Characteristics of Er-Doped Al_2O_3 Thin Films Deposited by Reactive Co-Sputtering

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Abstract—Er-doped Al_2O_3 thin films have been deposited by reactive co-sputtering onto thermally oxidized Si-wafers. The deposition process has been optimized with respect to the requirements originating from the application of these multilayer structures as integrated optical amplifiers for the third telecom window, i.e., the wavelength range 1.52–1.56 μm . The films obtained at a substrate temperature of only 400 °C are amorphous and show a homogenous structure, without columns or grains. For slabguides, background losses smaller than 0.25 dB/cm have been obtained, even without any annealing. A relatively broad luminescence band, having an FWHM of ~ 55 nm around the 1.533- μm wavelength, has been measured. From gain versus pumping power curves, an upconversion coefficient lower than $20 \cdot 10^{-25} \text{ m}^3/\text{s}$ has been derived, being half of the values reported up to now in the literature. Simulations based on experimentally determined material parameters and assuming a channel attenuation of 0.5 dB/cm indicate, for 0.24 at.% Er channel devices with an optimal channel length of 7.7 cm, an amplification of 8 dB at 1.533 μm for a pump wavelength of 1.48 μm , and a pump power of only 8.7 mW.

Index Terms—Er-doped Al_2O_3 , integrated optics, optical amplifiers, reactive co-sputtering.

I. INTRODUCTION

DOPING of planar optical waveguides with Er is gaining interest due to the possibility of applying these active waveguides as loss-compensating components in optical circuits around the wavelength 1.5 μm , the third telecommunications window. The success of Er-doped fiber amplifiers (EDFAs) [1] and the desire to insert into the optical networks integrated optical components that show low losses, even in spite of their complexity, have triggered the development of on-chip integrated optical amplifiers, also based on the optical transitions within the Er^{3+} -ion. Because of the limited length of integrated optical amplifiers, effective amplification can be obtained only by taking Er concentrations that exceed those in the fibers by some orders of magnitude. As a consequence, energy migration-related deteriorating phenomena such as quenching and upconversion become relevant, and the reduction of these effects poses additional requirements on the host materials. There have been considerable research efforts for host materials obeying all requirements, and a broad range of materials has been investigated or suggested [2], [3].

Of these materials, it is Al_2O_3 which possesses appealing characteristics as an excellent host for erbium. The waveguide fabrication technology for this material is well developed; high-quality waveguides with low losses ≤ 0.3 dB/cm at $\lambda =$

1.55 μm have been realized [4]. The relatively high refractive index of Al_2O_3 waveguides provides high confinement of the optical mode, leading to high intensities at low power levels, as is very advantageous for obtaining effective amplification. This is, however, with the penalty of applying special fiber-chip coupling functions in order to have an effective power transfer from fiber to chip and vice versa. Moreover, the similarity in valency and lattice constants between Al_2O_3 and Er_2O_3 [5] allows for incorporation of high concentrations of Er in Al_2O_3 without clustering of Er in the Al_2O_3 film, which is important for reducing energy migration and, hence, quenching and upconversion. The difference in ionic radii between Er^{3+} and Al^{3+} will lead to an appreciable inhomogeneous broadening of the Er^{3+} -transitions, which on one side reduces the energy migration and on the other side extends the bandwidth.

Indeed, much research has been done on Er-doped Al_2O_3 layers. Various techniques have been used, varying from Er implantation in already grown Al_2O_3 -films [2] to co-doping during production applying various chemical vapor deposition (CVD) methods including PECVD [6], MO-PECVD [7], and MO-LPCVD [7]. Promising results have been obtained. For example, a net gain of 2.3 dB for a pump power of only 9 mW has been demonstrated for a 4-cm-long Er-implanted Al_2O_3 optical waveguide amplifier, in which the Er peak concentration is 0.28 at.% [8]. Ion implantation, however, shows some drawbacks. After producing the Al_2O_3 -film, two additional technological steps are required: the implantation itself and a post-annealing step in order to repair the lattice damage caused by implantation. The latter, due to its relatively high annealing temperature, 950 °C [9], and annealing time, hampers the possibility of integration with electronics implemented in earlier processing steps in the Si-wafer, generally used as the substrate material for Al_2O_3 -based integrated optics. Also, it is quite cumbersome to produce optimal transverse Er-concentration profiles. Taken together with the larger probability of clustering in ion implanted materials, this will lead to higher energy migration in the center of the profile. Indeed, upconversion effects manifesting themselves as emission from higher excited Er-states are clearly observed in Er-implanted Al_2O_3 for an average Er concentration as low as 0.12 at.% [2].

Er: Al_2O_3 thin films fabricated by CVD techniques suffer from the presence of a considerable amount of hydroxyl groups in the films that increase the background attenuation and also function as quenching centers for the excited state energy [2], [6], [7]. Also, high-temperature annealing is needed in order to partially remove the hydroxyl groups.

We have produced the Er: Al_2O_3 films by reactive co-sputtering using sputterguns, a flexible method which avoids many

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of the drawbacks of the other methods. Based on experience with Er:Y₂O₃ [10], we expect that, using reactive co-sputtering, as-deposited Er:Al₂O₃ waveguides with low losses and a small amount of hydroxyl contaminants can be produced at relatively low temperature. Because of both the co-sputtering and low substrate temperature, the Er is expected to be homogeneously dispersed within the host material. Hence, it is expected that at relatively high Er-concentrations the energy migration will be low. This energy migration will be hampered more as a result of the inhomogeneity of the local stresses, leading to a distribution of the values of the excited state energy over the Er³⁺ sites and hence to the need of phonon assistance during energy migration. Co-sputtering offers the possibility of producing any transverse concentration profile, simply by controlling the time dependence of power fed to the Er-gun in an appropriate way. By using a multisputtergun configuration, hosts like the mixed compound Al_(2-x)Y_xO₃ can be produced and due to the low substrate temperature used there is some expectation that metastable single-phase compounds can be obtained, at least for some ranges of x . This offers an extra degree of freedom in the design of the host material.

In this paper, the properties of Er:Al₂O₃ thin films realized by reactive co-sputtering are presented and their optimization for application as integrated optical amplifiers for the third telecommunications window is reported. In Section II, the fabrication method and the deposition setup are described and the structural characteristics of the resulting films are shown and discussed. The optical properties of the layers are given in Section III just as some gain versus pump power curves for determining, amongst others parameters, the value of the upconversion coefficient. In Section IV, the results are discussed and compared to earlier results obtained for similar thin film materials fabricated by other techniques. A first-order estimate of the attainable gain in this type of amplifiers is made. The prospects of the reactive co-sputtering method are presented in Section V, followed by the conclusions in Section VI.

II. FABRICATION AND STRUCTURAL CHARACTERISTICS

Er:Al₂O₃ thin films were reactively co-sputtered onto 3.3- μ m-thick SiO₂ substrate layers that were grown by thermal oxidation on Si-wafers. The process was carried out in a vacuum chamber pumped by a cryo pump to a base pressure of $\leq 10^{-7}$ mbar, in order to remove all water, being a potential source of hydroxyl groups in the alumina. Two planar magnetron sputter guns (US Gun II) were used. One sputtergun containing a metal target, (99.999% pure) aluminum, was dc-powered and the other with erbium was connected to an rf power supply. The substrate was mounted 15 cm above the sputterguns on a substrate holder that could be rotated during sputtering to improve film homogeneity. The deposition was done in Ar:O₂ ambient. The Ar was injected inside the sputterguns to maintain both a high concentration of Ar on top of the targets, as needed for the gas discharge, and a low working pressure inside the chamber, for obtaining an acceptable growth rate. The O₂, required for obtaining an oxidized film, was injected through a port in the side of the chamber and the flow rate could be varied between 0 and 100 sccm.

TABLE I
VALUES OF THE SIGNIFICANT DEPOSITION PARAMETERS FOR ACHIEVING Al₂O₃ LAYERS WITH OPTIMAL PERFORMANCE

Deposition parameter	Optimum value
Argon flow into Al-gun [sccm]	20
Argon flow into Er-gun [sccm]	20
Oxygen flow [sccm]	55
Substrate temperature[°C]	400
DC sputter power (Al) [W]	235
Rf sputter power (Er) [W]	10 – 50
Er concentration range [at.%]	0.04 – 0.74
Working pressure [mbar]	4.6×10^{-4}

Fig. 1. Optical losses, at $\lambda = 0.633 \mu\text{m}$, of Er:Al₂O₃ thin films as a function of the O₂ flow rate in the deposition chamber. Other deposition parameters are substrate temperature (400 °C), dc power (234 W), rf power (20 W), and Ar flow rates (20 sccm for both guns).

The deposition process was optimized with the objective to obtain as-deposited films with low background losses and low energy migration while maintaining an acceptable growth rate. The parameters that influence the deposition process are listed in Table I. Two of these deposition parameters, the O₂ flow rate and the substrate temperature, are found to be of crucial importance for obtaining the stoichiometric composition and for the microstructure of the sputtered films and, consequently, for their optical losses.

A typical example of an optical loss versus O₂ flow rate relation is given in Fig. 1. The data are measured at an optical wavelength of 0.633 μm . It can be seen that the losses decrease as the O₂ flow increases. This is ascribed to the fact that in this flow rate range the films approach the stoichiometric composition as the oxygen flow increases. Fig. 1 suggests that losses will decrease even further by increasing the O₂ flow rate over 55 sccm. However, at such high flow rates, the surface of the target will be totally oxidized, having the consequences of an unac-

Fig. 2. Optical losses, at $\lambda = 0.633 \mu\text{m}$, of $\text{Er}:\text{Al}_2\text{O}_3$ thin films as a function of substrate temperature. Other deposition parameters are Ar flow rate: 20 sccm for both Al and Er guns; O_2 flow rate: 55 sccm; dc power: 234 W; rf power: 20 W; and working pressure of 4.6×10^{-4} mbar.

Fig. 3. Oxygen content (in at.%) of AlO_x films as a function of substrate temperature. The other deposition parameters are: O_2 flow rate: 25 sccm; Ar flow rate: 25 sccm; working pressure: 4.6×10^{-4} mbar; and dc power: 234 W. The dashed line indicates the oxygen content for stoichiometric Al_2O_3 .

ceptably small deposition rate and arcing of the target leading to enhanced scattering losses of the Al_2O_3 waveguides [11].

In Fig. 2, a typical example of the relation between the losses (at $\lambda = 0.633 \mu\text{m}$) and the substrate temperature is presented. The upper bound of the obtainable temperature range, 450°C , is limited by the system. The optical loss decreases as the substrate temperature is increased. This is attributed to both a better stoichiometry and a more regular microstructure. As for the film stoichiometry, it is evident from energy dispersive X-ray (EDX) measurements performed on films all sputtered at an O_2 flow rate of 25 sccm (see Fig. 3) that the amount of oxygen in the layers increases with increasing substrate temperature. The microstructure of the sputtered films will become more regular the higher the substrate temperature, and, as a consequence, the scatter losses will decrease. This is in line with Thornton structural zone model [12] and can be ascribed to an increasing adatom mobility. Applying an O_2 flow rate of 55 sccm where no arcing occurs yet and a substrate temperature of 400°C , stoichiometric Al_2O_3 layers are obtained.

The Ar flow rate is not very critical. A low Ar flow rate, just sufficient to maintain a stable plasma, was chosen as optimum in order to obtain a low working pressure. The optimized values of sputter parameters, used in fabricating films throughout this study, are listed in Table I. The optimization appears to be independent of the precise value of the rf sputter power fed to the Er-gun, at least within the range used in these investigations. Using these values, the sputter rate was ~ 20 nm/min.

EDX measurements performed on undoped Al_2O_3 films show that, under these conditions, the oxygen-to-Al ratio is stoichiometric within the accuracy of the measurement, being about 2 at.%.

In Fig. 4, a Rutherford backscattering spectroscopy (RBS) spectrum of an Er-doped Al_2O_3 film obtained by reactive co-sputtering is shown. Analysis of the spectrum shows that the Er is uniformly distributed in the transverse direction across the waveguide and that a presence of impurities cannot be observed. The Er concentration determined from the spectrum

Fig. 4. RBS spectrum of an $\text{Er}:\text{Al}_2\text{O}_3$ film deposited by reactive co-sputtering.

is 0.74 at.%. In samples sputtered at other rf powers under conditions given in Table I, however, the Er concentration ranges between 0.04 at.%, for 10 W of rf power and 0.74 at.%, for 50 W (see Fig. 5). It should be noted that it is possible to use a higher rf power to achieve higher concentration, but it was thought that a concentration of 0.74 at.% would be sufficient for the purpose of this study.

X-ray measurements have shown that the structure of the deposited films is amorphous (figure not shown). Ellipsometric measurements show that the resulting layers have a uniform thickness and refractive index, variations within a 4-cm^2 area being smaller than 2.4% and 0.12%, respectively. Fig. 6 shows a scanning electron microscope (SEM) photograph of the cross section of an $\text{Er}:\text{Al}_2\text{O}_3$ thin film. The photograph shows no columnar structure in the film and the surface appears to be smooth and without cracks. It should be noted that the lines

Fig. 5. Er concentration as a function of the rf power supplied to the Er-sputtergun. For deposition, the parameter set of Table I has been applied.

Fig. 6. SEM photograph of the cross section of as-deposited thin film of Er:Al₂O₃ fabricated by reactive co-sputtering.

visible in the picture are artifacts originating from the wafer cleavage.

III. OPTICAL CHARACTERIZATION

Most optical characterizations presented here were performed using a prism coupling setup, the description of the experimental details of which are given in [3]. From N_{eff} measurements using this setup, the thickness and the refractive index of the Er:Al₂O₃ layer can be derived. For an Er:Al₂O₃ slabguide with Er concentration of 0.2 at.% measured at $\lambda = 0.633 \mu\text{m}$, the refractive index and the thickness were determined to be 1.665 and $0.69 \mu\text{m}$, respectively. At a wavelength of $1.48 \mu\text{m}$, relevant for optical amplification, the refractive index was 1.640.

Fig. 7 shows the absorption and photoluminescence spectra of an Er (0.2 at.%) -doped Al₂O₃ layer in the wavelength range 1450–1580 nm. When recording the absorption spectrum (dashed line), a low-intensity polychromatic light source (tungsten halogen lamp) was used to avoid significant population

inversion buildup. The spectral resolution of the absorption measurements was 4.6 nm. The Er³⁺-absorption shows a broad one-shouldered band, the absorption being maximum (3.62 dB/cm) at a wavelength $\lambda = 1.531 \mu\text{m}$ and the shoulder being at a lower wavelength. The full width at half maximum (FWHM) is about 80 nm. The background losses given by the offset in the attenuation spectrum were determined to be $\leq 0.25 \text{ dB/cm}$. In measuring the luminescence spectrum (solid line), an argon-ion pumped DCM dye laser tuned at $0.660 \mu\text{m}$ was used as a pump source to excite the Er³⁺-ions in the waveguide. This wavelength coincides with the pump band of the Er³⁺-ion. A resolution of 2 nm was used to record the luminescence. The luminescence spectrum also shows up as a one-shouldered band, its maximum being at $\lambda = 1.533 \mu\text{m}$ and the shoulder being at a longer wavelength. The FWHM of 55 nm is smaller than that of the absorption band and the –3-dB points correspond to $1.515 \mu\text{m}$ and $1.57 \mu\text{m}$. In 0.2 at.% Er-doped Al₂O₃ slabguides, in contrast with 0.2 at.% Er-doped Y₂O₃ slab guides [3] under identical experimental conditions, no 0.98- μm luminescence could be detected and no green light was visible even when using a pump wavelength at $1.48 \mu\text{m}$. However, in samples with Er concentration $\geq 0.34 \text{ at.}\%$, under these conditions clear 0.98- μm and green luminescence bands were clearly detected (figure not shown).

Fig. 8 shows the dependence of the luminescence lifetime τ on the Er concentration (squares connected with dashed lines). The corresponding decay rate is also shown in the figure (filled circles). The lifetime decreases as the Er concentration increases, from 6.7 ms at a concentration of 0.04 at.% to 1.3 ms at 0.74 at.%. A simple diffusion process [13] can model the dependence of the lifetime τ on the concentration

$$\frac{1}{\tau} = \frac{1}{\tau_0} + q_1 \cdot N_{\text{Er}} \quad (1)$$

where τ_0 is the radiative lifetime, N_{Er} is the Er³⁺-concentration, and q_1 is the quenching coefficient. A fit of this model with the measurements gives a radiative lifetime of 11.3 ms and a quenching coefficient of $7 \cdot 10^{-25} \text{ m}^3/\text{s}$ and is shown in Fig. 8 (solid line). Note that the layers were not annealed.

The effect of annealing on this Er³⁺ lifetime has been studied. Fig. 9 presents the lifetime as a function of the anneal temperature at 1-h annealing time for samples with Er concentrations of 0.2 at.%. The lifetime increases from 4.4 ms to 5.5 ms as the anneal temperature increases. Similar effects of annealing have been observed by Mahnke *et al.* [7] in Er-doped Al₂O₃ films produced by MOCVD, and they appear to occur for any Er concentration. A noticeable drop in lifetime is observed at the annealing temperature of 600 °C. This has been confirmed by an accumulative annealing method [4] done on another set of samples.

From the measured absorption and emission spectra, the spectral distribution of the absorption and emission cross sections needed for calculating optical amplification can be determined. Here it is assumed that all erbium particles are optically active Er³⁺-ions [8]. In Fig. 10, the wavelength dependence of the absorption (solid line) and emission (dashed line) cross sections derived from the spectra in Fig. 7 are shown. The absorption

Fig. 7. Absorption spectrum (dashed line, right scale) and photoluminescence emission spectrum (solid line, left scale) of a 0.20 at. % Er-doped Al₂O₃ slab waveguide. The same sample was used for both spectra.

Fig. 8. Lifetime of the $^4I_{13/2}$ -state of Er³⁺-doped Al₂O₃ (squares + dashed line, right scale) and the corresponding decay rate (dark circles, left scale) as a function of the Er concentration.

Fig. 9. $^4I_{13/2}$ state lifetime versus the anneal temperature of a 0.2 at. % Er:Al₂O₃ layer.

cross section $\sigma^a(\nu)$ [cm²] was calculated from the measured attenuation $\alpha_{\text{Er}}(\nu)$ [dB/cm] using the relation

$$\sigma^a(\nu) = \frac{1}{10 \cdot \log(e)} \cdot \frac{\alpha(\nu)}{\Gamma \cdot N_{\text{Er}}} \quad (2)$$

where ν is the frequency and Γ is the mode confinement to the Er-doped region [3]. The emission cross section $\sigma^e(\nu)$ [cm²] was calculated using the Fuchtbauer-Ladenburg method [3]. This method implies the derivation of the emission cross section from the normalized luminescence spectral lineshape $g(\nu)$ scaled by the radiative lifetime

$$\sigma^e(\nu) = \frac{\lambda^2}{8 \cdot \pi \cdot n^2} \cdot \frac{1}{\tau_0} \cdot g(\nu) \quad (3)$$

where n is the refractive index of the guiding layer.

In order to assess the performance of the Er-doped Al₂O₃ waveguide amplifier realized by reactive co-sputtering, a first-

Fig. 10. The wavelength dependence of absorption (solid line) and emission cross sections (dashed line) of the Er³⁺ transitions in Er-doped Al₂O₃ layers.

TABLE II
EXPERIMENTALLY DETERMINED MATERIAL PARAMETERS, THE DIMENSIONAL
PARAMETERS, AND THE APPLIED WAVELENGTHS OF THE Er:Al₂O₃ CHANNEL
AMPLIFIERS AS USED FOR CALCULATING THE CURVES OF FIG. 11

Parameter	Symbols	Value
Film refractive index	n	1.64
Film thickness [nm]	d _{film}	800
channel width [μm]	w	2
Ridge height [nm]	h _{ridge}	230
Amplifier length[cm]	L	4
Er concentration [at.%]	N _{Er}	0.24
Er depth profile		Uniform
Pump wavelength [μm]	λ _p	1.48
Signal wavelength [μm]	λ _s	1.533
Pump absorption cross section [cm ²]	σ _p ^a	2.6 · 10 ⁻²¹
Signal absorption cross section [cm ²]	σ _s ^a	4.3 · 10 ⁻²¹
Pump emission cross section [cm ²]	σ _p ^e	0.9 · 10 ⁻²¹
Signal emission cross section [cm ²]	σ _s ^e	4.6 · 10 ⁻²¹
Radiative lifetime [ms]	τ ₀	11.3
Upconversion coefficient [m ³ /s]	u	0, (20 and 40) · 10 ⁻²⁵
background losses [dB/cm]	α	0.5
Quenching coefficient [m ³ s ⁻¹]	q ₁	7 · 10 ⁻²⁵

order estimate of the optical gain was made. The calculation was carried out using modeling tools developed in our group in collaboration with BBV Software [14]. The model takes into account the influence of the field profiles of the modes, the background attenuation, the quenching, and the upconversion. Values of basic amplifier parameters determined in this study, and optimized waveguide cross-section dimensions, as listed in Table II, have been used as input for the calculation, while channel losses of 0.5 dB/cm have been assumed. The calculations refer to a 4-cm-long ridge-type waveguide amplifier of which the core layer consists of 0.24 at.% Er-doped Al₂O₃. In Fig. 11, the small-signal gain at a signal wavelength of 1533 nm is shown as a function of the pump power at λ = 1.48 μm for various values of the upconversion coefficient. The first value 40 · 10⁻²⁵ m³/s is the value as determined for sputtered Al₂O₃ films with Er implantation [9], and the second value 20 · 10⁻²⁵ m³/s is the value we will deduce from measurements to be presented later on in this section. For clarity, a curve for a zero value of the upconversion coefficient has also been calculated.

From these curves, it can be concluded that the threshold powers are in the range 0–6 dBm (≈ 1–4 mW) and that at 10-dBm (10 mW) pump power the gain is in the range 4–7 dB/cm. Note that the chosen amplifier length is far from its op-

Fig. 11. Calculated small-signal gain at the 1533-nm wavelength as a function of 1.48-μm wavelength pump power of a 4-cm-long ridge waveguide 0.24 at.% Er:Al₂O₃ amplifiers for various values of the upconversion coefficient *u* (— *u* = 40 · 10⁻²⁵ m³/s, ····· *u* = 20 · 10⁻²⁵ m³/s, — *u* = 0). The values of the other parameters are given in the text.

TABLE III
DIMENSIONS OF THE AMPLIFYING CHANNEL GUIDES AS USED FOR THE GAIN
VERSUS PUMP POWER EXPERIMENTS, SAMPLES 1 AND 2

dimensions	Sample 1	Sample 2	Er:Al ₂ O ₃ [9]
Amplifier length [cm]	4	5.5	4
Channel Thickness [μm]	0.800	0.800	0.600
Channel width [μm]	2	2	2
Ridge height [μm]	0.250	0.250	0.300

timal value, i.e., the value defined by the local gain at the end of the amplifier section being zero dB/cm. For optimal values, higher gains are expected as will be shown later in Fig. 13. The results clearly illustrate the importance of lowering the upconversion coefficient, resulting in a lower threshold pump power and higher gain.

Especially for gaining more information about the upconversion coefficient for some 0.24 at.% Er doped Al₂O₃ channel structures (Sample 1 and Sample 2 of which the dimensions are given in Table III) made from different wafers, the small-signal gain at 1533 nm as a function of the pump power (1480 nm) has been obtained experimentally (see Fig. 12). Note that the low gain values obtained are mainly the result of nonoptimal dimensions and of channel losses exceeding the originally assumed value of 0.5 dB/cm. The origin of the latter can be found in the ion beam etching process (IBE) we have applied in these preliminary experiments for defining the ridge-type waveguide channels within the Al₂O₃ layers. As a result, the attenuation appeared to be dramatically increased to a value 10 dB/cm. This has to be ascribed to Ar- incorporation into the Al₂O₃ layer and the resulting lattice damage during the etching process. Annealing during 1 h at 700 °C appeared to be necessary for decreasing the attenuation

Fig. 12. Gain versus pump power curves for two Er: Al₂O₃ channel amplifiers. Solid lines: experimental curves; dotted lines: the best theoretical fits.

Fig. 13. Calculated gain versus pump power curves for various values of the upconversion coefficient [$u = 40 \cdot 10^{-25} \text{ m}^3/\text{s}$ (—); $u = 20 \cdot 10^{-25} \text{ m}^3/\text{s}$ (·····); $u = 0$ (- - -)], amplifier lengths being optimized for 9.4-dBm pump power. Dimensions: channel thickness is 790 nm, channel ridge height is 230 nm, and the channel width is 1.4 μm . The other applied parameters are given in the text.

to an acceptable value of $1.1 \pm 0.2 \text{ dB/cm}$, as has been measured by the cutback method on an undoped sample. It is expected that this annealing process will also deteriorate somewhat the value of the upconversion coefficient and hence wet etching of the amorphous Al₂O₃ layer is expected to be a preferable method. In spite of this high attenuation, the results of the gain versus pump power curves enable one to determine the values of the upconversion coefficient u , the quenching coefficient q_1 , the erbium concentration c , and background losses α by curve fitting. In this curve fitting, we start from the dimensions as given in Table III and the material parameters given in Table II, except, of course, for the four fitting parameters.

During the curve fitting, it appeared that the curves were especially sensitive to variations of the background losses and the upconversion coefficient. Sensitivities to the quenching coefficient and the Er³⁺-concentration were much smaller. The best parameter fits have to be considered as indicative, mainly be-

cause the model does not take into account all effects, such as ESA effects, expected to be relatively small compared to up-conversion effects [9]. Also, there are more sets of parameters which give the same fit quality. This has been expressed by the uncertainty limits of the parameters.

The parameters obtained from the curve fitting are given in Table IV inside the Sample 1 and Sample 2 columns. The values of the Er concentration and the background losses obtained from the curve fitting agree fairly well with the experimentally obtained ones. For comparison, values reported in the literature [9] for ion-implanted Er:Al₂O₃ materials are also given.

IV. DISCUSSION

The absorption spectrum shown in Fig. 7 with a peak at $\lambda = 1.531 \mu\text{m}$ is characteristic of the $^4I_{15/2} \rightarrow ^4I_{13/2}$ (ground state $\rightarrow$ first excited state) transitions in the Er³⁺-ion [15]. The pro-

TABLE IV
PARAMETER VALUES GIVING THE BEST FIT TO THE EXPERIMENTAL
GAIN VERSUS PUMP POWER CURVES GIVEN IN FIG. 12 (SAMPLES 1 AND
2) AND THEIR VALUES FOR A SIMILAR SYSTEM AS HAS BEEN
REPORTED IN THE LITERATURE

Parameters	Sample 1	Sample 2	Er:Al ₂ O ₃ [9]
Upconversion coefficient [10^{-25} m ³ /s]	20 ± 5	16 ± 5	41
Quenching coefficient [m ³ /s 10^{-25}]	6.0 ± 2	4.0 ± 2	?
Background loss [dB/cm]	1.1 ± 0.2	1.1 ± 0.2	0.35
Erbium concentration [at.%]	0.245 ± 0.01	0.23 ± 0.01	0.27

file of the spectrum is similar to that measured for Er-implanted in Al₂O₃ [8]. In Fig. 10, the wavelength dependence of the absorption and emission cross sections has been shown. The peak absorption and emission cross sections were determined to be $\sigma_s^a = 4.57 \cdot 10^{-25}$ m² and $\sigma_s^e = 4.63 \cdot 10^{-25}$ m² at wavelengths of 1.531 and 1.533 μ m, respectively. At the often used 1.48- μ m pump wavelength for Er-doped amplifiers, the absorption cross section is $\sigma_p^a = 2.6 \cdot 10^{-25}$ m² and the emission cross section is $\sigma_p^e = 0.9 \cdot 10^{-25}$ m². These values are in fair agreement with those determined for Er implanted in Al₂O₃ [8] and do not differ significantly from the peak emission cross sections in other host materials, $\sigma_s^e = 4.4 \cdot 10^{-25}$ m² in Al₂O₃ co-doped SiO₂ [17] and $\sigma_s^e = 5.5 \cdot 10^{-25}$ m² in Y₂O₃ [3]. Background losses have to be as small as possible because they have a severe influence on the obtainable gain. For obtaining low background losses in both undoped and Er-doped material in general, a post-anneal step is required [4]. In ion-implanted Er:Al₂O₃, the lattice damage caused by the incidence of highly energetic ions can be relaxed by annealing only [2]. Using our fabrication method, in slabguides, background losses of 0.25 dB/cm have been achieved without any annealing. To maintain this advantage in the real channel waveguide-type amplifiers, channel definition has to be done using wet etching methods.

For obtaining an appreciable gain over a large wavelength range, as is required for wavelength multiplexing, the relevant luminescence band around 1.54 μ m has to be broad and smooth. Er-doped Al₂O₃ is known to show such bands and indeed the luminescence spectrum, presented in Fig. 7, shows such a broad band. The value of the FWHM at ~ 55 nm is similar to values reported in the literature for Er-doped Al₂O₃ whether sputtered [2] or made by PECVD [6]. Here, the amorphous character of the Al₂O₃-films will lead to a severe inhomogeneous broadening as is also indicated from the fact that, in contrast with crystalline host materials such as Y₂O₃ and LiNbO₃, the individual transitions between the Stark levels cannot be distinguished. This band flattening will result in less wavelength dependence of the gain, as is desired by the application. The bandwidth is appreciably higher than that obtained in Er:SiO₂ (FWHM ~ 20 nm) [16] or in Er:SiO₂-Al₂O₃ (FWHM ~ 43 nm) [16].

Deteriorating effects like quenching and upconversion have to be small. It was stated before that inhomogeneous broadening should be beneficial to diminish the deteriorating quenching and upconversion effects, because now the energy transfer, being the core of both phenomena, is somewhat hampered. Indeed, with respect to other Er-doped Al₂O₃ materials reported in the literature [7], [9], an appreciably lower upconversion coefficient is obtained. This will be one of the origins of the observation

of the very low intensities of the 0.98- μ m and visible emission bands in our 0.2 at.% Er-doped Al₂O₃ slabguides. At higher doping levels, e.g., ≥ 0.34 at.%, 0.98- μ m and green luminescence were readily visible. However, no considerable decrease in the quenching coefficient with respect to Er-doped Y₂O₃ material [3] has been observed in spite of the reduced energy migration. This can be caused by a larger amount of quenching centers in our Al₂O₃ material. The difference between the quenching coefficients as obtained for the nonannealed and the annealed samples, $7 \cdot 10^{-25}$ and $4-6 \cdot 10^{-25}$ m³/s, respectively, suggests that annealing reduces the number of quenching centers. This is supported by the effect of annealing on luminescence lifetime, shown in Fig. 9, manifesting itself as a moderate lifetime increase as the annealing temperature increases. The discontinuous behavior at 600 °C resembles that observed in Er-implanted Al₂O₃ films around 825 °C [2]. Although the exact reason for that is not yet known, it might be due to annealing-induced changes in the structure of the films [3].

The gain at a signal wavelength of 1533 nm obtained at 9.4-dBm pumping power is still low, especially when compared to the gain obtained for a comparable Er-ion-implanted Al₂O₃ layer of 2 dB [9]. However, it has to be noted that the low gain is mainly the consequence of amplifier dimensions not being the optimal ones and of the relatively high attenuation originating from the IBE channel etching process. By adjusting the cross-sectional dimensions and by substituting wet etching for IBE, acceptable small-signal gain is expected to be obtainable. Using all parameter values derived before, for a given cross section of the waveguide (see the caption of Fig. 13), the gain-pump power curves have been calculated assuming background losses of 0.5 dB/cm at amplifier lengths being optimal at 10-dBm pumping power. The curves calculated for different values of the upconversion coefficient are shown in Fig. 13. From that figure, it can be concluded that using 9.4-dBm pump power and inserting a value of the upconversion coefficient equal to $20 \cdot 10^{-25}$ m³/s, 8-dB gain can be obtained. The reduction of the upconversion coefficient from $40 \cdot 10^{-25}$ to $20 \cdot 10^{-25}$ m³/s appears to translate into a 2-dB higher gain. This value is somewhat higher than was calculated for the 4-cm-long amplifiers (Fig. 11) as could be expected, because now, in the extra amplifier section, population inversion has to be obtained. That gain can be increased even further by a possibly lower value of the upconversion coefficient as a result of skipping the annealing process by optimizing the Er concentration with respect to the lower value of the upconversion coefficient and by optimizing the channel dimensions.

V. PROSPECTS OF REACTIVE CO-SPUTTERING

From the results that have been presented and discussed, it can be noticed that reactive co-sputtering is a flexible technique with many interesting features as compared to other techniques. It has been shown in this paper that optimum Er:Al₂O₃ films can be obtained at relatively low substrate temperatures and with no further annealing step necessary. The relatively low temperature makes the deposition process compatible with microelectronics technologies and will allow for the full integration of optics, being fabricated by reactive

co-sputtering, and electronic circuits already implemented in the substrate Si-wafer. Also, the low-temperature process affords the realization of complex multilayer structures where temperature-induced stresses could otherwise be a problem. Low-temperature reactive co-sputtering produces $\text{Er}:\text{Al}_2\text{O}_3$ films in which, due to the low adatom mobility, the Er^{3+} -ions are expected to be homogeneously distributed at the atomic scale over the Al_2O_3 host. Consequently, high concentrations can be achieved without clustering of Er^{3+} -ions. Furthermore, in reactive co-sputtering, the Er concentration in the transverse direction is a free parameter, by simply varying the power supplied to the Er-sputtergun, the Er profile in that direction can be adjusted to exactly match the distribution of the field profile of the optical mode in the waveguide. Using multisputterguns system, it is possible to co-dope Pr^{3+} or Nd^{3+} together with Er for obtaining amplification around 1.3 and 1.5 μm in one device. A multigun configuration also offers the possibility of obtaining layers of any Al/Y ratio of the host, the low substrate temperature hampering the phase segregation, and, indeed, undoped Al_2O_3 - Y_2O_3 films made by reactive co-sputtering with any Al/Y ratio have been reported only very recently [18]. This mixing possibility offers the prospect of varying and optimizing the shape of the Er emission spectrum.

VI. CONCLUSIONS

We have demonstrated the deposition of Er-doped Al_2O_3 films using reactive co-sputtering and we have optimized the deposition technology for application of these films in optical amplification. The films obtained at a relatively low substrate temperature (400 °C) are amorphous and show a homogeneous structure without columns or grains and the slabguides show background losses ≤ 0.25 dB/cm. These background losses, which have serious impact on the amplifier gain, are the lowest ever measured for as-deposited Er-doped Al_2O_3 layers. The relatively low deposition temperature and the fact that no post-annealing is needed make the realization of complex multilayer systems, where heat-induced stress is considered to be a problem, possible and further allows for the integration of reactively co-sputtered optics with microelectronic devices. Relevant for wavelength multiplexing, a broad photoluminescence band having a FWHM of about 55 nm has been measured. In the resulting layers, the upconversion effect was relatively small ($20 \cdot 10^{-25}$ m^3/s), enabling the optimal Er concentration and thus the gain to be increased. Simulations based on experimentally determined material parameters and optimized waveguide cross sections showed that a signal gain over 8 dB can be obtained on a 7.7-cm-long 0.2 at.% Er-doped Al_2O_3 amplifier channel pumped at $\lambda = 1.48$ μm with a pump power of 8.7 mW only. By improving the channel etching process and by further optimization of the dimensions, even higher gain is expected. The determined optimal deposition parameters for $\text{Er}:\text{Al}_2\text{O}_3$ films will greatly assist in optimizing the co-sputtering sputtering process of single-phase $\text{Er}:\text{Al}_2\text{O}_3$ - Y_2O_3 systems.

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