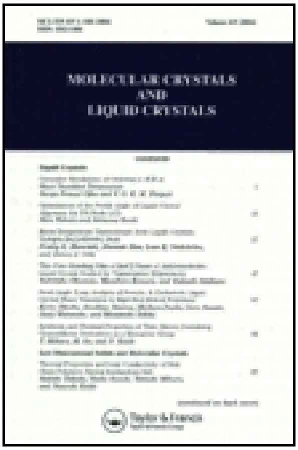

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First Approach to the Analysis of the Lasing Conditions in POLIPHEM© Structures

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First Approach to the Analysis of the Lasing Conditions in POLIPHEM© Structures

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We report a study devoted to the creation of a distributed feedback device on a basis of waveguide with periodical composition polymer – liquid crystal. Due to the refractive indices difference between the components the Bragg diffraction grating is formed, which provides coupling of the forward and backward propagating waves. The influence of the gain and conditions of laser oscillation threshold are analyzed for gain-type reflection grating. The conclusion is done on the advantage of second-order Bragg diffraction exploitation. Numerical simulations demonstrated the stability of the waveguide mode.

Keywords: Bragg diffraction; distributed feedback laser; soft materials

INTRODUCTION

In recent years there has been an increasing interest in the optical properties of complex dielectric materials. Continuous research efforts are dedicated to periodic structures, also called photonic crystals (PC) [1]. These materials have a periodic variation of the refractive index on the length scale of the wavelength in visible or near-infrared light and can be structured at one dimensional, two dimensional, or three dimensional structures. PCs are expected to have important applications as materials for photonic devices like optical components and light sources.

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There is a clear reason for the choice between inorganic and organic materials for such distributed-feedback (DFB) devices. Soft materials exhibit very attracting optical/mechanical/chemical/thermal properties and flexible processing techniques. Combined with holographic fabrication techniques, they can be patterned quite easily into many unique structures. Our activity in this view primarily concerns the investigation of soft-matter based structures to realize cheap, compact (i.e. microsized), tunable mirrorless laser sources operating in the visible and NIR regions of the spectrum. The most interesting aspect of these lasing systems is that optical and geometrical parameters can be modified by applying weak external influences (temperature, electric field, mechanical stress, optical field, etc.), hence resulting in a direct control of lasing features (wavelength tuning, bandwidth, emission direction). Several aspects of light transport in such materials are unknown up to now. Presented paper is devoted to an attempt of the analysis of such system in order to understand the requirements for experimental realization of the lasing devices, based on liquid crystal (LC) material. Namely a new composition POLIPHEM© is under test [2].

First, we start from a coupled-wave analysis of Bragg diffraction in a medium with gain. An analytic result shows some disadvantage of the first-order Bragg diffraction for the DFB device operation. Then the results of numerical simulations are reported for the case of second-order Bragg diffraction. The obtained picture of waveguide mode structure in DFB device is discussed.

COUPLED-WAVE ANALYSIS

Light diffraction in spatially modulated media has many applications, e.g. in holography, information storage and processing, etc. Our particular interest to the subject is connected with the possibility of exploitation of distributed feedback for the sake of laser operation. Different theoretical approaches to the problem are based on approximated solutions of wave equation which describes light wave propagation in a medium with periodically modulated gain or reflection of amplified wave from Bragg reflectors [3]. We are going to analyze wave coupling in a medium with spatial modulation of both phase (refractive index) and amplitude (gain) parts of dielectric permittivity. We shall follow the well-known method of Kogelnik's coupled-wave theory [4,5], with some modifications.

The transversal dimensions of the modulated medium are supposed to be infinite in x and y dimensions and finite in z dimension. The material dielectric permittivity can be written as $\varepsilon(z) = \varepsilon_0 + \Delta\varepsilon \cos(Kz)$, where ε_0 is the dielectric permittivity of the material without modulation, $\Delta\varepsilon$ is the magnitude of modulation and $K = |\boldsymbol{K}| = 2\pi/\Lambda$, Λ is the spatial period

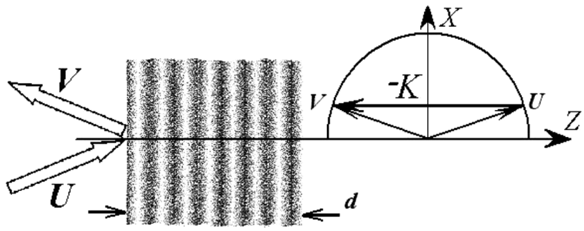


FIGURE 1 Geometry of coupled waves interaction. An incident wave U experiences Bragg diffraction in a periodically modulated medium, generating reflected wave V. Vector diagram is shown for the wave vectors.

of the grating and $\boldsymbol{K}$ is the grating vector. For simplicity, we suppose that the grating vector is directed along z-axis, and the dielectric permittivity outside the modulated medium is equal to ε_0. The input wave satisfies the condition of Bragg resonance, as shown schematically in Figure 1. Polarization of the field is chosen along y-axis (s polarization).

Let us first consider the situation with uniform gain (or losses) α in the medium. In an assumption of small amplification/losses at the distance of order the wavelength ($\alpha \ll k$, where k is the wave number), the wave numbers for the field components in the medium can be written as $k_z(1 - \frac{i\alpha}{k})$, $k_x(1 - \frac{i\alpha}{k})$. This choice corresponds to the growth/depletion of the wave intensity in the medium in the form

$$\left[U_0 \exp\left(ik_x x + \frac{\alpha k_x x}{k}\right) \exp\left(ik_z z + \frac{\alpha k_z z}{k}\right)\right][C.C.] = U_0^2 \exp(2\alpha r), \qquad (1)$$

where U_0 is the input wave amplitude, r is the propagation distance, $r^2 = x^2 + z^2$ and $C.C.$ denotes complex conjugate. Positive α corresponds to the amplification, and vice versa.

For the field in the medium $E(x, z)$ written as a superposition of incident and reflected waves (Fig. 1) we obtain

$$E(x,z) = \left[U(z) \exp\left(ik_z z + \frac{\alpha k_z z}{k}\right) + V(z) \exp\left(ik_z z - iKz - \frac{\alpha k_z z}{k}\right)\right] \times \exp\left(ik_x x + \frac{\alpha k_x x}{k}\right), \qquad (2)$$

where $U(z)$ is the forward propagating wave, and $V(z)$ is the reflected wave amplitudes, which vary along the z axis due to the coupling. Then we insert expression (2) into scalar wave Equation

$$\frac{\partial^2 E(x,z)}{\partial x^2} + \frac{\partial^2 E(x,z)}{\partial z^2} = -k_0^2 \varepsilon(z) E(x,\ z), \qquad (3)$$

where k_0 is the wavenumber in free space. With the presence of gain/losses in the medium, its dielectric permittivity will be expressed as a complex number, and the right side of Eq. (3) appears as

$$k_0^2\varepsilon(z)E(x,z) = -[k^2 - \alpha^2 - 2i\alpha k + k_0^2\Delta\varepsilon\cos(Kz)]E(x,\ z). \tag{4}$$

Neglecting of the terms corresponding to higher orders of diffraction, and assuming the Bragg resonance condition $k_z = K$ we come to the system of equations, combined along equal exponential factors $\pm ik_z z$:

$$\begin{cases} \frac{\partial^2 U(z)}{\partial z^2} e^{-\frac{\alpha k_z}{k} z} + 2ik_z\left(1 - \frac{i\alpha}{k}\right)\frac{\partial U(z)}{\partial x} e^{-\frac{\alpha k_z}{k} z} = -\frac{k_0^2\Delta\varepsilon}{2} V(z) e^{\frac{\alpha k_z}{k} z} \\ \frac{\partial^2 V(z)}{\partial z^2} e^{\frac{\alpha k_z}{k} z} - 2ik_z\left(1 - \frac{i\alpha}{k}\right)\frac{\partial V(z)}{\partial z} e^{\frac{\alpha k_z}{k} z} = -\frac{k_0^2\Delta\varepsilon}{2} U(z) e^{-\frac{\alpha k_z}{k} z} \end{cases} \tag{5}$$

In the case of weak coupling and absorption/amplification we can neglect second derivatives in the system (5). The solution is sought in the form

$$U(z) = u\exp\left(\sigma z + \frac{\alpha k_z}{k} z\right), \quad V(z) = v\exp\left(\sigma z - \frac{\alpha k_z}{k} z\right), \tag{6}$$

which leads to the system

$$\begin{cases} 2ik_z\left(1 - \frac{i\alpha}{k}\right)\left(\sigma - \frac{\alpha k_z}{k}\right)u = -\frac{k_0^2\Delta\varepsilon}{2} v \\ 2ik_z\left(1 - \frac{i\alpha}{k}\right)\left(\sigma + \frac{\alpha k_z}{k}\right)v = \frac{k_0^2\Delta\varepsilon}{2} u \end{cases}. \tag{7}$$

The multiplication of the equations in the system (7) gives the result

$$\sigma_{1,2} = \pm\left[\left(\frac{\alpha k_z}{k}\right)^2 + \frac{\left(\frac{k_0^2\Delta\varepsilon}{2}\right)^2}{\left(1 - \frac{i\alpha}{k}\right)^2}\right]^{1/2} \tag{8}$$

Supposing the thickness of the modulated medium d much higher than the period of modulation, we can write simplified boundary conditions [4]

$$\begin{aligned} u_1 + u_2 &= U_0 \\ v_1 e^{\sigma_1 d} + v_2 e^{\sigma_2 d} &= 0 \end{aligned} \tag{9}$$

These boundary conditions correspond to the equality of the incident wave amplitude U_0 to the input field amplitude within the medium (no reflection), and the absence of any input wave at the rear face. After mathematical operations we obtain

$$\begin{aligned} u_1 &= U_0\frac{\left(\sigma_1 + \frac{\alpha k_z}{k}\right)\exp(-\sigma_1 d)}{2\sigma_1\cosh(\sigma_1 d) - 2\frac{\alpha k_z}{k}\sinh(\sigma_1 d)} \\ u_2 &= U_0\frac{\left(\sigma_1 - \frac{\alpha k_z}{k}\right)\exp(\sigma_1 d)}{2\sigma_1\cosh(\sigma_1 d) - 2\frac{\alpha k_z}{k}\sinh(\sigma_1 d)} \end{aligned} \tag{10}$$

(here σ_1 is the positive root of Eq. (8)).

The complex amplitude of the field at the exit from the medium well be equal to (we must recall also the x-dependence in Eq. (2)

$$E(d) = U_0 \frac{\sigma_1 \exp(\alpha \frac{k}{k_z} d - \alpha \frac{k_z}{k} d)}{2\sigma_1 \cosh(\sigma_1 d) - 2\frac{\alpha k_z}{k} \sinh(\sigma_1 d)} \tag{11}$$

The condition of self-starting oscillations (threshold) corresponds to the non-zero output amplitude with zero input amplitude $U_0 = 0$. As seen in the expression for the amplitude $E(d)$, the threshold is reached with zero value of the denominator of Eq. (11):

$$\sigma_1 = \frac{\alpha k_z}{k} \tanh(\sigma_1 d) \tag{12}$$

Neglecting small imaginary component in Eq. (8), we rewrite it in the form

$$\sigma_1 = \sqrt{\gamma^2 + \kappa^2}, \tag{13}$$

where $\gamma = \frac{\alpha k_z}{k}$, $\kappa = \frac{k_0^2 \Delta\varepsilon}{2k_z}$, and come to the transcendent equation

$$\sigma_1 d = \gamma d \tanh(\sigma_1 d). \tag{14}$$

The derived equation (14) is the basis for the analysis of the self-starting oscillations threshold. Apart from a trivial root $\sigma_1 d = 0$, "oscillatory" root requires some special conditions to exist.

Let us consider first an ideal case with phase-only modulation and uniform amplification, when the modulation of amplification/losses is absent, and the coupling constant is real:

$$\kappa = \frac{k_0^2 \Delta\varepsilon}{2k_z} = \frac{k^2 \Delta n}{nK}, \tag{15}$$

where n is the refractive index and $k = k_0/n$. Real value of κ provides real σ_1, according to Eq. (13).

The oscillatory equation (14) can be rewritten as

$$\cosh^2 \sigma_1 d = -\frac{\gamma^2 d^2}{\kappa^2 d^2}, \tag{16}$$

which results in the absence of real solution, as left part of Eq. (16) is positive, and right part is negative. Oscillation threshold at the exact Bragg resonance seems not to be reached irrespectively on the gain level.

In another situation, let us take pure amplitude modulated medium. The coupling constant becomes imaginary:

$$\kappa = i \frac{k \Delta\alpha}{k_z} \tag{17}$$

The oscillatory equation (14) can be taken in the form which permits to find the dependence between the parameters

$$\sigma_1^2 d^2 = \gamma^2 d^2 \tanh^2 \sigma_1 d, \tag{18}$$

where now

$$\sigma_1^2 d^2 = \gamma^2 d^2 - |\kappa|^2 d^2. \tag{19}$$

The dependence between the threshold value of the modulation term and the uniform gain can be found in implicit form:

$$\begin{cases} |\kappa| d = \dfrac{\sigma_1 d}{\tanh(\sigma_1 d)} \\ \gamma d = \dfrac{\sigma_1 d}{\sinh(\sigma_1 d)} \end{cases} \tag{20}$$

(here $\sigma_1 d$ serves as a parameter). However, the obtained relations do not describe the whole picture. As seen, Eq. (13) permits pure imaginary value of σ_1 in the case $|\kappa|^2 > \gamma^2$. The threshold condition (14) gives now

$$\sigma_1^2 d^2 = \gamma^2 d^2 \tan^2(|\sigma_1| d), \tag{21}$$

and the relations (20) are written as

$$\begin{cases} |\kappa| d = \dfrac{|\sigma_1| d}{\tan(|\sigma_1| d)} \\ \gamma d = \dfrac{|\sigma_1| d}{\sin(|\sigma_1| d)} \end{cases} \tag{22}$$

Figure 2 shows the calculated threshold dependence on the uniform gain. The increase of the gain certainly diminishes the threshold. Lasing is possible in this scheme at the Bragg resonance.

A surprising feature is the possibility to reach the oscillation threshold even with negative uniform gain, i.e. with the absorption in the medium instead of amplification ($\alpha < 0$). With dominating absorption, however, due to the modulation $\Delta\alpha$, slices with effective amplification are present in the case $\Delta\alpha > |\alpha|$. The interference field in the grating $U(x, z) + V(x, z)$ is concentrated just in these slices, thus experiencing amplification for both forward and backward propagating waves. In contrast, the absorptive slices are overlapping with the minima of the interference field, which possesses the same periodic distribution as the grating [5].

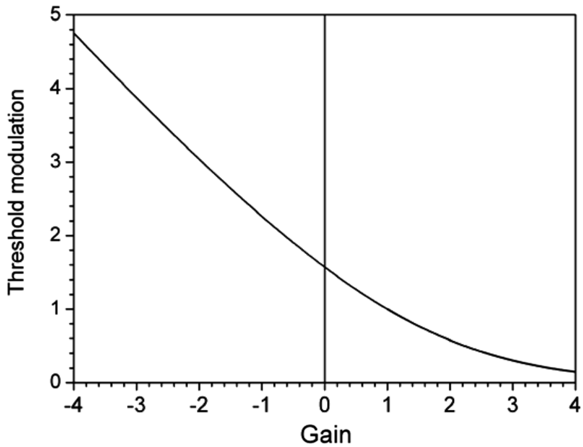


FIGURE 2 Calculated dependence (Eqs. (20), (22)) of the threshold value of the modulation term $|\kappa|d = \frac{k\Delta\alpha d}{K}$ on the gain factor $\gamma d = \alpha Kd/k$.

In the general case, both amplitude and phase modulations create a mixed-type grating. Without further detailed consideration, we can state that the presence of the phase component will increase the threshold and therefore changes to the worse the oscillator operation (in the sense of the off-Bragg resonance modes oscillation). In this view, we are going to analyze a scheme with second-order Bragg resonance.

SIMULATION OF PASSIVE DFB SYSTEM WITH STRONG SPATIAL MODULATION OF REFRACTIVE INDEX BY MEANS OF FINITE-DIFFERENCE TIME-DOMAIN (FDTD) METHOD

In this section an initial consideration of second-order Bragg DFB system is performed. It implies numerical simulation of a passive system, i.e. without light gain and losses. However, this consideration is based on direct numerical solution of the system of Maxwell equations without any approximations and takes into account the effects caused by guided light wave propagation and is valid even for strong spatial modulation of refractive index. The used configuration was chosen due to the expectation that in pure phase grating diffraction of a straight-propagating wave to counter-propagating one generates a phase shift of π in second-order Bragg condition, and after secondary diffraction to straight-propagating wave the phase shift contributes exactly 2π, thus obeying the requirement for occurrence of light generation in case of sufficient gain in the waveguide film.

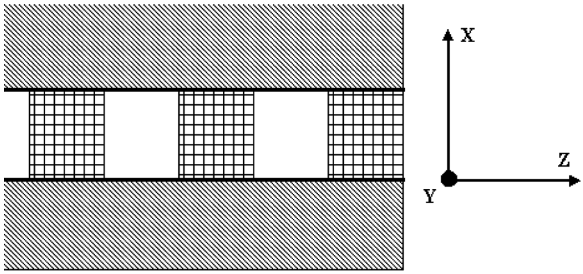


FIGURE 3 Geometry of the waveguide. Regions of polymer (square grid) and nematic LC (empty boxes) are periodically distanced between glass substrates (dashed blocks) with optically transparent electrodes (thick lines).

Geometry of the system is shown in Figure 3. Periodically located regions of polymer and nematic liquid crystal are confined between two substrates with optically transparent electrodes deposited onto their inner surfaces. Application of electric field to the electrodes causes variation of orientation of LC director. As a result, variable modulation of refractive index occurs in the system, which influences on the conditions for second-order Bragg diffraction and therefore for waveguide mode propagating in the film. Introducing an amplifier (dye) to the medium can provide light amplification in the system, which altogether with the feedback creates necessary conditions for lasing effect. Since average (along the waveguide) refractive index also changes under application of electric field, it enables the tuning of laser frequency in the range of the amplification band of the dye. The tuning range can be wide enough due to the significant variation of the refractive index (the difference between ordinary and extraordinary indices in LC is typically 0.2).

The analyzed system is unusual in the following aspect. Commonly, in DFB systems the strength of the feedback is preset for certain optimum value. In contrast, in the present scheme the strength of the feedback varies in a wide range. Moreover, it is unclear whether the system will retain ability to hold the light in a waveguide mode under conditions of such strong modulation of the refractive index. For clarifying the situation, numerical analysis of the system has been performed by means of direct solution of Maxwell equations without assuming an existence of any kind of waveguide modes in the system. At the initial step of the analysis we used somewhat simplified approach (no gain in the system, the electrodes are assumed to be absent, the system is assumed to be infinite in y and z directions, light losses due to absorption and scattering are set to zero, refractive index values are chosen in a convenience of numerical analysis, as explained below). The main purpose consisted in determination of the ability of the system to operate under conditions of strong spatial modulation of refractive indices of the waveguide components.

The standard point for used FDTD [6] formulations is the two Maxwell curl equations. They can be recast in the following form:

$$\frac{\partial \vec{H}(\vec{r},t)}{\partial t} = -\frac{1}{\mu}\nabla \times \vec{E}(\vec{r},t) - \frac{\rho'}{\mu}\vec{H}(\vec{r},t) \tag{23}$$

$$\frac{\partial \vec{E}(\vec{r},t)}{\partial t} = \frac{1}{\varepsilon}\nabla \times \vec{H}(\vec{r},t) - \frac{\vartheta}{\varepsilon}\vec{E}(\vec{r},t), \tag{24}$$

where ϑ is the electric conductivity for lossy dielectric material and ρ' is magnetic conductivity for magnetic losses. If we consider the material to be lossless, then $\vartheta = 0$ and $\rho' = 0$. Further we write out the vector component of the curl operators in Eqs. (23), (24) to yield the following six system components:

$$\begin{aligned}
\frac{\partial H_x}{\partial t} &= \frac{1}{\mu}\cdot\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right),\\
\frac{\partial H_y}{\partial t} &= \frac{1}{\mu}\cdot\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right),\\
\frac{\partial H_z}{\partial t} &= \frac{1}{\mu}\cdot\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right),\\
\frac{\partial E_x}{\partial t} &= \frac{1}{\varepsilon}\cdot\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right),\\
\frac{\partial E_y}{\partial t} &= \frac{1}{\varepsilon}\cdot\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right),\\
\frac{\partial E_z}{\partial t} &= \frac{1}{\varepsilon}\cdot\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right).
\end{aligned} \tag{25}$$

There is a common procedure of subsequent transformation of a system of equation in partial derivatives to that composed of finite differences of respective values. For that purpose, so called Yee lattice [7] is used, each cell of which is a cube with $\Delta x \Delta y \Delta z$ dimensions. Electric field components are defined at corners of the cube, and magnetic field ones – at centers of the cube faces. For temporal calculations of the fields, discrete time step Δt is introduced. When electric field values are known at respective points of Yee lattice for time point t, subsequent magnetic field values are calculated for $t + \Delta t/2$ time point, at that nearest-neighbor values of E components at Yee lattice are taken for calculations of H components. After that, new values of E components for time point $t + \Delta t$ are calculated on a basis of nearest-neighbor values of H components. This procedure is repeated until coming to stationary values of amplitudes of E and H components.

For numerical simulations of the system under study, freeware program EM Explorer was used which implements described above FDTD algorithm with periodical reproduction of considered region of the space in z and y directions, and x direction is limited from top and bottom by so called perfectly matched layers [8] which provide complete absorption of electromagnetic wave falling onto them. The region of the space was filled with a set of rectangular boxes for construction of required waveguide structure. Calculations were interrupted when the field amplitudes came to stationary values with better than 5% precision. Results of spatial distributions of all field components were stored in data files. These results were retrieved for subsequent considerations by means of freeware program Kitware ParaView.

Since the purpose of the simulations consisted in determination of the system ability to operate with refractive index variations in wide range, rather than modeling of behavior of the system with actual for LC parameters, some values, namely refractive indices, were "virtual" ones serving for the purpose of more convenient simulations. In general, finding the resonant conditions was performed by means of fitting absolute refractive index values in steps of 10^{-4} with holding the wavelength value in vacuum to be equal 0.6 μm. Tendencies of the system behavior determined from these simulations do not depend on particular choice of mentioned parameters. Taking into account the fact that working polarization for tuning of actual system is one along x-axis (p-polarization), which gives rise to excitation of TH waveguide mode, only the results for E_x component are considered below.

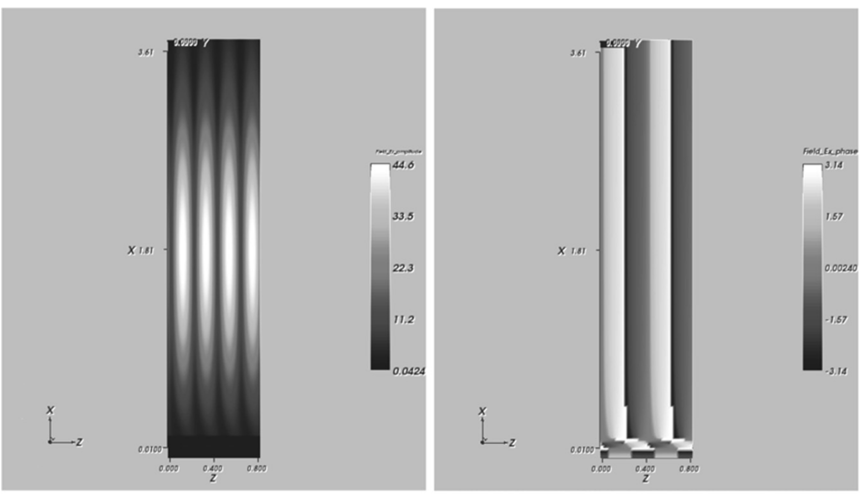
Light was introduced to the system from the excitation plane located at $x = 0.1\,\mu m$ inside a refractive coupler having "virtual" refractive index 3.0. Angle of incidence inside the coupler was fixed and equal to 30°, so that average refractive index of the waveguide n was in nearest vicinity of 1.5 (and the light wavelength inside the waveguide medium was about 0.4 μm). Refractive index of substrate medium was $n_s = 1.49$, thus ensuring light propagation in this medium in form of evanescent wave. Constant spacing between the coupler and the waveguide was chosen from viewpoint of obtaining quality factor of non-modulated waveguide of order of 10^3 (ratio of intensity inside the waveguide to that inside the coupler). The thickness of the waveguide was 2 μm. DFB grating period was exactly

0.4 μm with equal in thickness portions having different refractive indices. Defined waveguide part in z direction had the size of exactly two grating periods, and it was periodically replicated by the program from minus infinity to plus infinity. Size of Yee cell was 0.02 μm which comprised about 1/20 of wavelength in the media. The system thickness in y direction was one Yee cell (so that the behavior of two-dimensional system was actually simulated).

The calculations were performed for several values of refractive index modulation in wide range from 0 to 0.2. Main tendencies can be seen from two particular examples below.

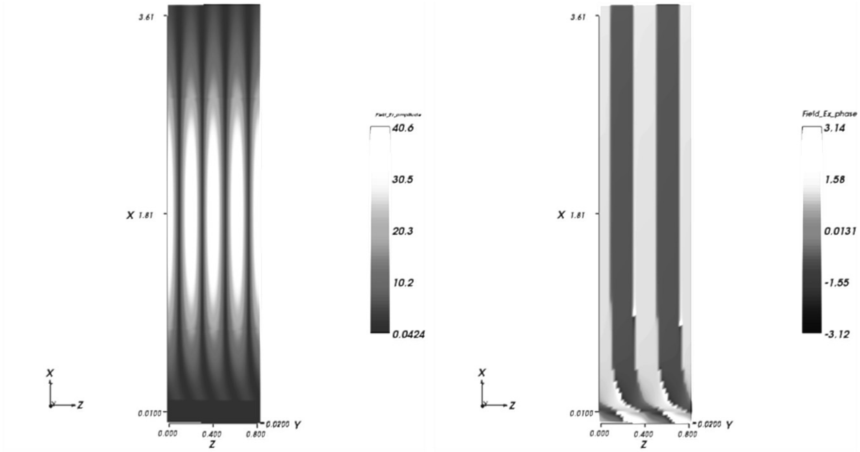
Figure 4 represents simulation of zero transverse index mode for the waveguide with moderate (0.01) modulation of refractive index (210000 time steps were used for coming to stationary state). Average refractive index value was $n = 1.5035$. One can see that counter-propagating wave causes about 75% spatial modulation of electric field value, and the phase variation in z direction is almost step-like with jumps by π value.

Figure 5 represents simulation of zero transverse index mode for a waveguide with strong (0.2) modulation of refractive index (210000 time steps were used for coming to stationary state). Average refractive index value was $n = 1.502$. One can see that counter-propagating



(a) (b)

FIGURE 4 Results for stationary E_x amplitude (a) and phase (b) distributions for the second-order Bragg DFB system with moderate (0.01) modulation of refractive index.



(a) (b)

FIGURE 5 Results for stationary E_x amplitude (a) and phase (b) distributions for the second-order Bragg DFB system with strong (0.2) modulation of refractive index.

wave causes about 100% spatial modulation of electric field value, and the phase variation in z direction is step-like with jumps by π value. It is possible to see very minor difference in spatial period of electric field maxima in the regions with two different refractive indices, and practically flat phase surfaces. As well, one can see shift of position of light intensity maxima in z-direction, as compared to the Figure 4.

From comparison of obtained results we can conclude that quality factor of the waveguide in case of second order Bragg DFB does not exhibit essential changes with variation of refractive index difference in wide range (up to 0.2). Also there are no visible traces of light leakage due to diffraction in direction exactly perpendicular to waveguide film, due to TH nature of the waveguide mode (one can easily see such light leakage for simulation for TE mode). As well, the system behaves in approximate agreement with average n value for the waveguide (0.0016 difference at 0.2 modulation value with respect to zero modulation value), and no leakage of light occurs even when low refractive index areas are well below by mentioned value than surrounding medium ($n_s = 1.49$). These circumstances give rise to possibility of usage of analytical solutions of the equations derived for light propagation in the waveguide with second-order Bragg phase grating and gain medium for determination of the threshold and parameters of lasing effect in the system.

CONCLUSIONS

In this part of the study of a distributed-feedback device based on periodical system LC/polymer created within a waveguide, we determined the main direction for the practical realization. To reach the tunable operation, an idea for exploitation of second-order Bragg diffraction is put forward.

By means of numerical simulations with the use of Finite-Difference Time-Domain method the light propagation in planar waveguide formed by a film with periodically distanced regions of liquid crystal and polymer was analyzed. It is demonstrated that in the scheme with second-order Bragg distributed feedback a waveguide mode with zero transverse index without loss of quality factor can be realized. Even in the case of very strong (0.2) difference of refractive indices between the polymer and LC components the waveguide mode still exists. Also, it was shown that in analyzed waveguide system the phase surface of propagating waves remains practically flat in a wide range of refractive index modulation (from 0 to 0.2).

The obtained results are promising for application of common analytical approaches (e.g. waveguide mode determination, Kogelnik's coupled-wave theory, etc.) for analysis of the system with spatially distributed light gain and losses as well as refractive index modulation.

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