# Er–Yb Waveguide Amplifiers in Novel Silicate Glasses

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***Abstract*—A set of novel silicate glasses containing ZnO and co-doped with $Er^{3+}$ and $Yb^{3+}$ was designed as substrates for optical waveguide amplifiers. Characterized by exceptionally low up-conversion, minimum Er concentration quenching and high mechanical as well as chemical stability, the reported glasses can compete with phosphate-based materials typically used in the state-of-art active devices. Straight channel waveguides with propagation losses as low as 0.18 dB/cm were fabricated in these substrates using $Ag^{+} \Leftrightarrow Na^{+}$ and $K^{+} \Leftrightarrow Na^{+}$ thermal ion exchange. Net on-chip gain values of 6.7 dB at 1537 nm were measured and a net fiber to-fiber gain of 5 dB was achieved when pumped at 976 nm. A six-level spatially resolved numerical model of an Er–Yb co-doped active waveguide was developed to analyze and optimize the amplifier performance. Modification of the rare-earth dopant concentration and the channel waveguide geometry was proposed to increase the gain figure and improve the overall amplifier efficiency.**

***Index Terms*—Channel waveguides, Er–Yb-doped glass, ion exchange, optical waveguide amplifier.**

## I. Introduction

OVER the past few decades, the huge expansion of telecommunication systems has led to development of many assorted optical components. In fiber optic communications, optical transmitters, fibers, fiber amplifiers and optical receivers are routinely used. Hand in hand with increasing speed of data transmission, the importance of integrated photonic devices and circuits grows. The use of dense wavelength-division multiplexing (DWDM) requires broad-band and code-transparent devices such as splitters, couplers, de/multiplexers, and waveguide amplifiers. In this concept, a lossless splitter for signal distribution into a number of outputs combined with an optical amplifier and a pump-signal de/multiplexer is highly desirable, especially in the local area networks. Many research groups have focused on the development of optical amplifiers operating at 1550 nm, frequently based on erbium-doped materials. Erbium-doped glass-based waveguide amplifiers are appealing because of their potential to realize broad-band and inherently linear IO components compatible with current optical communication technology (see [1]–[3] and references therein).

Traditional techniques of the active waveguide fabrication include flame hydrolysis, chemical vapor deposition with subsequent reactive ion etching, or ion exchange [4]–[6]. The latter is an effective and cheap fabrication technique [7], which has already allowed development of low-loss straight as well as bent channel waveguides. Concerning the devices, $1 \times 32$ coupler [8] is being commercially used, and the integrated pump-signal (980 nm/1550 nm) de/multiplexer [9] has been recently developed. The only major disadvantage of the ion exchange technique is that it requires thoughtful adjustment of the technological procedure appropriate for a certain combination of a chosen glass substrate [6] and the expected utilization of the waveguide. However, once the fabrication procedure is adjusted, this technique enables formation of huge amount of low-cost waveguides with fully reproducible properties.

Erbium-doped waveguides and lasers have been mainly developed in multicomponent silicate and phosphate glasses. Especially phosphate glasses are famous for enabling high concentration of rare-earth dopants to be dissolved in the glass matrix, which results in fabrication of active devices of small-size and high gain up to 4.1 dB/cm [10]. 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 (refractive index and subsequent coupling efficiency, material dispersion, etc.).

As for silicate glasses, $Al_2O_3$ is typically used to enhance the solubility and homogeneity of rare earth dopants and to reduce the rate of Er-pairs and clusters formation [1]. Nevertheless, we have shown recently [11] that the presence of ZnO in the glass can also contribute to a substantial enhancement of rare earth solubility. In this paper we report on optical gain measurements on waveguides in Er-doped and Er–Yb co-doped ZnO-$SiO_2$-based glasses. Preliminary results presented at ECIO 2007 conference [12] have been thoroughly revised and completed, and new results of numerical optimization of waveguide amplifiers showing great potential of new substrate glasses have been included.

## II. Fabrication

Three different types of Er-doped and Er–Yb-co-doped silicate glasses containing ZnO were prepared by standard melting technique from the following oxide constituents: $SiO_2$, $Na_2O$

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TABLE I
CONCENTRATION OF THE RARE-EARTH IONS [at/m$^3$]

| Glass label | MM64 | MM65 | MM66 |
|---|---|---|---|
| $Er_2O_3$ | $1.71\times10^{26}$ | $1.71\times10^{26}$ | $1.71\times10^{26}$ |
| $Yb_2O_3$ | – | $1.70\times10^{26}$ | $3.40\times10^{26}$ |

TABLE II
CONDITIONS OF THE THERMAL ION EXCHANGE

| Glass label | MM64 | MM65 | MM66 |
|---|---|---|---|
| $K^+\Leftrightarrow Na^+$ | 1.5 h / 400°C | 2.3 h / 400°C | 3.2 h / 400°C |
| $Ag^+\Leftrightarrow Na^+$ | – | 6 min / 280°C | 8 min / 280°C |

(14.2 mol%), ZnO, $Al_2O_3$, $Er_2O_3$ and $Yb_2O_3$. The samples, referred as MM64, MM65 and MM66, contain the same fraction of $Er^{3+}$ dopants (0.6 at.%) and differ in the $Yb^{3+}$ concentration, which is zero in purely Er-doped MM64 and increases to 0.6 and 1.2 at.% for MM65 and MM66, respectively, as summarized in Table I.

The exact glass composition followed from a detailed optimization study [11] with the aim to increase the solubility and homogeneity of $Er^{3+}$ and $Yb^{3+}$ ions using the network intermediate ZnO. ZnO decreases the optical basicity of the glass, which was 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 [11].

All glass components were melted together for 4.5 h in a platinum crucible at the temperature of 1470 °C. Removal of most of air bubbles and better homogenization was done by mechanical stirring in the first 75 min of the melting process. Afterwards, the melt was quenched in a water bath and then left to temper in the oven at 520 °C for another hour to reduce the residual stress. The glass bulk was finally cut into wafers and polished to dimensions of $40 \times 20 \times 2$ mm$^3$ for waveguide fabrication.

In order to define the channel waveguide boundaries, 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 $\mu$m. The major advantage of this pattern 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.

In the glass substrates, waveguides were formed using the $K^+ \Leftrightarrow Na^+$ and $Ag^+ \Leftrightarrow Na^+$ thermal 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-exchanged waveguides differ actually a lot in both their fabrication conditions and waveguiding properties. The process of ion exchange with $K^+$ ions was performed in a melt of pure potassium nitrate at 400 °C for various times, depending on the exact Yb concentration in the glass substrate. The $Ag^+$ ion exchange proceeded in eutectic $NaNO_3$-$KNO_3$ melt with addition of 3.6 wt.% of silver nitrate at 280 °C, as shown in Table II. While potassium channel waveguides exhibit lower propagation losses, the resulting refractive index contrast is low as well leading to large mode field area. Silver waveguides, on the contrary, can account for higher mode confinement; however, the inherent propagation loss is increased.

## III. SPECTROSCOPIC AND WAVEGUIDE PROPERTIES

The relative absorption and emission cross section spectra at both pump and signal wavelengths were obtained from the bulk transmission and photoluminescence measurements. An example for the MM65 glass is presented in Fig. 1.

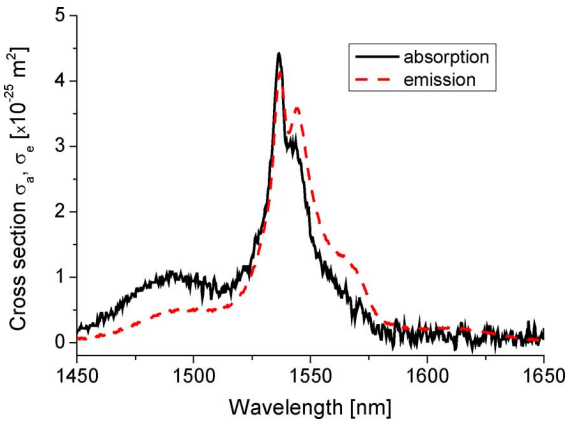


Fig. 1. Spectral dependency of the cross section of MM65 glass substrate.

The relative absorption cross section spectrum was normalized by means of the measured waveguide transmission at the signal peak absorption wavelength. Knowing the optical mode profile, waveguide transmission and the $Er^{3+}$ concentration, the peak absorption cross section at 1537 nm was found to be $4.42 \times 10^{-25}$ m$^2$. Absorption cross section of $Er^{3+}$ at the pump wavelength of 976 nm resulted in $1.25 \times 10^{-25}$ m$^2$, while the absorption cross section of ytterbium amounted to $8.4 \times 10^{-25}$ m$^2$ in both MM65 and MM66 samples.

Normalization constant for the emission cross section spectra was calculated using the McCumber procedure [14]. The peak emission cross section of $Er^{3+}$ at 1537 nm has the value of $4.22 \times 10^{-25}$ m$^2$ and the cross section of ytterbium at 976 nm equals $6.7 \times 10^{25}$ m$^2$.

Finally, the metastable level lifetime of $Er^{3+}$ ion was obtained from the photoluminescence decay measurement. The detected decay curve was first order exponential with the time constant of 9.43 ms in MM64 and 9.40 ms in Yb-doped MM65 and MM66 samples. Within the probed rare-earth concentration limit, the $Er^{3+}$ radiative lifetime did not substantially depend on the of the $Yb^{3+}$ concentration.

As regards the waveguide properties, intensity profiles of the guided modes as well as waveguide scattering losses were experimentally determined. The mode field profiles at the signal and pump wavelengths were obtained by near-field IR imaging of the waveguide output facets. In potassium waveguides, the mode dimensions at $1/e^2$ of the peak intensity were found to be $8 \times 12$ $\mu$m$^2$ at 980 nm and $11 \times 14$ $\mu$m$^2$ at 1550 nm. The silver ion-exchange waveguides had the mode dimensions of $7 \times 8$ $\mu$m$^2$ and $3.5 \times 5$ $\mu$m$^2$ at the pump and probe wavelengths, respectively. Although the large mode field area in the $K^+$ channel waveguides can ensure low coupling loss to

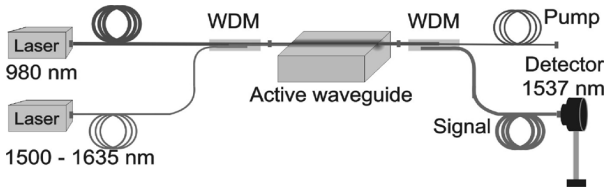


Fig. 2. Experimental setup for amplification measurement.

standard single-mode fibers, it naturally results in undesirably low pump efficiency. Both higher confinement of intensity distribution and better overlap of pump and signal intensity profiles could be achieved if more sophisticated waveguide fabrication techniques were utilized (e.g., two-step field-assisted ion-exchange, burying the waveguide below the glass surface [8]).

The channel waveguide scattering loss was determined outside the Er absorption bands at 1600 nm using the Fabry–Perot resonator method [13]. Potassium channel waveguides exhibited losses as low as 0.18 dB/cm, while the losses of silver exchanged channel waveguides were in the range of 0.8–0.9 dB/cm. In the latter case, the losses could be reduced by half after annealing for 30 min at 300 °C, however, at the expense of considerable mode field expansion.

## IV. Gain Measurement

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

The signal and pump radiation were combined by a 980/1550-nm fiber WDM and coupled into the channel waveguides using a SM 980 (4.5/125-$\mu$m) fiber exhibiting single-mode performance at both signal and pump wavelengths. At the waveguide output the amplified signal was separated from the pump radiation in the second 980/1550-nm fiber WDM coupler and detected using an InGaAs detector. At the waveguide input and output a coupling gel was used to suppress Fresnel reflections and thus to minimize the coupling losses. In potassium channel waveguides the resulting loss per interface was estimated to 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, approximately 1.8 dB.

First, the change in signal transmission as a function of pump power was measured at the central $Er^{3+}$ ion emission wavelength of 1537 nm. The signal power was set to 100 $\mu$W. The measured signal enhancement was converted to the net optical gain by setting the gain at 1600 nm, where the $Er^{3+}$ absorption is negligible, equal to the waveguide scattering loss.

Fig. 3 shows the results of gain measurement on potassium channel waveguides fabricated in MM64 and MM65 glass substrates. In the purely Er-doped sample the positive net optical gain is achieved at the pump power of 130 mW and upon pumping at 316 mW reaches up to 4.0 dB.

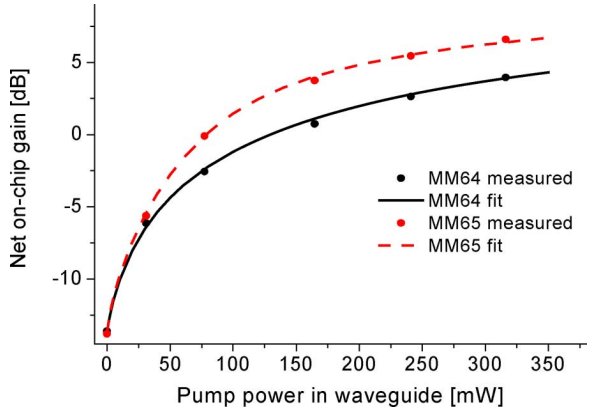


Fig. 3. Net on-chip gain versus pump power: measured and simulated data for $K^+$ channel waveguides in MM64 (Er only) and MM65 (Er : Yb $\sim$ 1 : 1) glasses.

TABLE III
Maximum Achieved Net On-Chip Gain

| | Net on-chip gain [dB per sample] | |
|---|---|---|
| | $K^+$ waveguide | $Ag^+$ waveguide / after annealing |
| MM64 | 3.95 | - / - |
| MM65 | 6.61 | 5.80 / 5.50 |
| MM66 | 6.63* | 6.31 / 6.71 |

* the length of the sample was only 34 mm

The performance of the Er–Yb-co-doped sample is even better with the threshold pump power reduced to 80 mW and with the maximum achievable gain of 6.6 dB. Thanks to sufficiently low input/output coupling losses of potassium waveguides, fiber to-fiber gain as high as 4.9 dB was observed.

The optical gain measurements on silver channel waveguides were performed on MM65 and MM66 glass substrates. Despite stronger mode field confinement as compared to potassium waveguides, the maximum net gain amounted for only 5.8 and 6.3 dB in MM65 and MM66, respectively. This was due to approximately five times larger scattering loss of $Ag^+$ channel waveguides. Furthermore, because of substantial coupling loss, fiber to-fiber gain of only 2.6 dB was observed.

The annealing process had a positive influence on both the scattering and coupling loss, however, the pump and signal field confinement was reduced. After annealing for 30 min at 300 °C the maximum net gain measured in MM65 and MM66 glasses was 5.5 and 6.7 dB, respectively. The fiber to-fiber gain increased to 4.1 dB. All measurement results are summarized in Table III.

Further, we focused on determining the amplifier bandwidth by measuring the spectral dependence of signal gain at several pump power levels.

The input signal level was kept constant at $P_s = 100\ \mu$W and the measurement was performed in the full achievable wavelength range from 1495 to 1635 nm. The gain spectrum of $K^+$ sample in MM66 glass is depicted in Fig. 4 and is characterized by a relatively narrow full-width at half-maximum (FWHM) bandwidth of 15 nm, which is quite typical for ordinary silicate glass [1].

Finally, spectral analysis of the amplified signal was performed and it showed that essentially no amplified spontaneous

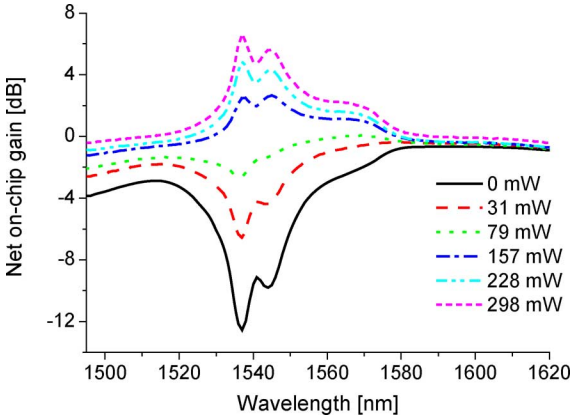


Fig. 4. Measured spectral dependency of the net on-chip gain of the $K^+$ channel waveguide in MM66 (Er : Yb = 1 : 2) glass for several different pump powers (converted to input power in the waveguide).

emission, degrading the amplifier performance and contributing to noise figure, was present.

## V. Model Simulation and Discussion

A six-level numerical model of Er–Yb-co-doped active waveguide was formulated to fit the measured gain and to 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 signal up-conversion as the most important quenching effect limiting the amplifier gain. Next, the Er-Yb cross-relaxation process as a mechanism of energy transfer between $Er^{3+}$ and $Yb^{3+}$ ions is considered [15].

All input data (Table IV) for the model calculations were taken from the experimental results reported above except for the nonradiative lifetimes and the $Yb^{3+}$ metastable level lifetime, which were taken from [1] and [16]. The up-conversion coefficient $C_{\rm up}$ and the cross relaxation coefficient $C_{\rm cr}$ as defined in [15] represented the unknown parameters to be found upon the fitting procedure.

First, the up-conversion coefficient $C_{\rm up}$, which governs the rate at which the $Er^{3+}$ ions are promoted to the inactive $4I^{9/2}$ level, was determined from the measurement on purely Er-doped MM64 glass. The best fit of the measured data was found for the value $C_{\rm up} = 1.1 \pm 0.2 \times 10^{-24}$ m$^3$s$^{-1}$. Here the inaccuracy reflects a 5% possible error in the measured mode field dimensions and uncertainty of 0.1 dB in the experimentally determined scattering loss of the channel waveguide.

This is one of the lowest $C_{\rm up}$ values reported for a glass material with $Er^{3+}$ concentration as high as 0.6 at.%. Low probability of the up-conversion can be also qualitatively deduced from the fact that no visible green luminescence indicating the pump up-conversion was observed during the measurement.

The cross-relaxation coefficient was obtained by fitting the data measured on MM65 and MM66 glasses. The best fit shown in Fig. 3 was achieved for $C_{\rm cr} = 0.12^{-22}$ m$^3$s$^{-1}$. The $Yb^{3+}$ – $Er^{3+}$ energy transfer efficiency can be estimated from the approximate equation for the cross-relaxation quantum efficiency [17]

TABLE IV
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 | $\tau_{21}^{Er}$=9.43 ms | |
| $Yb^{3+}$ metastable level lifetime | $\tau_{65}^{Yb}$=1.3 ms | |
| $Er^{3+}$-nonrad. lifetime of pump level | $\tau_{32}^{Er}$=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 @ 1550 nm | 10.6×14.2 µm$^2$ | 6.7×7.7 µm$^2$ |
| Mode-field dimensions @ 980 nm | 7.6×11.6 µm$^2$ | 3.5×5.2 µm$^2$ |
| Scattering loss @ 1550 nm | 0.18 dB/cm | 0.85 dB/cm |

TABLE V
Metastable Level Lifetime of Er:Yb Doped Samples.

| | Lifetime (ms) | | | | |
|---|---|---|---|---|---|
| Er (at.%) / Yb (at.%) | 0.5 | 1 | 1.5 | 2 | 2.5 |
| 1 | 9.49 | 7.30 | 5.46 | 4.40 | 3.69 |
| 2 | 7.67 | 6.92 | 5.38 | 4.27 | 3.52 |
| 3 | 8.82 | 6.60 | 5.42 | 4.14 | 3.51 |

*data were measured at IFAC-CNR in Firenze, Italy (Section of optoelectronics and photonics headed by prof. G.C. Righini)

$$\eta = \frac{C_{\rm cr} N_{\rm Er} \tau_{65}^{\rm Yb}}{1 + C_{\rm cr} N_{\rm Er} \tau_{65}^{\rm Yb} \left(1 + \dfrac{N_{\rm Yb} \tau_{32}^{\rm Er}}{N_{\rm Er} \tau_{65}^{\rm Yb}}\right)} = 72\%.$$

When fitting the cross-relaxation process we considered that the $C_{\rm up}$ coefficient keeps the constant value of $C_{\rm up} = 1.10^{-24}$ m$^3$s$^{-1}$.

This is equivalent to the assumption that the addition of $Yb^{3+}$ into the glass matrix does not influence the solubility and the radiative properties of $Er^{3+}$ (i.e., the Yb-co-doping does not change the up-conversion probability). Since neither the reduction of the metastable level lifetime of $Er^{3+}$ [see Table V], nor the degradation of an amplifier gain was observed with the increase in Yb concentration, this assumption appears to be reasonable.

It should be noted that the 38-mm length of the active waveguides is not optimum. In purely Er-doped MM64 substrate, only a small portion of pump power was absorbed (pump power decrease of only 2 dB was measured), which means that higher gain could be achieved in longer samples. The simulation results imply that the gain of 6.3 dB would be feasible in a 10-cm-long Er-doped waveguide. On the other hand, in MM66 samples, the

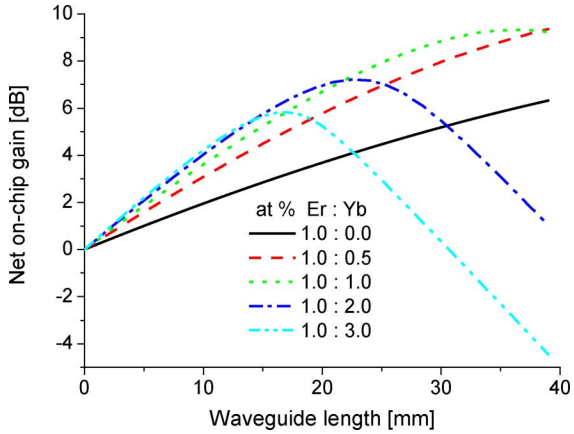


Fig. 5. Model simulation of the dependency of the net on-chip gain versus waveguide length and different Er:Yb concentration in $K^+$ waveguide.

end section of the waveguide is slightly "underpumped" due to strong absorption of pump power by $Yb^{3+}$ ions.

Finally, the optimization of the glass composition with respect to the $Er^{3+}$ and $Yb^{3+}$ ion concentration was numerically simulated. The optimal concentration depends on both the length of the waveguide and the signal/pump mode field confinement.

For 40-mm-long sample fabricated by $K^+$ ion exchange with the same channel waveguide geometry as in our experiments (see Fig. 5), the optimum Er–Yb concentration was found 1 at.% for both Er and Yb. According to the simulation, such glass exhibits the net optical gain of 9 dB. In shorter but otherwise identical samples, higher $Yb^{3+}$ concentration is desired to compensate for rather low absorption cross section of $Er^{3+}$.

For higher index-contrast waveguides with strongly confined guided field (e.g., signal $4 \times 4\ \mu m^2$, pump $3 \times 3\ \mu m^2$), the $Er^{3+}$ concentration of 2.5 at.% is optimum and no further addition of $Yb^{3+}$ is required. In this case, much higher net on-chip gain up to 17 dB (6 dB/cm) upon 100-mW pumping is predicted by the model calculations.

## VI. Conclusion

Channel optical waveguides in novel Er-doped and Er–Yb-co-doped ZnO-containing silicate glasses were fabricated by a standard ion-exchange technique. Net-on-chip gain of 6.3 dB and 6.6 dB (measured at the wavelength of 1537 nm) was achieved in 34-mm and 38-mm-long $Ag^+ \Leftrightarrow Na^+$ and $K^+ \Leftrightarrow Na^+$ ion-exchanged waveguides, respectively, when excited by a pump power of about 316 mW at the wavelength of 976 nm. The active waveguide samples exhibited exceptionally low up-conversion $C_{up} = 1.1 \pm 0.2 \times 10^{-24}\ m^3 s^{-1}$ and essentially no evidence for Er concentration quenching at the Er-concentration of 0.6 at.%. The low up-conversion is due to the addition of ZnO intermediate into the glass matrix, however, the physically chemical mechanism behind is not completely clear and requires further investigation.

A numerical model was developed to analyze and optimize the amplifier performance. Optimum concentration of rare-earth ions in the substrate glass was found to be $N_r = N_{Yb} = 1$ at.% for the potassium channel waveguide. Very large net optical gain (up to 17 dB/sample) was simulated for an ideal overlap of the pump and signal optical field in a glass containing 2.5 at.% of Er and no Yb. These results clearly demonstrate great potential of the reported silicate glass as a substrate material for advanced active waveguide devices.

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