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Integrated optical devices based on sol – gel waveguides using the temperature dependence of the effective refractive index

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Abstract. **A possibility of designing optical waveguide devices based on sol – gel $SiO_2 – TiO_2$ films using the temperature dependence of the effective refractive index is shown. The dependences of the device characteristics on the parameters of the film and optical-system elements are analysed. The operation of a temperature recorder and a temperature limiter with a resolution of 0.6 K mm^{-1} is demonstrated. The film and output-prism parameters are optimised.**

Keywords: *sol – gel film waveguides, effective refractive index, temperature recorder, temperature limiter.*

1. Introduction

Sol – gel $SiO_2 – TiO_2$ films [1, 2] have a number of specific characteristics, in particular, a large thermo-optic coefficient (TOC). Hence, these films are promising materials for integrated-optics devices and optical fibre communication lines (for example, for temperature tuning of interference integrated-optics devices, such as narrow-band filters, cavities, Mach – Zehnder interferometers, multiplexers/demultiplexers, etc. [3, 4]). Large TOC values are especially important in designing switches, commutators, and other thermally controlled integrated-optics elements [5].

In this paper we demonstrate a possibility of designing simple integrated-optics devices: a temperature limiter and a temperature recorder; their principle of operation is based on the temperature dependence of the effective refractive index (ERI) n_{eff} of optical waveguides based on sol – gel films. This dependence results in a change in the light output angle from a waveguide and the waveguide-mode spectrum with a change in temperature.

2. Dependence of the ERI temperature coefficient on the optical waveguide parameters

The investigations performed in [6] showed that the temperature coefficient of the effective refractive index (ERI TC) depends on the optical waveguide parameters, such as the refractive index, film thickness, and wave type, as well as on the technological parameters of film fabrication: the mixture component ratio, annealing temperature and time, etc. In addition, the ERI TC depends also on the temperature range used.

The temperature dependences of the characteristics of optical waveguides based on sol – gel $SiO_2 – TiO_2$ films were calculated using dispersion equations with allowance for two factors: the temperature dependence of the refractive indices of the film and substrate, $n(T)$, and the temperature dependence of the film thickness, $h(T)$

Using the polynomial dependences $n(T)$ and $h(T)$ obtained in [7], we calculated the dependence of the ERI on T and investigated the ERI TCs for TE_1, TM_1 and TE_2 waves in the temperature range of 20 – 100 °C for waveguides with different refractive indices n_2 and thicknesses h (Fig. 1).

The thermo-optic coefficient of $SiO_2 – TiO_2$ films is negative, and the film thickness, in correspondence with the thermal expansion coefficient, always increases upon heating. The ERI TC of optical waveguide is determined by both these factors and, depending on the film parameters, may have different values (in particular, positive). The largest (in modulus) value is obtained in the range of 30 – 70 °C; it amounts to about -4×10^{-3} °C^{-1} for a waveguide with h = 0.8 μm and n_2 = 1.8 in the case of TE_1 waves. As was shown in [6], the negative ERI TC value increases with increasing concentration of the wave field of a certain mode in the film.

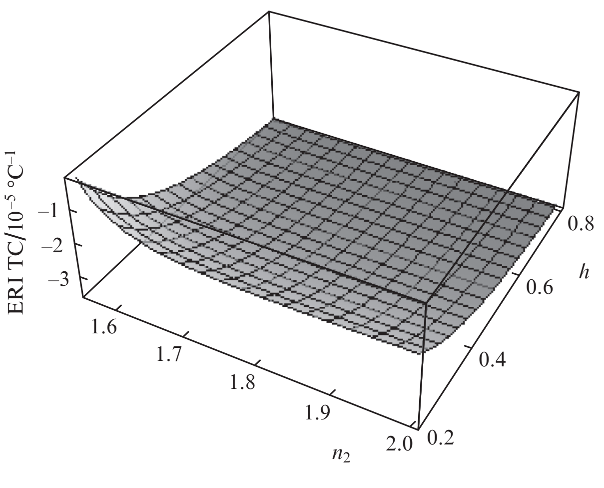

Figure 1. Dependence of the ERI TC on the film refractive index and thickness for a TE_1 wave.

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3. Temperature recorder based on a sol–gel waveguide

The operation of a temperature recorder (TR) is based on the temperature dependence of $n_{\rm eff}$ of a waveguide mode. The conditions for light output from a waveguide are known to depend on the ERI and the output-device parameters. Since the waveguide $n_{\rm eff}$ depends on temperature, the light output angle from the waveguide, φ, is also temperature-dependent. The relationship between these parameters for a prismatic communication device is given by the expression

$$n_{\rm eff}(T) = n_{\rm pr}(T)\sin\left(\alpha_{\rm pr} - \arcsin\frac{\sin\varphi(T)}{n_{\rm pr}(T)}\right), \quad (1)$$

where $\alpha_{\rm pr}$ and $n_{\rm pr}(T)$ are, respectively, the angle and refractive index of the prism.

The experimental waveguide consisted of a SiO_2-TiO_2 film (h = 0.3 μm, n_2 = 1.624) deposited on a quartz substrate. The prism refractive index was $n_{\rm pr}$ = 1.7497 at an He–Ne laser wavelength of 0.63 μm, and the angle $\alpha_{\rm pr}$ between the face adjacent to the film surface and the output face was equal to 60°.

The temperature dependence of the angle at which radiation is extracted from the waveguide using a prism output device is shown in Fig. 2. It can be seen that in the angular range of 25–85 °C the dependence $\varphi(T)$ is almost linear and the variation in light output angles $\Delta\varphi$ is ~ 4°.

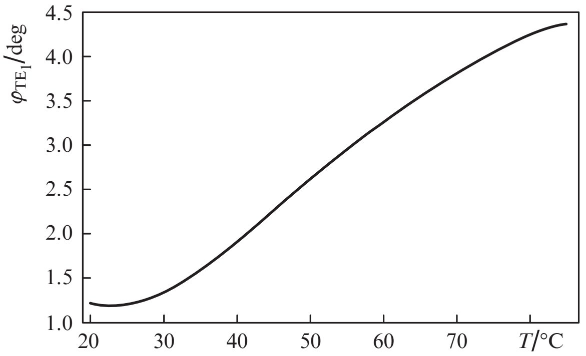

Figure 2. Temperature dependence of the light output angle from a waveguide for a TE_1 wave.

The angular resolution of the TR is defined as the $\Delta\varphi/\Delta T$ ratio and depends on both the ERI TC value (the higher the better) and the $n_{\rm pr}$ and $\alpha_{\rm pr}$ values. An analysis of the dependence of $\Delta\varphi$ on the waveguide parameters showed that, when the film thickness increases, the ERI TC also increases (in magnitude) (Fig. 1); hence, the range of variation in the output angle in a specified temperature range increases as well. Under these conditions, one must choose the TE_1 mode providing the largest ERI TC.

The TR characteristics are determined to a great extent by the prism parameters: refractive index and output angle. The dependence $\Delta\varphi(T)$ was studied on prism materials satisfying the light output conditions: TF-5 glass, GaP, and $LiNbO_3$. Calculations of $\Delta\varphi(T)$ for different prism angles $\alpha_{\rm pr}$ showed that the optimal output prism (providing high resolution and technologically simple) should be made of TF-5 glass and have $n_{\rm pr}$ = 1.7497 and $\alpha_{\rm pr}$ = 60° (Fig. 3).

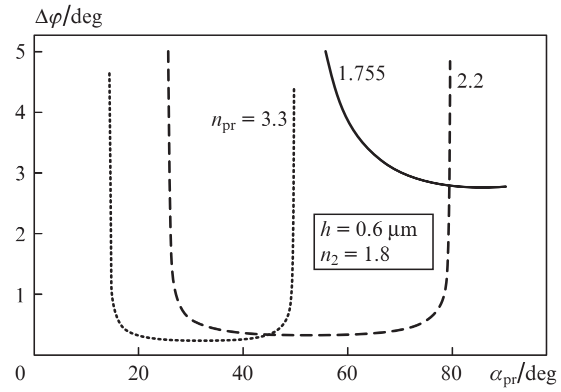

Figure 3. Dependence of $\Delta\varphi$ on the angle $\alpha_{\rm pr}$ of prisms made of TF-5 glass ($n_{\rm pr}$ = 1.755), GaP ($n_{\rm pr}$ = 3.3), and $LiNbO_3$ ($n_{\rm pr}$ = 2.2).

The experimental TR was calibrated using a Peltier module attached to the substrate. The TR temperature measurement scale was spaced from the prism output by 50 cm; in this geometry, the linear resolution was 0.6 K $\rm mm^{-1}$. This result can significantly be improved by choosing the film parameters corresponding to the optimal ERI TC, which exceeds the aforementioned value by a factor of about 4. In addition, as can be seen in Fig. 3, one can also make the TR much more efficient using a prism output angle of 55°.

4. Temperature limiter

The operation of a temperature limiter (TL) is based on the phenomenon of the waveguide mode cutoff with a change in temperature. Since $n_{\rm eff}$ of waveguide modes decreases with increasing temperature (because the ERI TC is negative), the propagation conditions for a certain waveguide mode can be violated at a certain temperature $T_{\rm cut}$. In this context, we investigated the temperature dependence of the critical film thickness.

The critical waveguide thickness was calculated (with allowance for the dispersion relations) from the formulas

$$h_{\rm cr}^{TE_v}(T) = \frac{\lambda}{2\pi[n_2^2(T) - n_3^2(T)]^{1/2}} \times\left[\arctan\left(\frac{n_3^2(T) - n_1^2}{n_2^2(T) - n_3^2(T)}\right)^{1/2} + \pi(v-1)\right],$$

$$h_{\rm cr}^{TM_v}(T) = \frac{\lambda}{2\pi[n_2^2(T) - n_3^2(T)]^{1/2}} \times\left\{\arctan\left[\frac{n_2^2(T)}{n_1^2}\left(\frac{n_3^2(T) - n_1^2}{n_2^2(T) - n_3^2(T)}\right)^{1/2}\right] + \pi(v-1)\right\}, \quad (2)$$

where n_1, $n_2(T)$ and $n_3(T)$ are the refractive indices of air, film, and substrate, respectively; v is the waveguide mode number; and λ is the wavelength.

The results of calculation at λ = 0.63 μm, n_1 = 1.0 and n_3 = 1.4575 for the temperatures T = 20 and 100 °C (the boundaries of the temperature range under consideration) and at different n_2 values are listed in Table 1.

The data of Table 1 indicate that the critical film thickness increases with increasing temperature in correspondence with

Table 1. Temperature dependence of the critical waveguide thickness h_{cr} for the TE_1, TM_1 and TE_2 modes at different n_2 values.

n_2	T/°C	h_{cr}/μm		
		TE_1	TM_1	TE_2
1.48	20	0.528295	0.578078	1.77050
	100	0.595548	0.645379	1.97281
1.55	20	0.211836	0.260781	0.81107
	100	0.218624	0.267615	0.831903
1.8	20	0.074859	0.120923	0.373365
	100	0.075679	0.121787	0.376129

the negative TOC of the film material but decreases with increasing film refractive index. The dependences of h_{cr} on the film refractive index for TE_1, TM_1 and TE_2 waves are shown in Fig. 4.

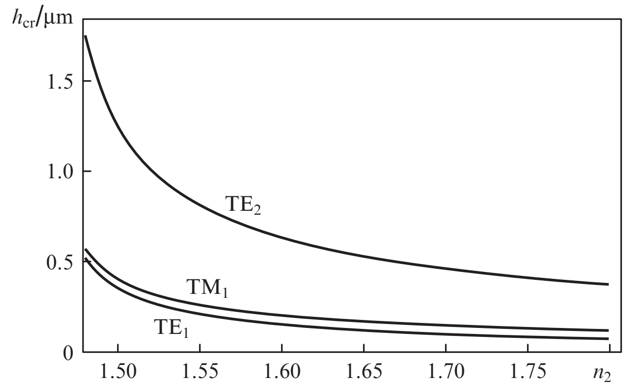

Figure 4. Dependences of the critical wavelength on the film refractive index for TE_1, TM_1 and TE_2 waves.

The refractive index h_{cr} sharply changes with an increase in n_2 from 1.48 to 1.6 but varies only slightly with a further increase in n_2.

The temperature dependence of the critical thickness for a waveguide with a TE_1 or TM_1 working wave is shown in Fig. 5 (the curve for a TE_2 wave has a similar shape).

The temperature dependence of the critical film thickness $h_{cr}(T)$ for the corresponding mode is characterised by the temperature coefficient $\Delta h_{cr}/\Delta T$. The TC values for the critical thickness in the temperature range of 20–90 °C for TE_1 and TM_1 waves are approximately the same (~0.36×10^{-3} μm °C^{-1}), but for the TE_2 wave the TC is larger by a factor of about 3. Note that TC is positive for the critical thickness, i.e., this parameter increases with an increase in temperature. Thus, an increase in temperature to some value T_{cut} may violate the waveguide-propagation condition for a wave of a certain type.

An analysis of the results obtained showed that, in order to optimise a thermo-optic TL, one should choose a film with a minimally possible refractive index and maximum ERI TC.

Preliminary experiments with a waveguide having a thickness h = 0.1673 μm and a film refractive index n_2 = 1.5117 revealed that the TM_1 wave disappears upon heating the waveguide to 65 °C, i.e., at this temperature the waveguide thickness became smaller than the critical.

An important factor for operation of thermooptical waveguide devices is that the temperature dependences of the ERI

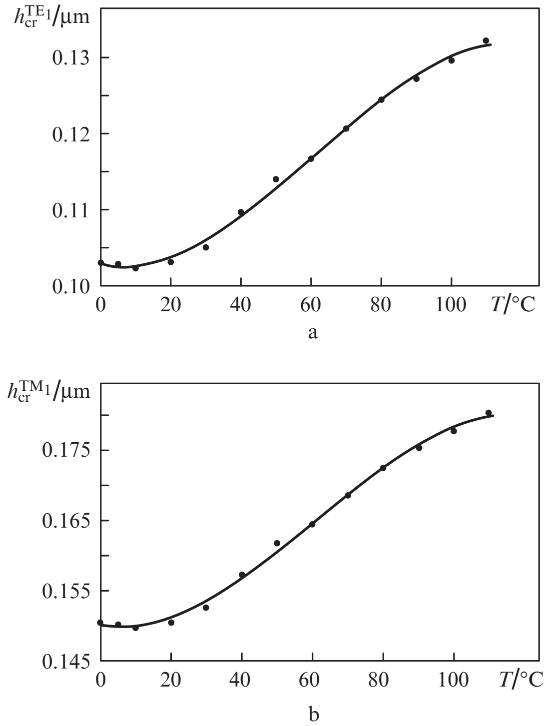

Figure 5. Temperature dependences of (a) h_{cr}^{TE1} and (b) h_{cr}^{TM1}; n_2 = 1.6977 (T = 0 °C).

are the same both upon heating and cooling the waveguide (experiments showed virtual absence of hysteresis). The largest difference in the ERI values (~20 %) was observed at a temperature of 10 °C, then this difference monotonically decreased with an increase in temperature to become zero at 55 °C and remain negligible at higher temperatures. Measurements showed that the ERI difference is even smaller for the TM_1 wave.

5. Conclusions

We showed a possibility of designing thermally controlled optical waveguide devices based on sol–gel films and demonstrated operation of model devices: temperature recorder and temperature limiter, the principle of operation of which is based on the temperature dependence of the effective refractive index of these waveguides.

It was shown that the resolution of a temperature recorder depends on the waveguide ERI TC, because this coefficient determines the temperature angular dependence of the output beam; note that the modulus of the waveguide ERI TC for the TE_1 mode exceeds that for TM_1. In addition, it was established that the temperature angular dependence is determined to a great extent by the parameters of the output prism (its refractive index and the angle between the output face and the face adjacent to the waveguide surface). Optimisation of the prism parameters showed the best results for a prism made of TF-5 glass with an output angle of 55 °C.

For a mode-cutoff temperature limiter, a smaller refractive index of the film and a maximum ERI TC value are preferred. Therefore, according to the data of Table 1, one should use the TE_2 mode as a working one and choose a film as thin as possible (near the critical mode of waveguide operation).

We have demonstrated the operation of temperature recorder and temperature limiter models with the following satisfactory characteristics: resolution of 0.6 K mm^{-1} for the temperature recorder and a temperature coefficient of 0.36×10^{-3} μm $°C^{-1}$ for the temperature limiter. Optimisation of the model parameters may significantly improve the characteristics of these devices.

References

1. Chekhlova T.K., Zhivtsov S.V., Pogosyan A.S. *Vestn. RUDN, Ser. Fiz.*, **13**, 35 (2005).
2. Innocenzi P., Martucci A., Guglielmi M., Armelao L. *J. Non-Crystall. Solids*, **259**, 182 (1999).
3. Fardad A.M., Mishechkin O.V., Fallahi M. *J. Lightwave Technol.*, **19**, 84 (2001).
4. Beregovski Y., Fardad A., Luo H., Fallahi M. *Opt. Commun.*, **164**, 57 (1999).
5. Wang X., Lei Xu, Liying Liu, Wang W. *J. Appl. Phys.*, **94**, 4228 (2003).
6. Chekhlova T.K., Zhivtsov S.V., Grabovskii E.I. *Radiotekh. Elektron.*, **51**, 834 (2006).
7. Nikolaev N.E., Pavlov S.V., Trofimov N.S., Chekhlova T.K. *Radiotekh. Elektron.*, **57**, 1 (2012).