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ALL-OPTICAL SELF-OSCILLATIONS IN AN INTERFERENCE FILTER

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Abstract. Interference filters, consisting of a thin plate of lithium niobate as a central layer with different absorptive and nonabsorptive multilayers deposited on both sides of the plate, are investigated. A bistable switching and self-oscillations are observed in the case of absorbing coatings. The performed numerical modeling gives an explanation of the obtained experimental results.

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1. Introduction

We investigate structures of the type: $(\mathrm{HL})^N(m\mathrm{M})(\mathrm{LiNbO_3})(m\mathrm{M})(\mathrm{LH})^N$, where the layers H(ZnS) and L(Na_3AlF_6) are nonabsorptive quarterwave either at Ar^+ (514.5 nm) or He–Ne (632.8 nm) laser wavelengths layers with high and low refractive indices, respectively. N ($N = 2$ or $N = 3$) is an integer that represents the number of (HL) periods in the stack, and mM represents the absorptive (ZnSe, $m = 8$) or the nonabsorptive (ZnS, $m = 1$) m-multiple quarterwave layer. The $LiNbO_3$ plates are c- or x-cut with a thickness of 0.7–1.0 mm. The surrounding medium is air. Filters with different numbers of periods N are manufactured to compare the influence of mirror reflectivity. The two mM layers can be either absorptive or nonabsorptive to clarify the influence of self-heating. Samples with a glass plate (≈ 1.0 mm thick) instead of a $LiNbO_3$ that have a similar finesse are also manufactured to clarify the role of photorefractivity. Self-oscillations of the transmitted intensity I_{out}, are observed experimentally for a constant input intensity I_{in}, from an Ar^+ laser ($\lambda = 514.5$ nm).

When there are absorptive layers and an anisotropic photorefractive layer (plate) in an interference filter construction its spectral characteristics and dynamical behavior is considerably modified. From one hand, the absorbed power leads to a temperature change in the whole structure and to consequent changes in the optical thickness of the multilayer structure, so an overdistribution of the temperature influence takes place. In this way, an internal feedback is realized and the phenomenon optical bistability is observed. On the other hand, the photorefractive material as a central layer leads to the presence of photorefracive effects as beam fanning. The combination of thermooptical and photorefractive effects in multilayer interference structure determines the appearance of self-oscillations even at relatively low incident powers (40 – 100 mW) and suitable focusing [1, 2]. Experimentally the following relations are established:

- at x-cut of the crystal when its optical axis lies in the crystal plane and is perpendicular to the incident plane, there is an essential photorefrative beam fanning effect;
- at x-cut of the crystal again and when its optical axis lies in the crystal plane but is in the incident plane there is not photorefrative beam fanning effect;
- when the optical axis lies in the incident plane and it is perpendicular to the crystal surface, i. e. c-cut of the crystal, the photorefrative beam fanning effect is not observed;
- when the crystal plates are without coatings, (x- or c-cut), or they are deposited with nonabsorptive coatings, independently of the presence of beam fanning effect (x-cut) the optical switching is not observed.

The reason for the beam fanning effect is the coupling of the incident power and the scattered beam (surface roughness, inhomogeneities, impurities) [3]. Usually for laser beams with a moderate power the scattered power increases with time and after time t_r a stationary scattered picture is reached [3]. Our experimental results give values for t_r in order of seconds while the time τ (the bistable thermooptical switching characteristic time) is in the order of 250 – 500 ms. Obviously, in the cases of the crystal plates without coatings or deposited with nonabsorptive coatings the beams overlap is not enough for the two-wave coupling, respectively for the arising of internal high level feedback, i. e. for creating of optical switching. The multilayer coatings allow increasing the power of the scattered light by temperature and, in this way, to ensure a considerable overlapping. This in turn, modifies the temperature influence and leads to a change of the internal thermooptical feedback and so on.

2. Experimental Results

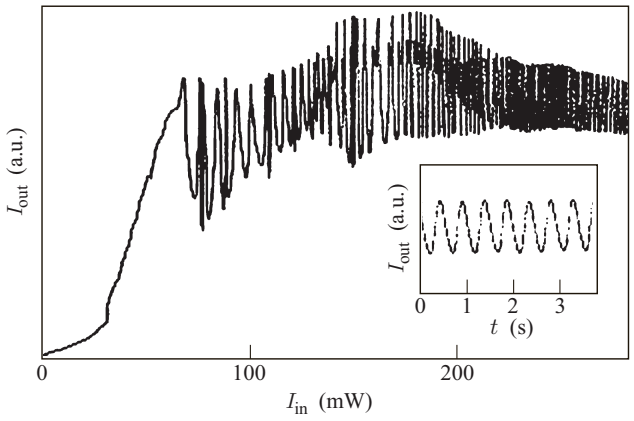

Fig. 1. Output intensity I_{out} plotted versus the input intensity I_{in} of $(HL)^3(8M)(LiNbO_3)(8M)(LH)^3$ structure (M denotes ZnSe)
Self-oscillations appear in the switched-on state. The inset shows self-induced oscillations in time at a constant input intensity I_{in}. The $LiNbO_3$ is x- cut; $\lambda = 514.5$ nm; $f = 70$ mm

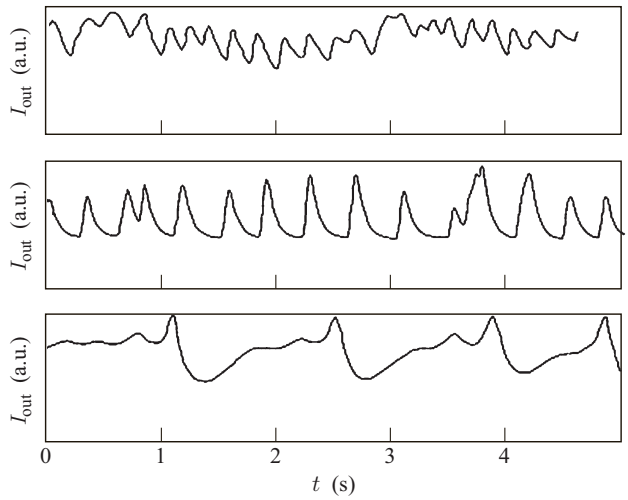

Fig. 2. Particular realizations of pulsations of the output intensity I_{out} over time of $(HL)^3(8M)(LiNbO_3(8M)(LH)^3$ structure (M denotes ZnSe)
The $LiNbO_3$ was x-cut; $\lambda = 514.5$ nm; $f = 70$ mm

Self-oscillations of the transmitted intensity I_{out} are observed experimentally for a constant input intensity I_{in} generated by an Ar^+ laser ($\lambda = 514.5$ nm). Figure 1 shows the transmitted light intensity plotted as a function of the input intensity. The appearance of self-oscillations in the switched-on state is clearly visible.

In Fig. 2 different types of self-oscillations are shown for a constant input intensity. Such types of self-oscillations with a frequency of 1–2 Hz for similar experimental conditions and input intensities have been observed many times. Their shape depends strongly on the input intensity, the focusing f, the angle of incidence θ, and the reflectivity of the resonator ($n = 2$ or $n = 3$). Because of this high sensitivity to the experimental conditions, it is difficult to reproduce a particular type of self-oscillations.

3. Discussion and Conclusions

When a laser beam with an intensity, I_{in} falls on the structure the temperature change is ΔT and it depends on the density, specific heat and temperature conductivity k in mW cm^{-1}K^{-1}.

According to [4, 5] the basic thermoconductivity equation in first approximation is reduced to a first order differential equation with a characteristic time τ. In the stationary case (we assume zero ambient temperature) the basic equation for the all-optical bistability is

$$T = \frac{I_{\text{in}}}{2\sqrt{\pi} r k} A(T) \tag{1}$$

where r is the laser beam radius and $A(T)$ is the interference structure absorption for a fixed incident light polarization. We examine the p-polarization and assume that in the internal feedback a delay exist, connected with the photorefraction in the anisotropic filter layer. The thermodynamically bistable behavior of the system, as a result of photorefractive processes modifies after the time t_r. We presume that the absorption at the moment t is determined by the system state at the former moment $t - t_r$. Small perturbation $\delta T(t)$ around the equilibrium point Eq. (1) is taken into account and, with an accuracy to the first order, a characteristic equation is obtained:

$$\tau \frac{\partial}{\partial t}(\delta T) + \delta T = \frac{I_{\text{in}}}{2\sqrt{\pi} r k} \left(\frac{\partial A}{\partial T} \right)_{T^*} \delta T(t - t_r)\,. \tag{2}$$

Setting $\delta T(t) = \text{const}\ \mathrm{e}^{s_i t}$, where s_i is complex, follows:

$$s_i + 1 = \frac{I_{\text{in}}}{2\sqrt{\pi} r k} \left(\frac{\partial A}{\partial T} \right)_{T^*} \exp(-s_i c) \tag{3}$$

Here $c = t_r/\tau$. The region where $c > 1$ is interesting. This region corresponds to the experiment. s_i are the eigenvalues of the differential equation. $\mathrm{Re}(s_i)$ and $\mathrm{Im}(s_i)$ are determined from Eq. (3), where $s_i = x_i + y_i$ and we set:

$$B = \frac{I_{\text{in}}}{2\sqrt{\pi}rk}\left(\frac{\partial A}{\partial T}\right)_{T^*} .$$

Then are obtained correspondingly:

$$\begin{aligned} x_i + 1 &= B\cos(cy_i)\exp(-cx_i) \\ y_i &= -B\sin(cy_i)\exp(-cx_i) . \end{aligned} \tag{4}$$

The independent solutions for $\mathrm{Re}(s_i)$ and $\mathrm{Im}(s_i)$ and the cross points of the two curves family give a consistency of points. Each couple solutions mean correspondingly:

- the real part is the amplitude of the oscillations(amplification or damping);
- the imaginary part is the oscillation frequency.

When $\mathrm{Re}(s_i) > 0$, for each eigenvalue s_i the system is unstable, i. e. the system is in the oscillations regime [6]. However, to obtain the type of the oscillations it is necessary to solve the ordinary differential equation with a delay, for example, by Runge-Kutt method. This approach is remarkable because at $t_r = 0$ (i. e. there is not delay connected to the time for the arising and developing of beam fanning effect) from (4) is obtained: $\mathrm{Im}(s_i) = 0$. Since, in the case of an isotropic central layer or anisotropic one c-cut, there is not a beam fanning effect, no oscillations are observed. This corresponds to the experimental results. When $t_r = 0$ only the thermal mechanism for all-optical switching takes place.

We investigate numerically the system behavior when $t_r \neq 0$ for different points of the hysteresis curve and for different delays. The points position on the hysteresis curve we determine by the parameter B. The values of this term show whether the system is in upper (switched-on) or lower (switched-off) state. For a definite interference structure and a certain temperature $T^($ the quantity $\left(\frac{\partial A}{\partial T}\right)_{T^*}$ is determined exactly and its position on the hysteresis curve is given by

$$\frac{I_{\text{in}}}{2\sqrt{\pi}rk}$$

i. e. by the relation between the incident light intensity and the laser beam radius (the focusing).

It is seen from the presented curves that a system (Fig. 3*a*) in the switched-on state possesses at least one mode with $\mathrm{Re}(s_i) > 0$, i. e. the system state is

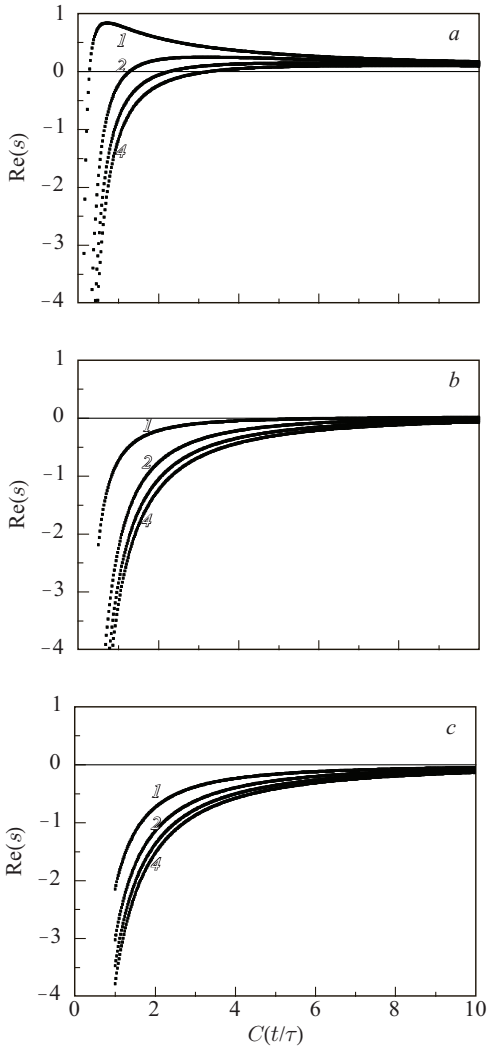

Fig. 3. The calculated dependence of $\mathrm{Re}(s_i)$ (only the first four modes are investigated, correspondingly the curves 1, 2, 3 and 4) on the delay time
(a) $B = -6.371$, the system is in switched-on state, far from the transition points; (b) $B = -0.794$, the system is in switched-on state, near the transition point from a lower into an upper state; (c) $B = +0.529$, the system is in switch-on state near the transition point from an upper into a lower state

unstable and it is in the oscillations regime. Increasing the quantity B, even though the system is in switched-on state, all modes are with $\mathrm{Re}(s_i) < 0$ and oscillations are not observed (Fig. 3*b* and *c*). We performed the investigations of the hysteresis curve for points in its negative slope. Again positive values for the real part of the eigenvalues for each mode are obtained, i. e. the system is unstable.

The obtained numerical results displayed in Fig. 3 are for a relatively wide range of the delay time. Of special importance are those delay values for which $\mathrm{Re}(s_i)$ change sign, i. e. the real roots of Eqs (4) change from negative to positive, at least for the first mode. In other words, such values of the delay time are interesting for which the system is unstable, $\mathrm{Re}(s_i) > 0$. In the cases when $\mathrm{Re}(s_i) < 0$ the system is stable and they are not interesting from the point of view of oscillations in the investigated structure. Thus it is interesting to determine the minimal delay time when $\mathrm{Re}(s_i) = 0$. From (4) we determine:

$$C = -\frac{\frac{1}{B}\arccos\frac{1}{B}}{\sin\frac{1}{B}} \tag{5}$$

And from this the following conclusions are derived:

- Since the delay time is positive, the negative value of C corresponds to unrealized system states. The detailed numerical analysis shows that $C < 0$ is obtained for the points on the negative slope of the curve.
- Since the delay time is a real quantity, it is necessary to fulfill the condition

$$\left|\frac{1}{B}\right| < 1 \qquad \text{or} \qquad |B| > 1\,. \tag{6}$$

When (6) is satisfied the system is unstable. In the opposite case the system is stable. This corresponds to the positive slope of the hysteresis curve in the lower (switch-off) state and in a part of upper branch.

The detailed numerical analysis shows that when

$$\frac{I_{\text{in}}}{2\sqrt{\pi}rk}\left|\frac{\partial A}{\partial T}\right|_{T^*} < 1 \tag{7}$$

the system is stable and the oscillations are not observed. This result coincides $t_r \neq 0$ with the criteria in [7].

The dependence of the minimal delay time on the ratio between incident light intensity and laser beam spot radius is presented in Fig. 4. The smaller the ratio (I_{in}/r) the longer delay time is necessary for the self-oscillations to appear. At a fixed ratio "intensity-radius" each delay time value corresponding to a point situated above the curve in Fig. 4, leads to self-oscillations of the

system. If the delay time is in the region below the curve (Fig. 4) the system is stable and correspondingly no oscillations are observed.

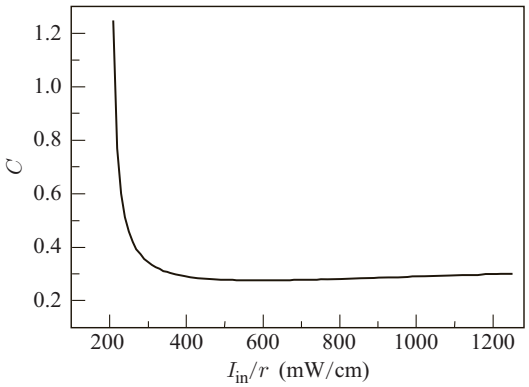

Fig. 4. The dependence of the minimal delay time on the ratio $\frac{I_{in}}{r}$

From (7) it follows that at

$$\frac{I_{in}}{r} > \frac{2\sqrt{\pi}k}{\left|\frac{\partial A}{\partial T}\right|_{T^*}} \tag{8}$$

the system is unstable and is in the oscillations regime. This condition gives possibility to estimate the necessary ratio between the incident light intensity and the focusing for creation of oscillations.

The roots of the equation system (4) are negative up to a certain value of the ratio intensity/radius (point A where the inequality (8) starts to hold) and hence the system is in the stable state. Further increasing of the ratio intensity/radius gives three real roots for each mode and depending on the delay time they are entirely negative, negative and positive or entirely positive. When the ratio intensity/radius reaches B the roots are only positive. It is easy to explain the presence of three roots between the points A and B taking into account that in the Eqs. (4) the quantity B depends on the temperature through the derivative of the absorption at a fixed ratio intensity/radius. We note, as seen from Fig. 5*a*, that for delay times corresponding to the points situated below the curve in Fig. 4 all roots are negative, and so the system is stable (as it was already mentioned).

Upon decreasing the ratio intensity/radius the system consequently passes from an oscillating to a stable state, accompanied by changing the oscillation frequencies which follows from the imaginary roots behavior (Eqs 4) but it is not presented here. These dependences are observed experimentally too. Increasing the incident light intensity (or respectively, decreasing the beam

spot radius) and the beam fanning has been developed, the system switches on with a jump and self-oscillations start. At further decrease of the intensity the oscillations persist, as they change their type, up to the system transition into switched-off state (Fig. 1). These experimental results can be understood from the dependences in Fig. 5.

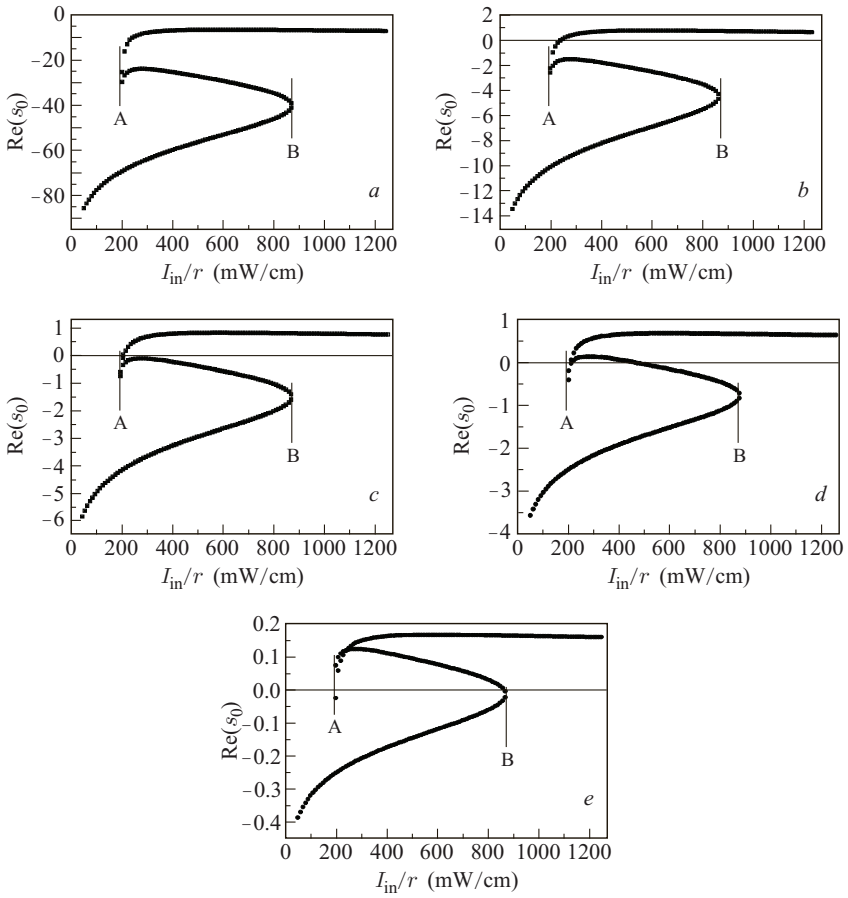

Fig. 5. Dependences of $\mathrm{Re}(s_0)$ (first mode) on the ratio intensity/radius for different delay times

(a) $C = 0.1$; (b) $C = 0.5$; (c) $C = 1.0$; (d) $C = 1.5$ and (e) $C = 10$

In conclusion, we would like to point out that the performed numerical investigation gives only a qualitative notion for the observed effects in the combination of the phenomena all-optical bistability and photorefraction. Nevertheless,

these investigations offer primary (for first time) picture for the self-oscillations arising in an interference thin-layers structure. The more detailed analysis needs fundamental approaches for the interaction between photorefraction and bistability that are under discussion yet.

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