Optical multivibrator

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Abstract: The unusual temporal dynamics of a semilinear optical coherent oscillator based on tin hypothiodiphosphate crystal ($Sn_2P_2S_6$, SPS) is described. The periodic non-harmonic modulation of the oscillator output intensity is revealed, with the pulse duration that depends on the overthreshold coupling strength and grating decay times. The pulse width changes in a wide range, decreasing closer to the threshold of oscillation. It is proved experimentally that every next pulse in a sequence is -shifted in phase with respect to the previous one while within each pulse the phase of the oscillation wave is constant. This suggests the analogy of the observed behavior to the optical multivibrator. The origin of this phenomenon nests in competition of two species of movable charge carriers in formation of the space charge grating.
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Introduction

SPS crystals have advantage of combining the fast response time (millisecond range) with rather high gain factor in red and near infrared region of spectrum [1]. They were successfully used for light amplification, phase conjugation and for coherent optical oscillation [2]. Quite often these crystals feature a pronounced competition of two space charge gratings, one formed with the light induced holes and the other which appears because of thermally excited motion of electrons [1,3]. The competition of two out-of-phase gratings with dramatically different decay times results in splitting of spectrum of a steady state gain factor into two maxima shifted symmetrically to the pump wavelength [4]. For coherent oscillators with the unclosed cavities this leads to appearance of two components in oscillation spectrum and to sinusoidal in time intensity modulation [5]. The frequency shift between the oscillation modes scales in this case as square root of the pump intensity.

In present paper we report on a new type of oscillation dynamics for unclosed semilinear coherent oscillator with two counterpropagating pump waves. The temporal envelope of oscillation intensity in saturation consists of a sequence of regular nonsinusoidal pulses with -shift in phase in every new pulse with respect to the previous one. The model that describes this new mode of operation is presented and its predictions are compared with the experimental results. The gain factors of two out-of-phase gratings that are evaluated from the threshold of coherent oscillation fit well to those measured directly from two-beam coupling experiments. The pulse duration calculated from these data taking into account the known decay time for the slow grating is in reasonable agreement with experimentally observed.

Experimental observations

The studied crystals of nominally undoped tin hypothiodiphosphate have been grown via gas transport reaction [6] in the Institute of Physics and Chemistry of the Solid State, University of Uzhgorod, Ukraine. The sample cut along the crystallographic axes measures 9 x 9 x 4.5 mm^3, it has optically finished faces normal to the Z-direction. The sample K3 belongs to the type I crystals [7] with a

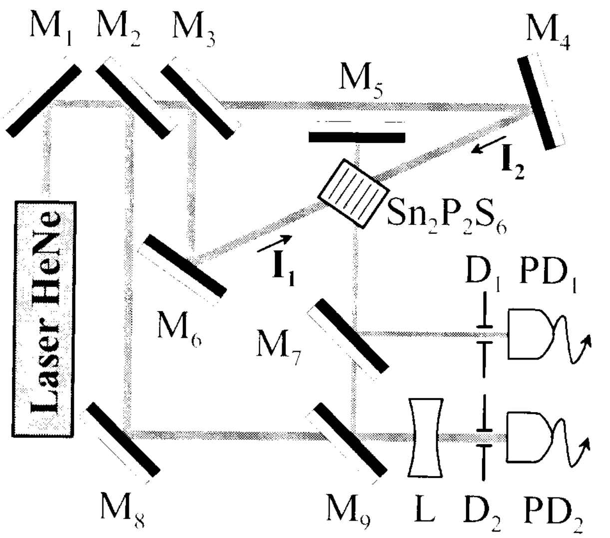

Fig. 1. Schematic of the experimental set-up. M: mirrors; D: apertures; PD: photodiode.

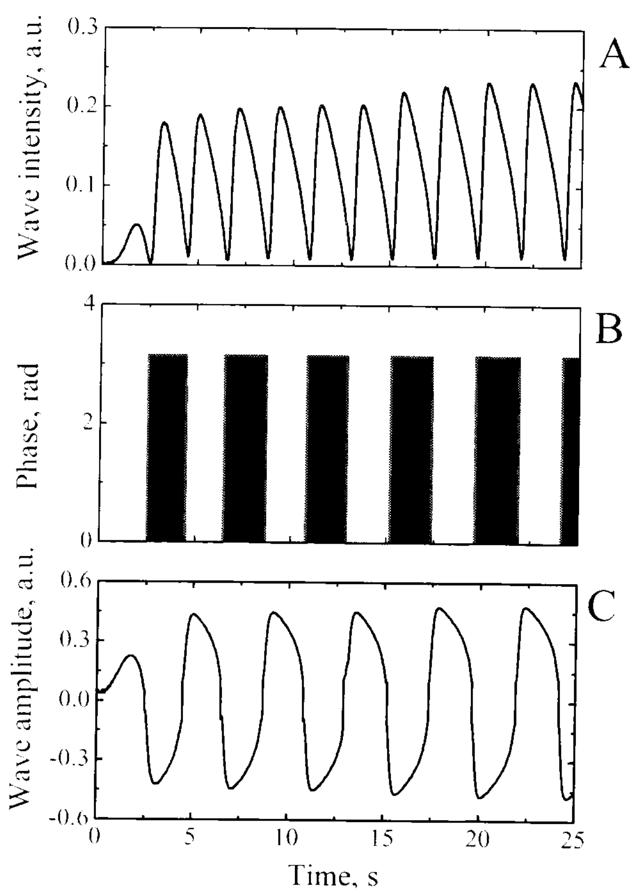

Fig.2. Temporal variation of (A) oscillation wave intensity, (B) phase, and (C) amplitude

pronounced contribution of secondary carriers to the grating formation. It is poled by application of an external field of about 1 kV/cm when the sample is heated to 90^{0} C.

A Helium-Neon laser with a 40 mW TEM_{00} output beam is used as a light source with the polarization in plane of drawing of Fig.1. The counterpropagating pump beams from M_4, M_6 are passing through the sample. With two pump beams SPS sample serves as a phase conjugate mirror and can form a cavity together with conventional mirror M_5 with reflectivity R. The oscillation occurs if all cavity losses are compensated by the amplified reflectivity of phase conjugate mirror R_{pc}, i.e.,

$$R_{pc} R = 1, \qquad (1)$$

(see, e.g., [8].) The sample is aligned so that its X axis is parallel to the grating vector of the selfdeveloping photorefractive grating. The mirrors M_2, M_8 and M_9 are used to check the stability of the fringe pattern from the oscillation wave and reference (pump) wave. The oscillation intensity is measured with the detector PD_1.

With this arrangement the oscillation was achieved, with the dynamics shown in Fig.2a. Every time when oscillation disappeared between two consecutive pulses the fringe pattern changed its position to half-period, i.e., its contrast was reversed. Within every pulse the position of fringes remained the same. This allows to construct the time variation of the oscillation wave phase (Fig.2b) and the temporal variation of the oscillation wave amplitude (Fig.2c). These variations, as one can see, are far from being sinusoidal. Figure 3 represents the pump ratio dependences for the oscillation intensity (a) and pulse duration (b). The oscillation intensity disappears rather abruptly at certain threshold values of pump ratio; the pulse duration also diminishes at the threshold. It is known that coupling strength in SPS is intensity dependent [1]. That is why the oscillation starts only when pump intensity is above a certain

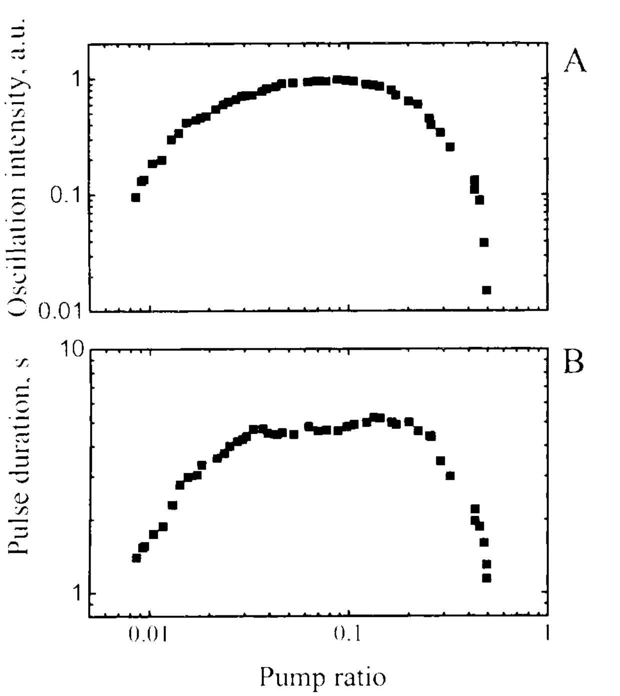

Fig.3. Pump ratio dependence of (A) oscillation intensity and (B) pulse duration. Pump intensity is 2.5W/cm^2

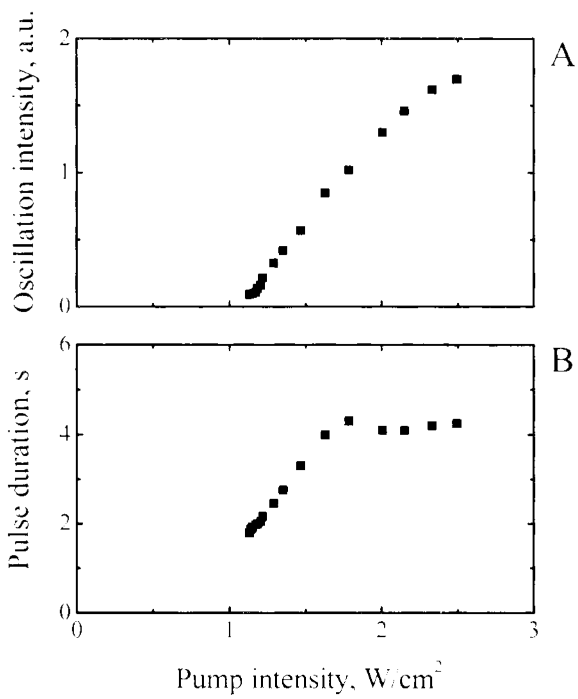

Fig.4. Pump intensity dependence of (A) oscillation intensity and (B) pulse duration. Pump ratio is 0.08

threshold value (about 1 W/cm^2 Fig.4a). It is clear from Fig.4b that pulse duration is diminishing if the pump intensity is decreasing to its threshold value.

Description of the model

We believe the oscillation dynamics can be explained in a following way: After beginning of illumination of a virgin sample with the pump wave at $t = 0$ the fast grating starts to develop because of the light induced redistribution of holes. Let us suppose that the instantaneous gain factor $(t) = 2\ (t)$ is proportional to the refractive index change at this particular moment $n(t)$. Then the gain spectrum is a Lorentzian with the FWHM equal to reciprocal decay time of the fast grating, $1/\ _F$. During the time interval equal to several $_F$ the gain is increasing up to its ultimate value shown in Fig.5a, when it becomes slightly above the threshold level (shown by dashed line). The oscillation appears and the phase of the oscillation wave is arbitrary (as for all photorefractive coherent oscillators with unclosed cavities), defined by the fluctuations that lock the initial fast grating inside the sample.

When the fast grating is already well developed the slow grating forms gradually, with much longer characteristic time $_S$. It is out-of-phase with respect to the phase grating and therefore the gain factor which is due to this grating is negative. The relevant spectrum has also Lorenzian shape but with much smaller FWHM equal to $1/\ _S$ (in Fig.5 we took relatively small difference between $_F$ and $_S$ for demonstration purpose only). The overall gain spectrum features a dip at zero detuning frequency, its maximum value diminishes and may drop below the threshold value (Fig.5b). If so, the oscillation disappears within the time interval of several $_F$ (erasure of the fast grating). The slow grating during this time remains practically unchanged and relevant gain spectrum is shown in Fig.5c. This remaining (slow) space charge grating diffracts the pump wave into the semilinear cavity; it is important to underline that the

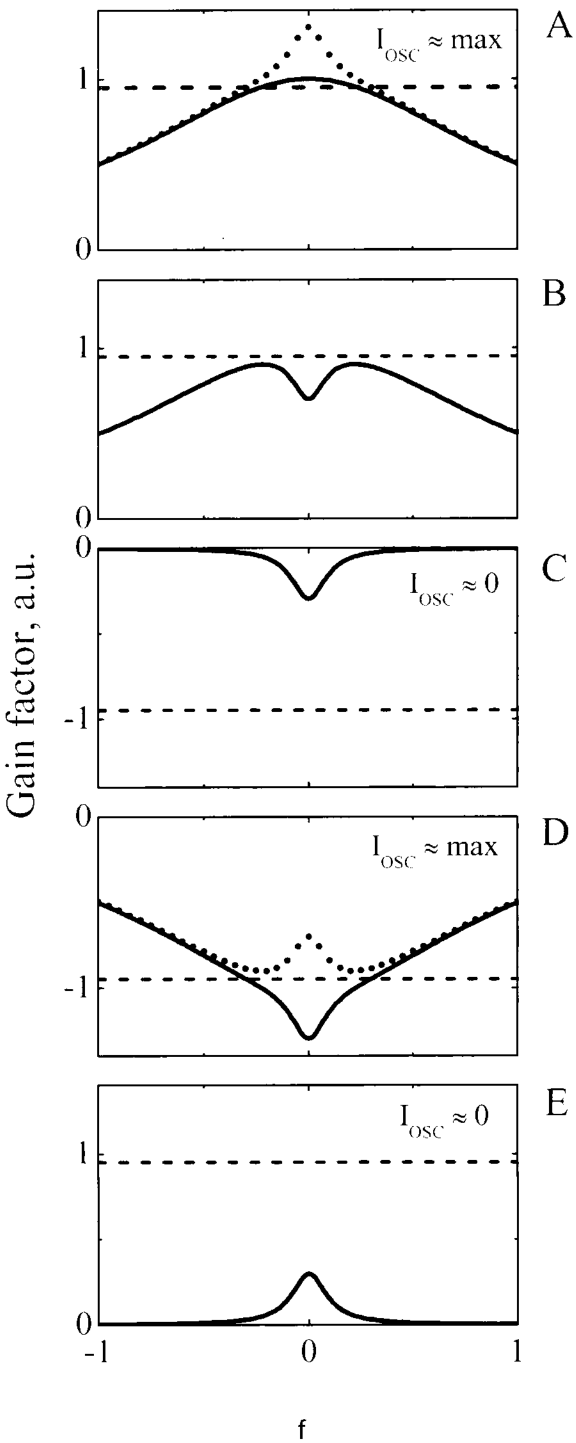

Fig.5. Gain factor versus frequency detuning. The dashed line shows threshold level. The dot shows changes of gain factor (solid line) due to formation of slow grating

phase of this diffracted wave is now -shifted with respect to the phase of oscillation wave in previous pulse.

The diffracted wave serves as a strong seed with well defined phase for the development of a new fast grating -shifted with respect to the initial fast grating. In such a manner two gratings, fast and slow, appear to be *in phase* and mutually enhance each other (solid profile in Fig.5d).

Further on the fast grating saturates and the electrons start to move to compensate the existing space charge field, i.e., to build up a new slow out-of-phase grating. Gradually an additional peak on flattop of gain spectrum transforms into a deep (dots in Fig.5d) and oscillation disappears once more. Now the remaining slow space charge grating gives small gain, which is positive (Fig.5e). This seed will give rise to the development of the next oscillation pulse. The only difference with respect to the very first oscillation pulse will be in somewhat increased gain factor as shown by dots in Fig.5a. Then the same cycle is repeated continuously. Note that one period of pulsation includes two intensity pulses with two different phases, 0 and .

In such a way in saturation the oscillation occurs in two modes that differ only in phase of the oscillation wave. When one mode is oscillating the other one is blocked; at the same time the oscillation of one mode introduces gradually the losses for itself (decreases gain factor) and improves, with the same rate, the gain for the other oscillation mode. This behaviour is similar to the self-oscillation in Abraham-Bloch multivibrator [9] that consists of two electronic amplifiers with the input of one of two feeded from the output of the other one.

The pulse duration in this model depends on the decay time of a slow grating and on over-threshold coupling strength. The closer is the gain to its threshold value the smaller time is necessary to develop out-of-phase grating which will put whole system below the threshold. This is why the pulse duration becomes smaller when above-threshold gain is diminishing. This behaviour is quite different from already known two-frequency coherent oscillation in the ring-loop oscillator [5] where the period of oscillation goes to infinity when approaching the threshold.

Numerical estimates

Taking into account that the phase conjugate reflectivity depends on coupling strength ℓ and pump intensity ratio r [8]

$$R_{pc} = \frac{\sinh^2 \frac{\ell}{4}}{\cosh^2 \frac{\ell}{4} + \frac{\ln r}{2}}, \tag{2}$$

it is possible to get several important parameters from the comparison with the experimental data presented above.

From Fig.3a it is possible to extract the value of pump ratio that optimizes the output oscillation intensity, r_{opt} = 0.07. It is reasonable to suppose that this value corresponds to largest possible phase conjugate reflectivity (Eq.2) at a coupling strength ensured by photorefractive sample, i.e., $\ell = 2\ln r_{opt}$ Thus we obtain for the coupling strength of a fast grating $(\ \ell)_{fast} \approx -5.3$.

The threshold values of r where oscillation disappears ($r_1 = 0.008$ and $r_2 = 0.5$) give an independent way to evaluate $(\ \ell)_{fast}$. The oscillation threshold corresponds to one and the same value of R_{pc} that is equal to $1/R$. This allows to write that $2\ln r_1 - \ \ell = \ \ell - 2\ln r_2$ and to get the ultimate value for coupling strength which is $(\ \ell)_{fast} \approx -5.5$ and coincides within 5% with the previous one. In addition, Eq.2 provides a value for the effective reflectivity of conventional mirror that incorporates all kinds of cavity losses: $R = 0.78$.

All these estimates are related to the fast component in grating recording because it is responsible for the oscillation switch-on at the threshold. The estimates for slow component can be done from the known pulse length in coherent oscillation. Neglecting the difference in Debye lengths for movable charge carriers we can write for dynamics of slow grating [4]

$$(\ \ell)_{slow} = \ \ell^{max}_{slow}\,[1 - \exp(-t/\ _s)] \approx \ \ell^{max}_{slow}\,(t/\ _s). \tag{3}$$

Taking the running time t equal to the pulse length t we get $\ell^{max}_{slow} = \ \ell^{max}_{fast}\,(\ t/\ _s)$. With t = 5 s, $\ell^{max}_{fast} = 5.4$ and $_s = 15$ s the slow grating can develop up to $\ell^{max}_{slow} = 1.8$.

Figure 6 shows the gain spectrum

$$\ell(\ \ ) = [\ \ \ell^{max}_{fast}/(1 + (\ \ /\ _f)^2\,]\ \ \ [\ \ \ell^{max}_{slow}/(1 + (\ \ /\ _s)^2\,], \tag{4}$$

=2 f being a frequency detuning of the oscillation wave. As it can be seen in strictly degenerate case (negligibaly low detuning frequencies in Fig.6) the overall gain is switching between two ultimate positions determined by positive and negative signes in Eq. 4.

The horizontal dashed line gives in the same figure the value of the threshold coupling strength, which appears to be slightly above overall gain for the case of destructive addition of two gratings. Thus the suggested model is confirmed by these estimates. Every time when the developing out-of-phase grating reduces ℓ to the threshold value the oscillation disappers and fast grating decays within 40 ms. At the

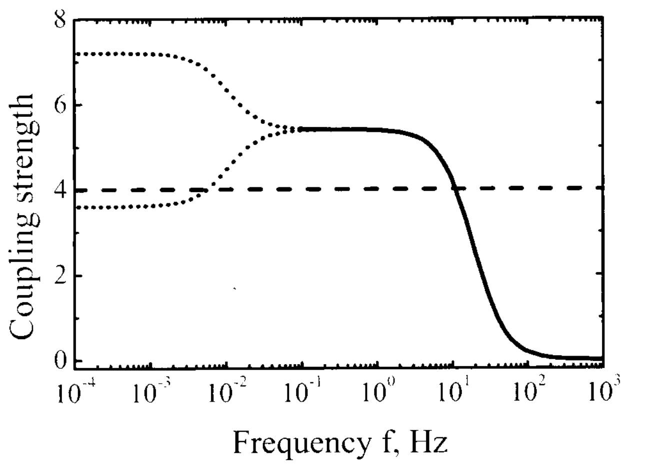

Fig.6. Coupling strenght versus frequency detuning.

same time much more inertial slow grating still exists and is seeding the development of a new fast grating, which is, naturally, in-phase with the seeding one. The gain in Fig.6 „jumps" to the upper branch and remains there until fast grating is saturated. Then new slow grating, -shifted with respect to initial one develops and moves gain down to the threshold level. The oscillation disappears and new period of pulsation is started.

It is obvious that the reported periodic pulsations reveal the interaction which is non-degenerate in frequency. It is important however that this regime is qualitatively new and can not be reduced to the known sinusoidal modulation of the oscillation intensity, with only two symmetric oscillation frequencies in the spectrum [5]. It appears and can compete with the known regime [5] because at least for a half of the pulsation period the gain factor is larger than that for the steady state two frequency oscillation.

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