INVESTIGATING THE ATTENUATION CHANGES OF MODES GUIDED IN WAVEGUIDES WITH ABSORBING COVER

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The paper is summarizing theoretical and experimental works carried out so far, involving the investigation on the influence of the absorption of the planar waveguide's cover on the attenuation of the guided modes – a phenomenon being a fundamental element for the functioning of optic sensors based on the effect of absorption change of the cover. Theoretical fundamentals of this phenomenon have been discussed, a new measurement method has been.

Keywords: planar waveguide, ion exchange, mode attenuation.

1. INTRODUCTION

Waveguide structures of integrated optics are not only applied in telecommunications sector (where they found application among others as modulators, multi and demultiplexers), but due to a number of advantages unavailable in the technology of optic fibers, they are more and more frequently applied in the construction of sensor systems which monitor physical quantities, biological and chemical processes, as well as a lot of other parameters in various branches of science and industry. It is manifested by a growing number of scientific publications offering new solutions and various improvements introduced to optic sensors whose operation is based on the interaction of the optic wave with the monitored medium.

One of the most essential parameters characterizing a produced waveguide of integrated optics, apart from optical properties, is the attenuation defined as the loss of optic power per unit propagation length. Since planar structures, as compared with optical fibers, have considerably higher attenuation, their proper design, production and application of optic systems necessitates thorough knowledge involving the mechanisms and quantities of loss taking place within the waveguide structure. Whereas the attenuation of the propagating lightwave in telecommunication applications of waveguides is considered to be an unwelcome effect, it can be successfully applied for the production of sensor systems – optical sensors whose work is based on amplitude detection, where the change of the intensity of the guided light is the parameter carrying information on the measured quantity. When we know the quantities of 'self-loss' taking place inside the waveguide, we can estimate to what degree the change of intensity recorded at the output of the structure is the response of the investigated external factor.

The paper presents application potentials of the attenuation effect in the construction of amplitude optic waveguides working on the principle of evanescence wave spectroscopy, based on the effect of attenuation change of the guided modes as a result of the reaction with the absorbing layer of the cover. Numerous publications presenting structural designs of such sensors are reflecting a growing demand principally for sensors which would make it possible to measure the concentration of the investigated substance as well as pH in an efficient and precise way.

2. THEORETICAL BACKGROUND

When an electromagnetic wave is propagating in the attenuation medium, a polarization effect of medium molecules is taking place, expressed by relative electrical permittivity ε_r. In the case when the polarization process does not effect the loss of energy of the wave running through the medium, the relative electrical permittivity εr is a real number. Most frequently, however, the polarization of molecules effected by the propagation of electromagnetic wave in a given medium is inseparably connected with the raise of wave attenuation. Taking into consideration the attenuation effect, the relative electrical permittivity, describing the properties of the medium, should be presented in the complex form $\varepsilon_r=\varepsilon_r'-i\varepsilon_r''$, where: ε_r' describes polarization effect without attenuation and ε_r'' stands for the loss in the medium [1]. If the medium is without loss, then $\varepsilon_r = \varepsilon_r'$. Since ε_r is the complex quantity, likewise the refractive index can be treated in the complex form $n_r=n'_r-in_r''$. Substituting the complex form of propagation constant k_r to the equation describing the propagation of wave in lossless medium we obtain:

$$E = E_0 \exp(-k_r''x)\exp[i(\omega t - k_r'x)] \tag{1}$$

It can be seen that as a result of attenuation, the amplitude of wave running through the absorbing medium is fading exponentially along the propagation length x. Since the wave intensity I is proportional to squared amplitude, we obtain:

$$I = |E|^2 = I_0 \exp(-2k_r''x) \tag{2}$$

The effect of light absorption in the medium can be discussed globally making use of Lambert's law which says that the intensity of monochromatic light wave is decreasing exponentially as it is running through the absorbing medium:

$$I = I_0 \exp[-\mu x] \tag{3}$$

where: I stands for the intensity of wave running through the absorbing substance, I_0-intensity of the wave introduced to the medium and μ - absorption coefficient. With respect to solutions of absorbing substance dissolved in a non-absorbing solvent the Beer's law is satisfied, according to which the absorption coefficient is proportional to the concentration of the solution ($\mu=\alpha C$). Therefore, the Lambert's law turns into the law of Lambert-Beer:

$$I = I_0 \exp[-\alpha C x] \tag{4}$$

where: C stands for the concentration of absorbing substance and α - molar coefficient of absorption, characteristic for a given substance [2],[3]. Comparing the above relation to the equation for wave intensity after it has come through the attenuation medium (1), we obtain a relation which combines the absorption coefficient and the imaginary part of refractive indx:

$$n_r'' = \frac{\mu \lambda_0}{4\pi} = \frac{\alpha C \lambda_0}{4\pi} \tag{5}$$

The value n_r'' can be determined by carrying out a typical spectrophotometric measurement of the investigated substance.

The discussed problem of light wave attenuation after its passage through absorbing agent is applied for the construction of waveguide amplitude sensors. The operation of such sensors consists in the utilization of the effect involving the influence of the absorption change of the cover on the attenuation of the guided modes; the said effect is treated as being analogous to the presented case of wave propagation in the absorbing medium. Following the presented considerations, the refractive index of the cover should be dealt with in the complex form: $n_r=n'_r - in''_r$.

The operation principle of the optical sensor was illustrated in Fig.1, where the influence of absorption change on the attenuation of the guided modes was applied.

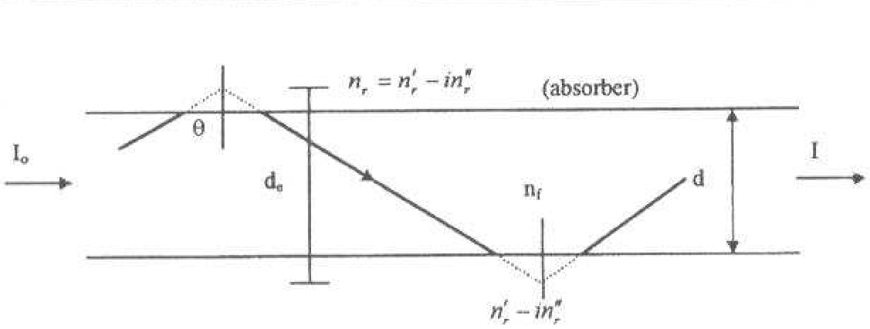


Fig. 1 Ray path in waveguide with absorber [2].

The interaction of light wave guided in the waveguide with the cover is, in view of ray optics, taking place each time when the light ray is subjected to total internal reflection. The wave along he boundary of the media waveguide layer – cover partially penetrates the cover where it exponential decay dependent on the refractive index of the media. The said effect was illustrated in Fig. 2.

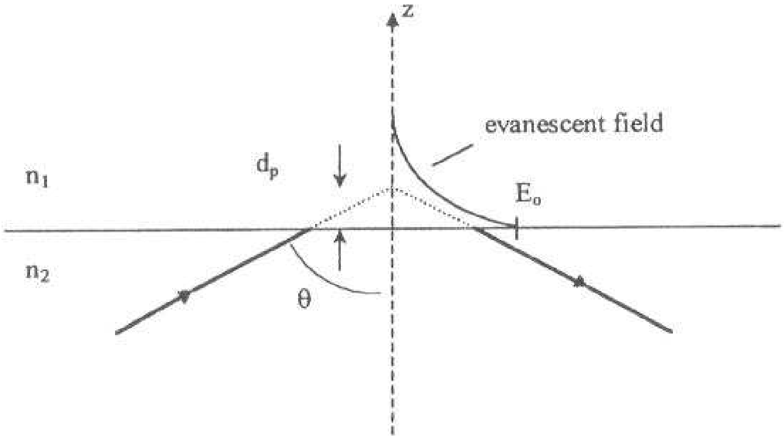


Fig. 2 Evanescent field from total internal reflection at a boundary [2].

In sensors where the principle of spectroscopy of evanescent wave has been applied, the evanescent field reacts either directly with the investigated absorbent or indirectly with the participation of a dye-indicator in which absorption change is taking place or fluorescence is effected due to the interaction with the investigated substance. If in the reaction area, there occurs substance or dye absorbing the guide wavelength, the reflection coefficient of the wave along the boundary of the media will be lower than one, and the guided light will be subjected to attenuation along the propagation length. The field intensity in the cover is decreasing exponentially according to the following relation:

$$|E| = E_0 \exp\left(-\frac{z}{d_p}\right) \qquad (6)$$

where E_0 stands for field amplitude at the reflection boundary and d_p – penetration depth, that is the distance along which the amplitude of the wave is e–times lower than the amplitude on the separation surface cover – core [2],[4].

Optical power guided in the waveguide by the m-th mode can be written in the similar form as the expression (1):

$$I_m(x) = I_m(0)\exp[-\frac{4\pi}{\lambda}N''_m(\lambda,C)x] \tag{7}$$

where $N''_m(\lambda,C)$ stands for the imaginary part of effective refractive index of the mode m, describing the loss of propagation in the waveguide, in the analogous way as the imaginary part n''_r describing the attenuation of light running through the absorbing medium [5]. In the denotation $N_m''(\lambda,C)$ the sum of two attenuation components is included:

$$N''_m(\lambda,C) = N''_{m,const}(\lambda) + \Delta N''_m(\lambda,C) \tag{8}$$

where $N_m''_{const}(\lambda)$ expresses constant part of wave attenuation resulting from absorption or dissipation in the waveguide, and $\Delta\ N_m''(\lambda,C)$ stands for the attenuation effected by the interaction of the evanescent wave with the cover layer along the distance $0<z<L$.

This induced part of attenuation is connected with the true part and imaginary part of the complex refractive index of the cover, which can be presented by the following general relation:

$$\Delta N''_m(C) = \frac{\partial N''_m}{\partial n''_r}\Delta n''_r(C) + \frac{\partial N''_m}{\partial n'_r}\Delta n'_r(C) \approx S_m\Delta n''_r(C) \tag{9}$$

S_m can be regarded as the sensitivity of the imaginary part of the effective refractive index to the changes of the imaginary part of the refractive index $\Delta n_r''$ of the cover.

The approximation is effected by the accepted assumption that the increase of attenuation connected with the effect of field distribution change inside the waveguide due to the change of refractive index of the cover is small. In view of the operative relation of Kramers-Kroning combining the true and imaginary parts of the refractive index, it should be remembered that the effect of the change of refractive index of the cover has also the influence on the imaginary part $\Delta n_r''$, and therefore, on the change of sensitivity S_m. The above expression is binding for the case when the attenuation of wave is taking place along the whole interaction distance between the evanescent wave and the cover, another words, when the absorbing medium is chemically homogeneous.

Taking into consideration the components of the imaginary part of the effective refractive index, after the substitution of (7) to (6) we obtain the power of m-th mode at the waveguide's output:

$$I_m(L) = I^0_m(L)\exp[-\frac{4\pi}{\lambda}S_m\Delta n''_r(C)L] \tag{10}$$

where:

$$I_m^0(L) = I_m(0)\exp[-\frac{4\pi}{\lambda} N''_{m,const} L] \tag{11}$$

expresses the power of output light in the case when there is no absorbing layer of the cover, and L stands for the propagation length of the m-th mode in the waveguide.

When we know the sensitivity and constant value of I^0_m (L), with the measurement of $I_m(L)$ taking place each time, we can observe the changes of the imaginary part of the refractive index of the cover:

$$\Delta n''(C) = -\frac{\lambda}{4\pi L S_m}\ln\frac{I_m(L)}{I_m^0(L)} \tag{12}$$

and consequently define the concentration change of the absorbing substance. The wave intensity at the output is therefore providing information on the properties of the medium surrounding the waveguide.

3. MEASURING STAND

The effect involving the attenuation change of the guided modes due to the reaction with the absorbing layer of the cover was investigated with the use of the method elaborated by the authors and basing on prism coupling and on the of *end-fire* coupling. The measurement method was illustrated in Fig 3.

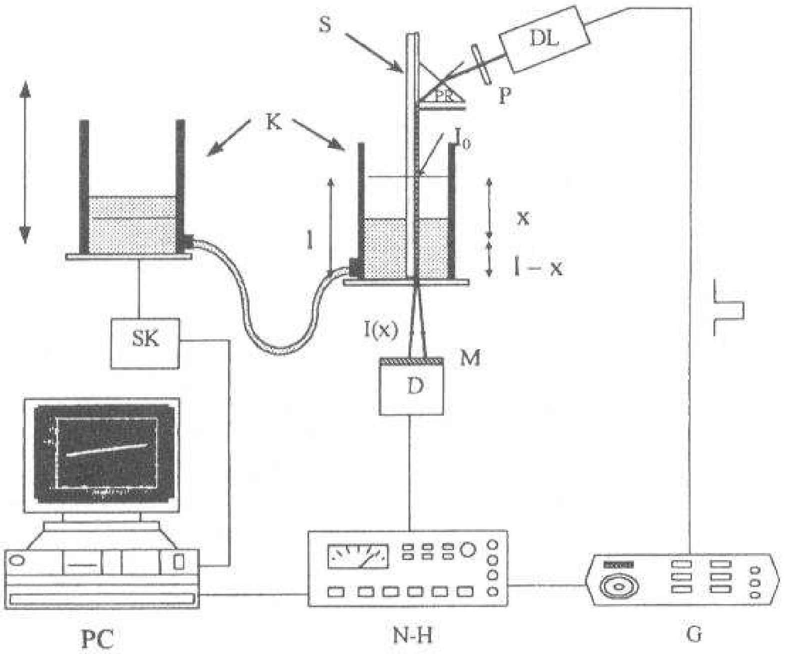


Fig.3. Measurement stand
S – waveguid, PR – prism coupler, K – kuweta, DL – laser diode,
P – polarizer, SK – step motor, G generator, N-H – homodine nanovoltmeter.

Laser light of the wavelength 666 nm is entered to the planar waveguide by a prism coupler and is led out at the front part. The waveguide is being gradually immersed in the absorbing substance placed in the cuvette, but it is done in the way ensuring that the a constant distance between the output front of the waveguide and the detector is maintained. The said condition was effected by combining two cuvettes, joining them with a pipe effecting in this way a system of connected vessels, where the position change of one vessel effects the increase of the volume of the liquid being in the immovable couvette, which means the change of immersion depth of the waveguide. The movements of the couvette are controlled by a step motor, effecting gradual increase of the reaction distance of the modes with the absorbing substance (l-x), and hence, gradual decrease of propagation length of the modes in the gaseous cover x.

The intensity of the wave recorded at the output of the structure is therefore determined by two components: attenuation of waveguide placed in the gaseous medium and the attenuation of guided modes reacting with the absorbing layer of the cover:

$$I = I_0 \exp[-\alpha_f\, x]\, A \exp[-\alpha_B (l - x)] \tag{13}$$

where αf stands for attenuation coefficient of the waveguide with the absence of the absorbing layer of the cover, α_B – attenuation coefficient along the reaction path with the absorbing cover, I_0 – intensity of input wave, l – maximum immersion depth, x – propagation length in the gaseous medium. The expression allows for the constant factor $A<1$ which describes the change of the intensity caused by the reconstruction of the distribution of the guided field on the contact surface air-liquid.

By transforming the above dependencies, we obtain the following relation;

$$I = A\ I_0 \exp[-\alpha_B\, l] \exp[-(\alpha_f - \alpha_B)\, x] \tag{14}$$

The first segment of the expression is constant, and therefore we can formulate the equation for the intensity of the recorded output light:

$$I = I_0' \exp[\,(\alpha_B - \alpha_f)\, x] \tag{15}$$

As it can be seen, the recorded characteristics depend in fact on the difference between attenuation coefficients. In extreme cases, when the attenuation of the investigated waveguide α_f is so small that it can be disregarded, we will be observing solely the attenuation effect of the guided modes reacting with the absorbing layer of the cover.

The difference between attenuation coefficients can be determined by the approximation of the recorded curved using the least squares method, as presented below:

$$I = I_0' \exp[\,(\alpha_B - \alpha_f)\, x] + I_t \tag{16}$$

allowing for the background signal It.

When we know the value of the attenuation coefficient of the investigated waveguide α_f, we can estimate the attenuation coefficient of the guided modes reacting with the absorbing layer of the cover α_B.

Attenuation coefficient α_B is the sum of attenuation coefficients of two components: constant value of loss α_f taking place within the waveguide and the attenuation change $\Delta\alpha_B$ resulting from the reaction of evanescent wave with the substance of the cover:

$$\alpha_B = \alpha_f + \Delta\alpha_B \tag{17}$$

This induced part of attenuation $\Delta\alpha_B$ covers, in turn, the effect of attenuation change $\Delta\alpha_{BN}$ due to the change of refractive index of the cover substance and the change of absorption of the cover $\Delta\alpha_{BA}$. Assuming that the first of the effects is small enough to be disregarded $\Delta\alpha_{BN}\approx 0$ [5], the change of attenuation $\Delta\alpha_B$ is solely a measure of power loss in the absorbing layer of the cover $\Delta\alpha_B\approx\Delta\alpha_{BA}$. Therefore, the difference between attenuation coefficients $\alpha_B - \alpha_f = \Delta\alpha_B$, determined basing on expression (16), is reflecting the attenuation of evanescent wave absorbed by the substance of the cover.

4. MEASUREMENTS

In the presented experiment, the role of the absorbing cover was taken up by a blue dye dissolved in distilled water ($n=1.33$) at the ratio 1/20.

Absorption coefficient of the cover substance for the laser wavelength $\lambda = 666$ nm was determined by carrying out a typical spectrophotometric measurement.

In the first place, transmission spectrum of the solvent was recorded, passing white light through the transparent couvette filled with distilled water and recording the intensity of the output wave with a waveguide spectrometer. A similar measurement was carried out for the cover substance. The testing of spectra was repeated three times. The recorded characteristics are presented in Fig 4a, b .

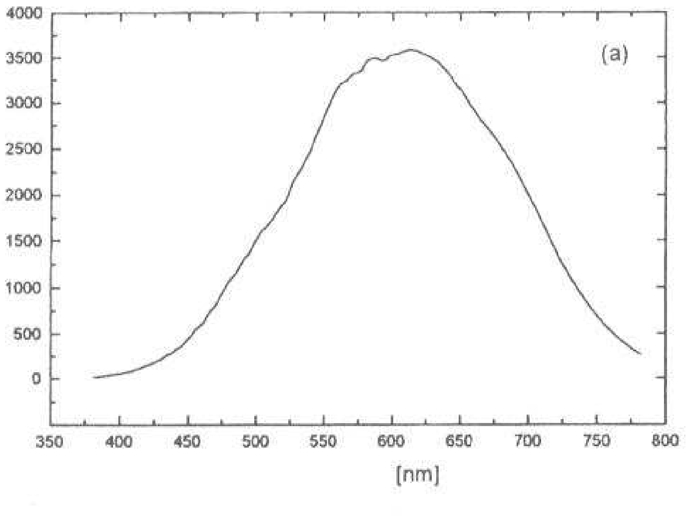


Fig.4a. Recorded transmission spectra of the solvent – distilled water.

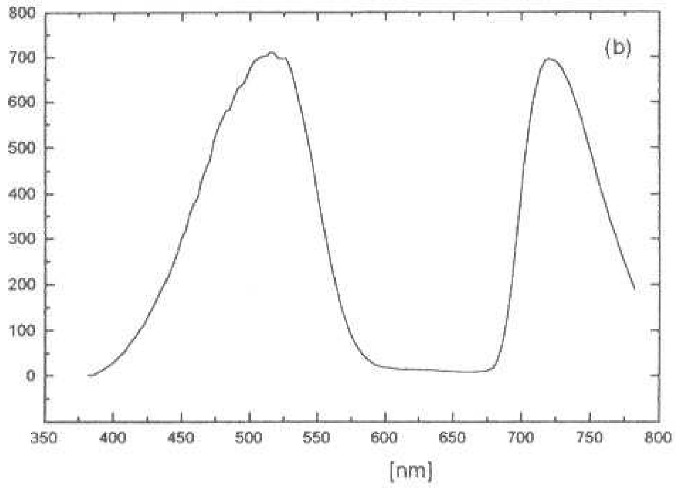


Fig.4b. Recorded transmission spectra of the cover substance – blue dye.

According to Lambert's law, the intensity of wave at the output for a given wavelength is described by the following relation:

$$I = I_0 \exp[-\mu L] \tag{18}$$

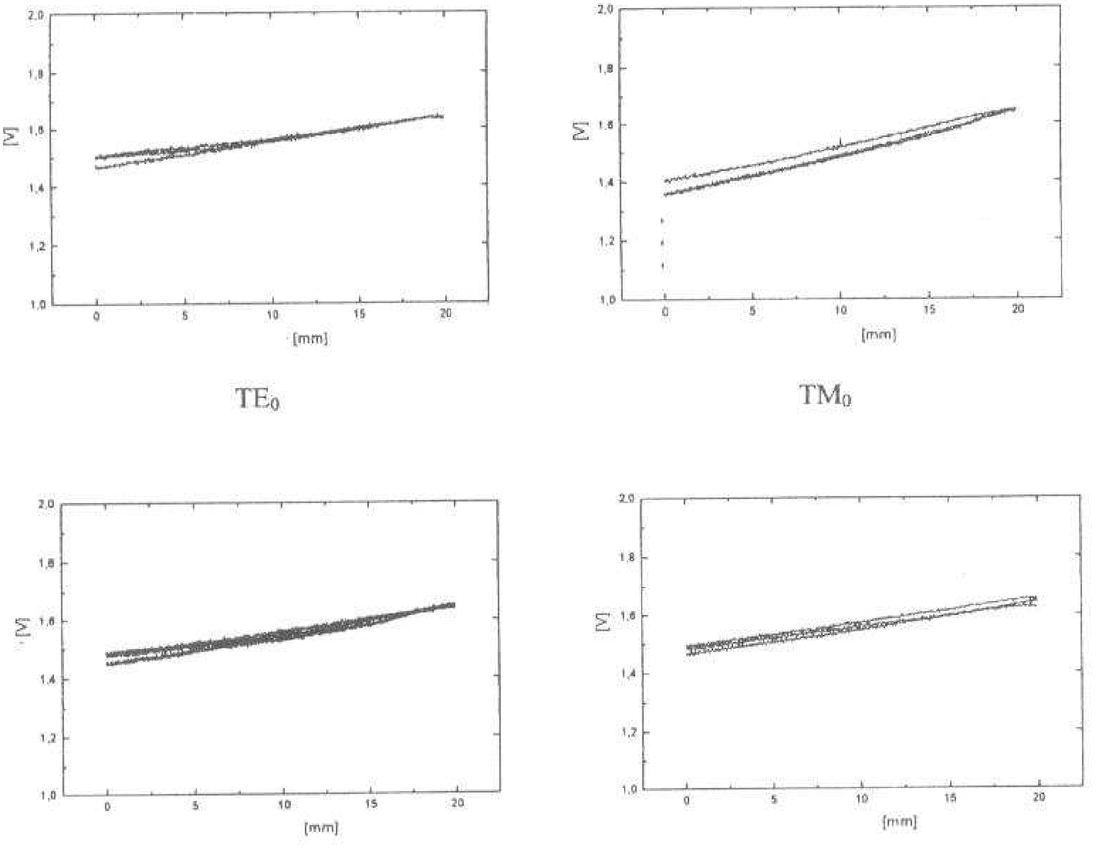
where L – width of the couvette in our experiment.
Having determined the value $\mu = 0.48$ [mm^{-1}] the imaginary part of the refractive index of the cover was determined, according to the following relation:

$$n_r'' = \frac{\mu \lambda_0}{4\pi} \tag{19}$$

which yielded $n_r'' = 0.025 \cdot 10^{-3}$.
Since in the measurements the increase of attenuation due to the change of refractive index of the cover was not recorded (immersion in water without a dye), we can assume that the difference between attenuation coefficients determined with the least squares method $\Delta\alpha_B = \alpha_B - \alpha_f$ is wholly reflecting the attenuation effect in the absorbing layer of the cover. When we know the attenuation coefficient of the modes in the dye, we can determine the imaginary part of the effective refractive index $\Delta N''_m(\lambda, C)$, and in this way estimate the sensitivity S_m of the mode guided in the waveguide to the changes of the imaginary part of the refractive index of the cover:

$$\Delta N_m''(C) \approx S_m \Delta n_r''(C) \tag{20}$$

The recorded characteristics reflecting the effect of attenuation change of the guided modes effected by the interaction with the absorbing layer of the cover were presented on the example of the investigated planar two-mode waveguide produced with the ion exchange method in glass BK7 over 5 hours with the temperature of potassium nitrate 400°C (Fig.5.).



TE$_0$ TM$_0$

TE$_1$ TM$_1$

Fig. 5. Attenuation characteristics of waveguide modes reacting with the absorbing layer of the cover – blue dye. Two-mode waveguide obtained as a result of ion exchange Na^+-K^+ over 5 hours at temperature 400°C.

5. CONCLUSION

For the investigated waveguides, the highest influence of absorption change of the cover on the attenuation of the guided modes is observed for a one-mode waveguide of low attenuation. Attenuation increase of the guided modes in the reaction area with the absorbing layer of the cover is higher for the modes of the polarization TM. The highest sensitivity to the changes of the imaginary part of the refractive index of the cover is exhibited by modes TM.

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