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Features of Temperature Dependence of Effective Refractive Index of TE_1 and TM_1 Modes in Optical Sol-Gel Waveguides over a Wide Temperature Range

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Temperature dependences of effective refractive index on the parameters of the sol-gel film are obtained. The differences of temperature characteristics of sol-gel waveguides for TE and TM modes are found and explained. Features of temperature dependence of effective refractive index at high temperatures are revealed and interpreted.

Key words and phrases: integrated optics, optical waveguide, effective refractive index, sol-gel method, optical temperature coefficient.

1. Introduction

Future development of telecommunication systems is targeted to use new technologies and materials. They provide improved characteristics for the basic elements of these systems, such as optical waveguides, splitters, triggers and others, based in thin films made of different materials.

In recent years, the attention of the researchers is attracted to waveguides based on the films manufactured with the use of the sol-gel method, which is simple and economical and ensures good optical characteristics.

Besides such films possess a number of interesting properties, among which the possibility of varying the refractive index in wide limits by changing the parameters of the manufacturing process, a relatively large negative optical temperature coefficient (OTC), high photosensitivity, etc. [1–4].

Using of sol-gel films for creating particular devices based on them generates a need for comprehensive research of material properties, in particular the dependence of optical characteristics on the parameters of manufacturing process and variation of ambient temperature.

The objective of this investiation is to study the characteristics of optical waveguides based on TiO_2-SiO_2 sol-gel films on the quartz substrate in a wide temperature range under changes of waveguide parameters for the TE and TM waveguide modes as well as to analyse the temperature coefficients (TCs) of the effective refractive indexes (ERIs) of the TE_1 and TM_1 modes as functions of the waveguide parameters.

2. Temperature Dependence of Effective Refractive Index

The effective refractive index of waveguide modes was calculated using the dispersion equations, which determine the relation between the ERI of the corresponding mode, the thickness of the waveguide layer, and the refractive indexes of the media forming the waveguide with consideration for their temperature dependences and the wavelength. Dispersion equations are as follows:

$$\frac{2\pi}{\lambda}h(T)\sqrt{n_2^2(T)-n_{\text{eff}}^2} = \\ = \operatorname{arctg}\left(\frac{\sqrt{n_{\text{eff}}^2-n_1^2(T)}}{\sqrt{n_2^2(T)-n_{\text{eff}}^2}}\right) + \operatorname{arctg}\left(\frac{\sqrt{n_{\text{eff}}^2-n_3^2(T)}}{\sqrt{n_2^2(T)-n_{\text{eff}}^2}}\right) + \pi(m-1)\,, \tag{1}$$

for the TE modes;

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$$\frac{2\pi}{\lambda} h(T)\sqrt{n_2^2(T) - n_{\text{eff}}^2} =$$
$$= \operatorname{arctg}\left(\frac{n_2^2\sqrt{n_{\text{eff}}^2 - n_1^2(T)}}{n_1^2\sqrt{n_2^2(T) - n_{\text{eff}}^2}}\right) + \operatorname{arctg}\left(\frac{n_2^2\sqrt{n_{\text{eff}}^2 - n_3^2(T)}}{n_3^2\sqrt{n_2^2(T) - n_{\text{eff}}^2}}\right) + \pi(m-1)\,, \quad (2)$$

for the TM modes,

where λ is the wavelength of the radiation source; n_{eff} is the effective refractive index of the waveguide mode; and n_1, n_2, n_3 are the refractive indexes of air, film, and substrate, respectively; and m is the index of the waveguide wave (mode).

Temperature dependences of the refractive index and the thickness of TiO_2-SiO_2 sol-gel films were calculated according to the technique described in [5], where experimentally obtained functions $n_2(T)$ and $h(T)$ are approximated by the following polynomials:

$$n_2(t) = -2.047 \times 10^{-7} \cdot T^2 - 2.185 \times 10^{-5} \cdot T + n_2\,,$$
$$h(t) = (1.168 \times 10^{-6} \cdot T^2 - 1.838 \times 10^{-5} \cdot T + 1) \cdot h.$$

The view of the characteristics for the TE_1 and TM_1 waveguide modes at temperatures near 100°C, presented in [6], suggests that some new features can show up on further raising of the temperature.

In this connection supplementary temperature researches of the characteristics of optical waveguides based on TiO_2-SiO_2 sol-gel films were carried out in a wide temperature range from 0 to 400°C. Temperature dependences of the ERI were calculated for the waveguides with the refractive index equal to 1.8 because features of characteristics are much more pronounced at high refractive index.

Temperature dependences of ERI for the TE_1 and TM_1 waveguide modes were calculated for several values of the parameter h from 0.14 to 0.5 μm. In the calculations the refractive index of the film was assumed to have values: 1.49, 1.55 and 1.8.

The analysis of the obtained results has shown that, for the values of the film thickness within stated range and refractive indexes of 1.48 and 1.55, the view of the function ERI(T) for the TE_1 and TM_1 waveguide modes is the same: for both modes, the ERI values monotonically decrease with the increasing temperature, and the curves are convex. This shows that the waveguides have negative temperature coefficient, and that the behavior of the dependence ERI(T) is conditioned by the negative OTC of the film material. Typical function ERI(T) corresponding to $h = 0.5$ μm and $n_2 = 1.55$ is presented in Fig. 1.

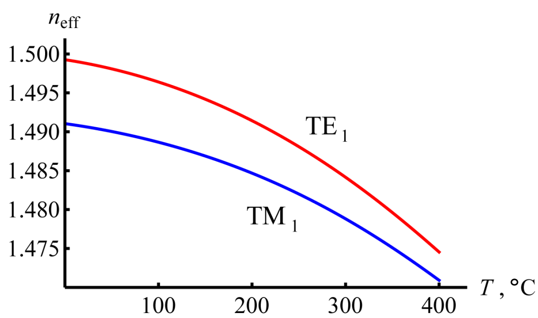

Figure 1. Temperature dependences of the ERI for the TE_1 and TM_1 modes at $n_2 = 1.55$ and $h = 0.5$ μm

Interesting dependences ERI(T) were observed for the refractive index $n_2 = 1.8$. The form of the curves of the dependences ERI(T) is determined by the wave mode and the film thickness. The behavior of the dependence ERI(T) varies sufficiently for thick (from 0.34 to 0.5 μm) and thin (from 0.14 to 0.34 μm) films. Functions ERI(T)

for a film thickness of 0.5 μm are shown in Figs. 2a and 2b. If the film thickness further increases, the behavior of this function coincides with that of the function corresponding to $n_2 = 1.55$, i.e., the curves corresponding to the TE_1 and TM_1 modes are convex and the degree of convexity increases with the film thickness.

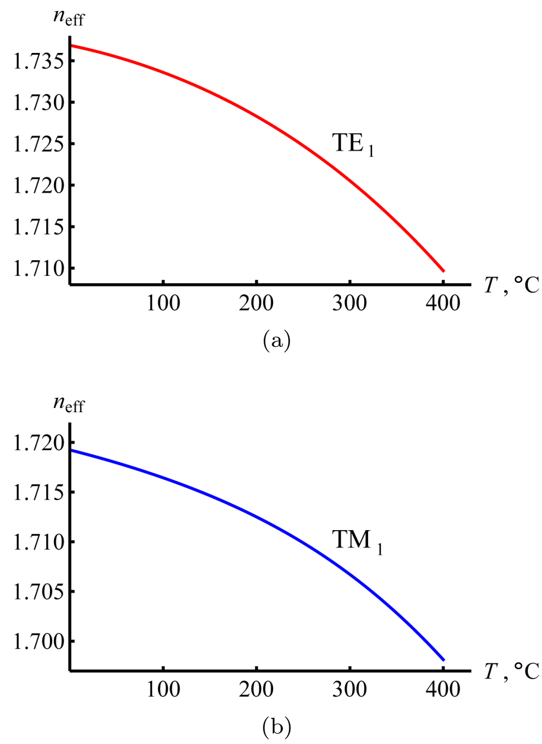

Figure 2. Temperature dependences of the ERI for the (a) TE_1 and (b) TM_1 modes at $n_2 = 1.8$ and $h = 0.5$ μm

However, the behavior of this function abruptly changes for films with small thickness (equal to or lesser than 0.34 μm) and the behavior of the curves corresponding the TE_1 and TM_1 modes becomes markedly different. For example, for a film thickness of 0.34 μm, function ERI(T) corresponding to the TE_1 mode is a convex curve (as in the preceding cases) and function ERI(T) corresponding to the TM_1 mode is a concave curve.

Let us consider how the function ERI(T) for the TE_1 mode changes with the variation of film thickness (from 0.14 to 0.30 μm).

At the value of the film thickness of 0.14 μm and at the temperature range from 0 to 80°C the curve is concave and has a minimum at 80°C.

As temperature increases the value of ERI also increases which corresponds to positive temperature coefficient of ERI (ERI TC) (Fig. 3a). Degree of increase and decay of the curves of the function ERI(T) is characterized by temperature coefficient. The negative ERI TC (decay of the curve) in the temperature range from 0 to 80°C has the value of 0.7×10^{-5}, and the positive ERI TC (increase of the curve) in the temperature range from 80 to 400°C is equal to 1.2×10^{-5}.

As the film thickness increases up to the value of 0.165 μm the curve has the second extremum at the temperature value near 400°C (Fig. 3b). At higher temperature values the TC becomes negative (decay of the curve). As this takes place, the position of the first extremum moves towards higher temperature values (120°C), and the ERI TCs have the same absolute values equal to 1×10^{-5}.

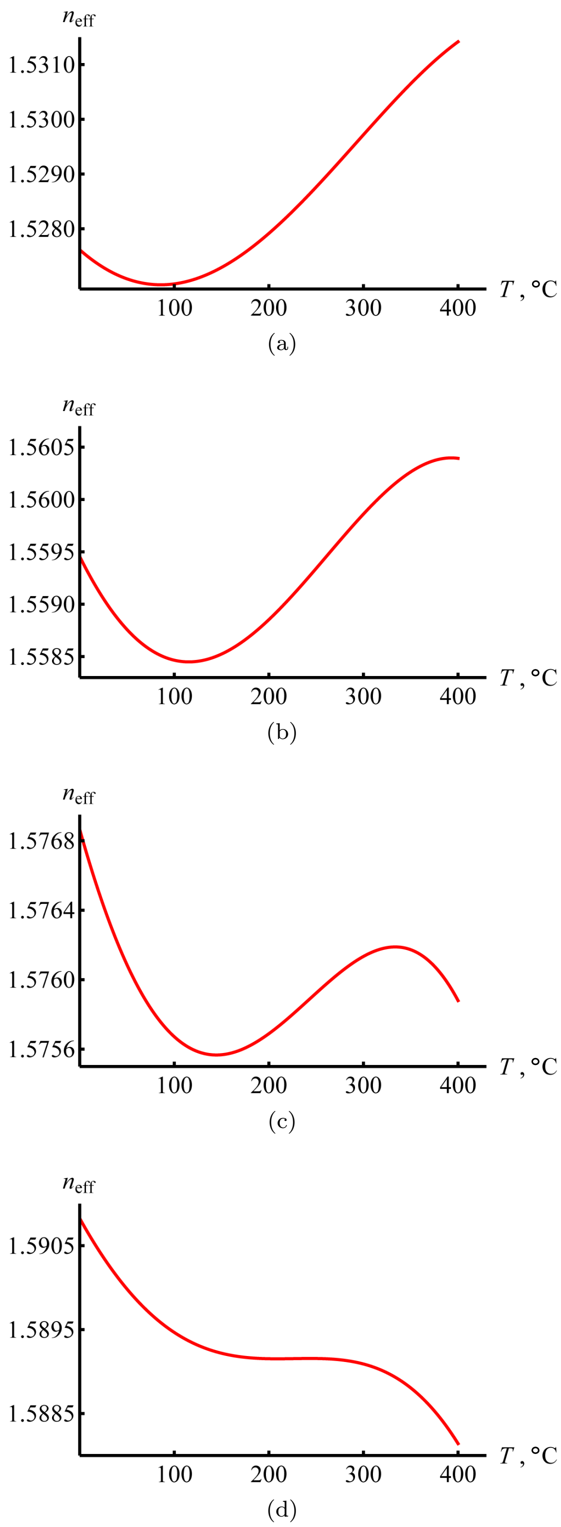

Figure 3. Temperature dependences of the ERI for the TE_1 mode at $n_2 = 1.8$ and (a) $h = 0.140$ μm, (b) $h = 0.165$ μm, (c) $h = 0.180$ μm and (d) $h = 0.193$ μm

As the film thickness increases further, the extremums moves towards each other, i.e., the low-temperature extremum moves towards higher temperature values, and the high-temperature extremum moves towards lower temperature values (Fig. 3c). In so doing the difference between extremum values decreases. At the film thickness of 0.180 μm the negative ERI TC increases in the temperature range from 0 to 140°C up to the value -1.2×10^{-5}, and the positive ERI TC in the temperature range from 140 to 400°C decreases to the value 0.3×10^{-5}.

At the film thickness equal to 0.193 μm, one can observe that the curve has a horizontal segment in the temperature range approximately from 180 to 260°C, with the value of ERI equal to 1.593. Within this segment the action of both temperature factors is neutralized, and the ERI is temperature independent (Fig. 3d).

Further increasing of the film thickness (0.20 μm) causes the form of the curve to change: in the temperature range from 0 to 200°C, the curve is concave, and in the temperature range from 200 to 400°C, the curve is convex, with the point of inflection at the temperature value of 200°C. When the film increases up to the value of 0.30 μm and higher, the curve becomes uniformly convex. The values of the ERI TC are equal to -3×10^{-5} in the temperature range from 0 to 200°C, and equal to -10×10^{-5} in the temperature range from 250 to 400°C.

For the TM_1 mode, the function ERI(T) for thin films (0.140–0.20 μm) also has extremum, whose position, in relation to TE_1 mode, is shifted to low-temperature region, and changes from 8 to 41°C with the increase of the film thickness within stated limits. At temperatures higher than the value corresponding to the extremum, the function ERI(T) is concave and increases (the ERI TC is positive), which is due to the prevailing influence of the temperature dependence of the film thickness. At the film thickness equal to 0.283 μm the second extremum arises at the temperature value of approximately 400°C, and in this case the first extremum is located at the temperature value of 88°C (Fig. 4).

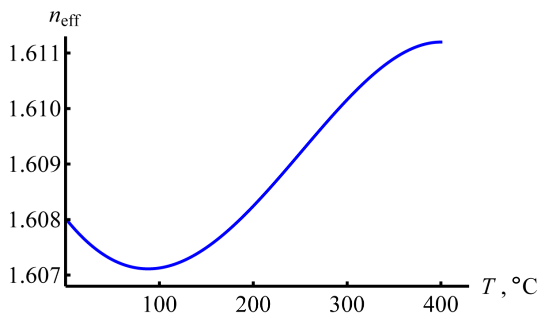

Figure 4. Temperature dependences of the ERI for the TM_1 mode at $n_2 = 1.8$ and $h = 0.283$ μm

Further increasing of the film thickness leads to the shift of extremum positions: the low-temperature extremum is shifted to high-temperature region, and the high-temperature extremum is shifted to low-temperature region, similar to the behavior described above for the TE_1 wave. However, for the TE_1 mode, all the characteristic points are shifted towards higher values of the film thickness.

3. Results and Discussion

The performed studies showed that the dependence ERI(T) is determined by two competitive factors: the temperature dependence of the film thickness (the positive factor), and the temperature dependence of the refractive index of the film material (the negative factor, since the film material has negative OTC). The action of the negative factor increases with increasing the film thickness, since in so do ing the concentration of the wave field in the film increases.

Lowering of the ERI values at higher temperatures and the convex shape of curves (see Figs. 1 and 2) reflect the fact that the influence of the negative OTC of the film material dominates. This conclusion follows from the estimated contribution of each of the stated factors, which was reported in [7] where the temperature dependence ERI(T) was calculated for two cases: (1) consideration for the negative OTC of the film material for the temperature-independent film thickness and (2) consideration for temperature variations in the film thickness at a fixed value of the film refractive index.

At small values of the film thickness (see Fig. 3), the factor related to the temperature dependence of the film thickness manifests itself and this contribution to the ERI is positive, whereas the influence of the negative OTC of the film material is small, which was presented in [6].

The extremums of the analyzed characteristics correspond to equal contributions of two factors and subsequent increase of function ERI(T) is caused by the greater influence of the positive factor (an increase in the film thickness with temperature) on the ERI, which increases the ERI value. As the temperature increases from the value corresponding to the first extremum to higher values, the increase of the ERI value at first becomes slower, since the competitive negative factor increases with the increase of the film thickness, then the action of both factors become equal (the second extremum), and after that the curve ERI(T) becomes convex and decreases, which indicates that the negative factor dominates.

The aforesaid is true for both considered modes. However, for the TM_1 mode, the features of the temperature dependence of the ERI (occurrence of the extremums and their behavior with the varying thickness) show themselves at higher values of the film thickness, in accordance with the portion of the mode power propagating in the sol-gel film.

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Особенности температурной зависимости эффективного показателя преломления TE_1- и TM_1-мод в оптических золь-гель волноводах в широкой области температур

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Получены температурные зависимости эффективного показателя преломления от параметров золь-гель пленки. Выявлены и объяснены различия температурных характеристик золь-гель волноводов для TE- и TM-мод. Выявлены и интерпретированы особенности температурной зависимости эффективного показателя преломления в области высоких температур.

Ключевые слова: интегральная оптика, оптический волновод, эффективный показатель преломления, золь-гель технология, термооптический коэффициент.