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Continuously tunable fibre attenuator operating in the wavelength range near 1.5 μm

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***Abstract*. A fibre attenuator is fabricated for the telecommunication wavelength range near 1.5 μm in which a single-mode silica fibre with side polishing is used. The fibre surface is covered by a layer of fluorine-containing polymer with a large thermooptic coefficient. The principle of attenuator operation is based on a change in the conditions of total internal reflection for a guided mode in the polished region due to thermally induced variation in the refractive index of the fluoropolymer layer. The attenuator is insensitive to light polarisation, it has a continuously variable attenuation coefficient in the range 0.2 – 27 dB, and can be easily incorporated into fibreoptic links.**

Keywords: *optical attenuators, side-polished silica fibres, fluorine-containing polymers.*

In recent years polymer materials are widely used in a variety of devices for fibreoptic communication links due to their high functional qualities, good technological properties, and a comparatively low cost. Among optical polymers of different types, fluorine-containing polymer materials are most promising [1, 2]. First, unlike usual hydrocarbon polymers such as PMMA, fluoropolymers have low absorption in all the three telecommunication wavelength ranges at 0.85, 1.3, and 1.5 μm. This is explained by the fact that the frequencies of the vibrational overtones of the C – F bond are shifted to the red with respect to the frequencies of the corresponding overtones of the C – H bond responsible for absorption in these spectral ranges [3]. Second, initial fluorine-containing oligomers have the low refractive index n (even lower than 1.33). This allows one, by performing their copolymerisation with oligomers with the high refractive index n, to vary in a broad range the refractive index n_p of a composition capable of polimerisation. In addition, fluoropolymers have a large negative thermooptic coefficient τ ($\tau = dn_p/d\theta$, where θ is temperature). This makes it possible to use fluoropolymers in tunable optical attenuators, modulators, switches, and sensors.

The fabrication of such devices operating at wavelengths near 0.85, 1.3, and 1.5 μm and based on single-mode side-polished silica fibres covered by a thin transparent film with the refractive index exceeding that of the fibre cladding was reported in papers [4 – 12]. The films were prepared from lithium niobate [4], organic electro-optical crystals [5], special liquids [6, 7], and hydrocarbon polymers [8 – 12] capable of changing the refractive index due to electro- or thermo-optical effects.

The film used in such devices represents a planar waveguide having the spectrum of guided discrete modes for which the effective refractive indices n_{eff} are determined by the film thickness and its refractive index. The interaction of a fibre mode with the modes of the film waveguide has a resonant nature when the values of n_{eff} for these modes coincide. In this case, the tunnelling of light from the fibre to the waveguide occurs. Therefore, by controlling the spectrum of the guided modes by changing the refractive index of the film, we can modulate the intensity of light transmitted through the fibre. Devices described in papers [4 – 12] were polarisation-sensitive because the effective refractive indices for the TE and TM modes in a thin-film waveguide are different.

In this paper, we report the fabrication of a polarisation-insensitive optical attenuator based on a single-mode side-polished silica fibre with a thick cover fluoropolymer layer having a quasi-continuous spectrum of guided modes. In this case, the light intensity can be controlled by restoring the conditions of total internal reflection for a fibre mode in the polished fibre region by decreasing the refractive index of a fluoropolymer layer from values exceeding n_{eff} down to values smaller than n_{eff} during heating due to the negative thermo-optical coefficient of the polymer material.

Figure 1 shows the scheme of the attenuator. The attenuator was made of a standard single-mode silica (at a 1.5-μm wavelength range) fibre with a step refractive index, the core diameter of 8.3 μm, and the numerical aperture of 0.13. The fibre was glued in a curved groove in a silica block and was side-polished to approach the fibre core by 1 – 2 μm (the method described in Refs [13, 14] was used). The radius of curvature of the fibre in the groove was 0.8 m, providing the interaction length of the fibre mode with the polished region equal to 3 – 5 mm.

A liquid composition capable of polymerisation was prepared from a methacryl fluorine-containing macromonomer with the refractive index $n_D = 1.39$ at a wavelength of 0.59 μm. The joining agent was a multifunctional

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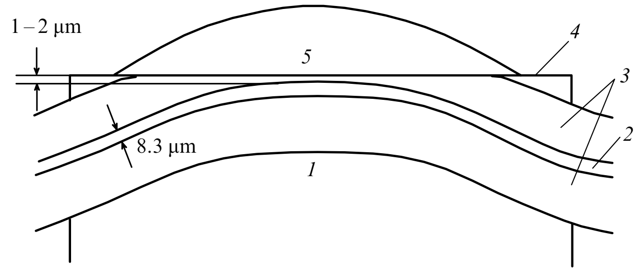

Figure 1. Scheme of the attenuator: (*1*) silica block; (*2*) fibre core; (*3*) fibre cladding; (*4*) side-polishing plane; (*5*) fluoropolymer layer.

oligoglycerolmethacrylate (OGM) with $n_D = 1.47$. By mixing the macromonomer and OGM in the 1 : 3 proportion, we selected the refractive index of the composition $n_p = 1.45$ at the wavelength 0.59 μm so that it was close at the operating wavelength 1.55 μm to the effective refractive index $n_{eff} = 1.446$ for the silica fibre mode, being, however, somewhat lower.

Linearly polarised radiation from a 1.55-μm diode laser was coupled into the fibre, and then the composition was applied to the polished region of the fibre in the form of a thick (~ 0.15-mm) layer and was polymerised under the action of UV radiation. The fluoropolymer shrank during polymerisation, which was accompanied by the increase in its refractive index n_p, which became higher than n_{eff} for the fibre mode. In this case, the intensity of light transmitted through the fibre strongly decreased due to its tunnelling from the fibre core to the polymer through a thin side-polished cladding layer. When the fluoropolymer was heated by a hot air jet, its refractive index decreased. This effect is caused by the thermal expansion of the polymer, which is accompanied by a decrease in its density and, hence, in the refractive index [15]. As the refractive index of the polymer layer became lower than the effective refractive index for the fibre mode, the transmission of light through the fibre again increased.

We measured the temperature dependence of the transmission coefficient T (the ratio of the light intensity transmitted through the fibre to the light intensity transmitted through the fibre when the attenuator is open) by placing the polished region of the fibre into a thermostat. The temperature in the thermostat was measured with a microcircuit with an accuracy of ± 0.09 K. The experimental dependence $T(\theta)$ is presented in Fig. 2. The accuracy of measurement of T was 0.5 %.

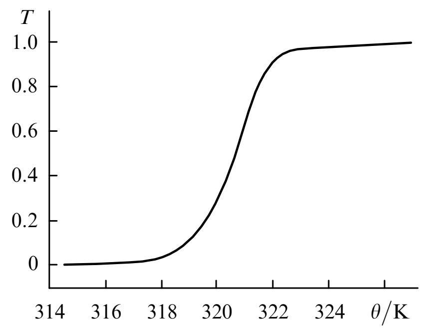

Figure 2. Temperature dependence of the transmission coefficient of the attenuator at a wavelength of 1.55 μm.

One can see from Fig. 2 that a change in the light transmission through the attenuator continuously occurs near the transition temperature $\theta_0 \approx 320.7$ K. The transition temperature can be increased or decreased by changing the percentage of OGM in the composition, thereby changing its initial refractive index. The temperature dependence of the transmission coefficient T upon heating or cooling of the device was the same and did not change after repeated heating/cooling cycles. As temperature was increased by 10 K from 316 to 326 K, transmission increased from 0.2 % to 99.9 %, corresponding to the modulation depth of 27 dB. To increase T from 5 % to 95 %, which corresponds to the 13-dB modulation depth, the temperature should be raised by 4.2 K (from 318.6 to 322.8 K). The attenuator parameters did not vary upon rotation of the polarisation plane of input radiation, demonstrating the insensitivity of the attenuator to polarisation of light. It follows from Fig. 2 that, to maintain the transmission coefficient T in the range between 316 and 326 K with an accuracy of ± 1 %, the temperature should be stabilised with an accuracy of ± 0.03 K. The inner losses, measured when the attenuator was fully open, were less than 0.2 dB.

Let us estimate the thermo-optical coefficient τ of the composition made of a methacryl fluoropolymer. Because to transfer the single-mode silica attenuator with the numerical aperture 0.13 and the cored diameter 8.3 μm from the closed to fully open state, it is necessary to change the refractive index of the external polymer layer by $\Delta n \approx -0.004$ [16], which is achieved by increasing its temperature by $\Delta\theta = 10$ K (from 316 to 326 K), we have $\tau = \Delta n / \Delta\theta = -4 \times 10^{-4}$ K^{-1}. This is in good agreement with the value of thermo-optical coefficient $\tau = -(2 \div 4) \times 10^{-4}$ K^{-1} for acryl fluoropolymers obtained in Ref. [2].

The time response of the attenuator was measured by heating the attenuator by radiation from a halogen lamp modulated with an optical chopper with a variable rate of rotation. As the modulation frequency was increased, the modulation depth of the transmitted signal decreased from 3 dB at 2 Hz down to 0.3 dB at 2 Hz. This is caused by the inertia of process of heating and cooling of a thick polymer layer. The modulation depth and response speed can be increased by using fluoropolymers with greater thermo-optical coefficients and also by optimising the attenuator design.

Thus, we have fabricated a continuously tunable attenuator for the telecommunication wavelength region at 1.5 μm which is insensitive to light polarisation, provides the signal modulation depth up to 27 dB, and can be easily incorporated into fibreoptic links. The attenuator can be also used as a temperature sensor and a low-frequency modulator of optical signals.

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