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Supplementary optical phase transition in photorefractive coherent oscillator

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Abstract

The semilinear photorefractive coherent oscillator with two counterpropagating pump waves may exhibit two optical phase transitions: one from a disordered state of wide-angle photorefractive scattering into a high-ordered state with the immobile photorefractive grating and the other one from the state with immobile grating into the state with two moving photorefractive gratings. We show, both experimentally and from calculations, that two these phase transitions are the second-order phase transitions. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Photorefraction; Optical phase transitions; Phase conjugation

1. Introduction

The semilinear coherent oscillator with two counterpropagating pump waves was proposed in [1] and first implemented with photorefractive $BaTiO_3$ [2]. A sample pumped with two conjugate counterpropagating waves is a phase conjugate mirror for any coherent signal wave; it may therefore form the coherent oscillator with the usual mirror that reflects the output (phase conjugate) wave into the sample as a signal wave. The steady-state characteristics of oscillation (threshold coupling strength, output intensity and frequency) can be calculated from the condition that the intensity of oscillation wave remains unchanged after one cavity round trip, $R \cdot R_{pc} = 1$, where R and R_{pc} are the usual mirror reflectivity and phase conjugate reflectivity of the crystal. To find the threshold of oscillation it is sufficient to use R_{pc} calculated in undepleted pump approximation while for the study of well-developed oscillation one should use the complete solution of nonlinear problem [3].

2. The order–disorder phase transition: threshold of coherent oscillation

We calculate at first the coupling strength dependence of the oscillation intensity for strictly degenerate nonlinear wave mixing in a medium with the diffusion-driven charge transport ($\pi/2$-shifted photorefractive gratings). The details of calculation will be published elsewhere [4]. The main conclusions are as follows: (1) two branches with the nonzero oscillation intensity exist, one describing the oscillation with the finite threshold value of the coupling strength and the other with the infinite threshold, resembling the known

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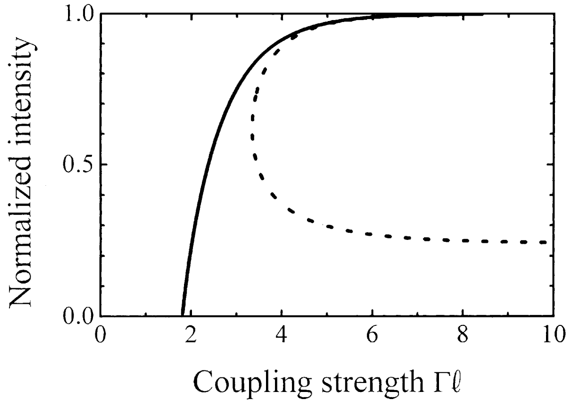

Fig. 1. Calculated coupling strength dependence of ocillation intensity.

solution [5] for semilinear oscillator with only one pump wave; (2) the first solution with the finite threshold is single-valued in a wide range of pump intensity ratio and therefore describes the soft mode of oscillation onset; (3) the first solution with the finite threshold becomes double-valued for the intensity of backward propagating wave smaller than ≈0.01 of the forward pump intensity, i.e., hard mode of oscillation and hysteresis effects [6] are not excluded in principle but very hard to observe. These results lead to the conclusion that the onset of oscillation in the considered coherent oscillator in a wide range of parameters is similar to the second order phase transition [4]. Fig. 1 shows the coupling strength dependence of the oscillation intensity for pump ratio 1:0.1 and highly reflecting cavity mirror, $R = 1$.

3. The supplementary phase transition: bifurcation in frequency spectrum

Until now only the frequency degenerate interaction has been considered, i.e., we supposed that the oscillation wave temporal frequency is exactly the same as that of the pump wave. As the oscillation wave self-develops in the coherent oscillators from the noise with broad frequency content and is not restricted, in case of semilinear oscillator, by the discrete spectrum of the optical cavity the additional arguments are necessary in favour or against the postulate on frequency degenerate oscillation.

In usual lasers the oscillation spectrum is imposed by the frequency profile of the gain medium and dispersion of the cavity losses. In a similar way, the oscillation in coherent oscillator occurs at those frequencies Ω for which the threshold condition $R \cdot R_{\mathrm{pc}}(\Omega) = 1$ is satisfied at the smallest coupling strength. Neglecting the spectral dependence of losses within the interval of the order of the reciprocal dielectric relaxation time we come to conclusion that the threshold oscillation frequencies will correspond to the maxima of the phase conjugate reflectivity spectrum $R_{\mathrm{pc}}(\Omega)$.

From calculations presented in [7] it is known that the largest phase conjugate reflectivity is reached at $\Omega = 0$ only for relatively small values of the coupling strength. Starting from a certain critical value of the coupling strength (that depends on pump intensity ratio [8]), the spectrum $R_{\mathrm{pc}}(\Omega)$ splits and two maxima appear, symmetric with respect to the pump frequency (Fig. 2). For the optimized pump ratio $r = \exp(\gamma\ell)$ the splitting occurs at $\gamma\ell = 3.83$. The bifurcation is subcritical, only one Ω corresponds to any particular value of $\gamma\ell$. Therefore this transformation of the spectrum is analogous to the second-order phase transition.

As distinct from the primary phase transition where the disordered state with arbitrary oriented low-amplitude space charge gratings is changed to the ordered state with only one grating of much

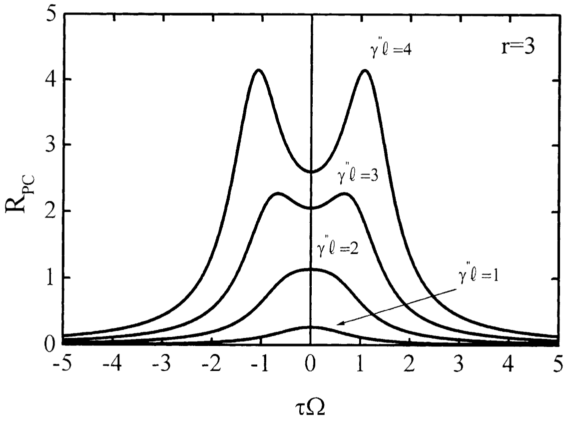

Fig. 2. Phase conjugate reflectivity R_{pc} versus normalized frequency detuning $\tau\Omega$.

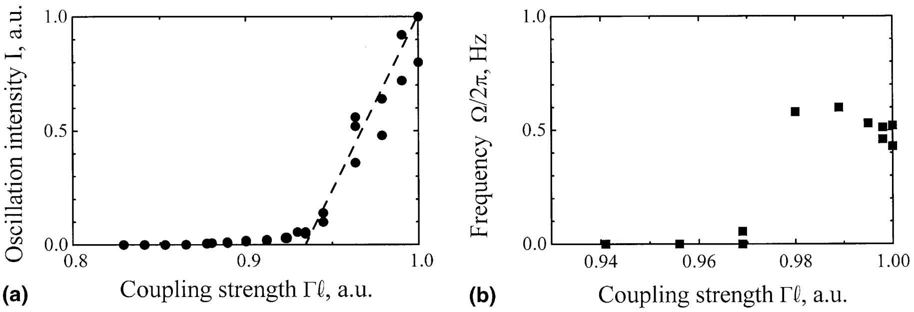

Fig. 3. Coupling strength dependences of the oscillation intensity for primary phase transition (a) and of the beat frequency in oscillation spectrum for supplementary phase transition (b).

higher amplitude, the secondary phase transition marks transformation from one ordered state to the other. Below the second critical coupling strength the dominant space charge grating is immobile and therefore there is no Doppler frequency shift in the oscillation wave diffracted from this grating. Above the supplementary phase transition the one immobile grating is replaced by two space charge gratings with the same grating vectors but moving with a certain speed in opposite directions. Two diffracted waves propagate in the same direction but with different Doppler shifts; as a result the oscillation wave acquires a high-contrast intensity modulation.

It should be reminded that the threshold of primary phase transition is imposed by the cavity losses only, $R_{\mathrm{pc}} = 1/R$ while the threshold of supplementary phase transition depends on pump intensity ratio and becomes smaller with r approaching unity. This may lead to an interchange in the sequence of the events with the increasing $\gamma\ell$: for large values of the pump ratio the oscillation may occur with the splitted spectrum already at threshold of primary transition.

4. Experimental verification

The semilinear coherent oscillator is built with $BaTiO_3$: Co sample measuring $4.5 \times 4.5 \times 2$ mm^3. The TEM_{00} multifrequency Ar^+-laser radiation is used to prevent the recording of the reflection gratings. All light beams impinge upon the sample in the plain that contains its optical axis and are polarized in the same plane. The pump wave comes to the sample nearly normally to its input face, the cavity axis makes the angle 40° with respect to the pump wave.

Fig. 3(a) represents the measured coupling strength dependence of the oscillation intensity. It can be seen that oscillation intensity is gradually increasing with coupling strength in accordance with our expectations (Fig. 1). Together with the observation of critical slowing down [4] in the photorefractive scattering below the primary threshold the observed behaviour of the steady-state oscillation intensity proves the analogy to the second-order phase transition.

Fig. 3(b) represents the measured coupling strength dependence of the beat frequency in the oscillation wave. Once more, the gradual increase of Ω near the supplementary threshold points to the similarity to the second-order phase transition.

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