Optical and Acoustical Methods in Science and Technology

Applications of Gradient Index Multimode Interference Structures in the Technology of Optical Sensor

A. Szewczuk* and M. Błahut

Department of Optoelectronics, Silesian University of Technology, B. Krzywoustego 2, 44-100 Gliwice, Poland

The aim of the work is the presentation of operating principle and properties of multimode interference structure devices made in gradient index technology by K^+ and Na^+ ion exchange method from the point of view of optical sensor design. Numerical analysis was performed using beam propagation method. Analyzed sensor structures are covered by nanolayers whose refractive index higher than the multimode interference section index is the reason for the concentration of wave propagation energy in the sensor layer area and its vicinity. Modifications of external propagation conditions change the refractive index and extinction coefficient of a sensor layer. The variation of optical properties leads to the modification of waveguiding conditions in the multimode interference coupler.

PACS: 42.79.Gn, 42.82.Ds, 42.79.−e

1. Introduction

Applications of multimode interference (MMI)structures in waveguide sensor technology have been a subject to research studies of recent years [1–5]. The paper [1] proposes an optical temperature sensor based on MMI structures in silicon. Temperature changes cause changes in the refractive index of the interference section. The intermode interference depends on the refractive index of MMI structure, so its modifications impact on relative phases between the propagating modes causing change of light intensity coming to output waveguides. In the works [2, 3] a waveguide refractometric sensor and a displacement sensor operating on the basis of the intermode interference phenomenon in multimode optical fibres are presented. The studies [4–6] apply to interference structures made in planar waveguides by sol–gel method and describe technological and experimental research of water vapour sensor and numerical simulation of the optical system of the interference gas sensor. There is no literature available on applications in the interference sensors technology of multimode interference structures based on gradient waveguides.

The aim of this work is an analysis of MMI sensor made in the technology of ion-exchange in glass. There are considered sensor structures covered by nanolayers whose refractive index higher than the MMI section index brings about concentration of wave propagation energy in the sensor layer area and its vicinity. Modifications of external propagation conditions change the refractive index and extinction coefficient of a sensor layer. Using metal oxide nanolayers in measurement gas detection systems where the sensor effects will occur both in refractive index and extinction coefficient changes is a new technological solution. WO_3 nanolayers seem an extraordinarily promising material which provides detection of several gas types i.e. NO_2, H_2, NH_3 [7]. The basic technological problem to solve in designing of MMI interference sensor with WO_3 nanolayer is selection of the nanolayer proper thickness.

2. Optical structures

A configuration of the interference sensor on the base MMI structures is shown in Fig. 1a. It includes an optical system composed of a single-mode waveguide, an MMI section of the length connected with the distance of a single image formation, and a single-mode output waveguide. Waveguide structure of analysed configuration, shown in Fig. 1b, consists of gradient index core on the glass substrate covered by a thin sensor layer of nanometre size and the refractive index value higher than the maximum of the gradient index core. Changes of its refractive index and extinction coefficient impact on the mode properties of multimode waveguides, as a result influencing location of the input field image. Attenuation in the sensitive layer decreases additionally the signal level. The output signal changes are registered by a single-mode output waveguide.

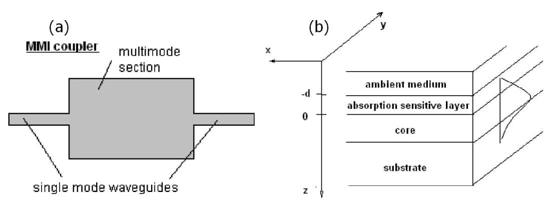

Fig. 1. Configuration of MMI interference sensor (a), sensor layers structure (b).

2.1. Refractive index profile

The investigated MMI sections are modeled for the K^+–Na^+ ion exchange process in the time of 0.75 h and

* corresponding author; e-mail: artur.szewczuk@polsl.pl

temperature of 400 °C in borosilicate glass. The distribution profile of refractive index of MMI section obtained in the diffusion process is calculated numerically from the nonlinear diffusion equation [8]:

$$\frac{\partial C_{\mathrm{K}}}{\partial t} = \nabla\left[\frac{D_{\mathrm{K}}}{1-(1-r)C_{\mathrm{K}}}\nabla C_{\mathrm{K}}\right], \tag{1}$$

where C_{K} is the dopant K^{+} ions concentration, proportional to the refractive index change. Material parameters of the technological process — self-diffusion coefficient of K^{+} ions D_{K}, the mobility ratio r of the ions K^{+} and Na^{+}, and the maximum of the refractive index change were determined by measurements of respective planar index profiles using IWKB method [8]. Technological parameters of the process are listed in Table.

TABLE

Technological parameters of diffusion process.

D_{K} [μm^2/h]	2.18
r	0.9
time of diffusion t [h]	0.75
Δn	0.0095

Widths W_{M} of the masks of MMI sections used in our simulations are 30, 40 and 50 μm and mask widths of monomode input and output waveguides are 5 μm. Multimode section is covered by WO_3 layer whose thickness has to be optimized. Material parameters of WO_3 layer used in simulations are taken from the paper [6]. Refractive index and extinction coefficient values needed for calculations are approximated on the base of experimental values shown in [7, 9] (Fig. 2) as a function of volumetric density of absorbed charge which is proportional to the density of absorbed gases. All calculations are performed for the wavelength of 633 nm.

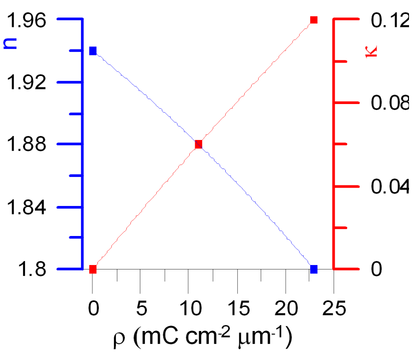

Fig. 2. Optical parameters of WO_3 layers — refractive index n and extinction coefficient κ as a function of absorbed volumetric charge ρ, on the base of experimental results from [7].

2.2. Optimization of layers geometry

The evanescent field of modes propagating in multimode waveguide penetrates the absorbing sensor layer (Fig. 1b). Due to relatively high value of the sensor layer extinction coefficient, light has been strongly attenuated just at short propagation sections. The choice of suitable sensor layer thickness is decisive. There is a possibility to select such a low sensor layer thickness to excite modes only in the MMI multimode section. For such instance, the impact takes place through scattered field of modes excited in the multimode waveguide. In case of thicker cover layers, modes are also excited in the sensor layer and the value of attenuation of light propagating in the MMI section may be influenced by selecting relevant value of overlap of wave functions of modes excited in the sensor layer and in the core.

The expression on modal attenuation coefficient γ_m^{TE} of TE modes of the order m can be expressed by the equation [10, 11]:

$$\gamma_m^{\mathrm{TE}} = \frac{2k_0 n\kappa}{N_m^{\mathrm{TE}}}\frac{\int_{-d}^{0} E_y^2\,\mathrm{d}z}{\int_{-\infty}^{\infty} E_y^2\,\mathrm{d}z}, \tag{2}$$

where k_0 denotes the wave vector in vacuum, n and κ are respectively the refractive index and extinction coefficient of the sensor layer, d denotes the sensor layer thickness, N_m^{TE} is the effective index of TE mode of order m, and E_y is its field distribution.

Basing on the mode analysis and the effective refractive index method mode function of waves propagating in MMI structure [12] can be obtained for different sensor layer thicknesses. Figure 3 shows for instance the calculated wave function distributions in the direction perpendicular to the substrate of TE [0, 0] mode propagating in multimode structure of the width of 30 μm. MMI structures are covered by the sensor layer of the refractive index of 1.94 and different layer thicknesses. Calculations are performed for equivalent refractive index distributions obtained by the effective index method. As we can see, for the sensor layer thickness below 60 nm, light propagates only in the core region and its evanescent part in absorbing region increases together with the sensor layer thickness. For larger sensor layer thicknesses the additional mode excited in the sensing layer region can be observed and the light energy guided in the core of MMI section shifts to the substrate. This part of light energy which propagates in the sensing layer region is strongly attenuated due to the large value of extinction coefficient.

The absorbing layer thickness is therefore the parameter which decides on operation characteristics of MMI sensor. Using the mode analysis of the structure the attenuation coefficient of TE modes guided in the core region can be determined on the base of Eq. (2) for different values of sensor layer thickness. Results of calculations are shown in Fig. 4.

As can be expected the attenuation is low for very thin sensor layers. In this case the mode energy is guided mainly in the core and its evanescent part is very small. Together with the layer thickness increase the part of mode field which penetrates the cover enlarges and the attenuation rapidly increases reaching the maximum

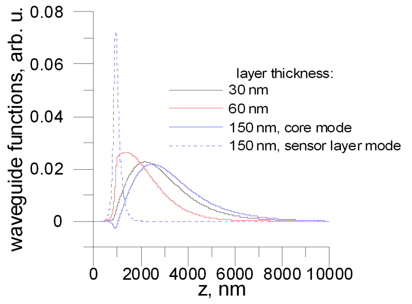

Fig. 3. Modal function distributions of analyzed waveguide structures for the MMI section width of 30 μm and different sensor layer thicknesses.

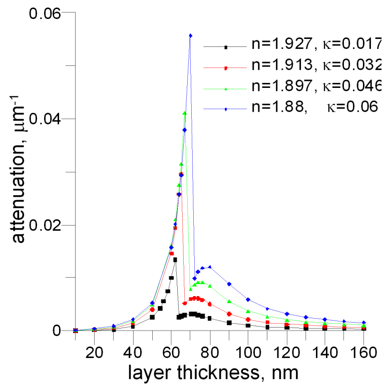

Fig. 4. Attenuation coefficient of TE [0,0] mode in MMI structure as a function of sensor layer thickness for different refractive index of the layer.

value. For suitable large thicknesses of the cover the sensing layer mode appears and the light guided in the core of MMI structure shifts to the substrate. Its evanescent part in the cover region decreases and attenuation also decreases.

Based on the presented mode analysis, such a structure geometry may be selected which provides for anticipated output signal amplitude course in the function of the sensing layer refractive index. The field distribution in MMI section and mode field amplitude distribution for the different thickness of the sensor layer is shown in Fig. 5. Optical field distributions are obtained by beam propagation method (BPM).

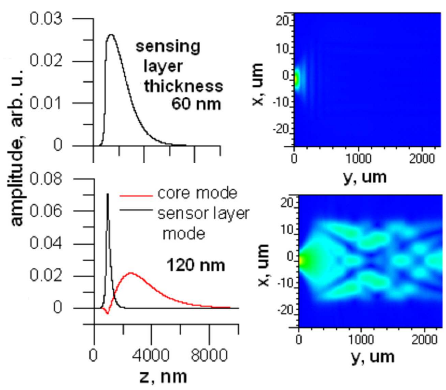

Fig. 5. Optical field distributions and wave functions of modes excited in the layered structure. Refractive index of the cover is equal to 1.927.

3. Calculations of operation characteristics

Taking into consideration results of mode attenuation the operation characteristics of MMI sensor are made using BPM method for different thicknesses of sensor layers. Calculations are carried out for MMI section of the width of 30 μm. Its length selected to obtain the 1-fold image of the input field amounts to 2300 μm for the refractive index of the cover equal to 1.94. This value of the refractive index with the proper value of extinction coefficient equal to zero (Fig. 2) fixes the reference operation point of the sensor. Figure 6 presents the output field amplitude as a function of absorbed volumetric charge in the sensor layer for different values of the layer thicknesses. The results confirm the impact of mode attenuation on operation characteristics of the structure. Changes of the layer thickness influence the sensitivity of the sensor response. Curves corresponding to sensing layer thicknesses having similar attenuation coefficients, for example for 30 nm and 120 nm, run similarly.

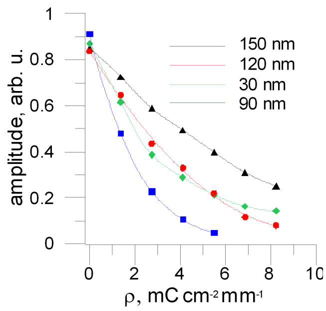

Fig. 6. Output field amplitude as a function of the optical and geometrical parameters of the sensing layer for the different sensing layer thicknesses.

In Fig. 7a,b the field distribution at the output of MMI structure is presented. The MMI section is covered by the sensing layer of the thickness of 150 nm. Waveguide modes are excited both in the core and in the sensing layer region for such layer thickness. The distribution shown in Fig. 7a corresponds to the structure of the refractive index of the cover $n = 1.94$ and extinction coefficient $\kappa = 0$. In this case the modes guided in the sensing layer and in the core can be seen at the output. The distribution shown in Fig. 7b corresponds to the optical parameters $n = 1.927$ and $\kappa = 0.017$, respectively. The sensing layer mode is strongly attenuated and only the core mode of MMI section can be observed at the output.

The operation characteristics calculated for the different geometries of MMI sections are also compared. MMI structures differ in their widths and consequently also

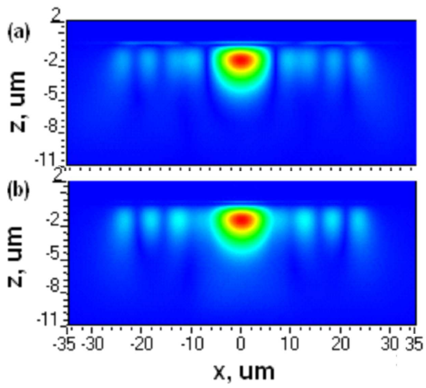

Fig. 7. Optical field distribution at the output of multimode section for the following parameters of the sensing layer: (a) $n = 1.94$, $\kappa = 0$ and (b) $n = 1.927$, $\kappa = 0.017$.

in their lengths to obtain the 1-fold image of input field at the output. The results are shown in Fig. 8. The section widths amount to 50 μm, 40 μm and 30 μm and their lengths adequately 2300 μm, 4150 μm and 6200 μm. The sensing layer thickness is 150 nm. As it can be seen, the sensitivity of the structures significantly depends on MMI geometry. This effect can be used in construction of optical sensors system on a single glass plate to provide simultaneous recognition of different measured values.

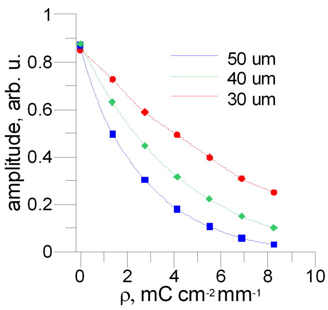

Fig. 8. Output field amplitude as a function of the optical and geometrical parameters of the sensing layer for the different geometry of MMI sections. Sensing layer thickness amounts to 150 nm.

4. Conclusions

In the paper there are shown the possibilities of the application of gradient index multimode structures made by ion exchange process in the technology of optical sensors. Analysis is carried out for nanometre layer of WO_3 which makes possible to use this sensor for the detection of several gases i.e. NO_2, H_2, NH_3. The results show that nanolayer proper thickness selection is decisive for the sensitivity of modelled configuration.

There are several advantages of such technological solution. Firstly, the planar technology allows fabrication on a glass plate in the same process of MMI optical structures of various geometries. Changes of MMI section widths will cause in connection with self-imaging effect also the length changes. The obtained interference sensor system will characterize various operation characteristics that will enable construction of optical sensors system on a single glass plate to provide simultaneous recognition of different measured values. Secondly, application of ion--exchange technology makes influencing mode properties of the interference structures possible through technological process parameters selection: time and temperature of mask diffusion and width. An important merit of the configuration is a wide region of interaction with the sensor layer related to the multimode waveguide size which must influence the sensitivity of the sensor designed.

Acknowledgments

The work was sponsored by the State Committee for Scientific Research (NCBiR) within the grant N R01 034 06/2009.

References

[1] A. Irace, G. Breglio, *Opt. Expr.* **11**, 2807 (2003).

[2] A. Mehta, W. Mohammed, E. Johnson, *IEEE Photon. Technol. Lett.* **15**, 1129 (2003).

[3] Q. Wang, G. Farell, *Opt. Lett.* **31**, 317 (2006).

[4] K.R. Kribich, R. Copperwhite, H. Barry, B. Kolodziejczyk, J.M. Sabattie, K. O'Dwyer, B.D. MacCraith, *Sensors Actuators B* **107**, 188 (2005).

[5] T. Mazingue, R.K. Kribich, P. Etienne, Y. Moreau, *Opt. Commun.* **278**, 312 (2007).

[6] C. Tyszkiewicz, T. Pustelny, *Opt. Appl.* **34**, 507 (2004).

[7] K. von Rottkay, M. Rubin, S.-J. Wen, *Thin Solid Films* **306**, 10 (1997).

[8] M. Błahut, D. Kasprzak, *Opt. Appl.* **34**, 574 (2004).

[9] T. Pustelny, J. Ignac-Nowicka, Z. Opilski, *Opt. Appl.* **34**, 563 (2004).

[10] P. Karasiński, R. Rogoziński, *Opt. Commun.* **269**, 76 (2007).

[11] T. Pustelny, E. Maciak, Z. Opilski, M. Bednorz, *Opt. Appl.* **37**, 187 (2004).

[12] D. Kasprzak, M. Błahut, E. Maciak, *J. Phys. IV (France)***137**, 93 (2008).