Optica Applicata, Vol. XXIX, No. 1–2, 1999

Applicability of interference TE_0-TM_0 modes and TE_0-TE_1 modes to the construction of waveguide sensors

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The paper presents exemplary application of the interference TE_0-TM_0 modes to monitor the presence of water vapour and ammonia. Also the possibility of applying the mode interference of the same polarization states (TE_0-TM_1) to monitor the changes of refractive index are presented. The planar waveguides have been produced using the ion exchange technique Na^+-K^+ in the glass BK-7.

1. Introduction

The application of planar and fibrous optimeters has recently become more and more popular in chemical analysis of liquids and gases. They have many advantages, such as small size, low cost, optical transmission of data and possibility to design sensor matrices, which makes them an attractive subject of investigative studies and application works [1] – [4]. Lukosz *et al.* [5] have recently proposed a new type of sensor – a planar difference interferometer (mode beat, polarimetric).

The difference interferometer makes use of the interference of base modes which have different polarization states (TE, TM). The polarization state of a beam at the waveguide output depends on the phase difference between TE and TM modes determined during the propagation through the waveguide structure. The said difference is to be understood as a function of parameters which characterise the waveguide layer and the cover. When the refractive index chenges in the cover due to the influence from the outside, then, also the change of phase difference between the propagating modes is induced. The functioning of chemical sensors in the system of difference interferometer is based on the mechanism described above. The work presents examples of possible applications of the interference between TE and TM modes to monitor the presence of water vapour and ammonia. Due to the applied technology of ion exchange, we can exercise a precise control (during the time of the process) over the depth of refractive profile and, hence, over the potential number

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of propagating modes. Therefore, it is possible to produce a waveguide having precisely two modes for a given wavelength. The paper presents the possibility of applying the interference of modes having the same polarization states (TE_0, TE_1) to monitor the changes in the refractive index of the waveguide cover.

2. Interference of fundamental modes TE_0-TM_0

The examination aiming at checking the possibility of applying the interference of fundamental modes (TE_0, TM_0) to monitor the presence of water vapour and ammonia was carried out in the system presented in Fig. 1. The selected planar waveguide was created in the process of ion exchange Na^+-K^+ in the glass BK-7 over 2 h at a temperature of 400 °C. Using a vapour technique, part of the waveguide was covered by a thin layer of polyaniline (50 nm thick), which changes its properties when subjected to the influence of water vapour and ammonia. A laser diode (λ = 670 nm) served as light source. In a planar waveguide the TE_0 and TM_0 modes were

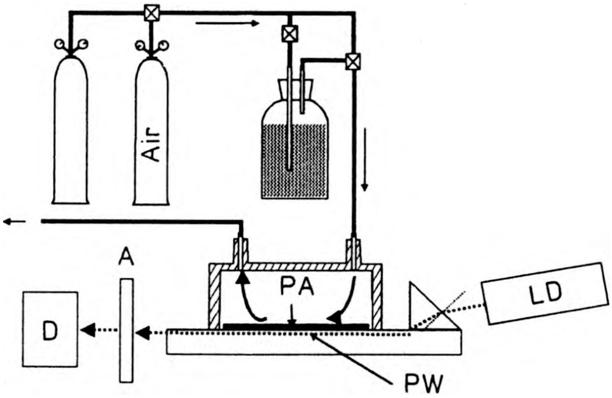

Fig. 1. Experimental set-up. LD — laser diode, A — analyzer, D — detector, PW — planar waveguide, PA — polyaniline film.

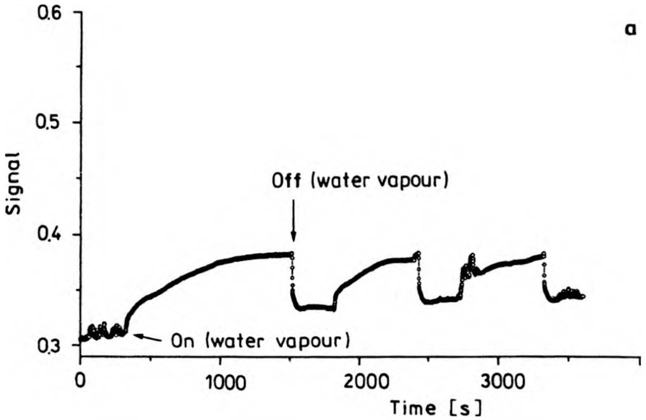

Fig. 2a

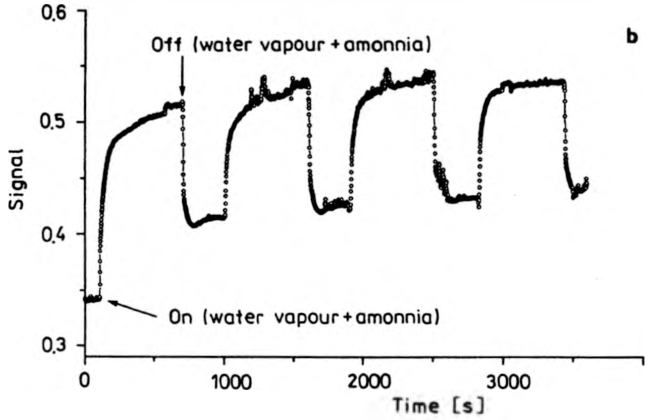

Fig. 2b

Fig. 2. Signal recorded by the detector as a function of time for dry air and with water vapour passed through in alternating way (**a**). Signal recorded by the detector as a function of time for dry air passed alternately with air passing through 25% water solution of ammonia (**b**).

coherently excited by a prism coupler. The changes of the polyaniline properties generated by changes in the composition of the surrounding gases induce a change of the phases difference between TE_0 and TM_0 modes at the waveguide output. A detector placed behind the analyzer records the interference signal. On the part of the polyaniline film, a cell joined with the feeding system was installed, which made it possible to test the sensor. Figure 2**a** presents the signal recorded by the detector as a function of time for dry air ir air with water vapour passed through in an alternating way. With the same positioning of the prism, dry air was passed alternately with air passing through 25% water solution of ammonia. The signal recorded by the detector is presented in Fig. 2**b**.

3. Interference of modes TE_0-TE_1

In order to present potential application of mode interference of the same polarization states (TE_0-TE_1) to monitor the changes in the refractive index of the cover, a double-mode planar waveguide was selected. It was produced in the ion exchange process Na^+-K^+ in the glass BK-7, over 2 hours and at a temperature of 400 °C. Refraction profiles for this waveguide were presented in paper [6], and the dependences involving the effective refractive indices as a function of the refractive index of the covers were calculated using the matrix method 4×4. Calculation results for the wavelength of 670 nm are presented in Fig. 3.

The effective refractive indices for the modes made for the structure of waveguide-air-type were determined using the prism excitation of the waveguide [7]. The values of effective refractive indices determined for the case where air served as a cover for the waveguide ($n_c = 1$) are presented in Tab. 1.

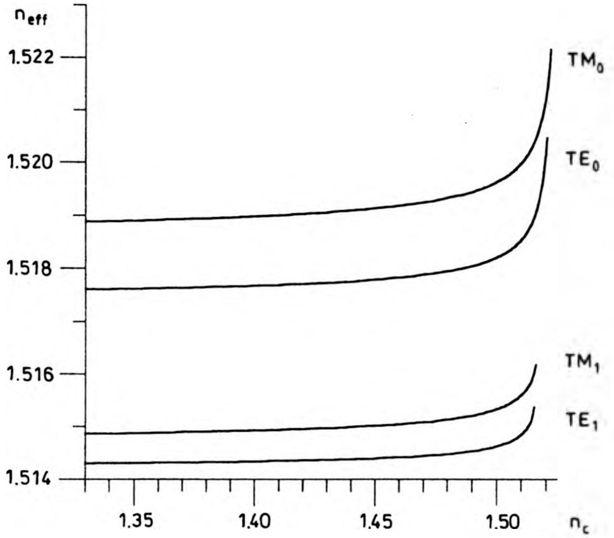

Fig. 3. Effective refractive indices n_{ef} as a function of the refractive index of the waveguide's cover n_c (diffusion K^+-Na^+ in glass BK-7, $t = 5$ h, $T = 400$ °C).

Table 1. Effective refractive indices determined using the method of synchronous angles measurement

$t = 5$ h, $T = 400$ °C	TE, n_{ef}	TM, n_{ef}
XX$_0$	1.5170 ± 0.0011	1.5183 ± 0.0011
XX$_1$	1.5141 ± 0.0011	1.5147 ± 0.0011

Knowing the differences of propagation constants $\Delta\beta$, we can calculate the length of path L, on which the difference of phases $\Delta\Phi$ between the modes changes by 2π

$$L = \frac{2\pi}{\Delta\beta}, \tag{1}$$

or

$$L = \frac{\lambda_0}{\Delta n_{ef}}. \tag{2}$$

With respect to the air, the beat lengths of the modes for the waveguide calculated using Eq. (2) and values from Tab. 1 are presented in Tab. 2.

Table 2. Approximate beat lengths of modes of the waveguide-air structure (diffusion K^+-Na^+ in glass BK-7, $t = 5$ h, $T = 400$ °C)

$t = 5$ h, $T = 400$ °C	Mode beat L [mm]
TE$_0$/TM$_0$	0.53
TE$_1$/TM$_1$	1.41
TE$_0$/TE$_1$	0.23
TM$_0$/TM$_1$	0.19

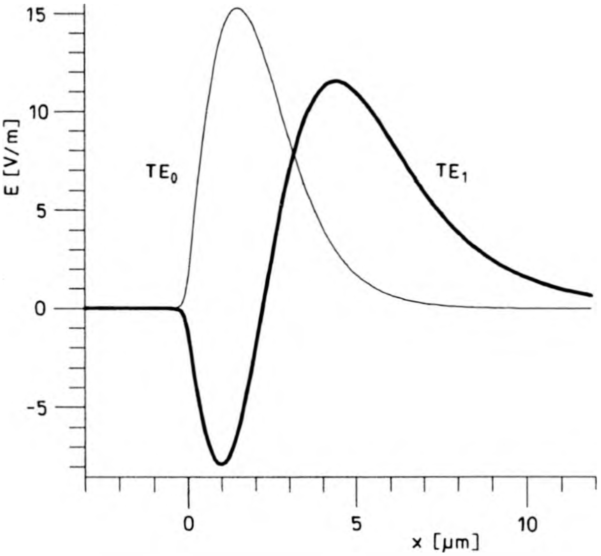

Fig. 4. Distributions of the field E amplitude of the modes TE (diffusion K^+-Na^+ in glass BK-7, $t = 5$ h, $T = 400$ °C, light wavelength $\lambda = 670$ nm).

Based on the refractive profile of this waveguide for the polarization TE, the distribution of the amplitude of the electrical field in modes TE_0 and TE_1 was calculated. Calculation results for the same refracting power made in both modes are presented in Fig. 4. Point 0 of the axis X in this figure corresponds with the air-glass border. A simulation of the predicted distribution of the interference field involving the modes having the same polarization values at the waveguide output was carried out. The modelling program makes it possible to change the amplitude of one of the modes with respect to the other, which reflects the differences in excitation level concerning both modes, and then the fields are put together following the equation:

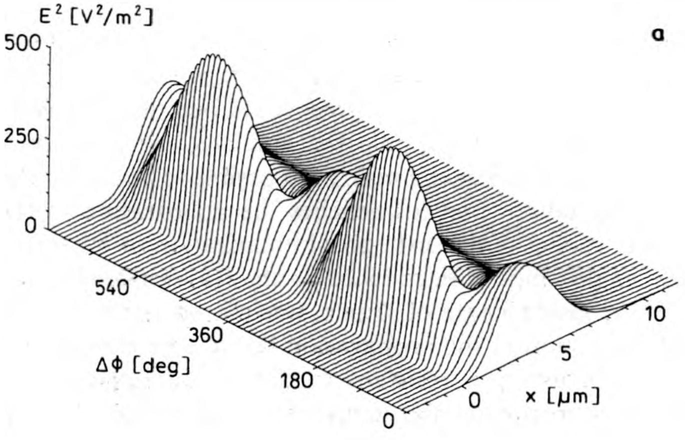

Fig. 5a

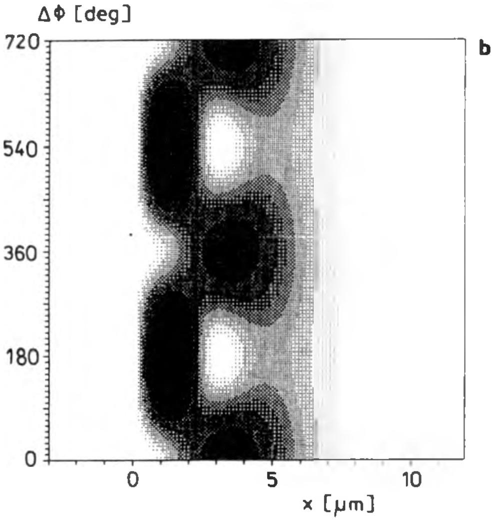

Fig. 5b

Fig. 5. Change in the distribution of light intensity in the field adjacent to the interference field of modes TE as a function of phase difference between them, with equal power provided for both modes: a — 3-D diagram, b — cartographic diagram.

$$E^2(x) = E_0^2(x)+E_1^2(x)+2E_0(x)E_1(x)\cos(\Delta\Phi) \tag{3}$$

as a function of phase difference between the modes $\Delta\Phi$.

To ensure the same excitation level with respect to both modes, the calculated interference patterns E^2 as a function of phase difference $\Delta\Phi$ are presented in Fig. 5. For better illustration of the results, 3-D and cartographic diagrams are provided.

4. Measurements of the interference field TE_0-TE_1 modes

Figure 6 presents the diagram of the measurement system used to record the interference pattern at the waveguide output.

The beam width applied in the laser diode system was about 3 mm, due to which, together with a cylindrical lens of the focal distance of 100 mm, the waveguide excitation of the angle range of 0.03 radian (*ca.* 1.7 degree) could be obtained. With appropriate positioning of the arm with the laser, polarizer and lens, also the modes TE_0 and TE_1 are excited. The system of polarizers makes it possible to select for the exciting beam a suitable refracting power, and it quenches the polarization in the beam which excites the waveguide modes of the orthogonal polarization to the tested one. The beam with a definite angle range is introduced to the waveguide through a prism. A cuvette for liquid, of the inside length of 31 mm, was placed on the surface of planar waveguide, along the direction of the propagation beam. The cuvette was pasted down using colourless silicone glue resistant to the liquid applied and maintaining its physicochemical properties at the temperature up to 100 °C. The

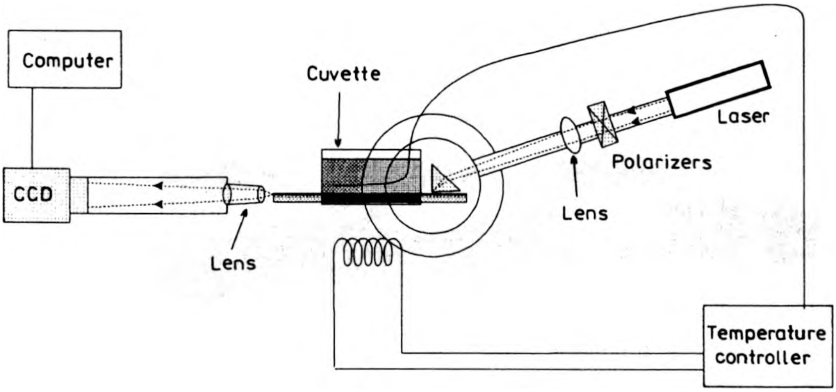

Fig. 6. Diagram of the stand for the observation of changes in the distribution of light intensity in the adjacent field coming from the interference of modes having the same polarization in the planar waveguide.

refractive index of the glue is lower than that of the glass BK-7 ($n_{\mathrm{BK-7}} = 1.515$, $n_{\mathrm{silicon}} = 1.433$ for $\lambda = 670$ nm), which does not allow the beam from the waveguide to be led within the area covered by the glue.

Chlorobenzene was applied as a means of changing phase velocities of the modes, due to its range of changes concerning the refractive index and the temperature within the range from 20 to 60 °C; it was located in the vicinity of cut-off area of the modes of the first order.

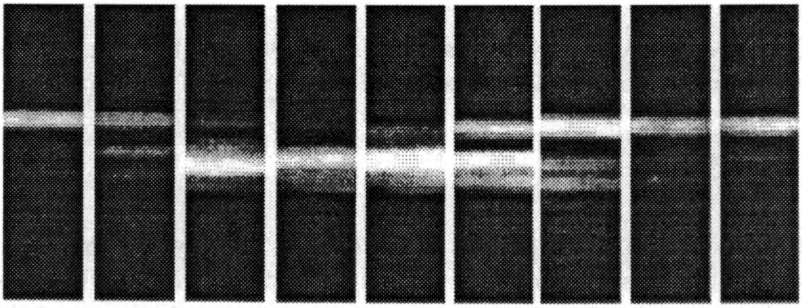

Fig. 7. Changes in the patterns of light intensity at the front of the waveguide along with the change in refractive index of the cover.

In the measurement system presented above, when changing the temperature of the liquid within the range of 25–60 °C stepwise by 0.1 °C, the video camera recorded the patterns (presented in Fig. 7) involving the light intensity at the front part of the waveguide.

Figure 8 presents the recorded distributions of light intensity as a function of liquid temperature covering the surface of the waveguide. (The scale of the vertical axis on the left is given in micrometers. On the top horizontal axis, the temperature of chlorobenzene covering the surface of the waveguide. On the bottom horizontal

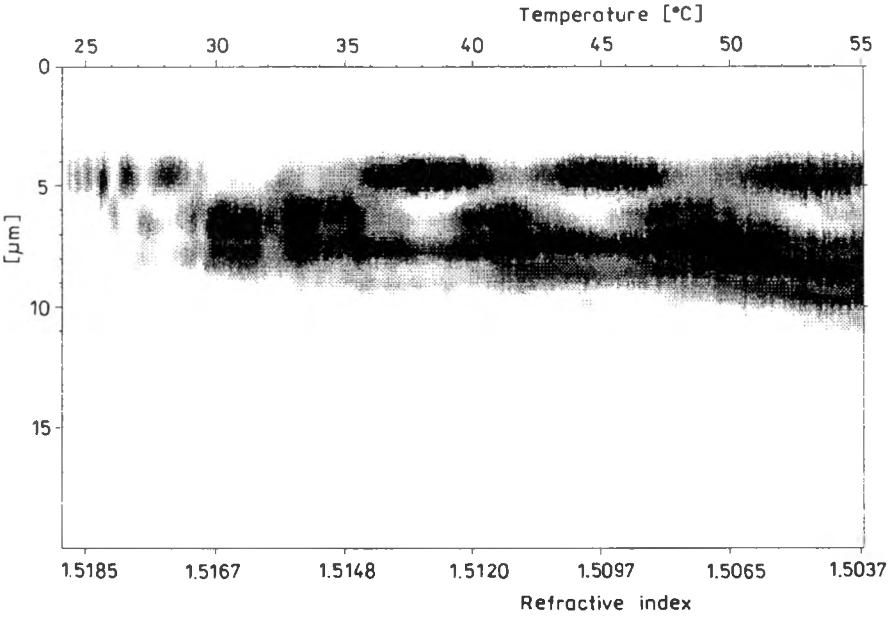

Fig. 8. Cartographic diagram presenting the distributions of light intensity perpendicular to the surface of planar waveguide (vertical axis) along with the change in refractive index of the waveguide's cover. Colour saturation corresponds with the light intensity recorded by CCD

axis, refractive indices of chlorobenzene are given, corresponding with the opposite temperature values).

Making use of the event described above, as well as of the double-mode planar waveguide, it is possible to monitor the changes of the refractive index.

5. Conclusions

The technology of ion exchange in glass offers the possibility to form the refractive profile of planar waveguides and to construct sensors whereof functioning is based on intermode interference. The main advantage of planar structure is simple technology used to produce such waveguides (the process of photolithography can be avoided), due to which the applicability of a given layer can be subjected to preliminary evaluation in view of definite applications in sensor systems. The technology of ion exchange can also be used to produce strip waveguides, whereby a lot of optical paths can be created on a common base, and hence a matrix of optical sensors can be constructed.

Acknowledgements — This work was carried out under the Research Project of the State Committee for Scientific Research (KBN), No. 8 T11B 084 014.

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Received October 20, 1998
in revised form January 13, 1999