Bistable oscillations with a self-pumped phase-conjugate mirror

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Optical bistable oscillation beams with a self-pumped phase-conjugate mirror are reported. The results of an experimental demonstration are given, and an explanation based on the threshold of oscillation is presented.

The phenomenon of two-beam coupling in photorefractive crystals can be used to obtain self-pumped phase-conjugate reflection.[1-3] One such reflector involving a ring geometry[3] is shown in Fig. 1. The oscillation takes place in the resonator consisting of the crystal and mirrors M_1 and M_2 with P_0 serving as the pump beam. We refer to this oscillation as the primary one, and it results in the appearance of a phase-conjugate reflected beam P_1. Since P_0 and P_1 are a phase-conjugate pair they should be capable of acting as pump beams for oscillation between a mirror (say M_3) and the pumped crystal.[4] We find that this is indeed the case and that oscillation in an auxiliary resonator (crystal–M_3) takes place that is sustained by the primary oscillation in the ring resonator. We find, however, that if we set up two auxiliary resonators, the second one involving the crystal and M_4, then the two secondary oscillations cannot coexist, the result being a bistable mode of oscillation.

The experimental arrangement is shown in Fig. 1. The argon-ion laser (514 nm, $P_0 = 10$ mW) was operated in a TEM$_{00}$ mode but in a multilongitudinal mode (without étalon) so that the coherent length L_c of the laser beam was about 7 cm. The length of the ring cavity for the primary oscillation was $L = 34.5$ cm. The distances of the two auxiliary mirrors M_3 and M_4 from the crystal were $L_1 = 14$ cm and $L_2 = 20.5$ cm, respectively. These auxiliary mirrors are used to form auxiliary oscillations with the crystal. We note that

$$|L - 2L_i| < L_c, \qquad i = 1, 2,$$
$$2|L_1 - L_2| > L_c. \tag{1}$$

These numbers are important in explaining the observed bistable behavior. Let P_0 be the power of the pumping laser beam, P_1 the power of the reflected phase-conjugate beam, P_2 the power of the beam circulating counterclockwise in the ring cavity, P_3 the power of oscillation between the crystal and mirror M_3, and P_4 the power of oscillation between the crystal and mirror M_4. B_1–B_3 are beam blocks used to study the bistable oscillations. The experimental procedures and results are as follows:

1. Initially B_1–B_3 were inserted, i.e., in the blocking position (● and ○ represent block and unblock in Fig. 2).

2. When B_1 was removed, the primary oscillation built up. The phase-conjugate reflectivity was about 1.26×10^{-2}. The small phase-conjugate reflectivity was due to a slight intentional misalignment of the primary oscillation produced by tilting M_2 horizontally.

3. When B_2 was removed, oscillation between the crystal and M_3 built up, and P_3 increased. Simultaneously, P_1 increased substantially and P_2 decreased. It seems that the auxiliary oscillation at M_3 dominated over the primary oscillation. The reason may be misalignment of the primary oscillation and the self-alignment of the auxiliary oscillation, so that the latter had an effectively larger coupling constant. P_2 decreased because its corresponding grating was partially washed out by the strong auxiliary oscillation beam.

4. When B_3 was removed, the system remained unchanged and no oscillation between the crystal and M_4 was observed.

5. When B_2 was inserted, the intensity of the oscillation at M_3 died out ($P_3 \to 0$) and P_1 decreased drastically, which shows that the major contribution to P_1 came from the oscillation between the crystal and M_3. P_2 increased because of the absence of the auxiliary oscillation, and oscillation at M_4 began to build up. Consequently, P_1 and P_4 increased and P_2 decreased to the steady-state value (same steady-state value as in Ref. 3).

6. When B_2 was removed, the system remained unchanged and no oscillation between the crystal and M_3 was observed.
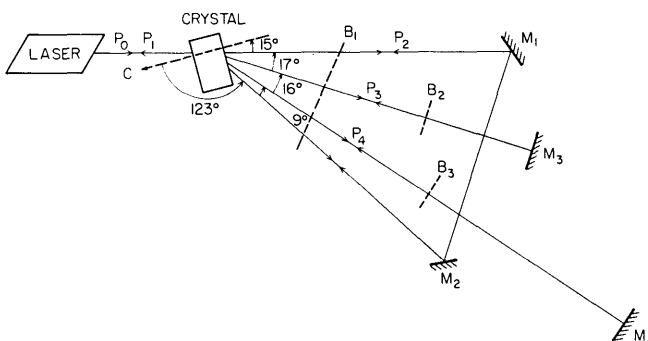

Fig. 1. Experimental arrangement to observe bistable oscillations. M_1–M_4 are mirrors of reflectivity $\simeq 1$. B_1–B_3 are beam blocks.
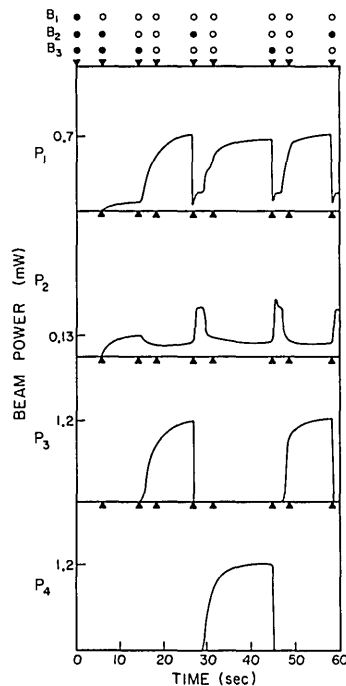
Fig. 2. P_1 is the power of the phase-conjugate beam, P_2 is the power of the beam circulating counterclockwise in the ring cavity, P_3 is the power of oscillation between the crystal and mirror M_3, and P_4 is the power of oscillation between the crystal and mirror M_4. ● and ○ represent B_i inserted and removed, respectively.

This cycle can be repeated indefinitely. We can consider these two auxiliary oscillations as two separate bistable states of the system: When the system, originally at one state, is disturbed, it will switch to the other state and remain in that state even when the disturbance is removed.

A complete theory of this phenomenon would require solution of eight coupled-wave equations. Nevertheless, we can still proceed to a qualitative understanding of the system by making some reasonable approximations.

A necessary condition for oscillation is that after a complete round trip the beam amplitude return to its original value, i.e., gain equals loss. Near the threshold of the auxiliary oscillation, we can assume that the oscillations are pumped by a phase-conjugate pair of beams[5] in the main ring resonator with a beam ratio r given approximately by P_2/P_0. Since the oscillation beams are weak compared with the pumping beams, at the threshold we can use the undepleted-pump approximation. The oscillation condition is then[2]

$$R = \frac{1}{r} \left| \frac{J(0)e^{-\alpha l/2}}{J(0)-1} \right|^2 \geq \frac{1}{MT^2} \simeq 1.24, \qquad (2)$$

where

$$J(0) = \int_0^{\gamma l} \frac{e^{-x} dx}{1 + r^{-1}e^{-\alpha l}e^{2\alpha x/\gamma}} \qquad (3)$$

and M includes the loss due to the finite reflectivity of

the cavity mirror and the loss due to diffraction, T is the Fresnel transmittance of the crystal surface, γl is the coupling constant, and αl is the intensity absorption coefficient of the crystal. In a separate experiment, we measured $\gamma l = 5.2$ and $\alpha l = 1.11$ for the same beam geometry. A theoretical plot of Eq. (2) for $\gamma l = 5.2$ and $\alpha l = 1.11$ is shown in Fig. 3. With the pumping-beam ratio $r = 1.26 \times 10^{-2}$, $R > 1.24$ (point A), and oscillation can occur. Now we can explain why there is no oscillation buildup in step 4 or for step 6. There are two reasons: (a) because of the auxiliary oscillation at M_3, r dropped to 6.63×10^{-3}, and (b) from Eq. (1), the auxiliary oscillation at M_3 was incoherent with the auxiliary oscillation at M_4; therefore P_3 can act as an erase beam for P_4. As a result, the effective coupling constant for the auxiliary oscillation at M_4 was reduced[6]:

$$(\gamma l)_{eff} = \frac{(\gamma l)_0}{1 + \dfrac{\text{erase beam intensity}}{\text{total beam intensity}}}$$

$$\simeq \frac{(\gamma l)_0}{1 + \dfrac{P_3}{P_0}} = \frac{5.2}{1 + \dfrac{1.2}{10}} = 4.64,$$

where $(\gamma l)_0$ is the coupling constant without erase beam. Therefore the net result is $R < 1.24$ (point B), and no oscillation can occur. Step 5 can also be explained in a similar way: when B_2 was inserted, the effective coupling constant increased from 4.64 to 5.2 (point B to point C). The beam ratio r increased gradually as the primary oscillation built up (P_2 increased), and eventually at $R > 1.24$ the auxiliary oscillation began to build up (point C to point A).

If the crystal does not have any prewritten grating except that corresponding to the primary oscillation, then the system does not prefer one oscillation state over the other. A small-intensity probe beam can be used selectively to excite one of the auxiliary oscillations. This was also confirmed experimentally. This bistable oscillation has been used as a thresholding
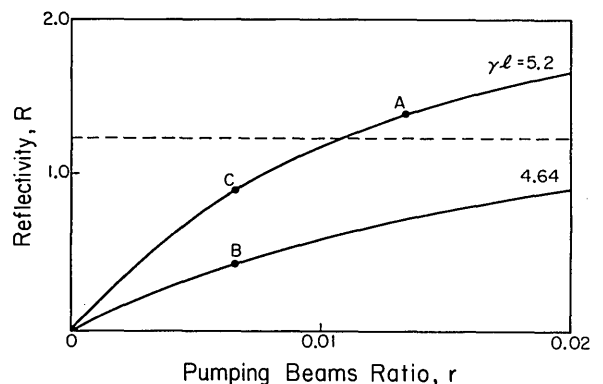

Fig. 3. Theoretical plots of reflectivity R versus ring phase-conjugate mirror reflectivity r for $\gamma l = 4.64$ and $\gamma l = 5.2$. For $R > 1.24$, oscillation can occur.

device in the first reported experimental demonstration of an all-optical associative holographic memory.[6]

Related work on bistability in a self-pumped phase-conjugate mirror with feedback erase beam was also reported recently.[7]

In summary, we have observed bistable oscillations with a self-pumped phase-conjugate mirror. An explanation based on the oscillation threshold concept has been presented. This device has potential applications in optical memory, bistable switching, and image processing.

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