Rare earth-doped integrated glass components: modeling and optimization

Lumholt, Ole; Bjarklev, Anders Overgaard; Rasmussen, Thomas; Lester, Christian

Published in:
Journal of Lightwave Technology

Link to article, DOI:
10.1109/50.365216

Publication date:
1995

Document Version
Publisher’s PDF, also known as Version of record

Citation (APA):
Rare Earth-Doped Integrated Glass Components: Modeling and Optimization

Ole Lumholt, Anders Bjarklev, Member, IEEE, Thomas Rasmussen, and Christian Lester

Abstract—For the integrated optic erbium-doped phosphate silica amplifier, a comprehensive model is presented which includes high-concentration dissipative ion-ion interactions. Based on actual waveguide parameters, the model is seen to reproduce measured gains closely. A rigorous design optimization is performed, and the influence of variations in the launched pump power, the core cross section, the waveguide length, the erbium concentration, and the background losses are evaluated. Optimal design proposals are given, and the process reproducibility of the proposed optimal design is examined. Requirements for process parameter control in the wafer fabrication are set up.

I. INTRODUCTION

FEW components have revolutionized the area of optical research as the rare earth-doped optical amplifier and laser. This is mainly due to the eye safe transition around 1.55 μm of erbium and the 1.3 μm emission of neodymium or praseodymium which, respectively, coincide with the low-loss window and the zero dispersion wavelength of standard optical fibers. Although fiber-versions of these components are already commercially available, the integrated optic version seems to be competitive and in some ways unsurpassed by fibers. This is because integrated optics offer prospects of active components to be integrated on the same substrate as filters, couplers, taps, and multiplexers so optical switching and multiplexing can be made locally on the wafer. The integration offers robust devices, compact size, multiple device fabrication on the same substrate, and packaging at lower cost.

From the variety of rare earth ions and integrated optic substrate materials, the main part of this paper will focus on the erbium-doped glass components, although differences from other rare earth ions are discussed when significant. Glass is chosen as host, as it is stable to changes of environment, has a low propagation loss, and the potential of low-loss coupling to standard optical fibers. The 1.55 μm narrow linewidth erbium source is of the utmost importance for high-bit-rate long-distance fiber optic communication and for coherent optical transmission, but also for spectroscopic, telemetry [1], and special metrological applications [2]. Combined with the advantages of integration and dense packing, a miniaturized diode-pumped eye safe source will be extremely attractive for the medical industry and applications as sensors, laser radars, free-space communication, tactical training range finding, security systems [3], and as superradiant sources for optical gyroscopes [4]. In addition, other wavelengths could be reached by using the transitions ranging from the IR part of the spectrum to the visible part, which are accessible through upconversion pumping schemes. In particular, compact visible laser sources are needed for optical disk storage purposes [5], medical, and sensor applications.

A rigorous design optimization of rare earth-doped integrated optic components are of extreme importance in the development and processing of high-performance devices, and are required far more than for fiber optimization. Compared to active fibers, we have, after the fabrication, one adjustment parameter less to compensate for minor deviations during processing, as the doped waveguide length is determined during the fabrication. This leaves the pump power as the only adjustable design parameter, and sets up requirements for accurate predicted design proposals before processing. In this paper, we present an overview of different rare earth incorporation techniques of active wafers, with their limitations to certain glass compositions, as the host glass development can be viewed as part of the integrated optical amplifier optimization. An overview of applications and the state of the art is given. For illustration and simplification, we then concentrate on the erbium-doped phosphor/silica-core silica-on-silicon wafer amplifier, present a numerical model for this component, verify the model with measurements, and perform a rigorous design optimization of the high-gain component.

II. HOW TO INCORPORATE RARE-EARTH IONS IN GLASS

Diffusion and deposition are two basic different methods used for core layer introduction in integrated optics (IO). Channel waveguides are formed in the former by diffusing index raising materials through a slide in a substrate surface covering mask, while for deposition, photolithography can be used to write structures on the surface, whereafter reactive ion-etching (RIE) is used to remove any core areas not masked. Buried waveguides are made in the diffusion process by extraction of core material near the surface [6], while in the deposition, an extra cladding layer is deposited on top of the ridged waveguide. Also, the techniques by which rare earth (RE) ions are impregnated to the core most often differ from these processes. Generally, rare earth ions are introduced into the core glass of deposited waveguides, while the core is introduced into the rare earth glass for diffused components. Fig. 1 shows different combinations of core layer fabrication.
tering due to the high RE concentration. The latter is the longer lengths during the drawing. The background loss results sidewall scattering (for rectangular cores), and Rayleigh scattering due to the high RE concentration. The latter is the few tenths to several dB/cm. Local deformations at material five-six decades larger than in fibers, typically between a in the case for the composite waveguides.

One should bear in mind that phosphate glasses (or, alternately, alumino-silicate glasses) seem to be the best suited host materials for most applications of rare earth-doped IO amplifiers. This is because phosphate (and aluminum) act as network modifiers in the glass, thereby eliminating the clustering tendency as reported for highly RE-doped fibers [7]. Phosphate increases the refractive index, and is therefore often used as a core material in deposited waveguides. In addition, it has a lack, compared to Ge-silica, of the un-effective phonon frequencies (high nonradiative transition rates), slightly reduced quantum efficiencies can be expected for some compositions [9].

### III. MODELING

The modeling of rare earth-doped channel waveguides differs on several points from the modeling of rare earth-doped fibers. One difference is the noncircular symmetric core cross section, which typically are rectangular for deposited and elliptical for diffused waveguides. Another is the noncircular symmetric rare earth doping profile; this can be a rectangular step-like profile for while deposition or solution doping, vertically Gaussian shaped for doping by ion implantation, homogeneous with the core confined within the doped area for ion-exchanged waveguides, or located outside the core as in the case for the composite waveguides.

Background losses of buried channel waveguides are around five–six decades larger than in fibers, typically between a few tenths to several dB/cm. Local deformations at material surfaces during manufacturing have a very significant impact upon the integrated component, while in fiber preforms, they are stretched and smoothed out on several thousand times longer lengths during the drawing. The background loss results from a combination of internal scattering, surface scattering, Rayleigh scattering due to the high RE concentration. The latter is the most insignificant of these, i.e., a high-concentration (86 \cdot 10^{24} \text{ions/cm}^3) Er fiber only exhibited a minor loss increase [22], while the sidewall scattering is the most difficult to handle, especially for small channel widths. The main contribution to this is the mask and etching process which creates a kind of waved walls [23]. Surface scattering is due to imperfections in the core-cladding boundaries and depends on the glass film processing, while the internal scattering depends on the purity of the deposited glass. Buried planar channel waveguides have been made with losses of 0.026 dB/cm [24], although typical values are three–ten times higher. Finally, rare earth concentrations two orders of magnitude higher than in fibers are necessary to achieve short lengths of amplifiers. At these concentration levels, ion–ion interactions, such as excited ion migration and cooperative upconversion or cross relaxation, are strongly present, yielding decreased amplifier performance. On the other hand, the fiber problem with RE clusters is not considered as a problem for RE-doped integrated components with an ample amount of phosphor or aluminum in the core.

Models that take some or all of the above-mentioned aspects into account have been presented [25]–[31], but with quite different solutions to the problems. Ab initio calculations of a multilevel system are extremely complicated, so one has to weigh the modeling between, on the one hand, the full scale model with all dissipative processes included and, on the other hand, a quick useful design tool. For erbium systems, the major cause for inefficiency is the cooperative upconversion, which schematically is shown on the left side of Fig. 2. Two excited Er ions can transfer energy from one to the other, leaving the first in the ground state and the second in the \(^{4}I_{13/2}\) state with a quick nonradiative relaxation back to \(^{4}I_{15/2}\). The net result is a conversion of pump photons into heat. A simple approximation to this process is made by including a term proportional to \(k_{2}n_{2}\) in the rate equations. \(n_{2}\) is the population in the upper laser level, and \(k_{2}\) is the upconversion constant of about \(1 \cdot 10^{-23} \text{m}^{3}/\text{s}\) [32]. Another model also includes higher order upconversion processes [29], while others have found that the upconversion constant is concentration-dependent [31], yielding a cubic equation for the determination of the population inversion. A similar equation appears when the performance degradation is modeled through the observed relation between fluorescence lifetime and the concentration [28], as will be described in detail below. The neodymium system acts different. Due to intermediate states between the upper and lower laser level, the inefficiency is caused by cross relaxations to these, involving one excited ion and one in the ground state, followed by a quick relaxation to the ground state (illustrated on the right hand side of Fig. 2). A term proportional to \(k_{ij}n_{i}n_{j}\) should be applied for the simple approximation in this case, \(k_{ij}\) being the cross-relaxation coefficient between levels \(i\) and \(j\).

For illustration, we have concentration our modeling on erbium-doped phosphate–silica waveguide cores confined in silica cladding, with erbium homogeneously distributed within the core. See Fig. 3. The model is developed from an experimentally verified and accurate Er-doped fiber amplifier model [7] with changes made to fulfill the above-mentioned differences in structure. The circularly symmetric LP\(_{01}\) mode
Authorized licensed use limited to: Danmarks Tekniske Informationscenter. Downloaded on February 9, 2010 at 11:14 from IEEE Xplore. Restrictions apply.
of less than 1 dB in the entire pump power interval. The $\tau_0 = 13.7$ ms lifetime reported in [10] was used in the calculations, but as different fabrication processes might yield different magnitudes of $\tau_0$, the correlation among gain, pump power, $\tau_0$, and Q has been examined. Gain curves deviate only a few tenths of a decibel from the case with $\tau_0 = 13.7$ ms if the Q factor at the same time is increased ($Q = 25 \cdot 10^4$ m$^{-3}$ for $\tau_0 = 8$ ms). In addition, significant Er ion–ion interactions have been observed at levels of $\sim 10^4$ m$^{-3}$ for both pure silica and Ge-doped silica fibers [9], and a rapid fluorescence lifetime decrease reported at concentrations above 0.1 wt% ($8 \cdot 10^4$ m$^{-3}$) in the amplifier experiment [35].

The gain versus concentration dependence is examined in Fig. 6 for a fixed pump power of 100 mW. Significant gain reductions are observed for concentrations above $10^4$ m$^{-3}$ (approximately ten times higher than the typical concentrations in Er-doped fibers). However, the pronounced gain differences to the case of no ion–ion interactions grow at higher concentrations to 50 dB at $\rho = 115 \cdot 10^4$ m$^{-3}$. By reducing the quenching concentration to $Q = 17 \cdot 10^4$ m$^{-3}$, the theoretical curve shows excellent agreement with the measured values for concentrations up to $60 \cdot 10^4$ m$^{-3}$. Experimental data display a stronger deflection than the calculated in the remaining interval, perhaps due to even higher order nonlinear ion–ion interactions.

V. RARE EARTH-DOPED COMPONENTS

The present research within rare earth-doped integrated components can basically be grouped into three different categories: lasers, lossless Y branches, and high-gain amplifiers, each group with optimal design parameters that deviate remarkably from the others. However, combinations of these, i.e., an amplifying Y branch or a Y branch laser with application for dual-output, mode-selected or Q-switched operation, may also find attraction.

Lasers are the most simple of these to realize, as they require relatively low rare earth concentrations. As in the case of active fiber development, the focus was first put on the transitions in Nd$^{3+}$ because neodymium acts as a four-level laser system, and it is therefore easier to handle (achieve population inversion) than the three-level erbium system, plagued by ground state absorption. Although Nd-doped glass waveguides were reported 20 years ago [36], the recent development was started by the presentation of an Ag$^+\text{K}^+$ ion-exchanged waveguide in highly Nd-doped silicate glass by Babukova et al. in 1985 [37]. But six years later in 1991, Mwarania et al. [38] presented the first truly single-mode glass channel waveguide laser. A 7.5 mW threshold and a 6% slope efficiency were measured on a 17 mm long Na$^+\text{K}^+$ ion-exchanged device. A detailed review of this six-year development is given in [5]. A pump threshold as low as 0.6 mW followed by a slope efficiency of 24% in a 5 mm long Ag$^+\text{K}^+$ ion-exchanged waveguide [39] is, to the best of our knowledge, the most pronounced low-power Nd laser results obtained so far. The development of low-power Nd lasers is illustrated in Fig. 7. As can be seen, the most significant results are obtained with phosphate glasses (solid lines). Apart from the dominant 1.06 µm transition [14] lasing, although less significant, others also have been reported around 0.91 µm [40], 1.33 µm, and 1.36 µm [8] for the Nd system.

Reports on erbium-doped glass lasers were seen in 1991 with the presentation of an FHD-processed silica-on-silicon laser by Kitagawa et al. [12]. Co-doping with ytterbium is generally used with the Er system so as to enhance the absorption efficiency by utilizing the Yb$^{2+}/\text{Er}^{3+}$ energy transfer process [7]. To our knowledge, the best low-power Er laser results obtained so far are a 16 mW threshold and 10% slope efficiency from a 2.5 mm thick and 4 mm diameter Er/Yb-phosphate disk [30].

Lossless Y branches can be viewed as a first step towards complex multichannel devices, as the $1 \times 2$ geometry can be extended to a large number of output ports. The lossless Y branch requires an amplification high enough to compensate for the 3 dB splitting loss, the background loss, and possibly coupling loss; in all, about 5–7 dB of amplification is needed. 85 mW of 807 nm pump was used to overcome the splitting.
loss in a 24 mm long Nd-doped device [41], defined by ion exchange in a silicate glass, while 60 mW of 980 nm pump was found sufficient to compensate for splitting and excess loss in a 23 cm Er-doped silica-on-silicon device [31]. In addition to the fabrication of single-output port amplifiers, the branch proportional \( L_1/(L_1 + L_2) \) is an extra design parameter that must be optimized to reduce the pump power required. \( L_1 \) and \( L_2 \) are the length of doped waveguide, respectively before and after the ramification, as illustrated in Fig. 8. Kitagawa [31] has reported the optimum position to be 0.9 for an Er-doped silica-on-silicon component.

Two significant deviating parameters for the high-gain amplifier are the rare earth concentration and the waveguide length, both considerably larger than for the laser and \( Y \) branch components. The promising silica-on-silicon components especially require very long lengths, but 170 cm long passive channel waveguides in a coiled configuration (bending radius of 5 mm) have been realized [42] with low propagation loss (0.038 dB/cm). Optimal design of this type of amplifier will be examined in detail below; here, it should be mentioned that the highest net gain reported for integrated glass amplifiers is 23 dB [31] from a 36 cm long erbium-doped P silica-on-silicon component, pumped with 240 mW of 0.98 \( \mu \)m light. Also, 10 dB net gain from an only 4.7 mm long Er/Yb-doped composite glass waveguide amplifier (~ 21 dB/cm) has been reported, applying only 30 mW of pump power [21].

**VI. HIGH-GAIN AMPLIFIER OPTIMIZATION**

We will now select the high-gain component for optimization, and take as reference the above-reported amplifier [35] \((A_m, B_m, L_m, \rho_m) = (8 \mu \text{m}, 7 \mu \text{m}, 19.4 \text{cm}, 48 \cdot 10^{24} \text{m}^{-3})\) applying 100 mW of pump power. Five different design parameters are evaluated, that is, waveguide length, core cross section, erbium concentration, pump power, and background loss. The reference gain, measured (symbols) and calculated (lower solid line), are shown again versus erbium concentration in Fig. 9, all determined from the fixed length of 19.4 cm. An optimum length exists, however, for each single concentration, whereas the gain reaches its maximum. Shorter lengths yield an incomplete utilization of the pump, whereas the pump for longer lengths cannot invert the Er ions sufficiently. The length-optimized gain and the optimum length for the reference component are shown as dashed lines in Figs. 9 and 10, respectively.

It is seen that the reference length (horizontal line) is less than half the optimum, and that the highest reference gain can be increased with 3 dB simply by changing the concentration to \( \rho = 30 \cdot 10^{24} \text{m}^{-3} \) and the length to 45 cm. The evolution in the optimum waveguide length is seen to increase from a few cm at very high concentrations to 60 cm at \( \rho = 13 \cdot 10^{24} \text{m}^{-3} \).

For smaller concentrations, the optimum length approaches zero because the total background loss becomes comparable with the gain accumulation. The length- and concentration-optimized amplifier gain may be further increased if the waveguide core cross section is also optimized. By decreasing the reference core, the overlap integral between the Er-doped region and the mode profile is increased, followed by gain improvements. However, for very small cross sections, yielding long optimum lengths the accumulated background loss will diminish the gain seriously, so obviously an optimum exists. The upper solid curves in Figs. 9 and 10 represents calculations where the core cross section and the waveguide length have been optimized to maximum gain simultaneously for each concentration considered. A quadratic core cross section is considered to achieve a fundamental mode that matches the circularly symmetric fundamental mode of optical fibers. The core size optimization yields an additional 3 dB gain at the optimum concentration \( \rho = 41 \cdot 10^{24} \text{m}^{-3} \), a core width of 4.6 \( \mu \)m, and a length of 53 cm. The optimum core size varies inversely proportional to the concentration from 6.2 \( (\rho = 10 \cdot 10^{24} \text{m}^{-3}) \) to 3.4 \( \mu \)m \( (\rho = 115 \cdot 10^{24} \text{m}^{-3}) \). Also, the evolution of the noise figure is shown for the latter optimization, yielding a minimum of 5.1 dB. An even lower noise figure can be obtained with increasing gain by increasing the pump power, or for a fixed pump power (and decreasing gain), by reducing the waveguide length.

The above-determined design combination of \( A, \rho, \) and \( L \) is optimum for a fixed pump power of 100 mW. By changing the power, the design must be changed, which is why a three-dimensional simultaneous optimization of these parameters is made for the pump power evolution. This is illustrated in Fig.
The relationship among background loss, pump power, optimal gain, and erbium concentrations is clarified in Fig. 14 for a fixed waveguide width of 4.65 μm. In the situation with extremely small background loss, gains in excess of 40 dB can be reached with 60 mW of pump. The design is very critical to variations of α, i.e., the slope around a state-of-the-art, realistic processed reproducible background loss of 0.08 dB/cm is up to 300 dB/(dB/cm). An almost linear relationship between background loss and optimal erbium concentration is observed for α > 0.05 dB/cm. The slope of around 105 m⁻³/(dB/cm) for pump levels considered is slightly increasing versus pump power from 100 m⁻³/(dB/cm) (P_p = 30 mW) to 130 m⁻³/(dB/cm) (P_p = 500 mW). A somewhat more complicated evolution is seen from Fig. 15 to exist for the optimal waveguide length. High background losses (> 0.07 dB/cm) yield increasing lengths versus pump power up to 100 mW. However, for lower loss values, a maximum length is observed. This maximum length arises from the correlation and weighting between, on the one hand, the gain degradation caused by concentration increase and, on the other hand, gain degradation caused by length increase. It is remarkable that the optimum length is unchanged over a 50 mW pump power interval for α = 0.07 dB/cm.

VII. PROCESS REPRODUCIBILITY

Reproducibility of the design parameters during the different processing steps will determine how accurately the above-shown design curves can be followed. These process parameters are core width, length, and height, the refractive index difference, background loss, and erbium concentration. It is expected that a specified concentration can be met within ±5% in the most controllable processes, although it might be much more uncertain for others. The refractive index and layer thickness are parameters related to the deposition process, and are strongly dependent upon deposition method and speed. A standard process yields typical variations over one 4 in...
silicon wafer less than ±0.007% in index for the core and
±0.014% for the buffer, each layer with a variation of ±3.0%
in thickness. A wafer-to-wafer examination for up to 30 wafers
in one deposition run [43] showed that 90% of all wafers
produced had a refractive index difference, Δn within ±0.07%
and a thickness within ±5%. The background loss is primarily
determined by the etching step in the waveguide fabrication
process. From an examination of 56 channel waveguides
over two wafers, it is seen [43] that 2/3 of all nondestroyed
waveguides had a background loss variation of ±0.015 dB/cm.
An even lower standard deviation of 0.003 dB/cm was recently
reported among 19 channel waveguides 170 cm long on Si
[42], although all were fabricated on the same wafer.

Consider the situation with α = 0.08 dB/cm as illustrated
in Fig. 13, yielding a maximal gain of 31.8 dB. If, also, the
core cross section were optimized, the overall optimum design
would be (A, ρ, L) = (4.16 μm, 43.7 · 10⁻⁴ m⁻³, 102 cm),
yielding the overall optimum gain of 32.0 dB. Gain variations
due to parameter deviations from this design are shown in Fig.
16. The "0" point on the x axis corresponds to the calculated
design. Five units on the x axis correspond to a 5% increase
in core layer thickness, a 0.07% increase in refractive index
difference, 5% increase in erbium concentration, and a 0.015
dB/cm decrease in background loss. The variation of buffer
layer thickness will have no effect on the performance as
long as the buffer is sufficiently thick to avoid leakage to
the substrate. Length and width of the channel waveguide
are determined accurately by a lithographic process, and are
therefore not considered to increase the uncertainties further.

As can be seen from Fig. 16, the background loss is the
most critical parameter for the design. Due to the extremely
long waveguide, the considered 0.015 dB/cm increase will
result in no less than a 4.2 dB gain decrease. If each process
parameter were allowed to yield an absolute variation of
0.5 dB in gain among the realized waveguides, there would
be no problems for concentration and thickness variations
of ±5%. However, variations of Δn should be less than ±0.02%
and the requirement to background loss would be less than ±0.001 dB/cm, the latter being impossible. When design-optimized active fibers are fabricated, deviation from the
specified performance, due to variations in the process
parameters, may be corrected by adjusting the fiber length,
while testing the realized component. This possibility of
correction is different for active wafers. Once realized, the
length cannot be adjusted, which is why, instead, a proper
design should use a pump power level on the dynamic part
of the gain-to-pump power curve so as to use the pump power
for the last adjustment after the processing. It should, however, be
noticed that the requirements for the background loss reduction
remarkably drop with the wanted gain and thereby length of
the waveguide.

VIII. CONCLUSION

A comprehensive model of an integrated, highly erbium-
doped phosphate glass amplifier has been found to reproduce
measured gains up to concentrations of 60 · 10⁻⁴ m⁻³. The
emission and absorption cross section peaks at 1.55μm of
Er-doped phosphate silica are found to be 5.6 · 10⁻²⁵ m².
Ion-ion interactions are found to reduce the amplifier gain
in excess of 50 dB for very high doping levels, and optimal
erbium concentrations have been determined as approximately
30κ·60 · 10⁻⁴ m⁻³ for realistic background losses and pump
power levels below 100 mW. The optimal concentrations are
found to increase linearly with a background loss of around
105 m⁻³/(dB/cm), having a slightly increasing slope for in-
creasing pump power levels. The optimal active waveguide
length is found to be up to 175 cm for background losses
of 0.03 dB/cm, and strongly decreases for increasing loss.
Net gains in excess of 40 dB are predicted for only 60 mW
of pump power in the situation with small background loss.
Performance degradation due to reported variations in process
parameters during a multiple wafer fabrication are found to
be very significant. The background loss is the most critical
parameter to control; a deviation of 0.015 dB/cm from the
assumed value in the design results in a 4.2 dB gain decrease.
Variations below 0.5 dB require control of core thickness better
than ±5%, Δn better than ±0.02%, and background losses
better than ±0.001 dB/cm. The latter requirement diminishes
significantly with the wanted amplifier gain, and thereby
required length.

IX. ACKNOWLEDGMENT

The authors thank Dr. E. Nicolaelsen for fruitful discussions.

REFERENCES

[1] P. Laporta, S. De Silvestri, V. Magni, and O. Svelto,


Ole Lumholt, photograph and biography not available at the time of publication.

Anders Bjarklev(M’92), photograph and biography not available at the time of publication.

Th omas Rasmussen, photograph and biography not available at the time of publication.

Christian Lester, photograph and biography not available at the time of publication.