Waveguide amplification of dye fluorescence in an NLC layer

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Abstract—The amplification of spontaneous fluorescence in a planar layer of a nematic liquid crystal doped with a DCM dye is experimentally studied in a waveguide mode of light propagation. The optical pumping threshold of superfluorescence is 0.65 MW/cm^2. The gain value reaches 0.0014 μm^{-1} at a pumping intensity of 1.38 MW/cm^2.

The study of the lasing effect in liquid crystals (LC) is one of the newest directions of fundamental research, which has been intensively developing in recent years over the world [1]. The idea of obtaining lasing under the conditions when feedback is not created by external mirrors, as in traditional laser circuits, but is due to the spatial periodicity of the dielectric constant or the periodicity of the medium gain, so called distributed feedback (DFB), was proposed by Kogelnik and Shenk [2]. For the first time the lasing in cholesteric liquid crystals (CLC) that have an internal spatially periodic (spiral) structure was experimentally obtained in 1980 [3]. Another type of DFB is associated with the use of spatially periodic structures (micro-gratings) at the boundary of an LC layer [4]. DFB is realized at the Bragg condition:

$$\Lambda = m\frac{\lambda}{2n}, \qquad (1)$$

where m is the set of integers pointing the diffraction order, λ is the wavelength of light in a vacuum, and n is the refractive index of the medium.

However, in order to obtain lasing, in addition to the distributed feedback condition, the LC medium must be amplifying the light. In this paper we have estimated the gain of an active nematic LC medium in the waveguide propagation mode for the fluorescence of a DCM dye. In [5], we demonstrated for the first time the possibility of amplifying LC lasing by a planarly aligned LC layer doped with a lasing dye. In that case, the gains reached the principal values $\alpha_{\parallel} = 0.066$ μm^{-1} and $\alpha_{\perp} = 0.056$ μm^{-1}.

To study the waveguide amplification of spontaneous fluorescence of a dye dissolved in a nematic LC, cells with a planar alignment were used (Fig. 1).

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Quartz plates having the refractive index ($n_q = 1.46$) lower than the principal ones of the LC were used as substrates providing light propagation in the waveguide mode. The thickness of the LC layer in the cells was set by Teflon stripes.

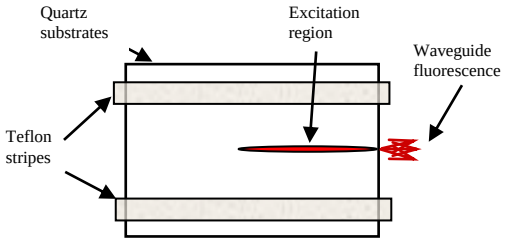

Fig. 1. The structure of the LC cell (top view).

As an LC material to study we used a solution of 0.62% fluorescent DCM (Exciton) dye in the nematic mixture LZhK-2 developed in our laboratory.

To form a waveguide channel for the propagation of fluorescent radiation in the cell plane, fluorescence was excited by a laser beam which was focused in the LC layer by a cylindrical lens in such a way that the excitation region had the form of a strongly elongated ellipse (Fig. 1). The focused beam pumping area provided by the cylindrical lens was 30μm × 2.3mm ($0.69 \cdot 10^{-3}$cm^2). In this case, fluorescence amplification appears in the direction of the long axis of the ellipse, because in this direction the highest number of dye molecules is excited, and the condition for amplifying the fluorescent radiation can be realized.

LC alignment boundary conditions were made by rubbing polyimide films either along the Teflon stripes (along the waveguide channel), or perpendicular to the waveguide channel.

Fluorescence was excited by either a semiconductor laser (a lasing wavelength of 445nm) or using a second (532nm) or third (355nm) harmonics of the pulsed neodymium laser (Nd^{3+}: YAG) with a pulse duration of about 10ns. The pumping intensity of the semiconductor laser did not exceed 180W/cm^2. The intensity of pump radiation of the Nd^{3+} laser was varied from 0.13MW/cm^2 to 1.98MW/cm^2.

In order to select the luminescence region, from which the fluorescence spectra were measured, we used a microscope with a lens of long focal distance (~10cm), Fig. 2.

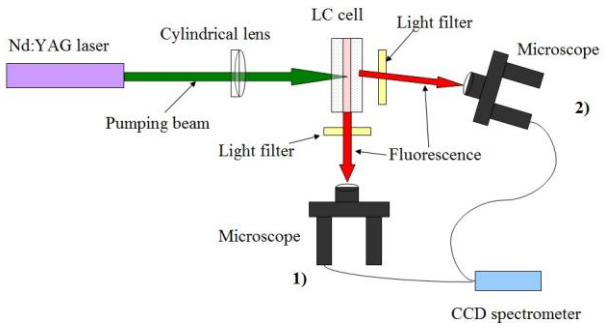

Fig. 2. Scheme for measuring fluorescence spectra.

The condenser lens of the CCD spectrometer for measuring the fluorescence spectra from the selected region of the cell is installed at the left ocular tube of the microscope. The spectra were measured by an AvaSpec-2048-USB2-UA fiber optic spectrometer. The right eyepiece tube of the microscope was used for searching the fluorescence region in the cell. To protect the eyes from pumping radiation, a filter was installed in front of the microscope lens. Fluorescence was measured in two geometries. In the first one, fluorescence was emmitted at the LC layer edge from the meniscus region (position 1). Namely, in this case we deal with the fluorescence waveguiding modes. In the second geometry, the fluorescence was almost normal (position 2) to the cell plane (small deviation of the spectrometer fiber from normal was made to escape direct influence of the pumping beam on the spectrometer sensor).

The laser light polarized along or perpendicular to the LC director (**n**) was used to study the polarized (below defined by light electric field vector **e**) spectra of fluorescence. The polarized fluorescence spectra were measured for TM- and TE- waveguide modes.

The polarized fluorescence spectra measured for the geometry defined above as "position 2" (normal to the LC layer, see Fig.2) are shown in Fig. 3. Pumping is done by a semiconductor laser at a wavelength of 445 nm. The intensity of fluorescence polarized parallel to the NLC director (curve 1) is almost 6 times higher than that polarized perpendicular to **n** (curve 2). It should be noted that the pumping intensity in this case is substantially lower than the intensities leading to nonlinear optical effects. This is explained by the anisotropy of dye molecules and their alignment in the LC matrix.

The fluorescence spectra measured for the same geometry but using a YAG laser at much higher intensities (λ_p=355nm) are shown in Fig. 4.

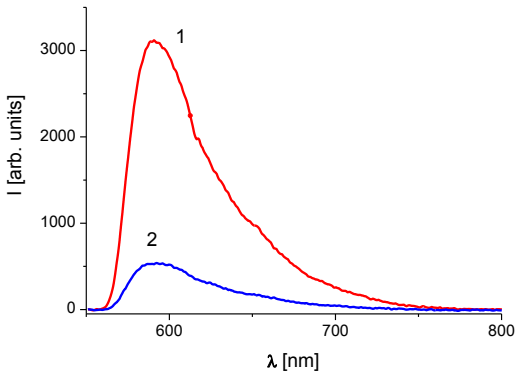

Fig. 3. The polarized fluorescence spectra of the DCM in LZhK-2 measured along the normal to the LC layer: curve 1 – **e**||**n**; curve 2 – **e**⊥**n**. Excitation polarization along **n**.

At lower pump intensities (0.13MW/cm^2 – curve 1, and 0.23MW/cm^2 – curve 2), the shape of the spectra is the same as in Fig. 3. However, at higher pump intensities (curves 3 – 0.46MW/cm^2, 4 – 0.59MW/cm^2, 5 – 0.99MW/cm^2, 6 – 1.98 MW/cm^2) another peak occurs in the range 606÷608nm.

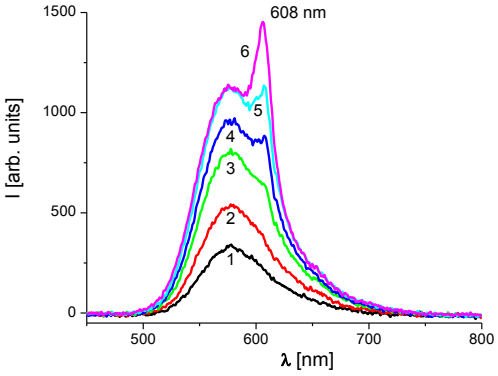

Fig. 4. Polarized (**e**⊥**n**) fluorescence spectra measured along the normal to the LC layer plane at the pumping by the third harmonic of a YAG laser. Excitation polarization along **n**.

The intensity of this peak increases substantially with increasing the pumping intensity. In contrast, the intensity of spontaneous fluorescence saturates. This peak we associate with the amplified fluorescence on the thickness of an LC layer (~ 5μm).

In the case of fluorescence in the waveguide mode (geometry defined as "position 1" in Fig. 2), we have only one amplified fluorescence peak, Fig. 5.

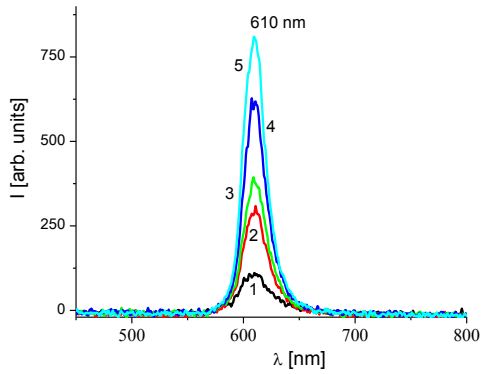

Fig. 5. The fluorescence spectra of amplified waveguide fluorescence (TM modes) measured from the meniscus at edge of the LC cell for different intensities of pumping beam: 1 – 0.94MW/cm^2, 2 – 1.09MW/cm^2, 3 – 1.16MW/cm^2, 4 – 1.23MW/cm^2, 5 – 1.38 MW/cm^2. YAG lasing polarization is parallel to the NLC director.

This peak of waveguide fluorescence is at 610nm, which coincides with the peak of amplified fluorescence in Fig. 4. For the waveguide modes, the path length is ~2mm (the length of the pump line), which is significantly higher than the thickness of the NLC layer, so we observe only amplified emission without any background spontaneous fluorescence, as in Fig. 4.

The dependence of maximum intensity of amplified waveguide fluorescence is shown in Fig. 6 (curve 1, left axis).

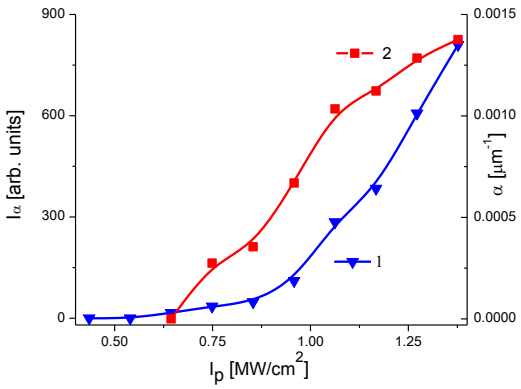

Fig. 6. Intensity dependences of amplified waveguide fluorescence (I_α) and magnitude of gain (α) versus pumping intensity (I_P).

To estimate the gain of an active medium we used a well-known formula for light amplification:

$$I_\alpha = I_s \exp(\alpha L), \tag{2}$$

where I_α is the light intensity at the output of the waveguide of length L, I_s is the intensity of spontaneous fluorescence of light at the input (in our case it is spatially distributed over the pumping region and not well-defined, so we can get only an estimation of the gain), and α is the gain parameter of an active medium. Figure 6 shows the dependence of gain on pumping intensity (curve 2, right ordinate). As one can see the threshold of amplification of spontaneous fluorescence is 0.65MW/cm^2 and maximum value of the gain is 0.0014μm^{-1}. This value is significantly less compared to the values found in [5]. The possible reason for the small values of gain parameters in the waveguide mode can be light scattering on both defects in the LC structure and on fluctuations of the LC director. Nevertheless, a homogeneously oriented thin NLC layer can act as an active laser medium at transverse optical pumping.

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