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Multimode planar refractometer produced in a waved channel lightguide structure

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In the paper, studies of the lightguide planar refractometer made by a multi-step Ag^+-Na^+ ion-exchange technique in glass substrate are presented. The basic element of the sensor is the channel waveguide, masked beyond the measurement area by the suitable dielectric layer. The refractive index changes of the cover in the window area affect the attenuation in the signal track. The studies concerned the straight channel lightguide and waved, in the shape of sine function in the window area. Transmission characteristics were measured and the sensitivity dependence on the period, amplitude and length of waving were determined. The results were used in the optimization of the sensor geometry.

1. Introduction

The multimode waveguide sensors present mainly the constructions based wholly on optical fibres. The use of the planar technology [1]–[3] seems to be attractive for this type of applications. An advantage of planar technology is possibility of free shaping of waveguide planar structures both in the aspect of geometry (dimensions, topology) and their optical characteristics (mainly the profile of the refractive index distribution, and within a certain range the value of the refractive index).

A suggestion and test results of a multimode waveguide refractometer made in planar technology have been presented. The aim of the work was to establish the influence of the technological process parameters and geometry on the transmission characteristics of sensor performance.

2. Technology of the planar refractometer

The configuration of the transducer is presented in Figure 1. Its basic element is a strip waveguide masked beyond the measurement area (window) by a suitable dielectric layer. The refractive index changes of the cover in the window area affect the attenuation in the signal track. The waveguide in the measuring area of the length L has the shape of a slowly changing sinusoid of the parameters P (period) and A (amplitude). The lightguide waving, similarly to the case of microbending optical fibre sensor [4], induces a coupling between the guided modes and as a result of which there occurs an energy flow to the modes interacting most strongly with the cover. This mechanism affects the intensity magnitude and sensitivity of the trans-

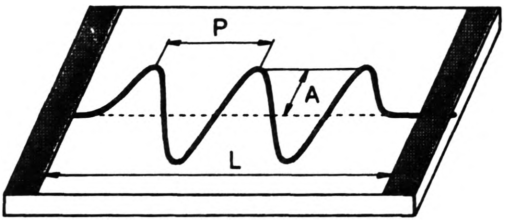
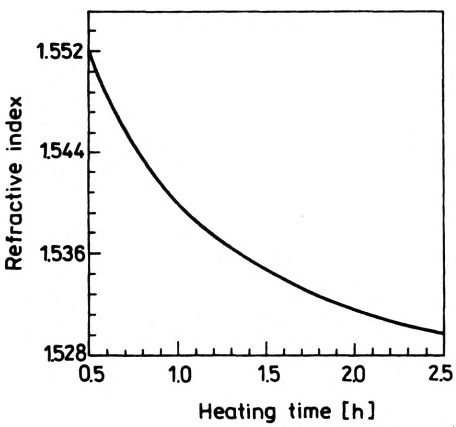


Fig. 1. Configuration of the planar refractometer

ducer performance. The waveguides were made by the technique of $Ag^{+}-Na^{-}$ ions exchange in borosilicate glass ($n = 1.5188$) in a process including initial diffusion of Ag^{+} ions from melted $AgNO_3$ during $t = 4$ h at the temperature $T_d = 300$ °C, through mask with different opening widths, and the heating in the time 0.5 h–2 h at the temperature 450 °C. In Figures 2 and 3 are presented the numerically calculated dependences of the maximum refractive index changes of the strip waveguides on the time of heating (for the mask width 20 μm) and on the masks width (for the time of diffusing 2 h) [5].



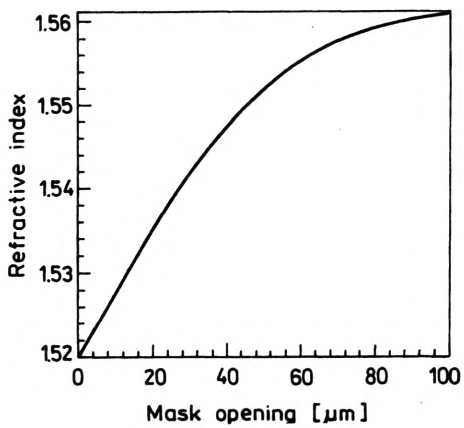


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Fig. 2. Dependence of the maximum change of refractive index on the diffusing time for the waveguide obtained in the process of initial diffusion ($T_d = 300$ °C, $t = 4$ h) through the 20 μm mask

Fig. 3. Dependence of the maximum change of the refractive index on mask width for the initial diffusion ($T_d = 300$ °C, $t = 4$ h) and the heating ($T_h = 450$ °C, $t = 2$ h)

Particular attention was paid to the surface quality of the glass plates tested. The surface quality (number of point defects and scratches) of each of the substrate plates, both before and after the technological process, was subject to accurate assessment under a microscope. For the further investigations were chosen only these structures which had no defects resulting from surface treatment or other technological processes. The substrate plates with the waveguides were masked by a layer of silicon gum SILGEL 600, leaving uncovered its middle fragment in the measuring area.

3. Methodics

The prepared structures were tested in the measuring stand presented in Figure 4. Used as the light source was LED (0.850 μm), fed by a modulated signal from the generator *G*. The strip lightguides were excited by a standard gradient telecommunication waveguide (50/125 μm). The standard liquids were water solutions of glycerol and solutions of kerosene with bromonaphtalene whose light refraction indices changed within 1.33 – 1.54. The testings concerned the determination of the

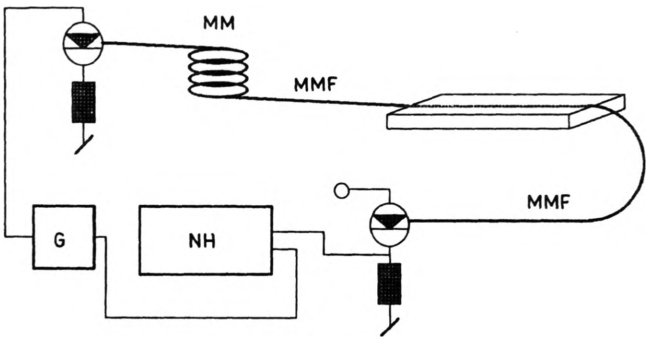


Fig. 4. Diagram of the measuring system. IS – structure tested, MM – modes mixer, MMF – multimode fibre, G – generator, NH – homodyne nanovoltmeter

effect of technological factors (times of heating and masks widths), and geometric parameters (length of the interaction section, amplitude and the waving period), on the transmission characteristics of transducer.

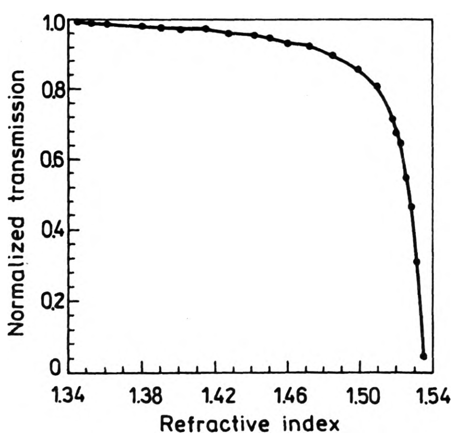


Fig. 5. Characteristics of a transducer with a straight waveguide ($A = 0$, $L = 8$ mm) produced by the initial diffusion ($T_d = 300$ °C, $t = 4$ h) and the heating ($T_h = 450$ °C, $t = 2$ h)

Figure 5 presents typical characteristics of a transducer with a straight waveguide ($A = 0$, $L = 8$ mm) for the technological process – the initial diffusion:

$T_d = 300$ °C, $t = 4$ h and the heating $T_h = 450$ °C, $t = 1.5$ h. The normalized transmission $T(n)$ is defined as the ratio of the measuring signal to the value of the signal obtained for the refractive index of the cover $n = 1$. Two ranges can be distinguished here. The first with a relatively small inclination of the characteristics, corresponding to the lower values of the refractive index, and the second, for the higher values of the refractive indices (from 1.50 to 1.54), in which the inclination rises steeply.

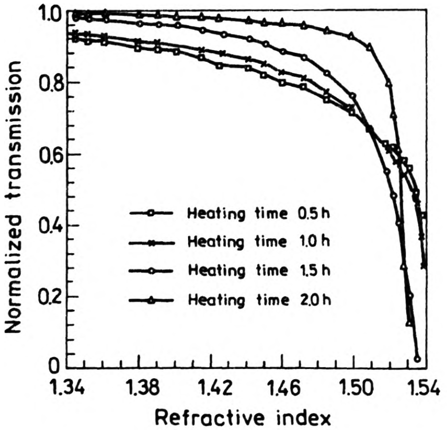
In the first range, the interaction of the light with the cover is realized mainly through evanescent fields of the guiding modes. With an increase of the refractive index the depth of the evanescent field penetration is increased and hence the area of wave interaction with the cover is also increased. This causes an increase of wave attenuation.

The second range refers to the values of the refractive index close to the points of the cut-off of waveguide modes whose energy, starting from the higher order modes, is led out to the cover.

The technological factors – time of the initial diffusion and heating, mask widths as well as the kind of glass and choice of the admixture – should affect first of all the characteristics of the second range. Geometrical factors should be decisive about the course of the characteristics in the first area.

4. Effect of the technological parameters

The influence of the time of diffusing on the transmission characteristics $T(n)$ obtained for the strip waveguides ($A = 0$, $L = 20$ mm) produced through a mask of the width $d = 20$ µm is shown in Fig. 6. The technological process, common to all the structures, was a four-hour diffusion at the temperature $T_d = 300$ °C. The values of



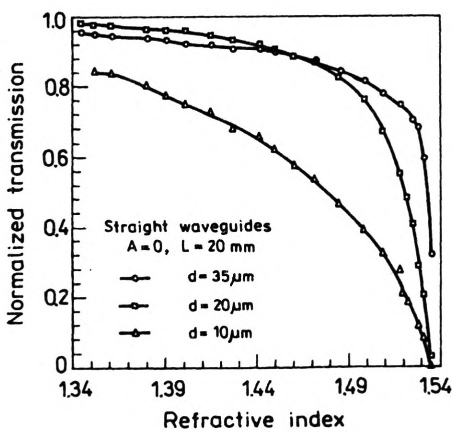


Fig. 6. Normalized transmission as a function of the refractive index for different times of heating of strip waveguides made through the 20 µm wide mask

Fig. 7. Normalized transmission as a function of the refractive index for different mask widths

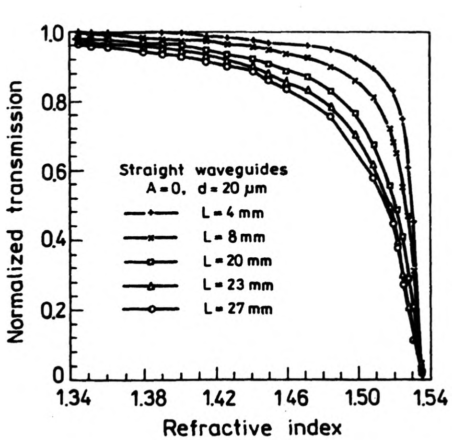
the refractive index corresponding to the points of cut-off are changed, from 1.532 for the two-hour time of heating to the value 1.550 for the time of heating equal to 0.5 hour. Similar characteristics with slightly different values of the point of cut-off were obtained for the strip waveguides made in the same technological processes by masks of the width 10 μm and 15 μm.

The influence of the mask width used on the refractometer characteristics obtained is given in Fig. 7. The strip guides ($A = 0$, $L = 20$ mm) were obtained in the process with the following parameters: the diffusion $T_d = 300$ °C = 573, $t = 4$ h and the heating $T_h = 450$ °C, $t = 1.5$ h. The mask width affecte the value of the point of the cut-off (Fig. 3) and the magnitude of the area interacting with the cover. In connection with this the effect of the mask width on both of the previously discussed measuring ranges is observed.

5. Effect of the geometrical parameters

Figure 8 presents the influence of the length of the measurement area on the transmission characteristics $T(n)$ for the straight strip waveguides ($A = 0$). The structures tested were made by the four-hour diffusion at the temperature 300 °C, through a mask of the width $d = 20$ μm, and the heating at the temperature 450 °C for 1.5 h. For technological reasons strip waveguides of the interaction section length from 4 mm to 27 mm were tested. An increase of the length of the measuring area, increasing the total value of wave attenuation, affects the dynamics of the changes of the normalized transmission of the waveguide.

A similar system of characteristics was obtained for the strip waveguides produced in the same technological process through an aluminium mask of the width 30 μm.



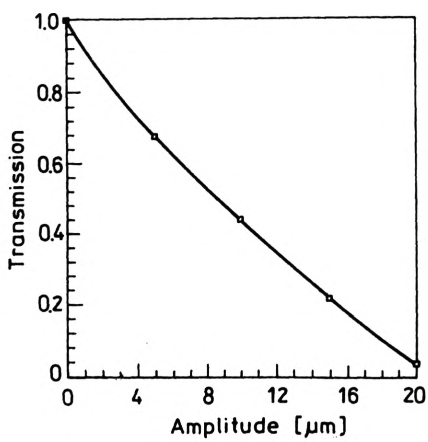


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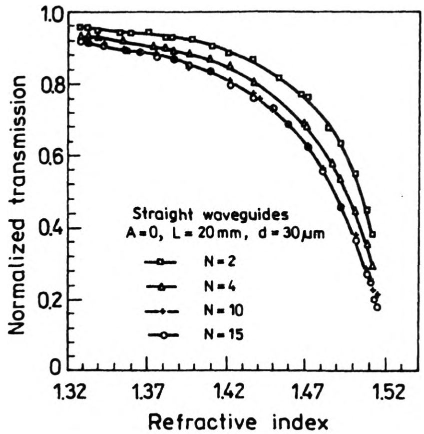
Fig. 8. Normalized transmission *vs.* refractive index for different lengths of the measuring area

Fig. 9. Dependence of transmission on the values of amplitude of waving; strip waveguides were made through the 20 μm wide mask



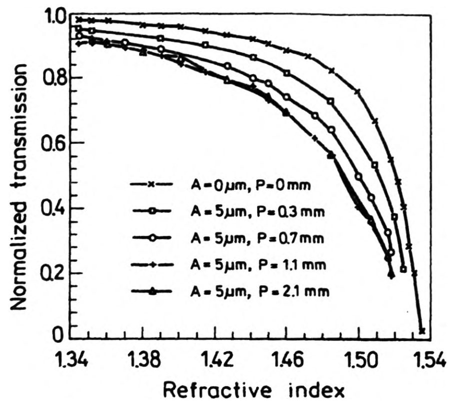


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Fig. 10. Normalized transmission *vs.* refractive index for a different number of waving. The waving period is 1.2 mm, amplitude 13 μm

Fig. 11. Normalized transmission as a function of the refractive index for waving waveguides and a straight strip. The length of the interaction section is 20 mm, the amplitude of waving is 5 μm

The testing of the waved structures, carried out for the waveguides obtained in the process of initial diffusion ($T_d = 300$ °C, $t =$ 4 h), concerned the effect of the amplitude, period and number of disturbances. The presence of waving affects the attenuation in the waveguide. The influence of the amplitude of waving on the magnitude of the transmission signal related to the signal obtained from the straight waveguide ($A = 0$) is presented in Fig. 9. The testing of the transmission characteristics $T(n)$ carried out in 20 mm area of interaction for the different amplitudes of waving ($A = 5$, 10, 15 and 20 μm) showed no dependence of the normalized transducer transmission on the amplitude of waving.

The effect of the number of waveguide disturbances in a 20 mm area of the interaction on characteristics $T(n)$ is given in Fig. 10. The results presented were obtained for strip waveguides made by a mask of the width $d = 30$ μm. Initially, for the increasing number of wavings the characteristics obtained are arranged lower and lower. For the number of disturbances of over 10, the course of the transmission characteristics of the transducer stabilizes. Similar results are obtained in the case of an optical fibre microbending sensor [6].

The studies on the determination of the influence of the waving period were carried out on strip waveguides of the waving periods varied within 0.1 mm to 2.1 mm and were tested at every 0.1 mm. Selected courses are presented in Fig. 11. For the waving periods from 0.1 mm to 1.1 mm the characteristics obtained are more and more separated from the characteristics of the straight waveguide. For the waving periods of over 1.1 mm no essential differences were found between the characteristics obtained.

Numerical calculations of the differences of the propagation constants $\Delta\beta = \beta(I, N-1) - \beta(I, N)$ of the selected modes guided in the structure tested which were

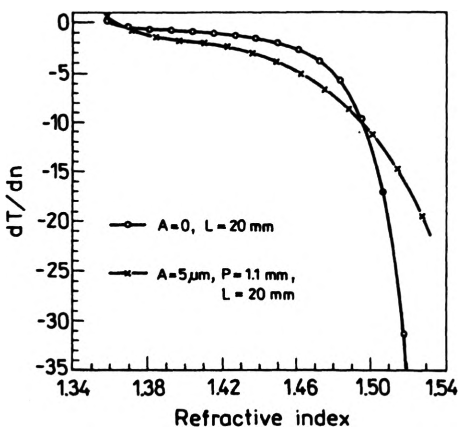

Fig. 12. Dependence diagrams of sensitivity on the values of the refractive index for a waved strip waveguide ($A = 5$ μm, $P = 1.1.$ mm) and a straight one. The length of the measuring area is 20 mm. Waveguides were made through a mask of 20 μm in width

carried out by the effective index method [7] showed that the distances between the propagation constants in the space of the wave vectors are different from mode to mode. Thus, to an effective coupling between the particular pairs of the guided modes correspond the different periods of the waveguide waving. This is the reason that for the waving periods from 1 mm to 2.1. mm, the same refractometer characteristics are obtained. In Figure 12, the sensitivities $dT(n)/dn$ of the transducer with a waved waveguide ($A = 5$ μm, $P = 1.1$ mm) were compared with a transducer with a straight waveguide ($A = 0$).

The waving causes an increase of sensitivity in the first measuring range. For the values of the refractive indices close to the cut-off, the transducer with the straight waveguide exhibited greater sensitivity.

6. Summary

The studies of the planar waveguide refractometer presented in the paper have demonstrated an essential influence of the parameters of the technological process and geometry on the measuring range and transmission characteristics.

A change in the length of the measuring window and the waving of the waveguide increases the sensitivity of the transducer for the values of the refractive index far from the point of the cut-off and widens its measuring range. A change of the waving amplitude over 5 μm does not affect the characteristics obtained. A change of the technological parameters of the ion exchange process – mask width and diffusing time, but also the choice of glass of different chemical composition or some other admixture – changes the sensitivity and transducer operations range in the vicinity of the point of cut-off.

The described waveguide planar refractometer can be particularly suitable for the measurements of the refractive index of light within the range from 1.40 to 1.54.

The discussed refractometer may be used for measurement of the other physical quantities such as density or temperature of liquids. Applying a suitable cover it may be used as a sensor of pH reaction or gas concentration.

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