Er/Yb Waveguide Amplifiers in Novel Silicate Glasses

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Abstract: Novel type of ZnO:silica-based glasses co-doped with Er^{3+} and Yb^{3+} for optical waveguide amplifiers were designed. They are characterized by exceptionally low upconversion and essentially no evidence for Er-quenching at the Er-concentration of 0.6 at. %. In the reported glasses, straight channel waveguides with propagation loss as low as 0.18 dB/cm at 1600 nm were fabricated using $Ag^+ \Leftrightarrow Na^+$ and $K^+ \Leftrightarrow Na^+$ ion exchange. Net on-chip gain values of 6.3 dB and 6.6 dB @1537 nm were measured in waveguides pumped at 976 nm in 38-mm-long $Ag^+ \Leftrightarrow Na^+$ and $K^+ \Leftrightarrow Na^+$ waveguides, respectively. In the latter case, net fiber-to-fiber gain of 5 dB was achieved.

Introduction

Multicomponent silicate and phosphate glasses have proven their potential as outstanding substrate materials for realization of Er-doped waveguide lasers and amplifiers. Especially phosphate glasses are famous for dissolving high concentrations of rare-earth dopants, thus enabling to fabricate active devices of small-size and high gain up to 4.1 dB/cm [1]. On the other hand, silica-based glasses have an advantage of higher mechanical rigidity and chemical stability, lower cost and better compatibility with current commercial fiber technology.

As for silicate glasses, Al_2O_3 is typically used as a means to enhance the solubility and homogeneity of Er-dopants and reduce the rate of cluster and Er-pair formation [2]. Nevertheless, we have shown recently [3] that the presence of zinc oxide (ZnO) in the glass melt can also attribute for a substantial enhancement of rare-earth solubility. In this paper we present for the first time to authors' knowledge optical gain measurements on a Er-doped and Er/Yb co-doped Zn-silica-based material.

Spectroscopic and waveguide properties

Three different samples of Er-doped and Er/Yb-co-doped glass substrates differing in Yb concentration were prepared by standard melting technique from the following oxide constituents: SiO_2, Na_2O, ZnO, Al_2O_3, Er_2O_3 and Yb_2O_3. The exact chemical composition and the rare-earth doping concentrations, reported in Table 1, followed from a detailed optimization study. Special effort was made to increase the solubility and homogeneity of Er^{3+} and Yb^{3+} ions by means of the network intermediate ZnO. ZnO decreases the optical basicity of the glass, which was also proven to have a positive influence on the metastable level lifetime, luminescence bandwidth and absorption and emission cross-section spectra of the Er^{3+} ions [3].

Table 1: Concentration of the rare-earth ions [at/m^3]

	MM64 Er/Yb - 1:0	MM65 Er/Yb - 1:1	MM65 Er/Yb - 1:2
Er_2O_3	1.71×10^{26}	1.71×10^{26}	1.71×10^{26}
Yb_2O_3	–	1.70×10^{26}	3.40×10^{26}

All glass constituents were melted together for 4 h in a platinum crucible at the temperature of 1470 °C. Afterwards, the melt was quenched in a water bath and left to temper at 520 °C for another hour. The ready-made glass preform was cut into wafers and polished to dimensions of 40mm×20mm×2mm.

In the bulk glass substrates the waveguides were formed using the $K^+ \Leftrightarrow Na^+$ and $Ag^+ \Leftrightarrow Na^+$ ion exchange technique. This was feasible thanks to a large fraction of network modifier Na_2O contained in the glass matrix. Potassium and silver ion exchange waveguides differ actually a lot in both their fabrication conditions and waveguiding properties. While potassium channels exhibit lower propagation losses, the resulting refractive index contrast is low leading to large mode field area. Silver waveguides, on the contrary, can account for higher mode confinement; however, the inherent propagation loss is higher.

In order to define the waveguide boundaries, a standard optical contact lift-off lithography was used. The actual waveguide pattern consisted of a series of straight waveguide channels varying in width from 2 to 6.5 μm. One major advantage of this design was that regardless of small inaccuracy in the ion exchange condition settings, one could find a channel that exhibited a single mode performance at both pump (976 nm) and signal (1537 nm) wavelengths.

The process of ion exchange with K^+ ions was performed in a melt of pure potassium nitrate at 400°C for 1-2.5 h, depending on the exact Yb concentration. The Ag^+ ion exchange proceeded in eutectic $NaNO_3$-KNO_3 melt with addition of 3.6 wt.% of silver nitrate at 280 °C for 4-8 min.

The mode dimensions of potassium waveguides were measured to be 10×13 μm at 1550 nm and 7×11 μm at 980 nm. In the silver ion-exchange waveguides, the mode field dimensions were 6×7 μm and 3×5 μm at the wavelengths of 980 nm and 1550 nm, respectively. Although the large mode field area can ensure low coupling loss to single-mode fibers, it

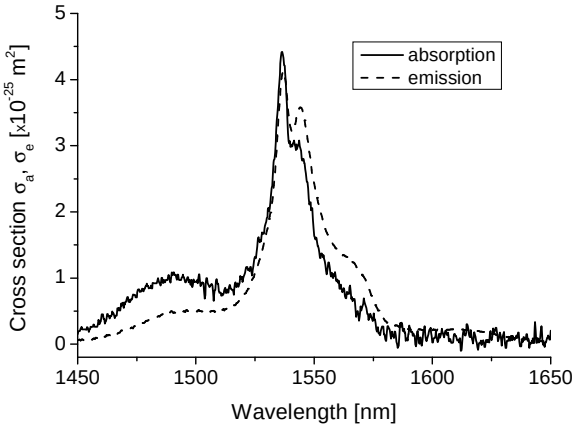

Fig. 1: Spectral dependency of the cross section of MM65 glass substrate

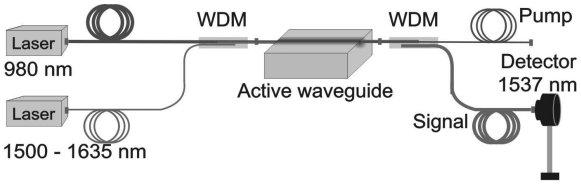

Fig. 2: Experimental setup for amplification measurement

naturally results in undesirably low pump efficiency. Higher confinement of intensity distribution and better overlap of pump and signal intensity profiles could be achieved if a more sophisticated technique (*e.g.*, a field assisted ion exchange burying the waveguide below the glass surface) were used.

The channel waveguide scattering loss was determined outside the Er absorption bands at 1600 nm using the Fabry-Perot resonator method [4]. Potassium waveguides exhibited losses as low as 0.18 dB/cm, while the loss of silver-exchanged channels read 0.8 to 0.9 dB/cm. In the latter case the loss could be reduced by about a half if annealed for 30 min at 300 °C, at the expense of considerable mode field expansion, however.

The relative absorption and emission cross section spectra at both pump and signal wavelengths were obtained from the bulk transmission and photoluminescence measurements and are presented in Figure 1. The relative absorption cross section spectrum was normalized by means of the measured waveguide transmission at the signal peak absorption wavelength. Using the known optical mode profile, waveguide transmission and the Er concentration of 1.72 at/m^3 (0.6 at.%) the peak absorption cross section at 1537 nm was calculated to be 4.42×10^{-25} m^2.

Absorption cross section of Er at the pump wavelength of 976 nm resulted in 1.25×10^{-25} m^2, while the absorption cross sections of ytterbium amounted to 8.4×10^{-25} m^2 in both MM65 and MM66 samples. Normalization constant for the emission cross section spectrum was calculated using the McCumber procedure [5]. The peak emission cross section at 1537 nm has the value of to 4.22×10^{-25} m^2 and the cross section of ytterbium at 976 nm equals 6.7×10^{25} m^2.

Finally, the metastable level lifetime of Er^{3+} was obtained from the photoluminescence decay measurement. The detected decay curve was single exponential with the time constant of 6.3 ms.

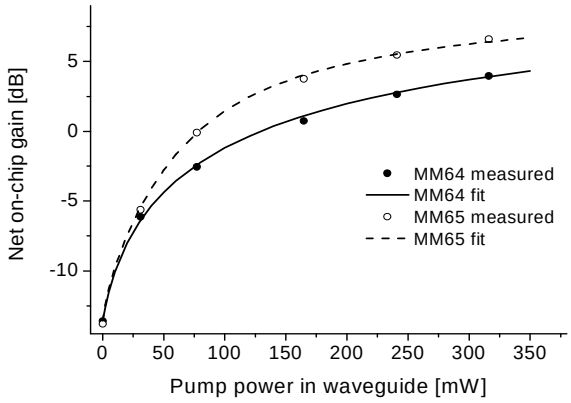

Fig. 3: Net on-chip gain vs. pump power: measured and simulated data for MM64 (Er) and MM65 (Er/Yb - 1:1) K^+ waveguides

Gain measurement and experimental results

Optical gain measurements were performed with 38-mm-long waveguide samples using the experimental setup depicted in Figure 2. A semiconductor laser diode of maximum optical power 375 mW emitting at 976 nm served as a pump source, and the signal light was provided by a highly monochromatic Agilent 81642B laser tunable in the wavelength range of 1495–1635 nm.

The signal and pump were combined by a 980/1550 nm fiber wavelength division multiplexer (WDM) and coupled into the waveguide using a SM 980 (4.5/125) fiber exhibiting singlemode performance at both signal and pump wavelengths. At the waveguide output the amplified signal was separated from the pump in second 980/1550 nm fiber WDM coupler and detected using InGaAs detector. At the waveguide input and output coupling gel was used to suppress Fresnel reflections and thus minimize the coupling losses. In potassium channel waveguides the resulting loss per an interface was estimated to be 0.8 and 0.85 dB at the signal and pump wavelengths, respectively. For silver waveguides with higher refractive index contrast and stronger mode field confinement the coupling loss was considerably higher counting approx. 1.8 dB.

First, the change in signal transmission as a function of pump power was measured at the central Er^{3+} emission wavelength of 1537 nm. Signal power at the waveguide input was set to 100 μW. The measured signal enhancement was converted to net optical gain by setting the gain at 1600 nm and zero pump power equal the waveguide scattering loss.

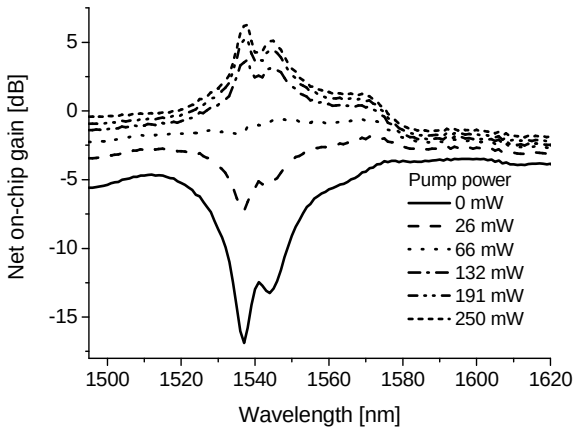

Fig. 4: Spectral dependency of the net on-chip gain of the MM66 (Er:Yb = 1:2) Ag^+ waveguide for several different pump powers (converted to input power in the waveguide).

Table 2: Maximum achievable net on-chip gain

	Net on-chip gain [dB per sample]	
	K^+ waveguide	Ag^+ waveguide
MM64	3.95	-
MM65	6.61	5.80
MM66	6.63*	6.31

* the length of the sample was only 34 mm

Figure 3 shows the measurements results on potassium channel waveguides fabricated in MM64 and MM65 substrates. In the purely Er-doped sample the net optical gain is reached at the pump power of 130 mW and upon pumping at 316 mW the positive on-chip gain achieves 4.0 dB. The performance of the Er/Yb-codoped sample is even better with the threshold pump power reduced to 80 mW and maximal achievable gain 6.6 dB. Thanks to low in/out coupling losses of potassium waveguides fiber-to-fiber gain as high as 4.9 dB was observed.
The optical gain measurement on silver channel waveguides was performed on MM65 and MM66 glass substrates. Due to higher waveguide scattering loss the maximum net gain amounted for 5.8 dB and 6.3 dB in MM65 and MM66 glasses, respectively. However, because of substantial coupling loss, fiber-to-fiber gain of only 2.6 dB was observed. All measurement results are summarized in Table 2.

The second part of the amplification measurement consisted in determining the amplifier bandwidth by measuring the spectral dependence of signal gain at several different pump powers. The input signal level was kept constant at P_s = 100 µW and the measurement was performed in the full achievable wavelength range from 1945 to 1635 nm. The gain spectrum of MM66 Ag^+ sample is depicted in Figure 4 and is characterized by a relatively narrow FWHM bandwidth of 15 nm, quite typical for ordinary silica-based glass materials [2].
Finally, spectral analysis of the amplified signal was performed and it showed that essentially no amplified spontaneous emission degrading the amplifier performance and contributing to noise figure was present.

Table 3 Model input data

Spectroscopic parameters		
Er^{3+} abs. cross section @ 1537 nm	$\sigma_{12}=4.42e^{-25}$ m^2	
Er^{3+} emis. cross section @ 1537 nm	$\sigma_{21}=4.22e^{-25}$ m^2	
Er^{3+} abs. cross section @ 976 nm	$\sigma_{13}=1.25e^{-25}$ m^2	
Yb^{3+} abs. cross section @ 976 nm	$\sigma_{56}=8.40e^{-25}$ m^2	
Yb^{3+} emis. cross section @ 976 nm	$\sigma_{65}=6.70e^{-25}$ m^2	
Er^{3+} metastable level lifetime	τ_{21}^{Er}=6.3 ms	
Yb^{3+} metastable level lifetime	τ_{65}^{Yb}=1.3 ms	
Er^{3+}-nonrad. lifetime of pump level	τ_{32}^{Er}=10 µs	
Up-Conversion coefficient	$C_{up}=1.1e^{-24}$ m^{3}s^{-1}	
Cross-relaxation coefficient	$C_{cr}=0.12e^{-22}$ m^{3}s^{-1}	
Waveguide parameters	K^+	Ag^+
Mode-field dimensions	9.6×12.9 µm	6.1×7.0 µm
Mode-field dimensions @ 980 nm	6.9×10.5 µm	3.2×4.8 µm
Scattering loss @ 1550 nm	0.18 dB/cm	0.85 dB/cm

Model Simulation and Discussion
A six-level numerical model of Er/Yb-co-doped active waveguide was formulated to fit the measured gain and analyze the amplifier performance. The model incorporates the Er/Yb rate and propagation equations on a 3-D grid to calculate the population inversion and the pump and signal evolution along the waveguide. It takes into account the cooperative upconversion as the most important quenching effect limiting the amplifier gain. Further, the Er-Yb cross-relaxation process as a mechanism of energy transfer between Er^{3+} and Yb^{3+} ions is considered [6].
All input data (Table 3) for the model calculations were taken from the previous measurements except for the nonradiative lifetimes and the Yb^{3+} metastable level lifetime that were found in literature [2], [7]. The up-conversion coefficient C_{up} and the cross relaxation coefficient C_{cr} constitute the unknown parameters to be found upon the fitting procedure.

First, the up-conversion coefficient C_{up} was determined from the measurement on purely Er-doped MM64 sample. The best fit of the measured data was found for the up-conversion coefficient $C_{up}=1.1\times10^{-24}$m^{3}s^{-1}. This is one of the lowest C_{up} values reported for a glass material with Er^{3+} concentration as high as 0.6 at. %. Low probability of the upconversion process can be also deduced from the fact that no visible green luminescence indicating the pump upconversion was present during the measurement.
Next, the cross-relaxation coefficient was obtained from fitting the data measured on MM65 and MM66 samples. The best fit shown in Figure 4 was achieved for $C_{cr} = 0.12^{-22}$m^{3}s^{-1}. The $Yb^{3+} – Er^{3+}$ energy transfer

efficiency can be estimated from the approximate equation for cross-relaxation quantum efficiency [8]:

$$\eta = \frac{C_{cr} N_{Er} \tau_{65}^{Yb}}{1 + C_{cr} N_{Er} \tau_{65}^{Yb} (1 + N_{Yb} \tau_{32}^{Er} / N_{Er} \tau_{65}^{Yb})} = 72\%$$

When fitting the cross-relaxation process we assumed the C_{up} coefficient keeps the unaltered value of $C_{up} = 1.10^{-24}\,m^3s^{-1}$. However, upon the measurement on MM65 and MM66 samples we did observe a certain amount of green luminescence, intensity of which grew with the Yb-doping concentration. Since Yb-codoping should not increase the upconversion probability, and moreover, no reduction of the metastable level lifetime of Er^{3+} as well as no degradation of amplifier gain was evident, we attributed the observation not to upconversion but to the presence of excited-state absorption facilitated by highly efficient Er-Yb energy transfer.

Finally, it should be noted that the 38-mm-length of the active waveguide samples is not optimum. In purely Er-doped MM64 substrate only a small portion of pump power (approx. 2 dB) is absorbed, which means that higher gain could be achieved in longer samples. The simulation results imply that a gain of 6.3 dB would be feasible in a 10-cm-long Er-doped waveguide. On the other hand, in MM66 samples, the full length of the waveguide is slightly underpumped due to strong absorption of pump power in Yb^{3+} ions.

Conclusions

Er doped and Er/Yb-codoped ZnO:silica-based waveguides were fabricated by standard ion exchange technique. A net on-chip gain values measured at the wavelength of 1537 nm were of 6.3 dB and 6.6 dB in 34 mm and 38 mm long Ag^+–Na^+ and K^+–Na^+ waveguides, respectively, when excited by a pump power of about 316 mW at the wavelength of 976 nm. The active waveguide substrates exhibit exceptionally low upconversion and essentially no evidence for Er-quenching at the Er-concentration of 0.6 at. %. The measurement results demonstrate a great potential of the reported silica-based glass as a substrate for up-to-date active devices.

Acknowledgments

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