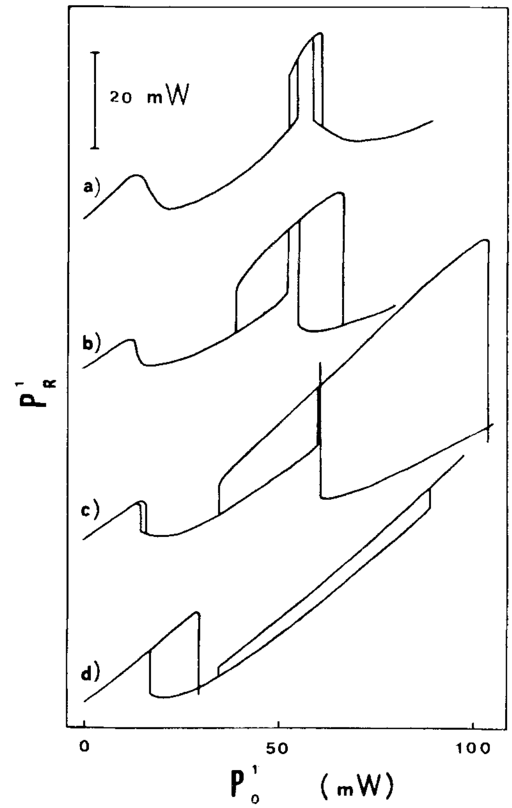

Fig. 6. The same as Fig. 5c for different light spot separation. Optimum superposition (*a*) and one (*b*), two (*c*), and seven (*d*) spot diameters of separation

of Fig. 6 point also out that the thermally active volume has a cross-section diameter of some mm.

Conclusion

In conclusion, we have experimentally investigated several aspects of the two-beam operation of a bistable interferometer with a thermally induced nonlinearity. In agreement with previous theoretical works [3, 4] we found that the presence of two holding beams introduces a variety of responses with potential utility for logical gate designing. In particular, we described the case of two beams in opposite tuning with the interferometer, where each holding beam exhibits successive hysteresis cycles of opposite logic. As discussed by Haus et al. [8], who found a similar double hysteresis loop in optical bistability due to increasing absorption with one holding beam, the double loop can be used for composite logic and multiplexing functions. The two-beam operation introduces more capability for composite logic in a natural way.

From the practical point of view, the two-beam operation based on spatially separated beams does not seems to be as useful as could be the case of an anisotropic device with the two polarization modes of a single laser beam. Besides the absence of beam superposition problems, this kind of two-beam operation is compatible for parallel signal processing and presents the possibility of polarization switching and hysteresis of potential interest for cascadable logic.

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