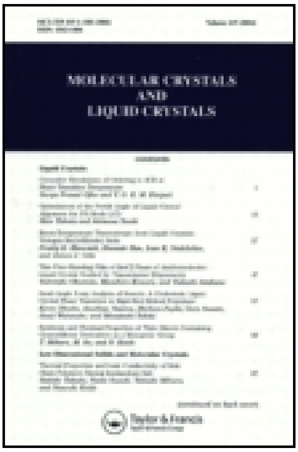

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OBSERVATION OF OPTICAL FREEDERICKSZ TRANSITION IN A RESONATOR

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Abstract

A nonlinear Fabry-Perot resonator (FPR) with a homeotropically aligned nematic liquid crystal (NLC) is experimentally investigated. Specific nonlinear optical features of this kind of FPR are connected with the threshold character of light beam orientational interaction with the NLC. Optical Freedericksz transition, bistability, power limiting and stabilization are realized for small radiation intensities. Transverse pattern formation and rich dynamics are observed.

INTRODUCTION

Optical resonators with nonlinear intracavity materials are very attractive candidates for optical devices such as switches, limiters and logical elements [1]. Investigations of nonlinear FPR´s and other optical feedback systems are motivated also by the possibility of observations of complex phenomena of transverse pattern formation and nonlinear dynamics [2,3].

Investigations of FPR´s with NLC´s as nonlinear intracavity material were presented in a number of articles [4-10]. The main advantageous property utilized in those investigations was the "giant optical nonlinearity" of NLC´s. That allowed observations of optical bistability, pattern formation and other effects with low power cw lasers.

The goal of the present paper is to reveal peculiarities of nonlinear FPR´s originating from the qualitatively distinguishing feature of the orientational optical nonlinearity of NLC´s, namely, the threshold character of NLC´s reorientation in certain experimental geometries (optical Freedericksz transition (OFT)). A simple analysis presented by Akopyan et al.[11] showed a possibility of power stabilisation over an extremely wide range of radiation intensities. However, that analysis neglected transverse and temporal instabilities.

In the present paper, we perform experimental investigations of OFT in a FPR. We observe pattern formation and nonlinear dynamics phenomena inevitably present and accompanying each other in high intensity regimes.

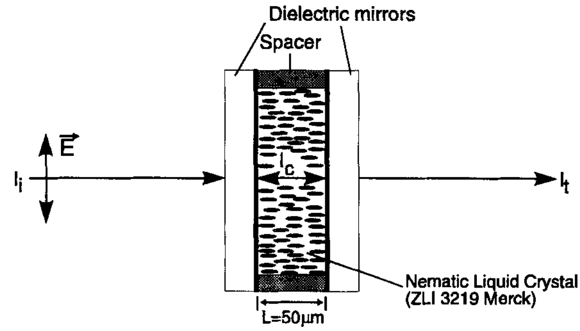

FIGURE 1: The principle of a Fabry-Perot resonator filled with homeotropic alligned nematic liquid crystal.

Fig. 1 shows the principle. The nonlinear material is a homeotropic aligned NLC (ZLI 3219, Merck) sandwiched directly between two dielectric mirrors. The light beam incidents normally to the FPR. Note that a similar situation was explored by Lloyd et al.[6] where, however, special care was taken to utilize only thermal nonlinearity of the NLC. Stress out that we are aimed at the threshold reorientation effect.

SIMPLE THEORY

Neglecting transverse effects and describing the NLC as a thin phase object with an intensity dependent refractive index, the intracavity intensity I_c in the resonator can be represented as an Airy function

$$I_c = \frac{(1+R)}{(1-R)} I_t = \frac{(1+R)}{(1-R)} \cdot \frac{\tau_{max}}{1 + F\sin^2(\phi)} I_i \qquad (1)$$

where I_i denotes the input and I_t the transmitted intensity; R is the mirror reflectivity and τ_{max} is the maximal transmission of the resonator, depending on the internal losses V of the FPR : $\tau_{max} = V((1-R)/(1-RV))^2$. The finesse $\mathcal{F}$ of the FPR is given by $\mathcal{F} = \pi/2\sqrt{F} = \pi(1-RV)^{-1}\sqrt{RV}$.

The total phase $\phi = \phi_0 + \phi_{ind}$ in Eq. (1) is the sum of the linear phase ϕ_0 and the induced phase ϕ_{ind} due to OFT in the NLC. This ϕ_{ind} strongly depends on the excess of the intracavity intensity I_c over the well known OFT threshold I_{th} [12]

$$\phi_{ind} = \begin{cases} \rho\left(\frac{I_c}{I_{th}} - 1\right) & \text{for } I_c > I_{th} \\ 0 & \text{for } I_c \leq I_{th} \end{cases} \qquad (2a)$$

$$I_{th} = \frac{c\varepsilon_{II} K_3}{\varepsilon_a \sqrt{\varepsilon_\perp}} \left(\frac{\pi}{L}\right)^2 \qquad (2b)$$

$$\rho = \frac{2\pi}{\lambda} L \frac{\varepsilon_a \sqrt{\varepsilon_\perp}}{2\varepsilon_{II}\left(1 - \frac{9\varepsilon_a}{4\varepsilon_{II}} - \frac{K_3 - K_1}{K_3}\right)} \qquad (2c)$$

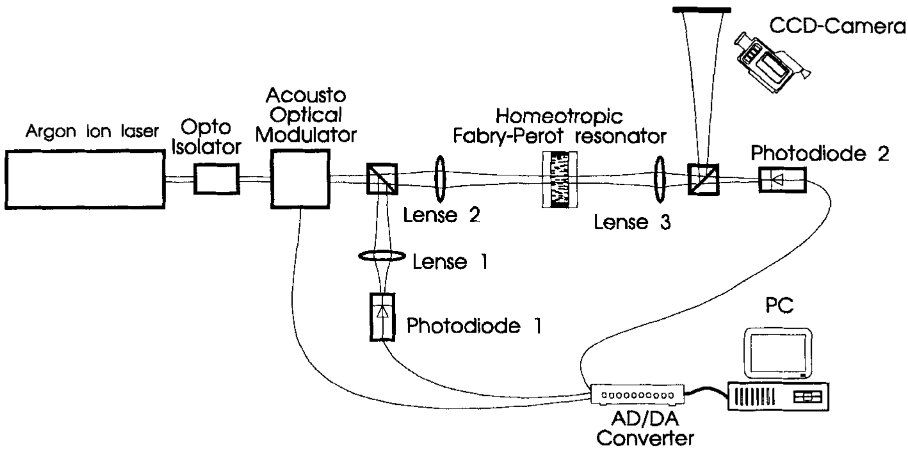

FIGURE 2: The experimental setup

Here K_i are the Franck elastic constants; L is the NLC-layer thickness; λ is the wavelength; $\varepsilon_\perp$ and ε_{II} are the dielectric constants perpendicular and parallel to the optical axis; $\varepsilon_a = \varepsilon_{II} - \varepsilon_\perp$ is the dielectric anisotropy; and c is the light speed in vacuum.Typically I_{th} is 10 kW/cm^2 and ρ is about 10^2.

Depending on the intensity I_c one can have the following two situations. First, $I_c < I_{th}$, the intracavity intensity is lower than the OFT threshold. Then Eq. (1) describes a linear dependence. In case the intracavity intensity exceeds the OFT threshold, $I_c \geq I_{th}$, molecular reorientation takes place inducing a phase shift ϕ_{ind}.

Above the OFT threshold, the behaviour of the resonator depends on the initial detuning phase ϕ_0. This is the modulo π phase difference to a resonance of the FPR. An increase in I_i increases the total phase $\phi = \phi_0 + \phi_{ind}$ if $\phi_0 > 0$. This gives a negative feedback leading to power stabilization and limiting effects. In the case of $\phi_0 < 0$, the phase ϕ increases with I_i, thus driving the system closer to the maximum transmission with $\phi = 0$. Therefore I_c increases by positive feedback until the system jumps to a state with high transmission. There $\phi > 0$ and the negative interaction stabilizes the output for further increase of I_i. Now a decrease in I_i reduces I_c until the system jumps into the state with low transmission, showing hysteresis. Thus the system is optically bistable.

EXPERIMENT

Fig. 2 shows the experimental setup. The resonator shown in Fig. 1 is illuminated with the beam of a linearly polarized cw argon ion laser (TEM_{00}, λ = 514nm) with normal incidence. The input intensity is varied by an acousto-optical modulator. The total transmitted intensity is measured and the near field of diffraction is projected onto a screen where it can be observed with a CCD camera.

To investigate the behaviour of the nonlinear FPR described by Eq. (1) it is necessary to control the linear detuning of the resonator. In principle this can be done by changing the refractive index of the NLC by heating or cooling the whole resonator [13].

Another possibility may arise due to a small tilt angle between the mirrors. The resonator then shows some bright stripes. At these stripes the resonator is in tuned and, between them, in detuned state. Thus

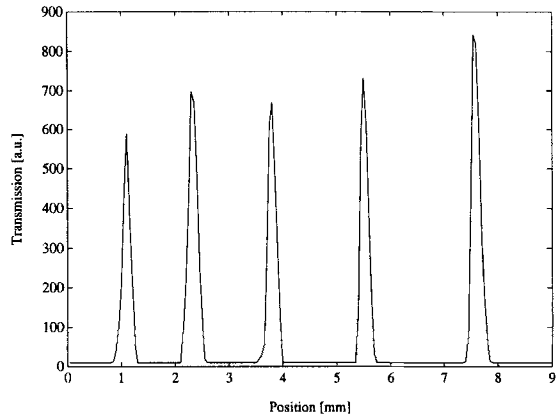

FIGURE 3: Experimental curve for the transmission of the FPR as a function of the cell position.

by varying the position of the resonator we can choose the detuning.

Fig. 3 shows the experimental curve for the transmission as a function of the resonator position varied perpendicular to the laser beam axis. As is seen, the maximal transmission of the FPR varies between 15% and 20% because of inhomogenities.

The intracavity field in the FPR can be either much higher than the incident intensity (when the resonator is tuned to maximal transmission ($\phi = 0$)) or much smaller than the incident intensity (when the resonator is detuned ($\phi = \pi/2$)). In the first case, the OFT threshold was achieved for remarkably smaller incident intensities than the original threshold value for the OFT in the "mirrorless" NLC cell (Eq. (2b)). In the second case it was impossible to induce reorientation for radiation intensities well above the original threshold value. For the given experimental parameters we found $I_c \approx 8\, I_i$ in the tuned state and $I_c \approx 0.025\, I_i$ in the detuned state.

Fig. 4 shows the experimental transmission characteristic for a small negative initial detuning of the resonator. It is in good agreement with the predictions of both the bistable behaviour and the remarkable decrease of the OFT threshold.

STABILIZATION

As pointed out above, the situation changes totally for $\phi_0 > 0$. There we had the case that OFT results in a negative feedback. So one can observe a power limiting and stabilization effect above the threshold. This behaviour is shown in Fig. 5. One can see that while the input intensity changes 5 times the output only varies 1.5 times.

For high finesse resonators this transmission characteristic should be more striking (see Fig. 6). As is seen, the behaviour is linear, up to the threshold. Above the threshold a change in input intensity does not cause any remarkable changes in the output intensity. So one could anticipate the design of a power stabilization device with extremely good characteristics.

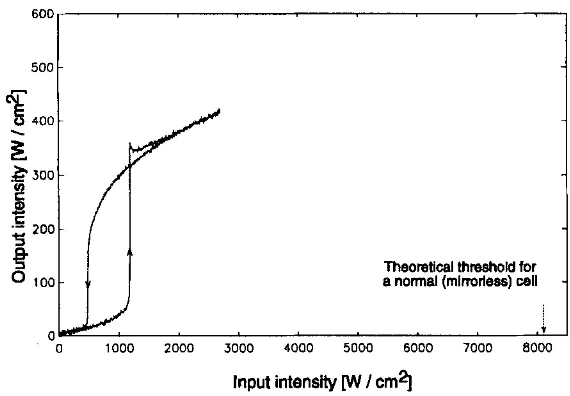

FIGURE 4: Experimental transmission characteristic for $\phi_0 < 0$.

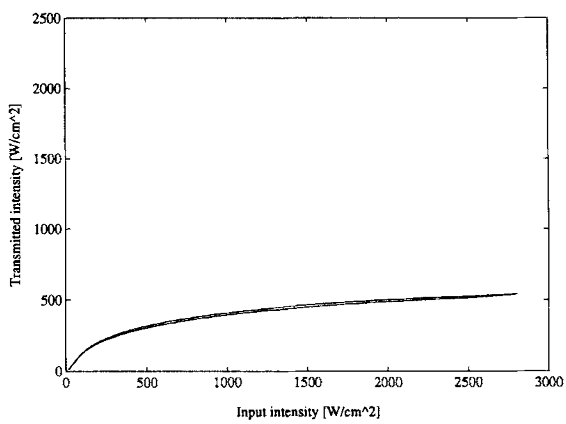

FIGURE 5: Experimental transmission characteristic for $\phi_0 > 0$

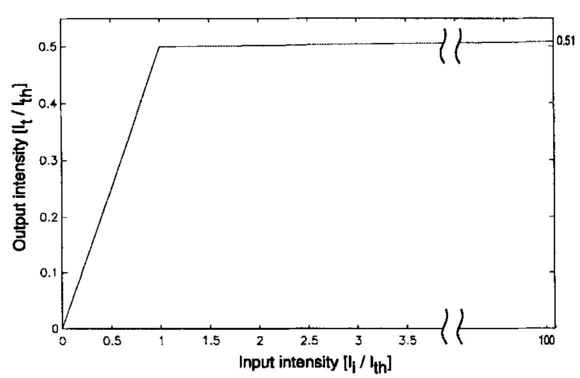

FIGURE 6: Theoretical transmission characteristic for a high finesse FPR ($\mathcal{F} \sim 40$) with $\phi_0 = 0$.

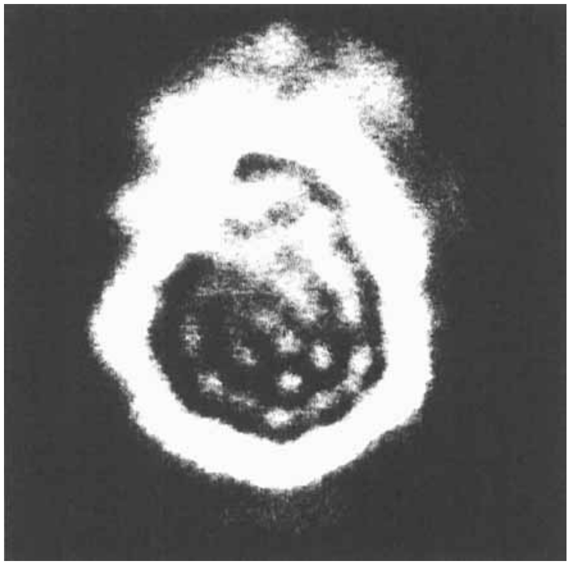

FIGURE 7: Typical observed transversal pattern.

NONLINEAR DYNAMICS AND PATTERN FORMATION

Nonlinear dynamic phenomena with all their complexity take place in simplest experimental situations of laser beam orientational interaction with liquid crystals [14]. Processes taking place in our case are even more complex since:

- the feedback is externally imposed and controlled;
- highly nonlinear regimes become available with moderate laser powers;
- a multitude of closely positioned metastable states is present;
- threshold effects due to the nonlinearity of the resonator may interplay with the threshold character of the nonlinearity itself.

Fig. 7-10 show several characteristic features of nonlinear dynamics and pattern formation during OFT in resonators. In Fig. 7 one can see typical observed transverse patterns. There the input gaussian beam breaks up into several small spots with a smaller transverse size than the original beam profile. In principle these spots can be explained as small induced lenses inside the resonator, each having a typical size and distance to its neighbours [15].

Formation of transverse patterns is always accompanied by complex dynamic behaviour. In the simplest case of low input intensities, self-oscillations, i.e. periodic changes in the output intensity with no changes in the input intensity arise (see Fig. 8). The frequency of these oscillations can be varied by changing the input intensity for a fixed initial detuning ϕ_0 (see Fig. 9). Below a certain intensity value no oscillations are observable and the system stays in the "off" state with low transmission. Above a certain intensity, self-oscillations also vanish but here the system stays in the high transmission state showing also transverse patterns.

There is evidence that these self oscillations are due to nonlinear dynamics of orientational effects

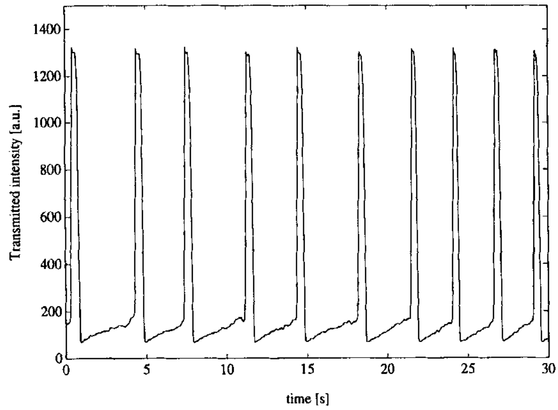

FIGURE 8:Typical self oscillation behaviour.

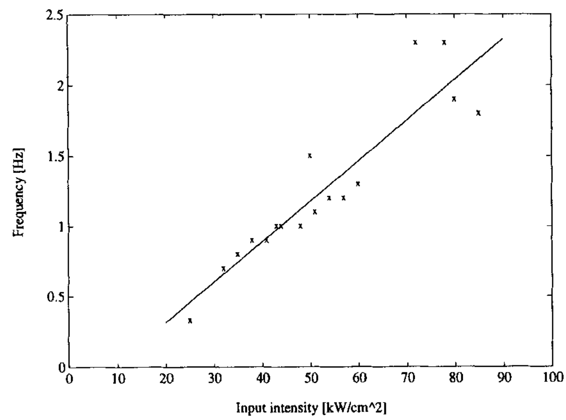

FIGURE 9: Dependence of the self oscillation frequency on the input intensity.

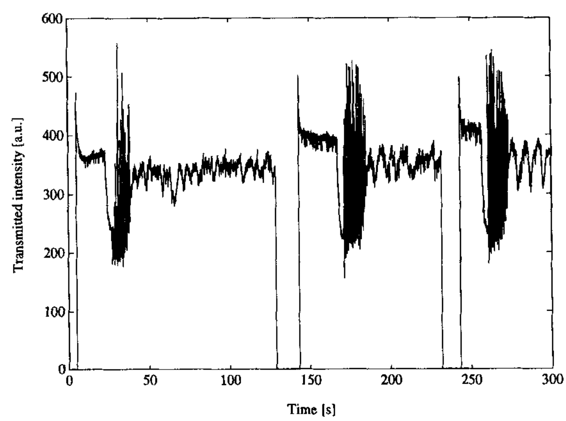

FIGURE 10: Observed complex dynamic behaviour

rather than being correlated with a competition of two - thermal and orientational - effects as in the case reported by Cheung et al. [5]. Since the propagation of the light beam in our case is along or near the director of the NLC, thermally induced changes in phase have the same sign as the phase change due to reorientation.

For higher input intensities the system can show oscillations on different time scales always accompanied with transverse patterns (see Fig. 10).

CONCLUSION

Homeotropically aligned NLC in a FPR leads to the following features of optically induced orientational phenomena. First, the threshold of OFT becomes strongly modified depending on the detuning of the FPR. Second, output power stabilization is possible in a large range of changes of input power. Third, pattern formation and complex dynamic behaviour take place. Quantitative investigation of these phenomena is under way.

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