Optica Applicata, Vol. XXVI, No. 2, 1996

Defining refractive diffusive profiles of planar structures in glasses by means of a fringe pattern field

R. ROGOZIŃSKI, A. OPILSKI

Institute of Physics, Silesian Technical University, ul. Bolesława Krzywoustego 2, 44–100 Gliwice, Poland.

In the paper, an analysis of a fringe pattern field with an observation of a chosen fringe course, for defining the profile of a refractive index of planar waveguides are proposed. With an application of the measuring method described, refractive profiles of planar waveguides produced in the soda-lime glass by means of an ion exchange $Ag^+ \leftrightarrow Na^+$ were examined.

1. Introduction

In designing the elements of an integrated optics produced by means of an ion exchange in glass, the following technological parameters of the process should be known: constant diffusion D, mobility ratio of the exchanged ions m and maximum change of the refractive index Δn obtained for a particular glass-admixture system. The easiest and most popular way of defining the above-mentioned parameters is to examine the refractive profile of a planar waveguide produced in a given type of base material by diffusing ions of a particular admixture, during assumed time at a given temperature. Next, measuring points defining the obtained refractive profile are adjusted to a curve, which is a solution of an equation modelling the ion exchange process. Parameters D, m and Δn, for which the adjustment of the curve mentioned above is the best, are assumed as the parameters of the ion exchange process [1]. The measurement of a refractive profile is usually done with an application of a prism coupler and goniometer (for defining synchronous angles for waveguide modes), and after calculation of corresponding effective indices $N_{\text{eff}}^{(i)}$ – by means of the IWKB procedure [2] to assign particular turning points $x_t^{(i)}$ to them. The set of points thus obtained ($N_{\text{eff}}^{(i)}$, $x_t^{(i)}$, where i is a successive mode number) is treated as an approximation of a refractive profile of a given waveguide.

As an advantage of the above method its non-destructive character should be mentioned, and, consequently, no special preparation of an examined waveguide and easiness of the measurement of a synchronous angle with a big accuracy. A drawback of the method results from the very principle of an approximate profile defining. Assuming a value of a refractive index on the waveguide surface and assumed criterion of the smoothness of an approximate curve are really important here. The

method gives reliable results for waveguides of a bigger number of guided modes and requires correct interpretation of the mode spectrum [3].

The application of interference methods in gradient examinations of waveguide structures by means of the "Biolar PI" microinterferometer is presented in a vast bibliography [4]–[6]. The testing of refractive profiles of opitc fibres by means of transverse interferometry method in a fringe pattern field [7] can be found there. In gradient testing of planar structures, a very interesting method is the phase-stepping interferometry described in paper [8]. For this method, a sample should be prepared by means of grinding the edges of a glass plate at a proper angle. The angle need not be known before the measurements are started. The measurements consist in recording three or four images for the known phase shifts between the reference and measuring beams. The measurements are conducted with a microinterferometer set up at a uniform-field interference.

The paper presents a method for analysing the fringe pattern field produced in a properly prepared sample of a planar waveguide. The method is destructive, *i.e.*, it requires a proper preparation of the sample. The "Biolar PI" microinterferometer, a linear variable interference filter, a CCD camera and computer with an adequate software are applied here.

2. Description of the measuring method

The method suggested here requires a special preparation of an examined waveguide sample. The plate is cut vertically to the axis z (Fig. 1), which is then ground to an appropriate thickness and polished on both sides. Because of required thickness in the range of tens of micrometers, the grinding process and polishing of one side are done after the plate has been glued to a glass plate. For this purpose, a glue hardened with UV light of a previously defined dispersion of refractive index is used. Figure 2 presents a cross-section of a sample prepared for measurements. Measurements are conducted after putting the prepared sample in an observation field of the "Biolar PI" microinterferometer, set up at fringe pattern interference with a large cross-wise image split, ensuring a complete separation of images of an examined waveguide

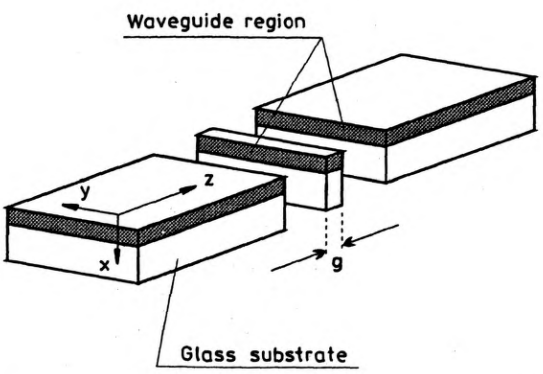

Fig. 1. Way of cutting out a sample from a planar waveguide

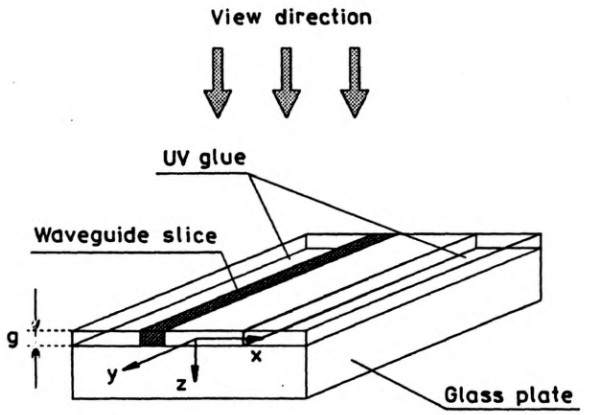

Fig. 2. Sample orientation in relation to the direction of observation in a microinterferometer

region. It is possible, owing to the objective with Wollaston's prism of a large prism angle, to produce an image split of about 100 μm set up at a position crossed with a prism tube W2 [9]. If the region of an examined waveguide in glass is more shallow than a complete split s of images, and the edge of sample which is the surface of a waveguide is directed vertically to the course of fringes, in the image plane of the microinterferometer, a picture like the one in Fig. 3 will appear, consisting of entirely separated waveguide images produced by ordinary and extraordinary wavefronts.

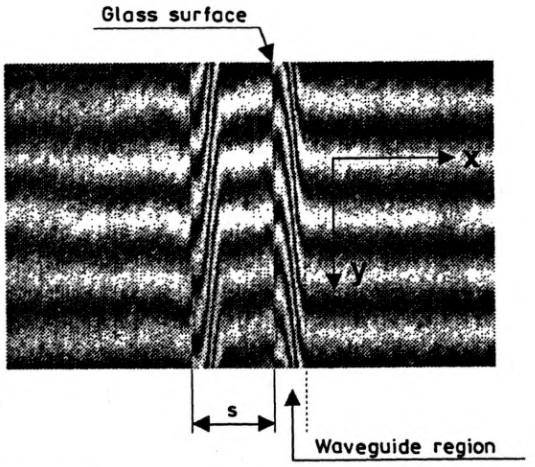

Fig. 3. Image of a sample in the "Biolar PI" microinterferometer field of view set up at a fringe pattern interference (prism W2) with a big image split s

Taking into consideration one of equivalent images of the sample thus prepared, it could be shown [9] that the deflection $c(x)$ of a fringe from a rectilinear course at a point defined by the x-coordinate (Fig. 4) informs us about an optical path difference Γ at a given point. This dependence is illustrated by a simple formula [10]

$$\Gamma(x) = \frac{c(x)}{b}\lambda \tag{1}$$

where: λ – the length of wave, b – the distance between fringes corresponding to a given value λ and prism tube position W2.

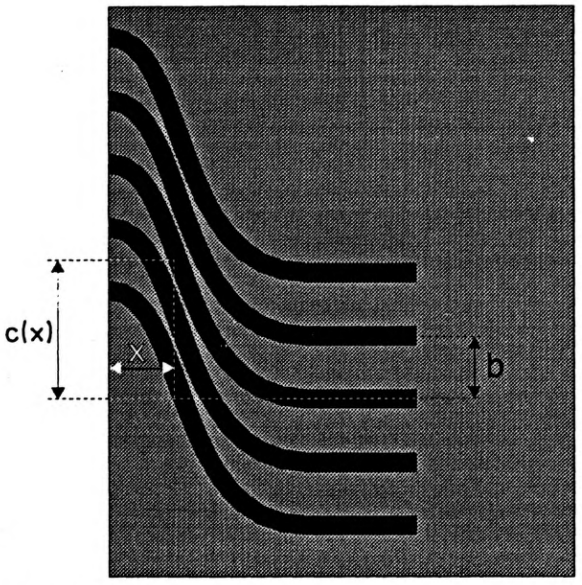

Fig. 4. Principle of defining refractive index change δn at a distance x from the waveguide surface on the basis of deflection $c(x)$ of a fringe at this point

After sample cutting (Fig. 1) and observation direction (Fig. 2), the optical path difference at a given point of the x-coordinate is defined by the thickness of a sample g and a local change of a refractive index δn in the following dependence:

$$\Gamma(x) = g \cdot \delta n(x). \tag{2}$$

Comparing Equations (1) and (2), it could be easily noticed that with the thickness of a sample and the length of light wave crossing the known sample, a local change of the refractive index $\delta n(x)$ is directly proportional to the deflection of a fringe $c(x)$ at a given point

$$\delta n(x) = \frac{\lambda}{bg} c(x). \tag{3}$$

This simple linear dependence is the basis for the measuring method described. However, the knowledge of the sample thickness g at a cross-section of an examined waveguide and the assumption that it is constant along x-direction in the waveguide field are essential. The measurement of thickness was done with an application of the VAWI-1 method [10]. For the known dispersion properties of the glue and glass applied, where an examined waveguide was produced, a local

thickness g of a sample can be defined by means of this method. The thickness obtained by sample grinding and polishing should be chosen in such a way that with maximum change of the refractive index obtained on the surface of a waveguide, the optical path difference would give a fringe deflection within the observation field of the microinterferometer.

3. Analysis of a fringe pattern course

The analysis of a fringe pattern course was conducted by means of the CCD camera recording the image of a fringe pattern field (a sample of waveguide prepared in the way described above) produced in the "Biolar PI" microinterferometer set up at a fringe pattern interference. Next, the image registered in the form of figures underwent a programme reconstruction procedure of a chosen fringe course. While analyzing the image vertically to the fringe course in an empty fringe pattern field (Fig. 5), a distribution of light intensity along a chosen line of a scan is obtained

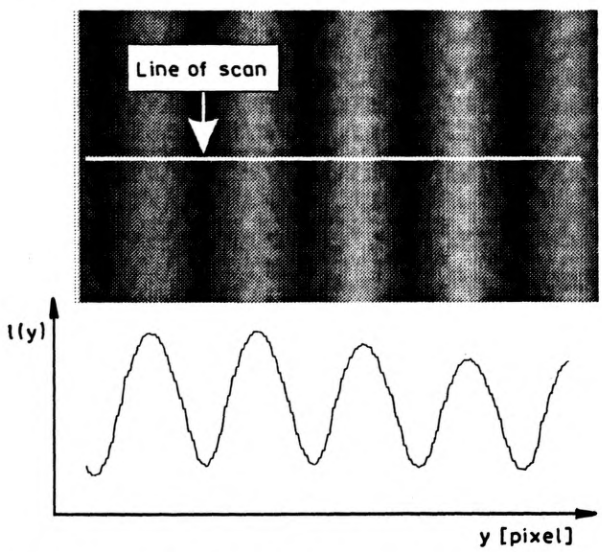

Fig. 5. Distribution of the light intensity along the line of an empty scan of the fringe pattern field

$I(y)$. Then, this distribution is approximated by a polynomial of the second degree in measuring window of an assumed width w-pixel, moving along an analyzing line of a scan. The value $y_m^{(i)}$ found in this way, for which the polynomial has a minimum extremum, is regarded as a coordinate of the middle of the analysed fringe if it meets the condition $w_{\min} < y_m^{(i)} < w_{\max}$, see Fig. 6**b**. The set of values $y_m^{(i)}$ ($i = 1, 2, \ldots, p$, where p is the number of countings $y_m^{(i)}$ included in the analyzing window w) is then averaged to give the value

$$\bar{y}_m = \frac{\sum_{i=1}^{p} y_m^{(i)}}{p} \tag{4}$$

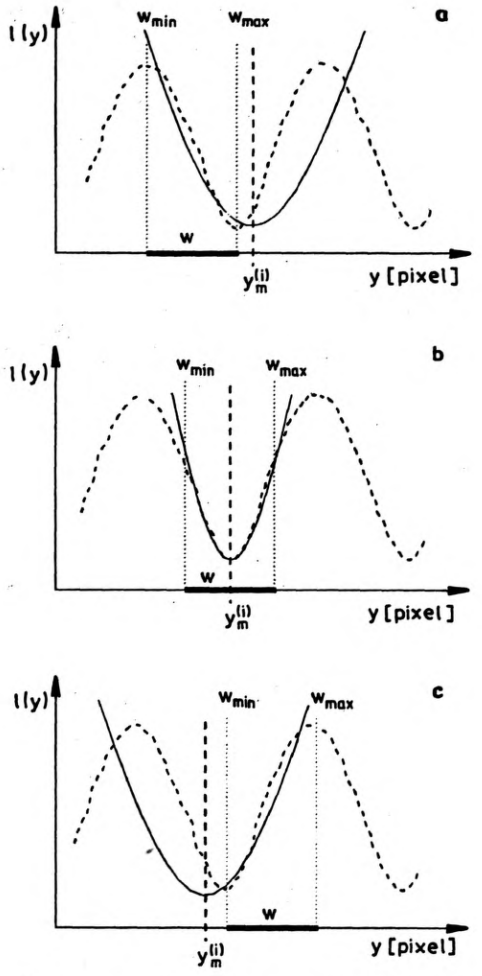

Fig. 6. Way of defining the middle of dark fringe (w — analyzing window); **a** and **c** — values of $y_m^{(i)}$ from outside the analyzing window, **b** — value of $y_m^{(i)}$ from the range of analyzing window (taking into account in Eq. (4))

as a coordinate of the middle of a dark fringe expressed in screen pixels. In this type of an analysis the choice of an analyzing window width w is very important.

The course of a dark fringe is defined by analyzing, in the way described above, successive scan lines towards the surface of a waveguide. Marking a fringe chosen for the analysis by means of a merker put into the recorded image (Fig. 7) with the application of an adequate analyzing procedure, a trace of the course for a chosen fringe $c(x)$ is obtained, and, consequently, by means of expression (3), also the profile $\delta n(x)$ of an examined waveguide. For the analysis of a fringe course in a waveguide region, a fringe of zero order located by means of a phase screw [9] in the observation field of the microinterferometer was chosen. The distance between fringes b occurring in Eq. (3) was defined in the way described above as a distance

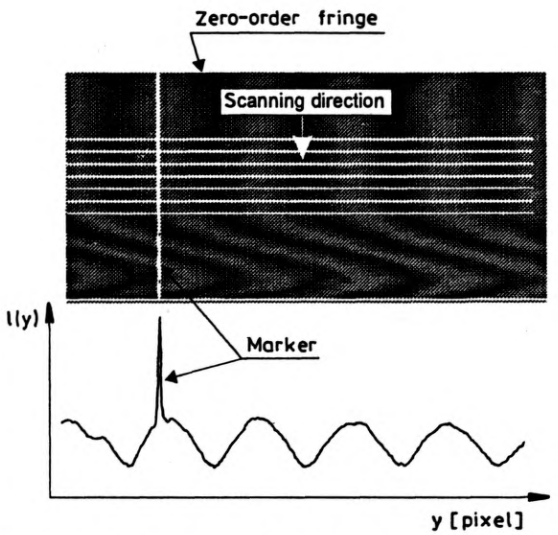

Fig. 7. Direction of scanning of the fringe pattern field during reconstruction of the course for dark interference fringe of zero order

between neighbouring fringes in the neighbourhood of a zero fringe and the value was averaged over a certain number of scans outside the waveguide region (Fig. 7).

4. Test results

The method described above served to define a refractive profile of planar waveguides produced in soda-lime glass by mans of ion exchange $Ag^+ \leftrightarrow Na^+$. Figure 8 presents a registered image of a fringe pattern field for a sample cut out from a planar waveguide obtained in the process of ion diffusion Ag^+ from the melted $AgNO_3$ at temperature $T = 573$ K during the time $t = 4$ h, and next heated during 2 h at temperature of 723 K, and by reconstruction of the refractive profile obtained according to the procedure described above. The measured thickness of the sample in the measurement field was equal to $g = (147 \pm 1)$ μm. The length of the wave for the produced fringe pattern field $\lambda = (641 \pm 6)$ nm.

Figure 9 presents the fringe pattern field and obtained reconstruction of refractive profiles for the planar waveguide samples produced in the process as above with an additional ion diffusion Na^+ from the melted $NaNO_3$ at temperature $T = 643$ K during the time $t = 2$ h. In this measurement, the sample thickness was equal to $g = (146 \pm 1)$ μm, and the length of the wave for the produced fringe pattern field $\lambda = (639 \pm 6)$ nm. The so-called "waveguide burying" effect can be observed here, consisting in reducing the refractive index on its surface and shifting a maximum value δn into the depth of glass.

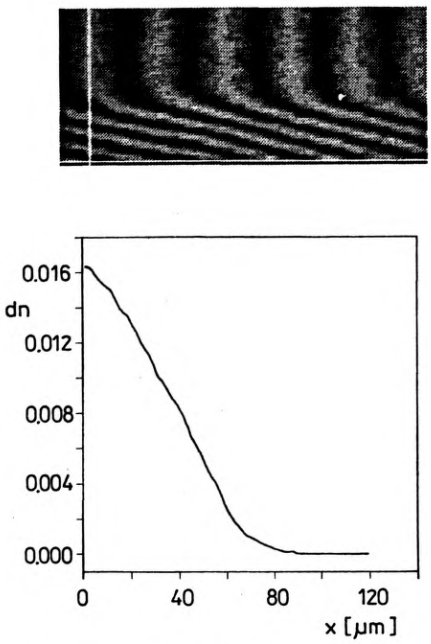

Fig. 8. Fringe pattern field and the reconstructed refractive profile of planar waveguide produced in the diffusion process of $AgNO_3$: $T = 573$ K, $t = 4$ h, + heating: $T = 723$ K, $t = 2$ h

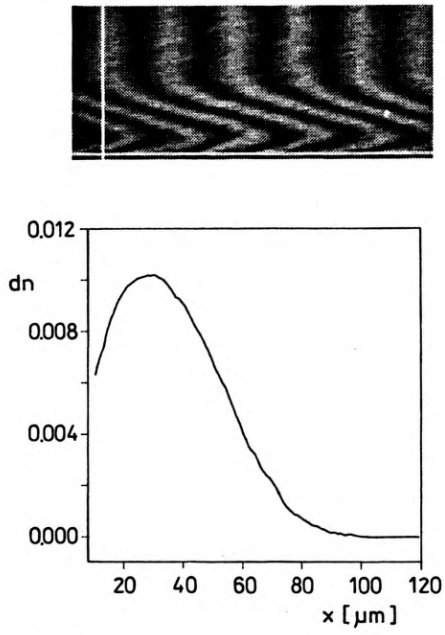

Fig. 9. Fringe pattern field and the reconstructed refractive profile of planar waveguide produced in the diffusion process of $AgNO_3$: $T = 573$ K, $t = 4$ h, + heating: $T = 723$ K, $t = 2$ h, + diffusion $NaNO_3$: $T = 643$ K, $t = 2$ h

5. Error analysis

Assuming in Equation (3) the change of the refractive index δn at a given point x as a function of independent variables λ, g, b and c an absolute error $\Delta(\delta n)$ – in the range where $c > 0$ – can be defined by means of the total differential

$$\Delta[\delta n(x)] = \delta n(x)\left(\frac{\Delta\lambda}{\lambda}+\frac{\Delta g}{g}+\frac{\Delta b}{b}+\frac{\Delta c}{c}\right) \tag{5}$$

where: $\Delta\lambda$, Δg, Δb, Δc are the unreliability of wave length measurements, sample thickness, distance between fringes and fringe deflection, respectively.

In the measurements conducted, the unreliability Δn was defined on the basis of calibration diagram $b_1(\lambda)$ made for the prism W1 of the microinterferometer (b_1 is a distance between fringes observed at the exit pupil of the microinterferometer objective for the wave length λ when prism W1 was applied) [11].

The value Δg results from the measurements of the waveguide sample thickness by means of the VAWI-1 method [10]. The unreliability Δb and Δc was assumed as one image pixel (the values b and c are defined here in image pixels). For the measuring unreliability mentioned the following values were assumed:

$\Delta\lambda = 6$ [nm], $\Delta g = 1$ [μm], $\Delta b = \Delta c = 1$ [pixel].

On the basis of dependence (5) the unreliability of defining δn as a function of location x calculated from the glass surface into the depth of a waveguide can be assessed. To obtain a relatively small value of relative error δn on the surface of a waveguide, the thickness of the sample should be chosen in such a way that the fringe deflection c on the surface would be the biggest (it is limited by the camera observation field). For the waveguide samples presented, relative errors of the defined value δn on the glass surface were equal to 3.8% and 4.5%, respectively.

6. Conclusions

The proposed method of the examination of planar refractive waveguide profiles is a destructive one, requiring a proper preparation of an examined sample. When compared with other methods, this is obviously its weak point. An unquestionable advantage of this method is a direct record of an examined profile just in the image of an interference fringe course. It is competitive in comparison to the IWKB procedure in the case of deep testing (of a range of tens of micrometers) of waveguide regions. In such cases, the mode spectra during synchronous angle measurements are very dense, which makes the measurements more difficult. On the other hand, however, in the case of shallow waveguide regions, the accuracy of the measuring method described herein is limited by the camera resolution.

In the method described above, the value of the refractive index change δn of a waveguide is defined, in relation to the refractive index of glass. This is an essential difference compared with the IWKB procedure, where the refractive profile of an absolute value of the refractive index is defined.

Acknowledgements — This work was carried out under the Research Project KBN 0997/T11/95/08.

References

[1] BŁAHUT M., OPILSKI A., ROGOZIŃSKI R., Opt. Appl. **22** (1992), 161.
[2] HELSZTYŃSKI J., KOZEK T., [In:] Materiały I Krajowej Szkoły Optoelektroniki, (in Polish), Unieście 1987, Z. 5, p. 64.
[3] KRUSZEWSKI J., Prace IET CEMI, (in Polish), Z. 5/6, p. 1, Warszawa 1985.
[4] BOŻYK M., [In:] I Sympozjum Techniki Pomiarowej Światłowodów, Lublin 1981, p. 265 (in Polish).
[5] BOŻYK M., Opt. Appl. **11** (1981), 371.
[6] BOŻYK M., Elektronika, No. 6, (1983), 10.
[7] BOŻYK M., [In:] III Krajowe Sympozjum *Światłowody i ich zastosowanie*, Jabłonna 1983, Vol. 2, PWN, Warszawa—Łódź 1983, p. 31; (in Polish).
[8] SOCHACKA M., [In:] *Research & Development Treatises*, SPIE/PL RTD, Vol. 3, 1995.
[9] PLUTA M., *Mikrointerferometria w świetle spolaryzowanym*, WNT, Warszawa 1990 (in Polish).
[10] PLUTA M., J. Microsc. **145** (1987), 191.
[11] PLUTA M., Opt. Appl. **20** (1990), 259.

Received February 13, 1996