Characterization of Erbium Doped Glass Optical Waveguides by a Fine Tunable Semiconductor Laser

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Abstract. *In this paper we describe some methods for characterization of the new active optical channel waveguides (suitable for waveguide lasers and amplifiers at 1550 nm) by means of a fine-tunable semiconductor laser. The channel waveguides were fabricated by ion-exchange technique* $K^+ \Leftrightarrow Na^+$ *and* $Ag^+ \Leftrightarrow Na^+$ *in the newly designed Er-doped silicate glass substrate. The effect of the used technology on the basic parameters of the waveguide, i.e. optical field distribution, spectral dependencies of absorption and optical losses, was investigated. In the conclusion, the results obtained are discussed mainly from the point of view of differences in the waveguides' fabrication technology; and new trend in the fabrication is suggested.*

Keywords: erbium doped glass, channel waveguides, optical losses, absorption

1. Introduction

Within the recent development of optical communication systems a need in waveguide optical amplifiers has occurred. In the field of integrated optics, a number of possibilities of active waveguide fabrication in various materials have been suggested. Special erbium doped silicate glasses have appeared as one of the potential candidates for active waveguides (*i.e.*, waveguide amplifiers and lasers). The advantage of such glasses is that they resemble mechanical and optical properties of currently used optical silica fibers (concerning, *e.g.*, refractive index, thermal expansion, chemical resistivity, *etc.*), which results in relatively easily obtainable and potentially highly effective coupling between the optical fiber and the active device (*i.e.* the channel waveguide).

The rare earth ions are suitable for provision of the active function of the waveguides (*i.e.* generation and amplification of the guided radiation). Er^{3+} ions were chosen in this case due to their emission at 1536 nm, which is very close to the often used telecommunication band of 1550 nm. The scheme of the three-level system of optical pumping in the Er^{3+} ion is depicted in Fig. 1. The radiation of 980 nm is used as a pumping source. This wavelength is absorbed and causes thus excitation of the erbium ions to the upper $^4I_{11/2}$ level. After the excitation the irradiative transition to the $^4I_{13/2}$ level follows practically immediately. And the process ends with radiative transition to the basic state (level $^4I_{15/2}$) with synchronous emission of the coherent radiation of the wavelength about 1536 nm. This three-level energetic system is expected to be more efficient than the quasi-two-level system with pumping at 1480 nm [1].

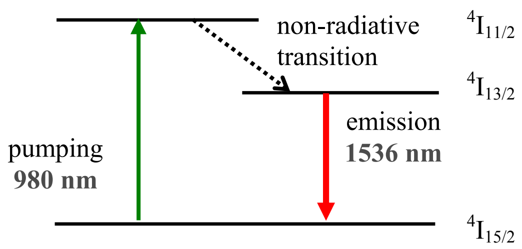

Fig. 1. The three-level system of optical pumping in the Er^{3+} ion.

2. Subject and Methods

Newly designed silicate (Na_2O-Al_2O_3-ZnO-SiO_2) glass containing 2 wt.% of Er_2O_3, marked MM63, was used in the channel waveguides fabrication. The masks with openings ranging from 1.5 µm to 8 µm were made by physical deposition of Ti and Al layers. Ion exchange occurred after immersing the pre-cleaned substrates into the melt of a pure KNO_3, and eutectic melt of $NaNO_3$ and KNO_3 with addition of 24 wt.% $AgNO_3$ for "K^+" waveguides and "Ag^+" waveguides, respectively. Duration of K^+ ion exchange was 4 min at 280 °C while Ag^+ ion exchange proceeded for 2 hours at 400 °C [2].

The following methods were used for the characterization of channel waveguides:

Near-field imaging for the mode field distribution measurement
Optical field distribution inside the optical waveguide brings important information about its optical properties, *e.g.,* on the number of guided modes, mode field distribution, refractive index profile in the structure and availability of the effective coupling to other optical components., *e.g.*, a fibre. The method is based on the detection of the radiation coming from the channel waveguide by vidicon camera and its subsequent computer evaluation.

Absorption and waveguide losses measurement
The spectral dependency of the waveguide absorption gives information about the radiation absorbed during the propagation in the waveguide. This dependency is related to the optical losses of the waveguide and this is the reason why the absorption of the radiation in the waveguide should be the lowest possible. However, in the case of pumping radiation the request is contradictory, i.e. the maximal absorption is needed at 980 nm for the most effective excitation of the Er^{3+} ions. The method is based on the detection of the radiation, which has gone through the waveguide, in dependency on the radiation wavelength.

Optical loss is one of the most important parameters of the waveguides; in the case of active waveguides this parameter affects directly the total optical gain. When the optical loss is high, the active waveguide could even lose its active ability. In our case the F-P (Fabry-Perot) resonant method [3], [4] was used for the determination of optical loss of the fabricated channel waveguides. Both end facets of the samples were polished and were then used as mirrors of the F-P. resonator. The optical attenuation coefficient of the waveguide (in dB/cm) can be obtained from the amplitude of the F-P. resonances using the equation

$$b = \frac{4.34}{L}\left(\ln\frac{1+\sqrt{K}}{-1+\sqrt{K}} - 2\ln\frac{N+1}{N-1}\right), \tag{1}$$

where L is length of the waveguide, K is the ratio between the maximum and minimum intensities of the F-P. resonances, and N is the effective refractive index of the guided mode.

3. Results

In Fig. 2, there are shown the results of the near field measurement. A comparison of channel waveguides fabricated by both types of ion-exchange while using the same width of openings is shown. The optical field distributions in the vertical and horizontal direction are depicted. The FWHM (Full Width at Half Maximum) parameter was evaluated and used for comparison of “K^+” and “Ag^+” waveguide; the horizontal FWHM of the field distribution is in the case of K^+ ion-exchanged channel waveguide 2.2× higher than in the other case (8.84 μm / 4.08 μm) while the vertical FWHM is 1.9× higher (6.18 μm / 3.2μm).

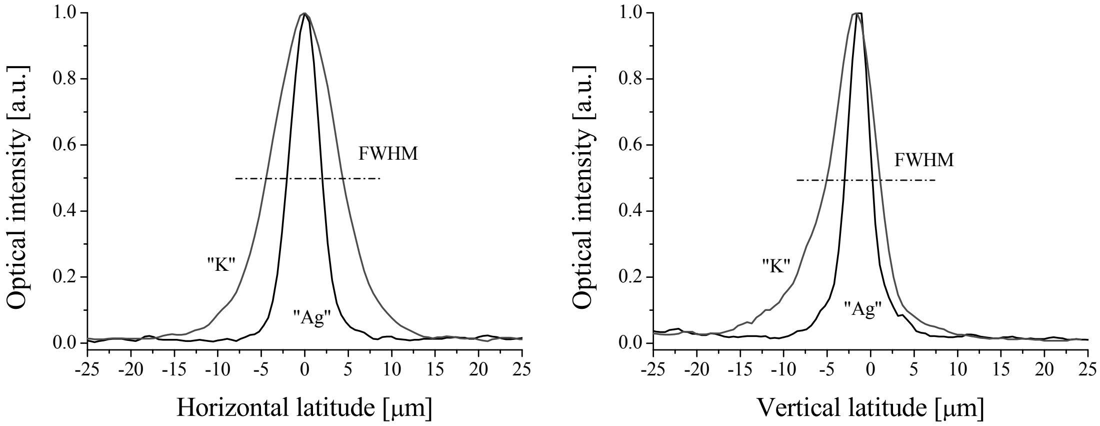

Fig. 2. Horizontal (on the left) and vertical (on the right) cross-section of the mode intensity profile of the single mode glass channel waveguides at 1500 nm. The waveguides fabricated by $Ag^+ \Leftrightarrow Na^+$ and $K^+ \Leftrightarrow Na^+$ ion-exchanges are compared (same width of the mask).

The spectral dependency of the absorption of both types of channel waveguides is shown in Fig. 3 (on the left); the absorption dependency of the used substrate is depicted as well. The strong increase in absorption with maximum at 1536 nm can be seen for both types of waveguides, caused by non-excited Er^{3+} ions absorption of the radiation. Maximum value of the absorption coefficient of the glass substrate is dependent on the content of erbium ions present in the glass matrix.

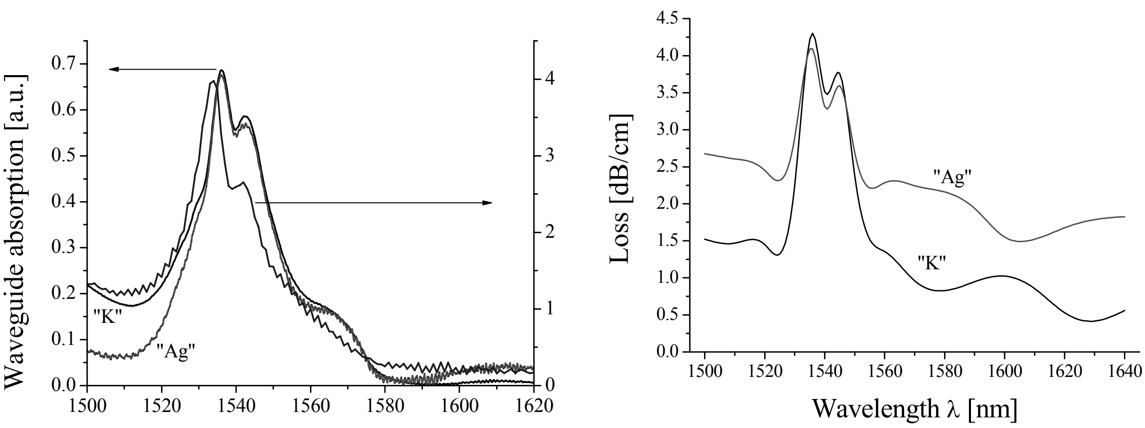

Fig. 3. Absorption spectral dependency of the glass substrate, “K” and “Ag” channel waveguides - on the left. Spectral dependency of optical loss in channel waveguides (same width of the mask) - on the right.

Fig. 3 (on the right) shows the spectral dependency of the optical loss of the channel waveguides fabricated by K^+ and Ag^+ ion-exchanges using masks with the same width of openings. Similarly as in the case of absorption spectral dependency, the significant increase in the optical losses in the vicinity of 1536 nm is observed as a result of absorption of the radiation by non-excited erbium ions. The graph also demonstrates that optical losses of the “Ag” waveguide in the other regions are approximately 1 dB/cm higher than of the “K“ ones.

4. Discussion and conclusions

In the paper we present single mode channel waveguides fabricated by K^+ and Ag^+ ion exchanges in the newly designed silicate glass containing 2 wt.% of Er_2O_3. The waveguides with the same width of the mask openings were chosen for characterization and comparison. The optical field distribution in the channel waveguides implies that the optical field in the “K” waveguides is much larger in both vertical and horizontal direction while the field of “Ag” waveguides is more confined. This difference is caused by the fact that in the optical layer formed by $Ag^+ \Leftrightarrow Na^+$ ion exchange, much higher refractive index increment occurred.

The measurement of the absorption spectra shows the difference between the absorption of “K” and “Ag” waveguides in the short wavelength region. The peak in absorption spectra of the waveguides is slightly shifted in comparison with the glass substrate absorption spectrum towards higher wavelengths.

When the spectral dependencies of the optical losses of the channel waveguides were measured we found out that the losses even out of the region 1525 - 1550 nm (i.e. region of non-excited erbium ions absorption) are relatively high. The peak of the optical losses corresponds to the peak in the absorption spectra and is strongly affected by Er^{3+} content in the glass. The higher optical losses in the case of “Ag” waveguides can be explained by partial photoreduction of silver ions.

From the point of view of the efficiency of coupling between these channel waveguides and glass optical fibers, the waveguides fabricated by $K^+ \Leftrightarrow Na^+$ ion-exchange seem to be more efficient as their optical field resembles field of the optical fiber much better. In the future work we will focus on improvement of Ag^+ ion-exchange to create low-loss optical waveguides with lower total refractive index increment and larger optical field distribution.

Acknowledgements

This work has been made in part within a cooperation with IFAC CNR in Florence and was financially supported by the Grant Agency of the Czech Republic under the contracts No. 106/03/0505 and 106/05/0706.

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