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Er³⁺/Yb³⁺ doped active optic Y splitter realized by diffusion waveguides with Ag⁺ - Na⁺ ion exchange

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Abstract:

We reported on the active channel waveguides, formed in novel types of silicate glasses, doped with rare-earth elements, and Zn were investigated. The silicate glass GZ4 with Er³⁺ and Yb³⁺ content was studied, and the best doping ratio was estimated about luminescent properties. The composition of the glass samples (GZ4) with the content of 0.25 at. % Er³⁺ and 5.0 at. % Yb³⁺ and Zn 4.0 at. % resp. 5.6 at. % Zn was optimized. This glass was evaluated as the most suitable material for integrated amplifiers in the telecommunication band of 1 530 – 1 565 nm. Other samples were prepared with an active channel waveguides and active planar optical power splitter Y with a splitting ratio of 1x2 by two-step ion-exchange Na⁺-Ag⁺. Diffusion profiles of the created samples were analyzed by the EMA microscope and compared with the near mode-field distribution measurement results. Afterward, the amplification properties of the designed structures were studied, and the differential gain from 1.2 to 1.6 dB (0.48 to 0.64 dB/cm) was achieved by pumping 200 mW at 980 nm.

Keywords:

Active optical splitter, gradient refractive index waveguide, erbium-doped waveguide amplifier, ion exchange.

1. Introduction

Passive optical splitters are a common component of fiber optic transmission networks. An active optical splitter compensates for its losses caused by splitting the optical signal from N to N transmission paths. The aim of the research of active optical power splitters is to achieve at least a level of structure gain that corresponds to the losses caused by the split ratio and the insertion loss of the component itself. According to ITU-T G.671, the basic structure of the optical splitter with a 1 x 2 ratio can bring a maximum insertion loss of 4.0 dB into the optical path. The optical splitter structure with a split ratio of 1 x 64 can introduce a maximum insertion loss of 22.3 dB into the optical path (ITU-T, 02/2012).

Nowadays, it is already possible to achieve such gains with integrated optical amplifiers produced by layer technologies was presented by Bucci et al.(2007) and Righini et al. (2002).. Traditional techniques of active waveguide fabrication include RF-sputtering, sol-gel technique, ion implantation, or proton exchange (Zigang et al. 2014). Erbium-doped waveguides have been mainly developed in multicomponent silicate and phosphate glasses. Especially, phosphate glasses are famous for enabling the high concentration of rare-earth dopants to be dissolved in the glass matrix, which results in the fabrication of active devices of small size and high gain up to 4.1 dB/cm [9]. On the contrary, silicate glasses have the advantage of higher mechanical rigidity and chemical stability, lower cost, and better compatibility with current commercial optical fibers (Jágerská et al. 2007). As for silicate glasses, Al₂O₃ is typically used to enhance the solubility and homogeneity of rare earth dopants and to reduce the rate of Er³⁺ - pairs and clusters formation. Nevertheless, we have shown recently (Ondráček et al. 2007; Míka et al. 2005 and Vytíková et al. 2018), that the presence of ZnO in the glass can also contribute to a substantial enhancement of rare-earth solubility. In this paper, the active channel waveguides, formed in novel types of silicate glasses (GZ4), doped with rare-earth elements and Zn were investigated. The silicate glass GZ4 with Er³⁺ and Yb³⁺ content was studied, and the best doping ratio was estimated concerning the luminescent properties. The samples of active planar optical power splitter Y with a splitting ratio of 1x2 were prepared with active channel waveguides by two-step ion-exchange Na⁺-Ag⁺. Afterward, the amplification properties of the designed structures were studied and the differential gain was evaluated.

2. Design of Y branching optical splitter with Er^{3+} - Yb^{3+} doped waveguides

The basis of the waveguide for the active optical splitter is a special silicate glass GZ4, where the diffusion waveguide itself is realized by a two-step ion exchange Na^+ - Ag^+ , which is immersed under the substrate surface with its entire volume. The composition of GZ4 glass is modified by rare earth oxides Er_2O_3 and Yb_2O_3 to optimize the absorption intensity in the 980 nm pumping region and the luminescence intensity in the 1 535 nm gain region. Silicate glass has a significantly lower solubility of rare earth elements in their structure compared to phosphate glasses (Yan et al. 1997). When studying the luminescence of silicate glasses, it has been shown that when the proportion of 6 at % of rare earth elements is exceeded, so-called clustering occurs, and the further increase in lanthanide concentration is counterproductive was presented by Salavcová et al.(2005) and Malinský et al (2009). . To achieve the highest possible amplification of the optical amplifier, it is possible to increase the luminescence properties of the substrate material by adding ZnO to the glass matrix (Vytykacova et al. 2018). For research of optical amplifiers fabricated by ion exchange technology, GZ4 silicate glass containing 0.25 at. % Er^{3+} , 5.0 at. % Yb^{3+} and ZnO modifier was prepared. The glass composition is shown in Tab. 1.

Tab. 1. The basic composition of glass GZ4.

oxides	Na_2O	SiO_2	Al_2O_3	ZnO
mass fraction [at. %]	14.33	72.55	0.65	12.47

In the absorption spectrum, as in the case of Zn-free enamel, there are five absorption bands at 378 nm, 521 nm, 655 nm, 908 nm, and 980 nm, corresponding to Er^{3+} energy levels $^4\text{G}_{11/2}$, $^2\text{H}_{11/2}$, $^4\text{F}_{9/2}$, $^4\text{I}_{9/2}$, and $^4\text{I}_{13/2}$ in combination with Yb^{3+} (see Fig. 1). The highest absorption intensity is seen at 980 nm. There is no significant influence of Zn concentration on the absorption intensity in the measured absorption spectrum. Two luminescence peaks at wavelengths 1 535 and 1 541 nm are evident in the luminescent spectra, which correspond to the energy transmission at $^4\text{I}_{13/2}$ and $^4\text{I}_{15/2}$ (see Fig. 1b). It can be seen from the measurement results that the Zn admixture has a positive effect causing an increase in luminescence intensity. The Zn acts as a separator of Er^{3+} - Yb^{3+} ions in the glass matrix, which limits the energy exchange between ions and prevents clustering of activator atoms (Vytykacova et al. 2018). As in the case of rare-earth doping, it is not possible to increase the concentration of Zn in the glass matrix without undesirable consequences, such as the phase separation effect causing the low optical quality of the glass, which is unacceptable for the application of optical waveguides. The recommended maximum Zn content for silicate glasses is approximately 6.0 at % (Stanek et al. vol.8).

Fig 1. a) Absorption spectrum of the GZ4 glass with 0.25 at. % Er^{3+} and 5 at. % Yb^{3+} and varying Zn content. b) Luminescent spectrum GZ4 glass with 0.25 at. % Er^{3+} and 5 at. % Yb^{3+} and varying Zn content.

For the realization of integrated optical amplifiers fabricated by ion exchange technology, GZ4, 0.25 at. % Er^{3+} and 5 at. % Yb^{3+} with Zn content of 4.8 at. % glasses were prepared.

The spectroscopic properties such as cross-sectional coefficients and metastable level lifetimes of these glasses were presented in the paper (Ondráček et al. 2008).

The structure of the passive optical power splitter is the key element of all-optical networks. It is a structure that allows the distribution of the optical signal from $N \times N$ branches. The basic structure is a splitter with a 1×2 split ratio. The cascade arrangement of this structure makes it possible to achieve more complex solutions, enabling the optical signal distribution in the required separation ratio with possible power unbalance. Due to the necessity of integrating all optical network components into one chip, it is necessary to consider the miniaturization of the solution with respect to the transmission parameters of the components. The optical power splitter structure with a 1×2 split ratio can be divided into three parts, see Fig. 2.

Fig. 2. The structure of the optical splitter with Y branching with outputs P1, P2.

The input waveguide is a single-mode field diffusion channel with L_{in} length, which is followed by the cosine S-bend area L_s in which the optical signal is distributed. These cosine S-bend segments consist of two arcs that smoothly connect. The L_{out} length's output waveguides continuously connect to the L_s segments and allow the output optical power to be coupled to another structure, possibly to the optical fiber. The critical element of the splitter is the area of the curved waveguide, where losses can occur due to exceeding the limit angle α . The length of the waveguide L_s is usually proportional to the number of output arms of the structure and their mutual spacing L_0 . The design of the splitter was done by the Beam Propagation Method (BPM) using the BeamPROP package from the RSoft program. The design was done for wavelength 1 550 nm for a single-mode waveguide with gradient refractive index with a dimension of the core $4 \mu\text{m}$ and refractive indices of the waveguide layer $n_f = 1.4926$ and cladding layer $n_s = 1.4923$ (Barkman et al. 2009).

The simulation results show that, with decreasing length of the L_s waveguides, the losses resulting from excessive curvature of the waveguides increase. By subtracting the normalized power from the simulation result (Fig. 3), it can be seen that an acceptable transmission is achieved for the branching angle α_s , in the range of $0.5^\circ - 2.0^\circ$. However, the optimal angle is only 0.5° , which corresponds to the waveguide length $L_s = 14\,324 \mu\text{m}$ and insertion attenuation 3.18 dB (for branching angle 2° is $L_s = 3\,579 \mu\text{m}$ and insertion attenuation 4.28 dB).

Fig. 3. Normalized power at outputs P1, P2 in BPM simulation 1x2 splitters for branching angles $\alpha = 0.5^\circ - 5^\circ$ ($n_f = 1.4926$, $n_s = 1.4923$ and $\lambda = 1550$ nm).

The optimized dimension of the splitter and propagation of the light is shown in Fig. 4.

Fig. 4. Results of BPM simulation for the optimized dimension of the design splitter (branching angle $\alpha_s = 0.5^\circ$, $n_f = 1.4926$, $n_s = 1.4923$ and $\lambda = 1550$ nm).

3. Experiment – channel waveguides

The channel waveguides for active optical Y-splitters were prepared by a two-step ion exchange. The surface channel waveguides of 4 μm diameter were embedded 2 μm by the applied electric field below the surface of the glass substrate. The embedded ion-exchange waveguides have the prerequisites for efficient coupling of the radiation to the optical fibers and lower radiation loss propagating in the diffused waveguide. A photolithographic mask with 2 μm slot dimensions was deposited on GZ4 glass substrates containing 0.25 at. % Er^{3+} , 5.0 at. % Yb^{3+} and 4.8 at. % Zn . A total of ten samples (M2-01 to M2-10) were produced and subsequently tested. The measured values were averaged. The average values from measured samples were designated M2-0X. The process data of used two-step ion exchange for sample processing is shown in Tab. 2.

Tab. 2. The process data for the used two-step ion exchange.

Sample	1. ion-exchange		2. ion-exchange		
	temperature (°C)	time (min.)	temperature (°C)	time (min.)	current (mA)
M2-0X	280	60	260	5	50

4. Experiment - active optical splitters

The structure of the active optical splitter does not differ in its typology from the passive optical splitter. Its essence lies primarily in the key advantage of ion exchange technology, which allows the creation of an active optical waveguide in substrates doped with rare earth elements.

In the case of an active optical splitter, the longest possible length of the structure is required for the active optical splitter structure as this is a prerequisite for a higher amplification rate. Two-step ion exchange was used to fabricate active power splitter chips with the 1x2 split ratio. The total length of the chips is approximately 25 mm after wafer separation, grinding, and polishing of the chip facet. The optical fiber Nufern HP 980 - XP was chosen to measure active optical waveguide splitters, as it allows a single-mode field operation in the wavelength from 970 to 1 550 nm. When comparing the magnitude of the waveguide mode field and the channel waveguides, we can observe a smaller difference for wavelength 1 550 nm and 980 nm (Tab. 4). Refractive profile analysis performed on channel waveguides have shown that the shape of the diffusion profile of the waveguide within one wafer is preserved for both types of samples.

Given the analysis of direct active channel waveguides, the attention was mainly focused on measuring optical activity in the case of active optical splitters. The optical properties of active splitters were determined by measuring the individual spectral characteristic of the ten samples, when the signal from the input port was passed to the individual output ports P1 and P2. The structure of the realized active optical splitter is shown in Fig. 5.

Fig. 5. Active power splitter 1x2 chip assembly with input and output fibres in the v-grooves.

5. Results and Discussion

The scanning electron microscope carried out the analysis of the shape and depth of the immersion (SEM) JEOL JSM-6510LV, for close-field measurement was used Spiricon Beam Gage – XEVA 5331 equipment. In addition to the correlation of the diffusion profile and geometry of the field, it is also possible to measure the energy intensity distribution and analyze the waveguide modes (Hui et al. 2009). The measurements have shown that the channel waveguides have immersed about 2 μm below the substrate surface. The images of the samples taken by SEM and the measurement of near-field are shown in Fig. 6. It is evident that the maximum silver concentration is at the bottom of the waveguide. As a result of the plunging process, the waveguide area was enlarged, and its shape changed.

Fig. 6. a) The image of the diffusion profile of the immersed waveguide obtained by SEM
b) The mode near-field distribution of the channel waveguide for wavelength 980 nm
c) the mode near-field distribution of the channel waveguide for wavelength 1 550 nm

Measured sizes of diffusion profiles of immersed waveguides are shown in Tab. 3.

Tab. 3. The measurement results of the diffusion profile of immersed waveguide.

sample	the size of the diffusion profile in the x-axis (μm)	the size of the diffusion profile in the y-axis (μm)	the maximum concentration of silver in the channel (at. %)
M2-0X	11.6	7.3	3.17

Due to the applied electric field at immersion, the mobility of the high silver concentration gradient region of the channel is significantly higher relative to the marginal regions. The results of the near-field measurement confirm this phenomenon very well. From the measurement results, shown in Fig. 6, is apparent that the area of highest power intensity correlates with the area of maximum silver concentration in the channel. When comparing the magnitude of Nufern HP980-XP connecting fiber field waveguide and the channel waveguides shown in Tab. 4, we can observe a small difference in the mode field distribution, mainly at the wavelength 980 nm.

Tab. 4. The measured field size of HP 980-XP fibre and ion exchange waveguide on sample M2-0X.

sample	$\lambda = 1\,550\text{ nm}$		$\lambda = 980\text{ nm}$	
	the size of the mode field in the x-axis (μm)	the size of the mode field in the y-axis (μm)	the size of the mode field in the x-axis (μm)	the size of the mode field in the y-axis (μm)
Nufern HP 980-XP	11.0	11.0	7.1	7.0
M2-0X	11.6	8.0	11.5	8.5

The measured mode field diameter of the channel ion-exchange waveguide in Fig. 6b, c shows the filling of the waveguide layer corresponding to the refractive index distribution. If the waveguide is excited by a fiber waveguide at a wavelength of 1 550 nm, part of the energy is bound to the upper region of the waveguide due to the increase in the mode field. Due to the insufficient amount of silver and the low and inhomogeneous refractive index, the energy is poorly guided. This results in the deformation of the mode field shown in Fig. 6c.

Measurement of the optical activity has always been performed on structures made on the ten glass samples, where the average value sample was designated M2-0X. A block diagram of the measured spectral loss and differential gain waveforms characteristic is shown in Fig. 7. First, it is possible to create an optimal optical bond of a fiber waveguide and a channel waveguide DUT (device under test) by a three-axis micromanipulator. This device uses piezo-crystal actuators that are voltage-controlled depending on the electrical feedback signal from the detector to the piezo-controller. After the optimal signal connection is found, DUT is fixed against a V-groove Fiber Array (FA) using UV curable adhesive.

Fig. 7 The block diagram of measured spectral loss and differential gain waveforms characteristics.

The core of the assembly for the measurement of the spectral loss and differential gain characteristics were the signal source in the range of 1500 nm – 1600 nm HP85651A, highly stabilized pumping laser source of radiation CKSS-980-B-650-1, capable of increasing the pumping power up to 600mW and the optical spectrum analyser HP86140A enabling spectral measurement in the range of 900 nm - 1700nm. Further in the assembly, there are WDM couplers for merging and separating the signal and pumping power complemented by the absorbing elements to capture pumping radiation. The measured spectral loss and differential gain characteristics of samples M2-0X optical active splitter 1x2 of depending on wavelengths 1 520 to 1 560 nm for pumping power 980 nm of 50, 100 and 200 mW are shown in Fig. 8 and Fig. 9. The typical results of attenuation characteristics were obtained for optical splitters labeled M2-0X. The measured spectral loss characteristic for the signal passage state without pumping and at a pumping power of 200 mW is shown in Fig. 8. When the signal passes without pumping, the insertion attenuation in the area of the expected maximum gain of the structure reached an average of 3.8 dB on P1 (OUT1) and 4.1 dB on P2 (OUT2) arbitrary units. After the activation of the pumping radiation, the signal component is amplified, and thus the attenuation is compensated. In P1 the average differential gain of 2.1 dB is obtained; in P2 the gain of 1.6 dB is obtained.

Fig. 8. Spectral insertion loss (IL) characteristics of the active splitter. Status without pumping solid line, with pumping power 200 mW dashed line.

Typical differential gain values measured for active optical splitters M2-0X are listed in Tab. 5.

Tab. 5. Typical differential gain measured for active optical splitters M2-0X.

pumping power (mW)	Differential average gain	
	P_{out1} (dB)	P_{out2} (dB)
50	1.2	0.9
100	1.5	1.3
200	2.1	1.7

Fig. 9. a) Differential gain of output P_{out1} 1 optical active splitter M2-0X at pumping power 50 mW, 100 mW and 200 mW. b) Differential gain of output P_{out2} 2 optical active splitter M2-0X at pumping power 50 mW, 100 mW and 200 mW.

6. Conclusion

This paper reported on the research of active optical integrated structures made by ion exchange technology into glass substrates. We have presented here the results of the design and realization of structures of optically active planar waveguides on new silicate glass GZ4 doped by Er^{3+} , Yb^{3+} and Zn. The main result is the realization and measurement of the optical activity of the Y-branch power splitters, which allows compensation of its insertion losses. Based on simulations in the Beam Prop RSoft program, an optical power splitter was designed with Y - branching with the 1x2 ratio. The created splitter model simulates the passing of the signal through the structure and allows for selecting the optimal split angle 0.5° at which insertion losses caused by the curvature of the waveguide are minimized. Based on the simulations, the topological and technological constants were derived and new silicate glasses were prepared to contain the optimized number of elements, such as erbium, ytterbium and zinc. Subsequently, the mutual concentration ratios of these elements were studied, having in mind the absorption and luminescence properties. The glass was designed with the prerequisites for application in the integrated optical amplifiers.

The result is a setting of 0.25 at. % Er^{3+} and 5.0 at. % Yb^{3+} activators with Zn modifier of 4.8 at. %. In this case, the samples exhibited acceptable transfer properties. In particular, our samples showed the average differential gain of 1.2 dB to 1.6 dB. The maximum differential gain was up to 4.0 dB. The small measured gain differences between different samples can be made with small different amounts of zinc in the matrix, preventing clustering of activator atoms. The negative effect of zinc on the diffusion of silver atoms into the glass matrix results in a small increase in the insertion loss of the active optical splitters. These waveguides created splitters exhibit a maximum differential optical gain of up to 1.6 dB /cm at a pumping of 200 mW, which is four times more than that of Er^{3+} doped fiber optic amplifiers. In practice, active optical splitters can be used to build metropolitan networks, whereby the optical attenuation caused by splitting the signal among a large number of end-users needs to be compensated. With ion exchange technology, such a splitter can be made by diffusing silver directly into a substrate that contains, as part of an integrated optical circuit, rare earth elements.

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Declarations

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Conflicts of interest/Competing interests

Not applicable

Availability of data and material

Not applicable

Code availability

Not applicable

Figures

Figure 1

- a) Absorption spectrum of the GZ4 glass with 0.25 at. % Er^{3+} and 5 at. % Yb^{3+} and varying Zn content.
- b) Luminescent spectrum GZ4 glass with 0.25 at. % Er^{3+} and 5 at. % Yb^{3+} and varying Zn content.

Figure 2

The structure of the optical splitter with Y branching with outputs P1, P2.

Figure 3

Normalized power at outputs P1, P2 in BPM simulation 1x2 splitters for branching angles $\alpha = 0.5^\circ - 5^\circ$ ($n_f = 1.4926$, $n_s = 1.4923$ and $\lambda = 1550 \text{ nm}$).

Figure 4

Results of BPM simulation for the optimized dimension of the design splitter (branching angle $\alpha_s = 0.5^\circ$, $n_f = 1.4926$, $n_s = 1.4923$ and $\lambda = 1550$ nm).

Figure 5

Active power splitter 1x2 chip assembly with input and output fibres in the v-grooves.

Figure 6

a) The image of the diffusion profile of the immersed waveguide obtained by SEM b) The mode near-field distribution of the channel waveguide for wavelength 980 nm c) the mode near-field distribution of the channel waveguide for wavelength 1550 nm

Figure 7

The block diagram of measured spectral loss and differential gain waveforms characteristics.

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Figure 9

a) Differential gain of output Pout1 1 optical active splitter M2-0X at pumping power 50 mW, 100 mW and 200 mW. b) Differential gain of output Pout1 2 optical active splitter M2-0X at pumping power 50 mW, 100 mW and 200 mW.