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Optical hysteresis in a semilinear photorefractive coherent oscillator

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Abstract
High contrast optical bistability is found experimentally in the pump-ratio dependences of the output intensity of a semilinear photorefractive coherent oscillator with two counterpropagating pump waves. The data are in qualitative agreement with the results of calculation.

Keywords: optical bistability, frequency degenerate four-wave mixing, coherent oscillators

1. Introduction

Optical bistability in coherent four-wave mixing was predicted long ago (Winful and Marburger 1980, Cronin-Golomb *et al* 1984), and several successful attempts at its experimental observation in coherent oscillators are known: in semilinear geometry with one pump beam (Kwong *et al* 1984), in two-interaction phase conjugate mirrors (Rodriguez *et al* 1987), in optical hexagon generation (Odoulov *et al* 1999) and in other different oscillators (Mamaev and Zozulya 1990, Królikowski and Cronin-Golomb 1991, Petrossian *et al* 1992, Zozulya 1993, Ackemann *et al* 1999). In practically all the above-mentioned experiments, the bistability and the hysteretic behaviour were observed by changing the strength of nonlinear coupling between the pump wave and the oscillation wave. The results of Petrossian *et al* (1992), Ackemann *et al* (1999) and other publications of these groups on the same subject are an exception from this rule: for nonlinear wave mixing in gases the frequency detuning from the resonance is also an efficient control parameter for observing the hysteresis.

For coherent oscillators with two pump waves there exists one more control parameter: the intensity ratio of the two pump waves. It does not influence the nonlinear constant itself, but it strongly affects the amplitude of the three-dimensional (3D) refraction index gratings that self-develop in the medium. From the experimental point of view it is quite often easier to manipulate this parameter than, for example, the coupling strength; the whole procedure is reduced in this case to the control of the pump intensities.

It should be underlined however that not all the coherent oscillators (and then not always) show optical bistability. According to calculations (Mathey *et al* 2007), bistability is expected in a semilinear photorefractive oscillator with transmission gratings while it is impossible if reflection gratings couple the pump and the oscillation waves. The other sensitive condition is the necessity to ensure rather small cavity losses: for $\gamma\ell < 2.493$ the width of the optical hysteresis diminishes with the increased losses until it disappears completely (Mathey *et al* 2007). For too large coupling strength, $\gamma\ell \geqslant 2.493$, mirrorless oscillation should occur, which prevents the observation of optical hysteresis.

Figure 1 gives an example of the calculated dependences of the oscillation intensity as a function of the pump intensity ratio $r = I_2(\ell)/I_1(0)$ for several values of the crystal coupling strength and the high reflectivity of a conventional cavity mirror (Mathey *et al* 2007). Here $I_2(\ell)$ and $I_1(0)$ are the intensities of the pump waves at the input faces of the sample and ℓ is the sample thickness.

One can see that with the increase of the coupling strength a range of pump ratios with two-valued solutions appears and becomes wider. Just within this range the oscillation intensity can either be zero or take a value in the branch shown by the solid line (the unstable solution is shown by dashes). If the pump ratio is gradually and slowly increased the oscillation will last until the end of the stable solution is reached (solid line). With a further increase of the pump ratio the oscillation intensity suddenly drops to zero. From this state, if the pump

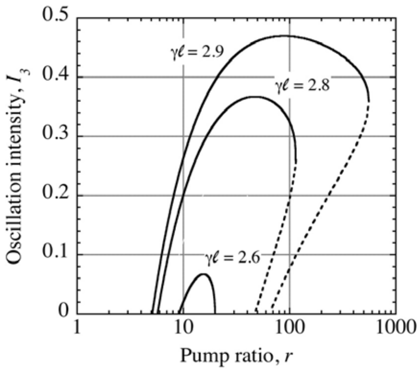

Figure 1. Calculated dependences of the output oscillation intensity on pump intensity ratio for coupling strength $\gamma\ell = 2.6$, 2.8, 2.9 and conventional mirror reflectivity $R = 0.4$.

ratio is decreased the oscillation will reappear only at the value of the pump ratio for which the unstable branch takes zero value; in other words, optical hysteresis will be observed.

2. Experimental evidence

To study such a behaviour the semilinear oscillator shown in figure 2 was selected. Cobalt-doped $BaTiO_3$ (20 ppm in the melt) with the dimensions $a \times b \times c = 3.7 \times 4.0 \times 6.1$ mm^3 or silver and iron co-doped $KNbO_3$ with the dimensions $a \times b \times c = 8.4 \times 4.3 \times 7.0$ mm^3 (Evans *et al* 2006) was used as photorefractive crystal. The cw Ar^+-laser beam (TEM_{00}, no etalon inside the cavity, $\lambda = 514$ nm) is sent to the sample from the right (pump wave 2). The transmitted beam is retroreflected to the sample with a conventional highly reflecting mirror M_1 forming in such a way the pump wave 1. The spherical mirror M_2, with 50 cm radius of curvature, is placed 25 cm from the photorefractive crystal. This mirror forms, together with the photorefractive crystal, PRC, a semilinear cavity. The axis of the cavity makes an angle of about 4° with the direction of the pump propagation. The sample is tilted with respect to the pump waves to 45°. A converging lens with the focal length $F = 100$ cm is placed in pump wave 2 at a distance 100 cm from the mirror M_1. This ensures the phase conjugation of the two pump waves inside the sample: the two spherical wave fronts have the same curvature with opposite signs. With the above-mentioned orientation of the pumps and oscillation waves in the sample the expected coupling strength evaluated as proposed by Fainman *et al* (1986) is $\gamma\ell \approx 2.45$.

To control the pump intensity ratio two crystalline polarizers and a half waveplate are placed between the photorefractive sample PRC and the mirror M_1. The detection of the optical hysteresis requires careful adjustment and control of the pump ratio providing that all the other parameters of the oscillator are kept unaffected. Any technical factors that can result in the disappearance or a considerable decrease of the oscillation intensity must be eliminated. In addition, the rotation velocity of the half waveplate must be sufficiently small to ensure an adiabatic variation of the pump ratio. To satisfy these conditions the rotation of the half waveplate is accomplished by a step motor that guarantees a half waveplate rotation velocity down to 2 min of arc per second and a smallest change of angle equal to 0.45 s of arc. A PC-controlled data acquisition system is used to record the intensity measurements from the two photodetectors D_1 and D_2.

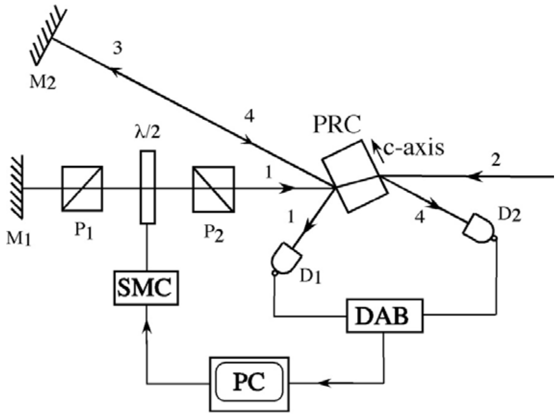

Figure 2. Schematic representation of the experimental arrangement. The laser beam arrives at the photorefractive crystal (PRC) from the right and the transmitted beam is returned back to the sample by a mirror M_1. Thus two counterpropagating pump waves, 1 and 2, are present in the sample. The polarizers P_1 and P_2 with the half waveplate $\lambda/2$ are used to adjust the pump ratio. The oscillator cavity is closed by a spherical conventional mirror M_2. The detectors D_1 and D_2 continuously monitor the intensity of the oscillation wave and the intensity of the pump wave 1, respectively. All light beams are polarized in the plane of the drawing. The arrow near the sample indicates the orientation of the crystal polar axis. The computer (PC) collects and stores the measured data with the help of the data acquisition board (DAB); it also governs the pump ratio variations via the step motor control system (SMC).

The optical length between the photorefractive sample PRC and mirror M_1 is equal to that of the cavity length (the distance between PRC and M_2). With this condition fulfilled, the path difference of the wave reflected from mirror M_1 (pump 1) and the wave reflected from mirror M_2 (oscillation wave 4) is zero, which ensures an efficient recording of the transmission photorefractive gratings. At the same time the path difference between the pump wave 2 and the oscillation wave 4 in the sample is 50 cm, i.e., much larger than the coherence length of the Ar^+-laser and different from the double path length of the Ar^+-laser cavity (220 cm). In such a manner the appearance of the reflection grating is excluded.

With the above experimental arrangement the dependence of the oscillation intensity $I_4(0)$ (detector D_2) versus the half waveplate rotation angle is measured with the permanent monitoring of pump 1 intensity (detector D_1). This allows us to calculate the dependences of the oscillation intensity on the pump ratio r, both for increasing and decreasing pump ratios. An example of such a dependence is shown in figure 3(a). A pronounced hysteresis loop is easily seen in this graph. However, particular care must be taken with the interpretation of this result because of the possible influence of transient effects: it is well known that when the oscillator is close to the threshold the build-up time of oscillation increases drastically because of critical slowing down (Mathey *et al* 2001). Thus when increasing the pump ratio we can have a 'tail' of oscillation that slowly decays even after the threshold is passed. In the same manner, when decreasing the pump ratio we can have a delay in build-up that will look like a smaller threshold value of the oscillation onset. Both effects

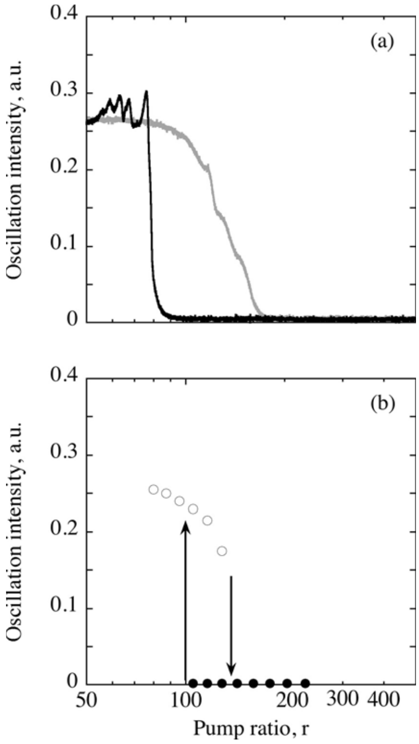

Figure 3. Experimental dependences of the oscillation intensity in $BaTiO_3$ versus pump intensity ratio obtained with the rotation of the half waveplate by a step motor (a) and by manual adjustment of discrete positions for the half waveplate. The data for increasing pump ratio are shown by the grey line in (a) and open dots in (b), while the black line and filled dots correspond to the decreasing of the pump ratio.

will expand the hysteresis loop as compared to its true width. Moreover, they can create an apparent hysteresis loop.

To avoid such misinterpretation we performed the following procedure. The motion of the step motor was programmed in such a way that we started from a pump ratio giving a well developed oscillation and stopped at an angle that ensured a pump ratio within the hysteresis loop shown in figure 3(a) or not far away from the loop. At the moment when the motor is stopped the oscillation certainly exists. Then it may decay to zero or reach (after certain time) a steady-state value. If it vanishes we mark in figure 3(b) only one zero-value steady state by a filled dot. If the nonzero steady state is reached we mark this value by an open dot in figure 3(b), and check if it is possible to reach this value from a zero intensity of oscillation. To do this, the oscillation is stopped by introducing a shutter inside the cavity and leaving it closed for a sufficiently long time to erase all the gratings responsible for oscillation. After that the shutter is removed and the system once again has two physical possibilities, either to return to a nonzero steady state or to remain with no oscillation. If the oscillation does not occur, this proves the bistability, and we mark the corresponding second stable state in figure 3(b), which is zero valued, by a filled dot. A comparison of figures 3(a) and (b) confirmed the bistable operation in the pump-ratio range in question, obviously with somewhat reduced width of hysteresis loop.

The optical hysteresis and bistability were also observed in a silver and iron co-doped $KNbO_3$ (Evans *et al* 2006). This

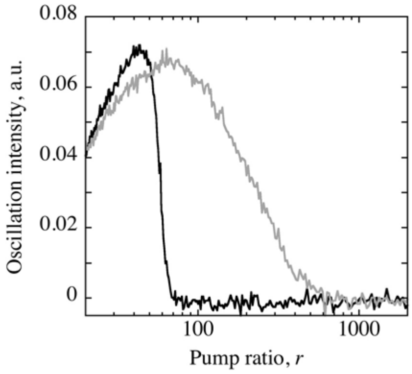

Figure 4. Experimental dependence of the oscillation intensity in $KNbO_3$ versus pump intensity ratio obtained with the rotation of the half waveplate by a step motor. The data for increasing pump ratio are shown by the grey line while the black line corresponds to decreasing pump ratio. The coupling strength is reduced by an incoherent light illumination of the sample.

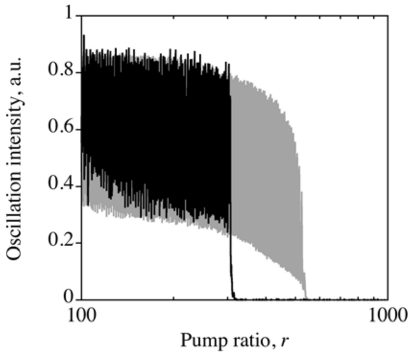

Figure 5. Experimental dependence of the oscillation intensity in $KNbO_3$ versus pump intensity ratio obtained with the rotation of the half waveplate by a step motor. The data for increasing pump ratio are shown by the grey line while the black line corresponds to decreasing pump ratio.

crystal possesses a much smaller response time as compared to $BaTiO_3$:Co (several hundreds of milliseconds instead of several seconds) and therefore the technique with permanently rotating the half waveplate is even more suitable for the observation of the optical hysteresis. Figure 4 shows an example of hysteresis curve that is obtained with the sample illuminated, in addition to with an Ar^+ laser beam, with an incoherent light source (halogen lamp). This was done to reduce the coupling strength and to avoid the oscillation being nondegenerate in frequency (Mathey *et al* 2002). The behaviour is similar to that observed with $BaTiO_3$:Co (see figure 3(a)).

At sufficiently high coupling strength (no incoherent illumination) and relatively small reflectivity of the conventional cavity mirror M_2, the oscillation intensity has a deep intensity modulation that proves a simultaneous excitation of two modes shifted in frequency. The reason for the appearance of the frequency split was discussed by Mathey *et al* (2002). There is no analytical solution for the dependence of the oscillation intensity versus the pump ratio when the oscillation is nondegenerate. From the experimental data (see figure 5) we can conclude that the hysteresis is also present in the nondegenerate case.

The optical arrangement of figure 2 can be transformed easily to ensure the recording of only the reflection gratings: it is sufficient to move the mirror M_2 to the right from the sample and to adjust the cavity angle to the maximum of the gain factor of two-beam coupling with reflection gratings (see, e.g., Mathey 2005). We observed the oscillation in such a geometry but no bistability was detected with all the other experimental conditions kept identical to those described above. This is in accordance with the results of the calculations of Mathey *et al* (2007); on the other hand it confirms that the transient effects that are due to the critical slowing down do not dominate in the formation of the hysteresis loops in our experiments.

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