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Differential interferometry in planar waveguide structures with ferronematic layer

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The paper presents a differential interferometry phenomenon in a planar optical structure, which uses a ferronematic layer of a liquid crystal. This layer changes propagation conditions for TM modes in external magnetic field. Due to the magnetic field action on a ferronematic layer which covers the planar waveguide coated with an additional orientative layer, the ellipsoid of the refractive index changes its orientation in a polarization plane of the TM mode. In consequence, the phase difference of the TM mode occurs under magnetic field influence. This paper provides an analysis of the influence of a thickness and a refractive index of the orientative layer on interference phenomenon in analyzed structure.

Keywords: differential interferometry, planar optics, ferronematic liquid crystals, magnetooptic effects.

1. Introduction

The ferronematic liquid crystals are magnetic complex fluids. The ferronematics (FN) comprise the monodomain, elongated, fine ferromagnetic particles suspended in a nematic liquid crystal (NLC) [1]. The FN are very promising materials for technical applications due to magnetic susceptibility which is several orders of magnitude higher than in the case of pure NLCs. Liquid crystal molecules in a FN materials can be reoriented by a relatively weak magnetic field [2], [3]. If the FN layer covers a planar waveguide and when the FN is suitably oriented relative to the waveguide axes, it is possible to make an effective refractive index of a TM mode depend on magnetic field intensity. In effect, a phase difference between TE and TM modes depends only on the change of a TM mode. The origin of this change lies in a shift of a NLC spatial structure that is supported by the presence of ferromagnetic particles. If the optical power density of each mode is the same and the axis of a polarizer is tilted to both mode polarization planes at an angle of 45°, then the light intensity behind the polarizer is given by the formula [4]:

$$I = I_0\left[1 + \cos(\Delta\Phi)\right] \tag{1}$$

where: I_0 – light intensity of TE and TM modes; $\Delta\Phi$ – phase difference between TE and TM modes at the end of the waveguide.

The phase difference of interfering modes is given by the formula [4]:

$$\Delta\Phi = \frac{2\pi}{\lambda}\Delta N_{\mathrm{eff}}\, z \tag{2}$$

where: ΔN_{eff} – the difference between effective refractive index of interfering modes, z – light propagation length, λ – the wavelength of light in vacuum.

2. Interferometer construction

The planar waveguide created using ion-exchange method is covered with two layers. The first layer – polymeric one orders NLC molecules and the second layer – ferronematic one (Fig. 1).

The NLC molecules are perpendicularly ordered against the surface of the planar waveguide. Since in real ferronematics, NLC molecules are perpendicularly oriented

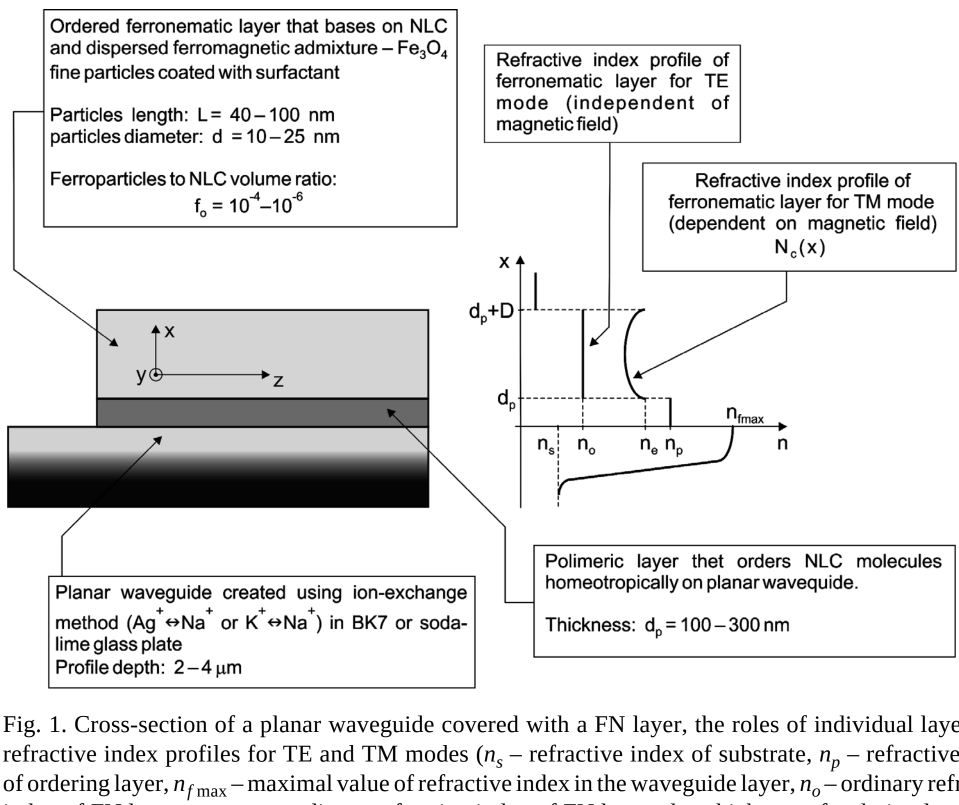

Fig. 1. Cross-section of a planar waveguide covered with a FN layer, the roles of individual layers and refractive index profiles for TE and TM modes (n_s – refractive index of substrate, n_p – refractive index of ordering layer, $n_{f\,\max}$ – maximal value of refractive index in the waveguide layer, n_o – ordinary refractive index of FN layer, n_e – extraordinary refractive index of FN layer, d_p – thickness of ordering layer, D – thickness of FN layer).

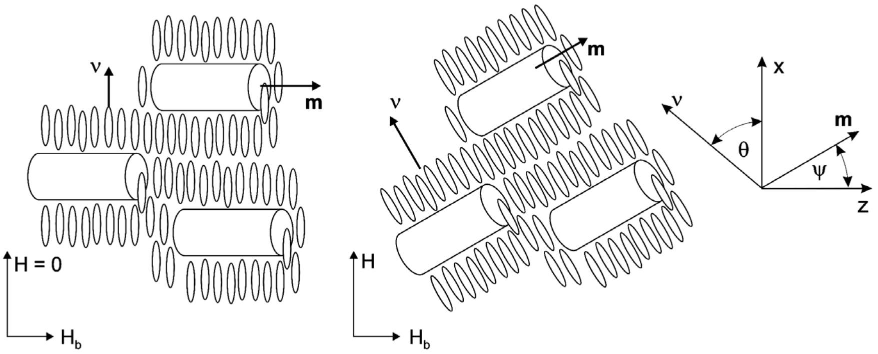

Fig. 2. Structure of ordered FN layer and its orientation change under influence of magnetic field (ν – nematic liquid crystal director, **m** – unit vector of ferroparticle magnetization director, θ – nematic molecule tilt angle, ψ – ferroparticle magnetic moment tilt angle).

to ferroparticles which are on the surface, which is shown in Fig. 2 [3]. In the absence of magnetic field, the director ν of liquid crystal molecules is parallel to the x-axis and the magnetic moment of ferroparticles is parallel to the z-axis. In consequence, the refractive index of the cover layer for the TM mode is equal to n_e, while for the TE mode is equal to n_o. When a magnetic filed of intensity H parallel to the x-axis is applied, a spatial orientation of the NLC matrix changes only in x-z plane. Since in the initial state, the FN layer has to be magnetized, the small bias field H_b is needed to fix the direction of magnetization inside the y-z "easy plane", along the z-axis. It was shown in paper [3] that the terrestrial magnetic field can fix the magnetization of the FN layer. The boundary conditions at the FN layer geometrically and physically limiting the planes determine the refractive index distribution of the cover layer for the TM mode, along the x-axis described by an angle $\theta(x)$.

3. Theoretical analysis

In the planar interferometer structure shown in Fig. 1, change of the refractive index of propagating modes is caused by the so-called refractometer effect [5].

Based on the geometrical analysis of the ellipsoid of refractive index (see Fig. 3), the refractive index of the FN layer for the TM mode is given by the formula:

$$n_{c\mathrm{TM}}(x) = \sqrt{\frac{n_o^2 n_e^2}{n_e^2 \sin^2\left[\theta(x)\right] + n_o^2 \cos^2\left[\theta(x)\right]}}. \tag{3}$$

In order to calculate a distribution of a tilt angle $\theta(x)$, the full free energy functional of the FN layer has to be minimized for a given magnetic field H. For the FN layer oriented in a way shown in Fig. 2, the free energy functional is given by the formula [6]:

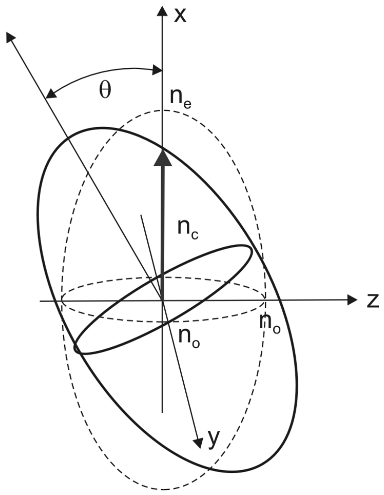

Fig. 3. Change of a spatial structure of the ferronemtic layer's refractive index ellipsoid (n_c – refractive index of FN layer for TM mode).

$$G = S\int_0^D \mathrm{d}x\left[\frac{1}{2}\left(k_{11}\cos^2\theta + k_{33}\sin^2\theta\right)\left(\frac{\mathrm{d}\theta}{\mathrm{d}x}\right)^2 - M_s f\left(H_b\cos\psi + H\sin\psi\right)\right]$$
$$+ S\int_0^D \mathrm{d}x\left[\frac{2wf_o}{d}\sin^2(\theta+\psi) + \frac{f_o k_B T}{V}\ln f_o\right] \tag{4}$$

where: S – the surface of the FN layer; k_{11}, k_{33} – Frank elastic constants [6]; M_s – magnetization of a ferroparticle saturation; f_o – volume concentration of ferroparticles in NLC; w – the anisotropic part of the anchoring energy of NLC molecule on a ferroparticle; d – ferroparticle diameter, V – ferroparticle volume.

For weak magnetic fields the bonding of NLC molecules on ferroparticles can be treated as rigid one $\psi(x) = \theta(x)$. It was shown in [6] that the magnetic field may be treated as a weak one if the following condition is fulfilled:

$$H < \frac{4w}{M_s d}$$

The function $\theta(x)$ that minimizes the functional (4) acquires parabolic profile [6]:

$$\theta(x) = \frac{M_s f_o}{8k_{33}}\left(Dx - x^2\right)H. \tag{5}$$

Substituting Eq. (5) into Eq. (3), the refractive index profile $n_{c\mathrm{TM}}(x)$ for the TM mode can be calculated. Having the refractive index profile in the whole structure, the change

$\Delta N_{\mathrm{effTM}}$ of effective refractive index of the TM mode can be calculated by solving the wave equation of the TM mode:

$$\frac{\mathrm{d}^2 H_y}{\mathrm{d}x^2} + n^2(x)\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{1}{n^2(x)}\right)\frac{\mathrm{d}H_y}{\mathrm{d}x} + \frac{2\pi}{\lambda}\left(n^2(x) - N^2_{\mathrm{effTM}}\right)H_y = 0 \tag{6}$$

where $n(x)$ is refractive index distribution along all layers of the structure.

The phase difference between TE and TM modes may be calculated using Eq. (2).

4. Results of numerical analysis

The possibility of realizing the structure shown in Fig. 1 depends on optical and geometrical parameters of the ordering layer. The existence of the ordering layer is very essential for the structure analysis. However, this layer makes a barrier between the waveguide and the FN layer, which decreases the degree of the penetration of the FN layer by an evanescent field of the TM mode. In order to determine the influence of optical and geometrical parameters of the ordering layer on structure efficiency, the phase difference between the TE and TM modes was calculated for different values of a refractive index n_p and a thickness d_p of the ordering layer, and for the different mode orders r. Calculations were carried out with the following assumptions. A three -mode planar waveguide is made by means of the ion exchange method $\mathrm{Ag}^+ \to \mathrm{Na}^+$ in a soda-calcium glass substrate with the refractive index $n_s = 1.511$ (for $\lambda = 677$ nm). The maximum value in the refractive index profile of the planar waveguide is equal to $n_{f\,\max} = 1.600$ (for $\lambda = 677$ nm). The FN is made of the NLC mixture type 1550

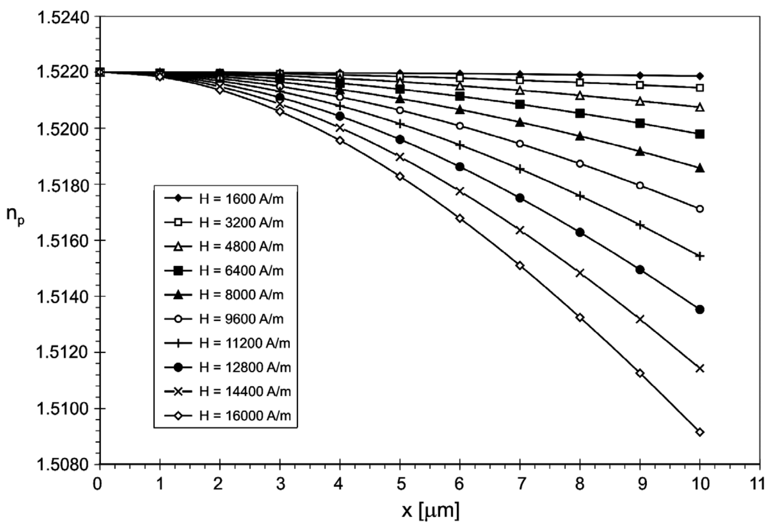

Fig. 4. Calculated refractive index profiles of FN layer for growing values of magnetic field intensity.

which has the refractive indexes: n_o = 1.460 and n_e = 1.522 (for λ = 632.8 nm), doped with ferromagnetic nanoparticles of the length L = 70 nm and the diameter d = 40 nm.

The saturation magnetization of ferroparticles is M_s = 0.25 T, their volume concentration is $f_o = 10^{-6}$. The anchoring strength of NLC molecules on ferroparticles is $w = 5\times10^{-5}$ N/m. The Frank elastic constant is equal to $k_{33} = 8\times10^{-12}$ N. The wavelength of a laser light beam is λ = 677 nm. The role of H_b is played by the terrestrial magnetic field. The thickness of the FN layer is D = 125 μm. The interaction length is z = 1 cm.

Figure 4 shows calculated refractive index profiles of the FN layer for growing values of the magnetic field intensity. Figures 5–7 show calculated phase difference

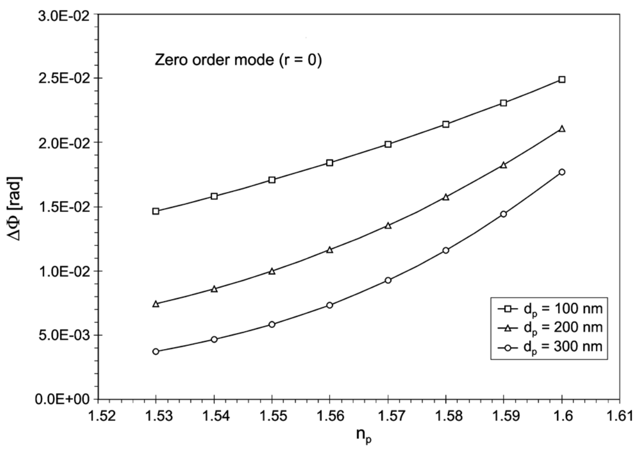

Fig. 5. Phase change of a zero order TM mode in magnetic field of intensity H = 16000 A/m *vs.* refractive index of ordering layer n_p for different values of ordering layer thickness d_p.

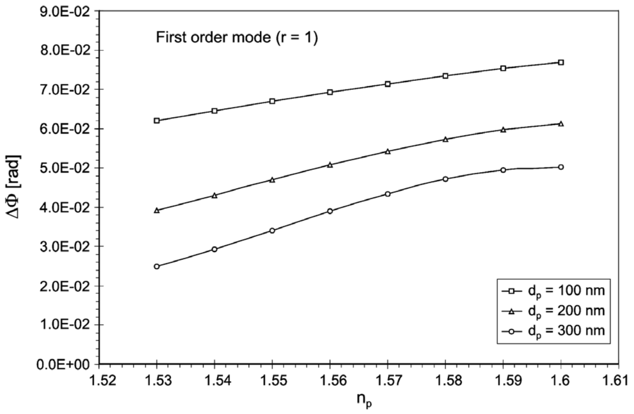

Fig. 6. Phase change of a first order TM mode in magnetic field of intensity H = 16000 A/m *vs.* refractive index of ordering layer n_p for different values of ordering layer thickness d_p.

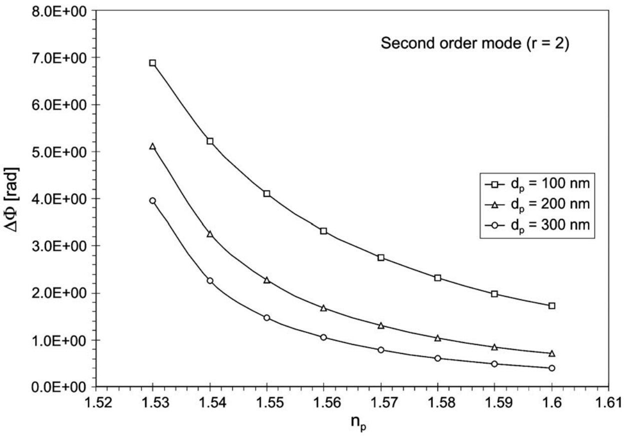

Fig. 7. Phase change of a second order TM mode in magnetic field of intensity H = 16000 A/m *vs.* refractive index of ordering layer n_p for different values of ordering layer thickness d_p.

$\Delta\Phi$ (Eqs. (1) and (2)) of the TE and TM mode versus a refractive index of ordering layer n_p for different values of an ordering layer thickness d_p and for TM modes of the different orders. The calculations were carried for the magnetic field intensity $H = 16000$ A/m. For this value the distortion of the refractive index profile in the FN layer is the biggest and can be described with an analytical function.

5. Conclusions

Calculation results presented in Figs. 5–7 show that for all the modes ($r = 0, 1, 2$) the phase change $\Delta\Phi$ grows with a decrease in the ordering layer thickness d_p. This is related to an increase of the evanescent field penetration depth. For the modes of zero and first order ($r = 0, 1$) the phase change increases with the ordering layer refractive index n_p, which is also related to an increase in the evanescent field penetration depth. However, for the second mode ($r = 2$) an increase of n_p causes the diminishing of $\Delta\Phi$. The evanescent filed of the second mode penetrates the FN layer the most of all the modes existing in the structure. Increasing n_p causes that the evanescent field penetrates the FN layer region in which the refractive index is sufficiently small to decrease the effective refractive index and in consequence changes the $\Delta\Phi$.

It is possible to create an optical differential interferometer based on the ferronematic magnetosensitive layer. The results obtained show that the refractive index and the thickness of the ordering layer must be suitably selected. The ordering layer should be as thin as possible. From a practical standpoint the structure should be the monomode. In this case the refractive index of the ordering layer should be equal to the maximum value in the refractive index profile of the planar waveguide.

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