

CONTROL OF LASER RADIATION PARAMETERS

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New method to control the shape of spectral characteristics of Bragg gratings in electrooptical materials

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***Abstract*. A new method is proposed to control the shape of spectral characteristics of Bragg gratings, which is based on the introduction of electrically controlled shifts of the average refractive index. The shape of the spectral characteristics of Bragg gratings with a complex step structure of the spatial distribution of the average refractive index is calculated. The operative electric control of their shape in a channel optical $LiNbO_3$ crystal waveguide is experimentally demonstrated.**

Keywords: *Bragg gratings, optical switches, tunable optical filters.*

1. Introduction

One of the most widespread classes of narrowband optical filters is based on the diffraction of light from a phase Bragg grating [1]. The reflection spectrum of a simple sinusoidal Bragg grating consists of a narrow peak with a central wavelength corresponding to the exact fulfilment of the Bragg law

$$\lambda_0 = 2n\Lambda, \tag{1}$$

where λ_0 is the central reflection wavelength (the Bragg wavelength); n is the average refractive index of the grating material; and Λ is the grating period. The spectral selectivity of such a grating in the case of small amplitudes ($\delta n/n < \Lambda/l$) can be estimated from the expression

$$\frac{\delta\lambda}{\lambda_0} \approx \frac{\Lambda}{l}, \tag{2}$$

where δn is the phase grating amplitude; l is the grating length; and $\delta\lambda$ is the deviation of the wavelength of light from the Bragg condition at which the diffraction efficiency vanishes. Therefore, a Bragg grating of length $l = 5$ mm can provide the spectral selectivity $\delta\lambda \approx 0.1$ nm for $\lambda_0 = 1550$ nm.

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Bragg gratings with controllable spectral characteristics attract the most interest [2]. The simplest type of control is spectral tuning, or changing the central reflection wavelength. One can see from expression (1) that this can be performed either by changing the average refraction index or the grating period. The latter can be done with the help of mechanical deformation. This principle is used in piezoelectric tuning of fibre Bragg gratings (FBGs) [2]. The main disadvantage of this method is a relatively low tuning rate. The typical variation time of λ_0 is 10 ms.

If the grating is produced in an electrooptical material, the central Bragg reflection wavelength can be changed by applying an external electric field and changing the average refractive index. The main advantage of this method of spectral tuning is a high rate – the variation time of λ_0 can be less than 1 ns. A change in the central wavelength is proportional to a change in the average refractive index, which is determined by the electrooptical properties of the material

$$\Delta\lambda = 2\Delta n\Lambda,$$
$$\Delta n = \frac{1}{2} n^3 r_{\text{eff}} E, \tag{3}$$

where E is the external electric field strength; r_{eff} is the effective electrooptical coefficient depending on the mutual orientation of a sample, the external electric field, the propagation direction and polarisation of light. The dependence of the electrooptical properties of a $LiNbO_3$ crystal on its orientation was analysed in detail in paper [3].

In [4], a $LiNbO_3$ crystal was optimally oriented by continuously electrically tuning a narrowband optical filter based on a volume reflection holographic Bragg grating. The main disadvantage of this system is high control voltages and a narrow continuous tuning range due to low electrooptical coefficients of electrooptical materials used (for example, $LiNbO_3$).

Earlier, new methods were proposed to control the spectral characteristics of Bragg gratings, which are based on the production of spatial discontinuities or shifts of the main parameters of the grating such as its period, phase, or average refractive index [5, 6]. The discontinuities in the phase, period or average refractive index of the Bragg grating drastically change the shape of spectral characteristics. For example, when the phase shift equal to π is introduced between the two halves of a homogeneous grating, a narrow transmission peak appears at the centre of the reflection range of an unperturbed grating, and the grating transforms from the reflection spectral filter to the transmission filter. This substantially expands the functional possibilities of controllable Bragg grating filters and, thereby expanding the field of their potential applications.

The spectral characteristics of Bragg gratings with spatial discontinuities and shifts of parameters were theoretically investigated in papers [5, 6]. The theoretical results obtained in these papers were verified in experiments on the control of spatial inhomogeneities of the Bragg grating parameters and the shape of their spectral characteristics. Experiments were performed with mechanical-deformation- or temperature-controlled FBGs. However, these methods for producing controllable inhomogeneities have obvious disadvantages. First of all this is a low control rate and impossibility to produce abrupt controllable discontinuities in the grating. This considerably restricts the number of different realisations of spatial inhomogeneities of grating parameters.

Recently, a new method was proposed to introduce controllable phase shifts by using a dynamic holographic grating in photorefractive crystals [7]. Phase shifts in the grating were produced by the spatial phase modulation of one of the beams writing the dynamic holographic grating. However, this method has a low control rate. The rate of a change in a spectral characteristic is determined by the rate of rewriting of the dynamic grating inside a photorefractive crystal and is ~ 1 s for a $BaTiO_3$ crystal for the writing light intensity 100 mW cm^{-2} at a wavelength of 532 nm.

The aim of this paper is to develop and study a new method for rapid control of the spectral characteristic of Bragg gratings. This method provides a high sensitivity to control electric voltages and high control rates of the central reflection wavelength and the shape of the spectral characteristic of a Bragg grating.

2. Basic physical principles

The method proposed here uses the electrooptical effect to produce controllable shifts of the average refractive index of a Bragg grating. The grating is formed inside an electrooptical material, and controllable shifts are produced by applying a spatially inhomogeneous external electric field. The possibility of a universal control of the spatial distribution of the external electric field is determined by the configuration of control electrodes and the type of their connection with a voltage source; in this case, the abrupt shifts of the electric field and the average refractive index can be produced. The central reflection wavelength can be also tuned without a change in the shape of the spectral characteristic by applying a homogeneous electric field.

The method is realised with the use of a $LiNbO_3$ crystal. This crystal was chosen for several reasons. First, the methods for holographic writing highly efficient Bragg gratings in a $LiNbO_3$ crystal are well developed [8]. Second, this crystal has good electrooptical properties and is widely used in high-frequency electrooptical modulators [2]. Third, the manufacturing technology of $LiNbO_3$ optical waveguides is well developed and widely used [9]. All this makes it possible to fabricate controllable integrated optical Bragg gratings, which will provide a reduction in the control voltage and an increase in the control rate.

3. Theoretical description

Consider first qualitatively the reasons for a change in the shape of the spectral characteristic of a Bragg grating caused by a shift in the average refractive index. A simplest Bragg grating consisting of two identical sections (halves) of length $l/2$ with different average refractive indices ($n + \Delta n/2$ for one half and $n - \Delta n/2$ for the other) in shown in Fig. 1a. The amplitude of an optical signal reflected from such a structure is a sum of amplitudes reflected from each of the sections (in the general case, taking into account possible multiple reflections of the wave reflected from the second section). Note that the contributions from different sections are added coherently, taking phase relations into account, and it is the phase relations that are mainly responsible for a change in the shape of the spectral characteristic.

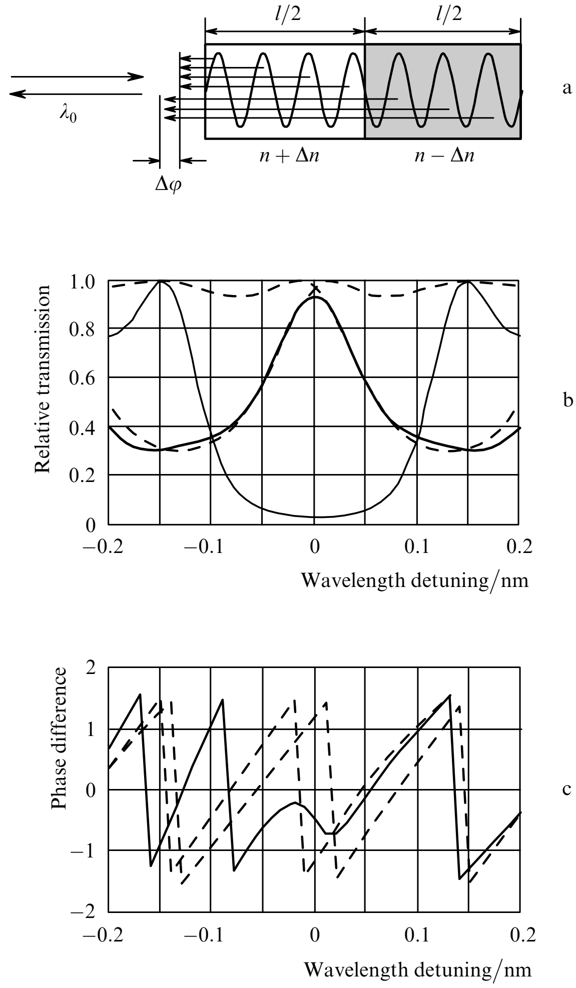


Figure 1. Effect of the abrupt change in the average refractive index of the Bragg grating on the shape of its spectral characteristic. Scheme of the interference of signals from the two halves of the grating with different average refractive indices (a) and the amplitude spectral characteristics of the homogeneous Bragg grating (solid thin curve), two individual sections with different refractive indices (dashed curves), and the total amplitude spectral characteristic of the Bragg grating with the shift of the average refractive index (solid thick curve) (b), and also phase spectral characteristics of two individual sections (dashed curves), and the total phase spectral characteristic of the Bragg grating with the shift of the average refractive index (solid curve) (c).

The spectral dependences of the homogeneous sections represent the spectral dependences of homogeneous Bragg gratings with shifted central wavelengths (Fig. 1b). The distance between the central wavelengths of the sections is $\Delta\lambda = 2\Delta n\Lambda$. The phase difference $\Delta\varphi$ between signals reflected from different sections also depends on the difference between the refractive indices and is $(2\pi/\lambda_0)\Delta nl$ (Fig. 1c). When the phase difference between two signals reflected from two parts of the grating with different refractive indices is π, the reflection minimum (transmission maximum) appears because the reflected waves are mutually compensated due to destructive interference.

The spectral characteristic of a Bragg grating with controllable shifts of the average refractive index can be rigorously described by using the formalism of scattering matrices, which is based on the theory of coupled waves [5, 6]. Consider a Bragg grating with a shift of the average refractive index, which consists of a set of the homogeneous sections of sinusoidal gratings with different refractive indices (Fig. 2). The propagation of light through each section is described by the matrix expression

$$\begin{pmatrix} A^i_{\text{out}} \\ B^i_{\text{out}} \end{pmatrix} = \begin{pmatrix} S^i_{11} & S^i_{12} \\ S^i_{21} & S^i_{22} \end{pmatrix} \begin{pmatrix} A^i_{\text{in}} \\ B^i_{\text{in}} \end{pmatrix}, \quad (4)$$

where A and B are the amplitudes of the incident and reflected light waves (the subscripts in and out corresponds to the amplitudes of waves at the input and output of the ith section of the grating), and the elements S^i of the scattering matrix are determined by using the standard Kogelnik theory of coupled waves [10]

$$S^i_{11} = \left(1 - r_i^2\right)^{-1}\left[\exp(\mathrm{i}q_i l_i) - r_i^2 \exp(-\mathrm{i}q_i l_i)\right],$$

$$S^i_{22} = \left(1 - r_i^2\right)^{-1}\left[\exp(-\mathrm{i}q_i l_i) - r_i^2 \exp(\mathrm{i}q_i l_i)\right], \quad (5)$$

$$S^i_{21} = -S^i_{12} = \left(1 - r_i^2\right)^{-1} r_i\left[\exp(\mathrm{i}q_i l_i) - \exp(-\mathrm{i}q_i l_i)\right],$$

where $q_i = \pm[(\delta\beta_i)^2 - \kappa_i^2]^{1/2}$; $r = (q_i - \delta\beta_i)/\kappa_i$; i is the ordinal number of a section; l_i is the length of a homogeneous section with a given average refractive index; $\kappa_i = \pi\delta n_i \lambda_{0i}^{-1}$ is the coupling coefficient, which is determined by the grating amplitude δn_i; $\delta\beta_i = 2\pi\times(\lambda^{-1} - \lambda_{0i}^{-1})$ is the wavelength detuning parameter characterising the deviation of the wavelength λ of the reading light from the Bragg reflection wavelength λ_0, which is determined for each of the sections by the grating period Λ and the average refractive index n_i.

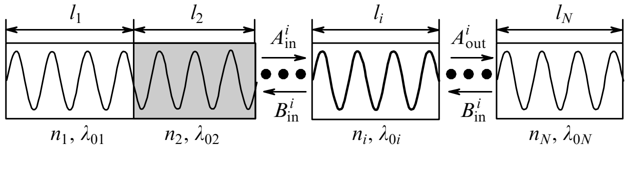


Figure 2. Scheme of the Bragg grating consisting of many sections with different average refractive indices.

The phase shift acquired by reflected and transmitted light also depends on the spatial position of a given section. This contribution can be taken into account by multiplying the matrix S^i from the left and right by the corresponding phase-shift matrices:

$$S_\phi(x_i) S^i S^*_\phi(x_i + l) = \begin{pmatrix} \exp(\mathrm{i}\delta\beta_i x_i) & 0 \\ 0 & \exp(-\mathrm{i}\delta\beta_i x_i) \end{pmatrix} \quad (6)$$

$$\times \begin{pmatrix} S^i_{11} & S^i_{12} \\ S^i_{21} & S^i_{22} \end{pmatrix} \begin{pmatrix} \exp[-\mathrm{i}\delta\beta_i(x_i + l)] & 0 \\ 0 & \exp[\mathrm{i}\delta\beta_i(x_i + l)] \end{pmatrix},$$

where x_i is the coordinate of the origin of the homogeneous section under study. For a completeness of the theoretical analysis, we also consider reflection appearing from the shift of the average refractive index between homogeneous sections

$$S_{i,i+1} = \begin{pmatrix} 1 & \dfrac{n_i - n_{i+1}}{n_i + n_{i+1}} \\ \dfrac{n_i - n_{i+1}}{n_i + n_{i+1}} & 1 \end{pmatrix}. \quad (7)$$

However, for the typical variations in the refractive index caused by the electrooptical effect (of the order of 10^{-4}) the influence of this factor on the spectral characteristic can be neglected.

The total scattering matrix of the system is obtained by the successive multiplication of matrices corresponding to each of the sections

$$S = \prod_i S_\phi(x_i) S^i S^*_\phi(x_i + l) S_{i,i+1}. \quad (8)$$

The spectral dependences of the reflection coefficient R and the transmission coefficient T of the system are determined from the total scattering matrix with the boundary conditions $B(\Sigma l_i) = 0$ (the amplitude of the reflected signal at the system output is zero):

$$T = \left|\frac{A_{\text{out}}}{A_{\text{in}}}\right|^2 = \left|S_{11} - \frac{S_{12}S_{21}}{S_{22}}\right|^2,$$

$$R = \left|\frac{B_{\text{in}}}{A_{\text{in}}}\right|^2 = \left|\frac{S_{21}}{S_{22}}\right|^2. \quad (9)$$

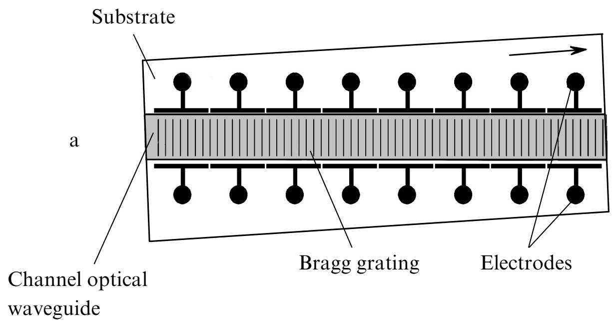
The above theoretical expressions describe a Bragg grating containing an arbitrary number of sections with shifts of the average refractive index. In a particular case of a grating consisting of two sections of the same length $l/2$ with different average refractive indices ($n + \Delta n/2$ for the first half of the grating and $n - \Delta n/2$ for the second half), the shape of the spectral characteristic of the structure calculated by using scattering matrices (4)–(9) is in good agreement with the results of qualitative analysis (Fig. 1). At the centre of the reflection band (at the central Bragg reflection band λ_0), the transmission maximum appears, which is caused by the mutual compensation of light waves coming from two different sections with the phase shift equal to π.

4. Fabrication of a controllable integrated optical Bragg grating

We developed and fabricated an electrically controlled integrated optical Bragg grating for experimental studies. At the first stage of its fabrication, a channel optical waveguide was prepared on the $LiNbO_3$ surface by the standard method of multicomponent doping. The thermal diffusion of titanium ions provided the formation of a waveguide channel with a higher refractive index, the difference between the refractive indices of the channel and substrate being ~ 0.001. The additional doping with copper ions provided the enhancement of the photosensitivity of the material at a wavelength of 532 nm, which was later used for holographic writing of a Bragg grating. Doping with copper ions was also performed by the method of thermal diffusion. In this case, the concentration of copper ions in the region of the optical waveguide was $\sim 10^{19}$ cm^{-3}. The waveguide fabricated in this way had a high optical quality and the level of internal losses less that 1 dB cm^{-1}. The transverse dimensions of the channel 4 μm × 10 μm provided the single-mode regime of light propagation in the telecommunication wavelength range (1500 – 1600 nm). The asymmetric configuration of the surface waveguide and the inequality of the transverse dimensions of the channel lead to different conditions for the propagation of two orthogonal polarisations and to the removal of the degeneracy of the TM and TE modes.

To make the experimental study more convenient (by increasing the frequency interval between the maxima of the spectral characteristics of different modes), we fabricated the waveguide channel directed at a small angle of $\sim 1^\circ$ to the optical axis C of the $LiNbO_3$ crystal (Fig. 3), thereby enhancing the anisotropy of the optical waveguide due to natural birefringence, which was ~ 0.0005 for this angle. This configuration allows one to study independently the control of the spectral characteristics of the TM and TE modes. A system of eight control electrodes prepared by depositing copper on the waveguide surface made it possible to apply an external electric field with different spatial distributions in the geometry of transverse electrooptical effect. To prevent the electric breakdown and oxidation, the electrodes were covered with a silicon oxide (SiO_2) layer. At the final stage of fabrication of the integrated optical structure, the sample was placed inside a protective housing, and two single-mode fibres were glued to the waveguide ends to couple in and couple out the optical signal.

a



b

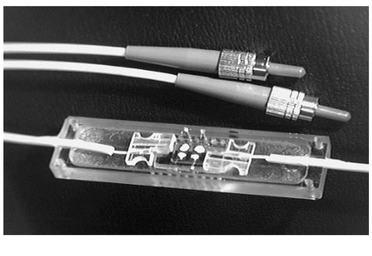


Figure 3. Scheme (a) and the appearance (b) of the electrically controlled integrated optical Bragg grating.

A Bragg grating was produced inside the integrated optical structure by holographic writing. We used the symmetric scheme for holographic-grating writing in the transmission geometry. The gratings were written by the 532-nm second harmonic of a Nd : YAG laser. Despite a high degree of doping with copper ions, the writing time was several tens of minutes. In the case of such long exposures, the writing stability is especially important. To produce gratings with the high diffraction efficiency, we used a specially developed system for active stabilisation of writing [8], which monitored the phase change between writing beams.

The grating period was determined by the angle of incidence of the writing beams. For the angle of incidence of 49.5°, it was 349.5 nm, which corresponds to $\lambda_0 \approx 1554$ nm for the reflection reading geometry. It is important that the wave vector of the grating should be directed strictly perpendicular to the constant phase surface of modes propagating in the optical waveguide, i.e., parallel to the waveguide channel. The deviation of the direction of the wave vector from the waveguide channel direction results in the appearance of leaky modes and additional losses.

Highly efficient Bragg gratings with reflectivity above 95 % were written by this method. We performed experiments with unfixed photorefractive holographic gratings, which could be easily erased to write new gratings with different parameters, thereby providing additional experimental possibilities. In the case of permanent reading at the wavelengths in the telecommunication range (1550 – 1600 nm), the unfixed grating persisted for a few days without a considerable decrease in its diffraction efficiency. If a more prolonged storage is required, the grating can be fixed by using the well developed method of thermal fixation [8].

5. Experimental results and discussion

We studied the spectral dependences of the transmission of an integrated optical Bragg grating for different spatial distributions of an external electric field (dependences of the radiation intensity transmitted through the integrated optical structure on the wavelength of the reading beam). The measurements were performed by using a tunable PRO 800 semiconductor laser. The polarisation of the reading beam was controlled by means of a fibre controller. We studied two orthogonal linear polarisations of the reading beam: ordinary polarisation corresponding to the TM mode and extraordinary polarisation corresponding to the TE mode. The diffraction efficiency, which was above 95 %, and the spectral selectivity (FWHM = 0.2 nm) were measured in the absence of an external electric field for both polarisations of the reading beam. The transmission minimum for extraordinary polarisation is shifted to the blue by 0.3 nm with respect to the transmission minimum for ordinary polarisation (Fig. 4a), which is caused by natural birefringence in a negative uniaxial $LiNbO_3$ crystal with the optical axis oriented at an angle to the waveguide channel. When a homogeneous external field with the amplitude 10 V μm^{-1} was applied, the transmission minimum shifted in the opposite directions for two different polarisations, the shift for extraordinary polarisation being considerably larger than that for ordinary polarisation (Fig. 4).

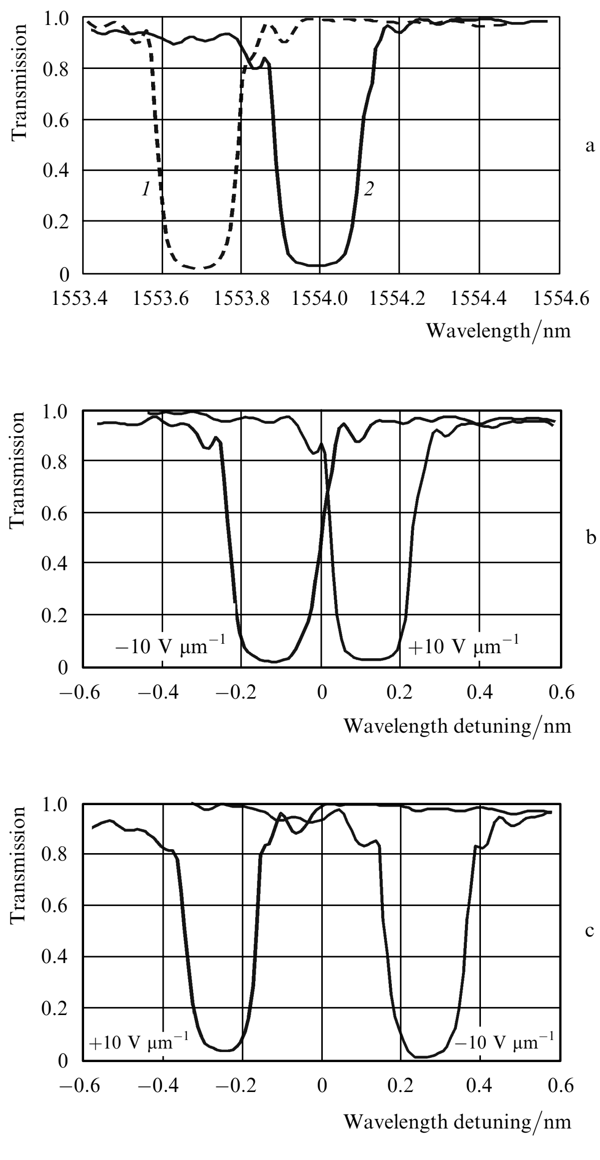


Figure 4. Spectral characteristic of the integrated optical Bragg grating in the zero electric field for the TE (*1*) and TM (*2*) modes (a) and the electric tuning of the central wavelength for ordinary (b) and extraordinary (c) polarisations.

The effective electrooptical coefficients for ordinary (-3.3×10^{-12} V cm^{-1}) and extraordinary (6.9×10^{-12} V cm^{-1}) polarisations were found from the shift of the central wavelength by using expression (3). These values well agree with estimates made by theoretical expressions obtained in [3] for this orientation of the crystal. Note that due to anisotropy of the electrooptical effect, the device has a very pronounced polarisation dependence.

The physical mechanism of controlling the shape of the spectral characteristic of the Bragg grating is completely identical for the two orthogonal polarisations of the eigenmodes. We performed experiments for both these polarisations. However, because the electrooptical effect is stronger for the extraordinary polarisation of light, it is obvious that the electric control of the spectral characteristic for this polarisation will be more efficient. Therefore, we present below the experimental dependences of the shape of the spectral characteristic of a Bragg grating controlled in the case of the extraordinary polarisation of light.

Figures 5a,b present the experimental dependences (solid curves) of the spectral characteristic of the Bragg grating consisting of two identical sections to which external electric fields of the same amplitude (10 V μm^{-1}) but with opposite

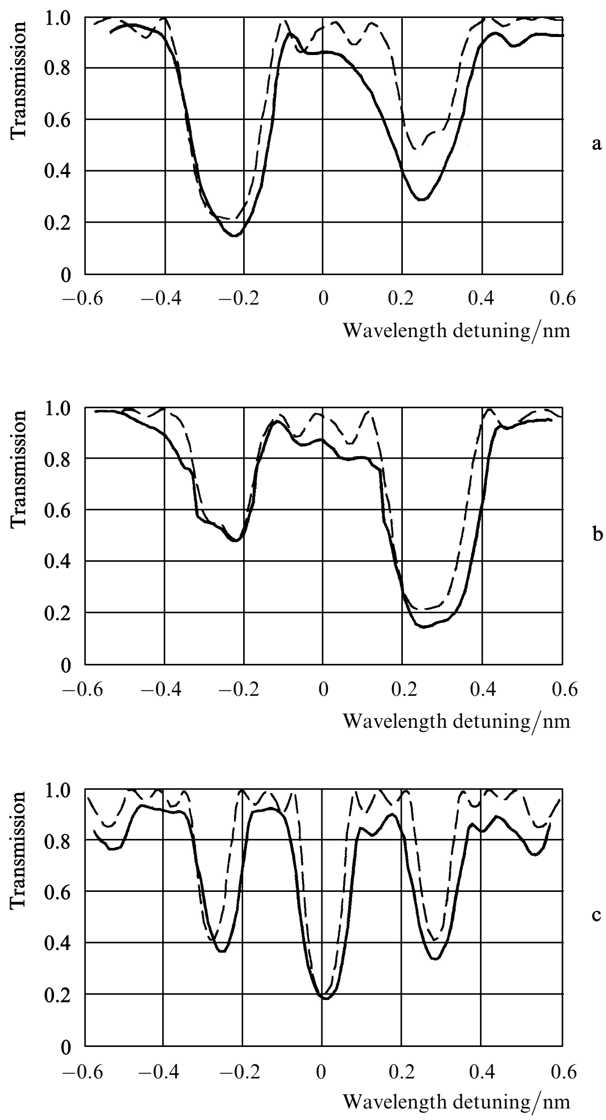


Figure 5. Electric control of the shape of the spectral characteristic of the Bragg grating consisting of two identical sections in the cases when the electric field with the amplitude +10 V μm^{-1} is applied to its left half, while the field with the amplitude −10 V μm^{-1} is applied to its right half (a), and vice versa (b), and also when the external electric field with the amplitude 10 V μm^{-1} is applied to eight pairs of electrodes with alternating polarities (c). The solid and dashed curves are experimental and theoretical dependences, respectively.

polarities are applied. As mentioned above, a shift in the average refractive index produced at the centre of the Bragg grating gives rise to the transmission maximum because optical signals reflected from different sections are added out of phase. A small asymmetry of the modified spectral characteristic is caused by the inequality of diffraction efficiencies of the two sections of the grating. The amplitudes for different sections of the grating were different because of the inhomogeneous distribution of the radiation intensity in the beams writing the holographic grating. In the case of Gaussian writing beams, a small shift of the maximum of the grating amplitude with respect to the centre of a sample leads to different effective amplitudes for the two sections, as was observed in the experiment.

A change of the polarity of the applied external electric field results in the mirror reflection of the modified spectral characteristic with respect to the central wavelength, which also confirms the assumption about the inequality of the effective amplitudes of two sections, which amounts approximately to 20 %. The dashed curves in Fig. 5 present theoretical dependences calculated by expressions (4) – (9) for the effective electrooptical coefficient measured experimentally (6.9×10^{-12} V cm^{-1}) by using the effective grating amplitudes for two sections as fitting parameters. The theoretical dependences are in good agreement with experimental results for both polarisations of the applied inhomogeneous electric field.

In the last experiment, a periodic inhomogeneity of the average refractive index was produced in the Bragg grating. The external electric field with the amplitude 10 V μm^{-1} and the opposite polarity was applied alternately to each of eight pairs of electrodes. Therefore, the spatial distribution of the electric field inside a sample had the form of a meander. Such a distribution of the electric field produced a periodic spatial distribution of the average refractive index. In this case, the shape of the spectral characteristic changed in the following way (Fig. 5c). Transmission at the central wavelength increased from 5 % [curve (*1*) in Fig. 4a] to 20 % (Fig. 5c) and two pronounced side lobes appeared (additional transmission minima). The central wavelengths of the side lobes (Fig. 5c) corresponded to the shift of the central wavelength of the Bragg grating caused by the applied homogeneous electric field with the amplitude 10 V μm^{-1} (Fig. 4c). Theoretical curves presented in Fig. 5 were calculated for the grating parameters determined in previous experiments. The theoretical dependences well agree with experimental results.

6. Conclusions

We have proposed a new method to control the spectral reflection characteristic of Bragg gratings, which is based on the introduction of electrically controlled shifts of the average refractive index of individual sections of the grating. The theory is developed which describes in detail the shape of spectral characteristics of Bragg gratings with a complex step structure of the spatial distribution of the average refractive index. We have developed and manufactured a prototype of an integrated optical device based on a channel waveguide in a $LiNbO_3$ crystal and a holographic Bragg grating. The diffraction efficiency above 95 % and spectral selectivity of 0.2 nm were obtained for a homogeneous integrated optical Bragg grating. The prompt electric control of the shape of the spectral characteristic of the holographic Bragg grating in the channel optical waveguide in the $LiNbO_3$ crystal was experimentally demonstrated and good agreement between theoretical and experimental results was obtained.

A homogeneous external electric field applied to the grating should cause the shift of the central reflection wavelength without a change in the shape of the spectral characteristic. In real experiments, the shape slightly changes due to inhomogeneities of the electric field at the edges of discrete electrodes and also due to a small displacement of the middle of the holographic grating with respect to the middle point of the electrode system. A continuous tuning of the central wavelength was experimentally demonstrated in the $\pm$0.3-nm range in the telecommunication wavelength region (1500 – 1600 nm). The high tuning rate and accuracy even within such a relatively narrow spectral range can be quite interesting for locking and stabilisation of laser wavelengths.

The shape of the spectral characteristic of the integrated optical Bragg grating changes most drastically when the electric field applied to the two halves of the grating provides the destructive interference of optical signals reflected from them. In this case, the transmission maximum appears at the central reflection wavelength of the homogeneous Bragg grating. This control regime is of interest for applications requiring the spectral selection and control of many discrete spectral channels in a broad wavelength range, for example, in the WDM telecommunication systems. For these applications, several integrated optical Bragg gratings with different central reflection wavelengths can be formed on the same substrate. The reflectivity of each grating can be controlled by applying independently the appropriate inhomogeneous electric field to each grating. A set of such gratings can be used to build controllable spectral multiplexers, selective optical attenuators and modulators for modulation only at the specified wavelengths, to develop optical power equalisers and wavelength switches in resonators of tunable lasers.

Therefore, good technical parameters and the integrated optical design make the method developed to control the spectral characteristics of Bragg gratings quite promising for many practical applications.

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