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Analysis of the Possibilities of Long Period Gratings Usage in the Planar Gradient Waveguides in the Sensor Aspect

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This paper introduces the application possibilities of long-period waveguide gratings produced in gradient structures of planar waveguides and their possible usage as the detectors of changes in the refractive index. The influence of technological processes and corrugation's parameters on the resonant characteristics and transmission spectrum (obtained by the numerical simulations) of such structures was presented. The influence of changes in the refractive index of the environment on the transmission spectral characteristics was shown. The possibilities of sensor applications of such structures was presented as well. The calculations were performed for two types of gradient waveguides' structures: produced in BK7 glass with the use of $K^+ \leftrightarrow Na^+$ ion exchange and produced in soda-lime glass with the use of $Ag^+ \leftrightarrow Na^+$ ion exchange.

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1. Introduction

The main driver of continuous improvement and the search for new solutions is the need for automation, control and monitoring of all types of processes. This applies to all industries as well as medical technology and others where the emphasis is on reliability and precision. Wherever there are severe conditions or the continuous monitoring is required, the sensors are designed which with a high accuracy and in a short time will allow the detection of the desired parameters. Among these the optical sensors are often used. These devices compared to their electronic counterparts are mainly characterized by insensitivity to the presence of changes in electric and magnetic fields. There are different types of solutions to this type of sensors. They use the interaction of the field of propagating modes in the waveguide structure with the waveguide's environment. Sources of electromagnetic waves used in optical sensors may be either narrow-band, quasi-monochromatic — the lasers (FWHM < 1 nm), average broadband — light-emitting diodes LEDs (FWHM ≈ dozen to several dozen nm), or broadband covering the entire visible range of the spectrum — halogen lamps.

The optical structures that utilize broadband sources as sensors can be the waveguides with produced long period gratings (LPG). By suitable selection of the corrugation period the power coupling between propagating modes is obtained in such waveguides. Such a coupling has a resonant character and this kind of waveguide acts as a selective filter. The first LPG filters were produced on fiber waveguides [1–5]. However, due to limitations of materials that are used for producing waveguides and the technological difficulties of exposing the core and the physical embodiment of the grid for LPG systems, the attention was directed toward the planar structures. Such structures, as opposed to the waveguides, are referred to as long period waveguide gratings (LPWG) [6–9]. A wide range of materials with known parameters as well as well-known and controlled technological processes, allow to model and execute the desired systems in many configurations. In this paper, the potential of LPWG system based on gradient planar waveguides in terms of its use as a sensor was presented.

2. Configuration of the planar system of the LPWG structure

The LPWG systems couple the modes propagating through the waveguide to the coating modes (which propagate in the area directly adhering to the area of the waveguide). This is accomplished by creating a periodic corrugation in the form of relief on the surface or periodic changes in the refractive index. The condition of coupling is to meet the Bragg equation

$$\boldsymbol{\beta}_0 + q\boldsymbol{K} = \boldsymbol{\beta}_m, \tag{1}$$

where $\boldsymbol{\beta}_0$ and $\boldsymbol{\beta}_m$ — propagation vector of the modes of zero and m-th order, q — coupling order ($q = \pm 1, \pm 2 \ldots$) and waveguide vector $\boldsymbol{K}$ which can link directly to the period of corrugation

$$|\boldsymbol{K}| = 2\pi/\Lambda, \tag{2}$$

where Λ — the period of produced corrugation.

If a planar waveguide is designed as a single-mode and its area, in which the period corrugation was created, is multimode, the power coupling (in the case of TE polarization modes) occurs between the basic TE_0 mode and the higher-order modes ($\beta_m < \beta_0$). In this case, the coupling row displays negative values ($q < 0$). For $q = -1$ Eq. (1) takes the form

$$(N_0 - N_m)\,\Lambda = \lambda_r, \tag{3}$$

where λ_r is the resonant wavelength for the coupling of the modes of zero and m-th order.

Since the effective refractive indices of the modes $N_0(\lambda)$ and $N_m(\lambda)$ are of dispersion character, the refractive dispersion of the waveguide medium and the surrounding area has also an important influence on Eq. (2).

There are many examples of LPWG structures' configuration. The earliest proposed structures were step-index, where both the single and multimode area were the step-index waveguides [1, 4]. The mixed structures can also be found [6], in which the gradient area serves as a waveguide and the power is decoupling to the modes propagating in the multimode homogeneous area deposited directly on the structure of the gradient. A system in a completely gradient configuration, where both the single-mode waveguide and the multimode structure are gradient areas, has also been proposed [10].

Figure 1 presents a graphic proposal for such a system. A physical disorder in the form of a relief is produced on a single-mode gradient waveguide. The multimode coupling area is obtained through a process of additional diffusion of admixture to the glass through the corrugation area. In this case the decoupling area is in the glass substrate.

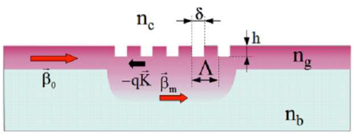

Fig. 1. The LWPG structure in a gradient configuration.

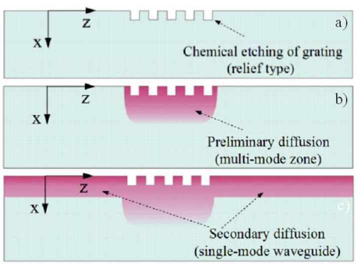

Fig. 2. The sequence of technological processes of implementation of the structure of Fig. 1.

Figure 2 presents the sequence of technological processes allowing to implement the structure of Fig. 1. The first technological step is to produce a corrugation (relief) in the glass substrate (Fig. 2a). This is accomplished by chemical etching prior to the doping of glass. In the next step through the surface of the glass (relief) a selective ion exchange process is performed (Fig. 2b). The resulting planar waveguide is a multimode structure. After this step, it is possible to have an optional annealing step, which provides an additional diffusion of admixture introduced into the glass, resulting in a reduction of refractive index profile of the waveguide. At the same time the range of admixture in the glass increases (the depth of the waveguide increases). This procedure allows forming the characteristics of the resonant coupling of modes in the final LPWG structure. The last technological step is to create a single-mode gradient waveguide across the whole surface of the glass substrate (Fig. 2c), which is achieved through the short process of secondary diffusion. In this process the refractive index of the multimode waveguide also increases. The duration of the secondary diffusion process must be chosen so that the resulting waveguide was single-mode throughout all of the used range of spectrum.

3. Simulation methods and numerical calculations

Numerical simulations based on the assumptions presented in the previous section were carried out on the basis of the actual technological processes. The LPWG structure was simulated based on the gradient waveguide by means of the processes of the $K^+ \leftrightarrow Na^+$ ion exchange in BK7 glass and the $Ag^+ \leftrightarrow Na^+$ ion exchange in soda--lime glass. The ion exchange processes were described by the two-component exchange model [11]. In the case of $K^+ \leftrightarrow Na^+$ ion exchange in BK7 glass, which is characterized by a polarizing birefringence of the produced waveguide [11], simulations were limited to the TE polarization. On the basis of the calculated refraction profiles using the matrix method for the analysis of planar waveguides [12], the dependences of effective refractive indices of guided modes on the wavelength were determined.

On the basis of these relationships with the use of Eq. (3) the characteristics of resonant coupling of modes $TE_0 \to TE_m$ were determined. Taking into account the $N_m(\lambda)$ relationship, the spectral dependences of the $E_{y0}(x,\lambda)$ and $E_{ym}(x,\lambda)$ mode fields' distribution for the mode coupling areas in the LPWG structures were calculated. The distributions of these fields allow to calculate the coupling coefficients of modes in disturbed areas according to the relationship [10]:

$$\kappa_{-1,\mathrm{TE}_0\to\mathrm{TE}_m}(\lambda) = \frac{1}{\lambda}\frac{\sin(a\pi)}{\sqrt{N_0(\lambda)N_m(\lambda)}} \times \frac{\int_0^h E_{y,0}(x,\lambda)E_{y,m}(x,\lambda)\left[n_\mathrm{g}^2(x,\lambda)-n_\mathrm{c}^2(\lambda)\right]\mathrm{d}x}{\sqrt{\int_{-\infty}^{\infty}E_{y,0}^2(x,\lambda)\,\mathrm{d}x\int_{-\infty}^{\infty}E_{y,m}^2(x,\lambda)\,\mathrm{d}x}}, \tag{4}$$

where κ_{-1} — coupling coefficient of the coupling row ($q=-1$), $a=\delta/\Lambda$ — duty-cycle of corrugation, h — depth of corrugation, $n_\mathrm{g}(x,\lambda)$ — dispersion dependence of gradient area refraction in the glass, $n_\mathrm{c}(\lambda)$ — dispersion dependence of the refraction of the waveguide surrounding.

On the basis of the determined coupling coefficients (4) the spectral transmission in the basic mode linked to the decoupling spectrum from the mode of m-th order is calculated [10]:

$$T_{\mathrm{TE}_0\to\mathrm{TE}_m}(\lambda,\Lambda,h,a,p) = 1-\frac{\sin^2\left(\sqrt{\kappa_{-1,\mathrm{TE}_0\to\mathrm{TE}_m}^2+\Delta^2}p\Lambda\right)}{1+\Delta^2/\kappa_{-1,\mathrm{TE}_0\to\mathrm{TE}_m}^2}, \tag{5}$$

where Λ — corrugation period, p — number of corrugation periods, Δ — a factor describing the deviation from phase matching according to Bragg's Eq. (1):

$$\Delta(\lambda,\Lambda) = \pi[(N_m(\lambda)-N_0(\lambda))/\lambda-1/\Lambda]. \tag{6}$$

4. The LPWG system as a spectral filter

Spectral transmission characteristics calculated using Eq. (5) for specific refractive profiles of waveguide structures in the coupling modes' area have their filtering properties. Transmission characteristics of this filter is shaped by many factors. The position of minimum transmission of such a filter, its depth and width, is affected by: the geometric properties of corrugation, dispersion properties of the glass substrate, and the implementation processes of the ion exchange and their sequence. The knowledge of the effects of ion exchange in the glass allows the design of the spectral transmission characteristics of this filter for a selected wavelength. The starting point is assumed to be the temperature characteristics of diffusion coefficients of ions exchanged in the glass. Along with the spectral characteristics of the glass refraction, it allows to determine the parameters of the diffusion process to produce a single-mode area for a given range of the spectrum. The spectral dependence of the refraction in the multimode area of a LPWG structure is also determined based on knowledge of these characteristics. Knowledge of spectral dependences of refraction in both the single and multi-mode area of the structure allows the calculation of spectral dependences of effective refractive indices of the propagating modes. This in turn allows the determination of the characteristics of their resonant coupling. On this basis, the period of corrugation allowing the coupling between the basic mode and a particular mode of a higher order is determined (3). The form of the transmission characteristics is also affected by the amplitude (depth) of the corrugation h, its duty-cycle a and the number of periods p.

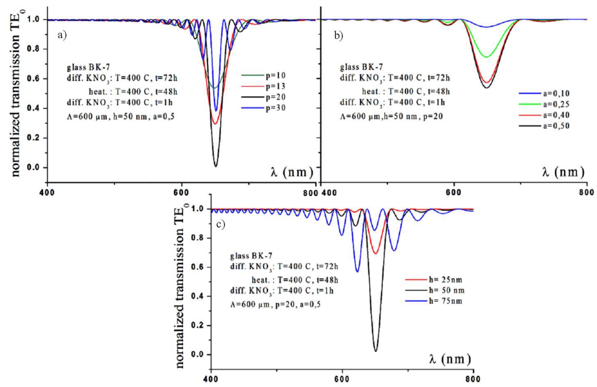

Fig. 3. Transmission characteristics of the LWPG structure with the period of $\Lambda = 600$ μm based on the planar waveguide produced in BK7 glass by the $K^+ \leftrightarrow Na^+$ ion exchange method. (a) The influence of corrugations' number, (b) the influence of duty-cycle, and (c) the influence of the corrugation's amplitude.

Figure 3 presents the influence of these parameters on the transmission characteristics of the filter on the basis of a sample LWPG structure produced in BK7 glass by the $K^+ \leftrightarrow Na^+$ ion exchange method (with KNO_3 as a source of admixture) in the following technological processes: preliminary diffusion $T = 400\,°C$, $t = 72$ h (multimode area Fig. 2b), heating $T = 400\,°C$, $t = 48$ h (multimode area Fig. 2b) and secondary diffusion $T = 400\,°C$, $t = 1$ h (whole Fig. 2c).

The obtained results of calculations indicate the existence of the optimum number of periods, the duty-cycle and the depth of corrugation in the depth and width of the transmission characteristics of such a filter. It is therefore essential to optimize the structure of such filters designed for a specific range of the spectrum.

5. The possibility of using a spectral filter based on the LPWG structure as a sensor

The effective refractive indices of the modes propagating in a planar waveguide depend on the refractive index of the surrounding n_c. This dependence also applies to the mode fields corresponding to the particular modes. Thus, on the basis of Eq. (4) there is the influence of the refractive index of the waveguide's surrounding on the coupling coefficients of modes and consequently on the transmission characteristics of the LPWG structures. Therefore the possible use of the LPWG structure as a selective filter modulated by the changes in the refractive index of the waveguide's environment can be expected. The use of such a filter as a sensor of changes n_c may be reasonable in the case of the use of narrow-band radiation source (laser). The appropriate design of spectral characteristics of the filter based on LPWG allows to set a minimum rate of its transmission near the maximum of the spectral characteristics of the laser radiation. It will then be possible to directly modulate the laser radiation transmitted through the filter by changing the refractive index coefficient of the surrounding n_c.

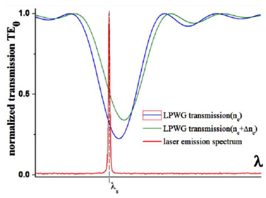

Fig. 4. Rule of using the LPWG structure as a sensor.

Figure 4 shows the idea of the use of the planar waveguide structure in the LPWG system as a sensor using narrow-band radiation source (laser). The narrow spectral line of the source (FWHM < 1 nm) causes that the changes in the intensity of the laser light transmitted through the filter are proportional to changes in normalized transmission of a filter at the given wavelength of the source λ_s. Therefore the concept of the sensor sensitivity S can be defined as:

$$S = \frac{dT(\lambda_s)}{dn_c}. \qquad (7)$$

Such defined sensitivity will depend on the position of the spectral characteristics of the filter in relation to the spectral line of the radiation source. For a gradient waveguide structure with a fixed refraction characteristics of the position of minimum transmission filter determines the period of generated corrugation.

Figure 5 shows the calculated changes in the filters' transmission as a function of changes in the refractive

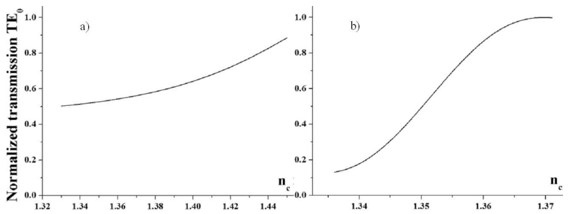

Fig. 5. The changes of transmission for the wavelength $\lambda_s = 676$ nm in a planar LPWG structure caused by a change in the refractive index of the environment n_c. (a) The structure based on a waveguide with the refractive profile as in Fig. 6a with a corrugation's period $\Lambda = 249$ μm, (b) the structure based on a waveguide with the refractive profile as in Fig. 6b with a corrugation's period $\Lambda = 155$ μm.

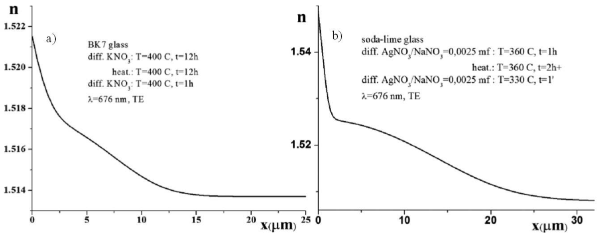

Fig. 6. Sample refractive profiles of LPWG structures in the gradient configuration, produced: (a) in BK7 glass in the $K^+ \leftrightarrow Na^+$ ion exchange processes, (b) in soda-lime glass in the $Ag^+ \leftrightarrow Na^+$ ion exchange processes.

index of the environment n_c. In both cases, the spectral characteristic of the semiconductor laser generating the wave $\lambda_s = 676$ nm (FWHM = 0.8 nm) was assumed for the calculations. The dependence of the transmission in the TE_0 mode on the refractive index coefficient n_c shown in Fig. 5a refers to the LPWG structure produced in BK7 glass by the $K^+ \leftrightarrow Na^+$ ion exchange process. The refractive profile of this structure for a wavelength $\lambda = 676$ nm is shown in Fig. 6a. The corrugation's parameters are: $\Lambda = 249$ μm, $h = 50$ nm, $a = 0.5$, $p = 40$. The same dependence presented in Fig. 5b refers to the waveguide structure produced in a soda-lime glass with the use of $Ag^+ \leftrightarrow Na^+$ ion exchange. The refractive profile of this structure for a wavelength $\lambda = 676$ nm is shown in Fig. 6b. The corrugation's parameters are $\Lambda = 155$ μm, $h = 20$ nm, $a = 0.5$, $p = 30$.

To calculate the transmission's changes shown in Fig. 5a and b it was assumed that the medium of the environment constitutes a dispersion characteristics $n_c(\lambda)$ the same as water. In both cases, the minimum transmission of the filter was set to a wavelength $\lambda_s = 676$ nm for the refractive index of the environment $n_c = 1.33$. The average sensitivity in the range of changes in the refractive index of the environment is defined as $S_{av} = \Delta T(\lambda_s)/\Delta n_c$. In the case of changes of transmission as shown in Fig. 5a the average sensitivity is $S_{av} = 3$ for $\Delta n_c = 0.12$, whereas for the transmission as shown in Fig. 5b it is: $S_{av} = 24$ ($\Delta n_c = 0.035$). The obtained results of the calculation for such LPWG structures show their potential for sensor applications.

6. Conclusions

The research has shown that it is possible to use the LPWG structures built on the planar gradient waveguides as a spectral filter in the visible spectrum. Transmission characteristics of such filters can be shaped in a wide range by using parameters of waveguide structures from which they are produced. The study shows such a possibility with an example of two types of ion-exchange method for BK7 glass and soda-lime glass. These characteristics also depend on the geometry of the corrugated area (period, duty-cycle, and depth of the corrugation). The influence of the refractive index coefficient of the LWPG structure's environment on the TE_0 mode coupling with the modes of higher order was also presented in this paper. This enables the use of such structures as sensors of changes in the refractive index of the environment. The results of theoretical calculations carried out in this paper are based on the experimentally determined parameters of the ion exchange: $K^+ \leftrightarrow Na^+$ in BK7 glass and $Ag^+ \leftrightarrow Na^+$ in soda-lime glass and chromatic dispersion characteristics of these glasses.

Acknowledgments

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References

[1] A.M. Vengsarkar, P.J. Lemaire, J.B. Judkins, V. Bhatia, T. Erdogan, J.E. Sipe, *J. Lightwave Technol.* **14**, 58 (1996).

[2] P.J. Lemaire, R.M. Atkins, V. Mizrahi, W.A. Reed, *Electron. Lett.* **29**, 1191 (1993).

[3] O. Duhem, A. DaCosta, J.F. Henninot, M. Douay, *Electron. Lett.* **35**, 1014 (1999).

[4] C.Y. Lin, L.A. Wang, *Photon. Technol. Lett.* **13**, 332 (2001).

[5] H.C. Tsoi, W.H. Wong, E.Y.B. Pun, *Photon. Technol. Lett.* **15**, 721 (2003).

[6] K.S. Chiang, K.P. Lor, C.K. Chow, H.P. Chan, V. Rastogi, Y.M. Chu, *Photon. Technol. Lett.* **15**, 1094 (2003).

[7] V. Rastogi, K.S. Chiang, *Appl. Opt.* **41**, 6351 (2002).

[8] S. Pal, B.R. Singh, *J. Lightwave Technol.* **25**, 2260 (2007).

[9] D.-L. Zhang, Y. Zhang, Y.-M. Cui, C.-H. Chen, E.Y.B. Pun, *Opt. Laser Technol.* **39**, 1204 (2007).

[10] T. Kotyczka, R. Rogoziński, *Elektronika* **11**, 25 (2012) (in Polish).

[11] R. Rogoziński, in: *Ion Exchange in Glass — The Changes of Glass Refraction*, Ed. A. Kilislioğlu, In-Tech, Rijeka 2012, Ch. 7, p. 155.

[12] C. Chen, P. Berini, D. Feng, S. Tanev, V.P. Tzolov, *Opt. Expr.* **7**, 260 (2000).