# Optical gain at 1.53 $\mu$m in Er3+-Yb3+ codoped oxidised porous silicon waveguides

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# Optical gain at 1.53 μm in $Er^{3+}$–$Yb^{3+}$ co-doped porous silicon waveguides

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Erbium–ytterbium (Er–Yb)-co-doped porous silicon planar waveguides were prepared from $P^+$-type (1 0 0) oriented silicon wafer. Erbium and ytterbium ions were electrochemically introduced into the porous structure of the waveguide core. The doping profiles of erbium and ytterbium ions were determined by EDX analysis performed on sample cross-section. The mean concentration in the guiding layer is of about $1 \times 10^{20}$ cm $^{-3}$. The refractive indices were measured from co-doped porous silicon and undoped waveguides after the thermal treatments. The photoluminescence (PL) peak of optically activated erbium ions at 1.53 μm was recorded. The PL enhancement is the result of the energy transfer from the excited state of Yb to the state of Er. Optical losses at 1.55 μm were measured on these waveguides and were of about 2 dB/cm. An internal gain at 1.53 μm of 5.8 dB/cm has been measured with a pump power of 65 mW at 980 nm.

*Keywords:* Optical gain; Erbium–ytterbium; Porous silicon; Waveguides

## 1. Introduction

Since the last few years, erbium (Er) and ytterbium (Yb) doped material such as glasses have received much attention due to their applications as amplifiers in optical telecommunication in the 1.55 μm [1]. Recently, progress has been achieved in this field, one of the most successful application is the Er doped optical amplifier [2]. However, it would be difficult to further enhance the emission efficiency of Er, because of its low absorption cross-section at 980 nm. A good alternative is to codope Yb with Er into a material. The ytterbium ion has a strong absorption at 980 nm and thus has made it an obvious candidate for its use as a sensitizer for other luminescing ions. Codoping with Yb has been shown to increase the photoluminescence (PL) emitted by the rare earth like Er. Sensitization in this case relies on the fact that the $^2F_{5/2}$ level of Yb and the $^4I_{11/2}$ level of Er are nearly resonant in energy [3,4]. Due to its high absorption cross-section, Yb absorbs the pump radiation at 980 nm efficiently and can transfer this absorbed energy to Er. This process is more efficient than direct excitation of Er in many materials. The success of codoping Er/Yb technique has been demonstrated in various materials, as porous silicon [5,6]. Porous silicon (PS) offers a large range of refractive indices and present a high specific surface for elements incorporations. The modulation of the experimental parameter (current density) process allows to modify the porosity during anodization to obtain the refractive index jump between the core and the cladding layers. Erbium and ytterbium ions were successfully introduced in porous silicon by many methods such as ion implantation [7], molecular beam epitaxy [8,9], co-sputering [10] or by electrochemical deposition [11,12].

In this paper, we present a study of the optical properties performed on planar porous silicon waveguide (PSWG) prepared by varying the anodization current density during the formation of porous silicon. Erbium and ytterbium ions were introduced into the PSWG by electrochemical deposition. The concentration profiles of Er and Yb in the planar PSWG was determined by Energy Dispersive X ray (EDX) analysis. Refractive index measured at 1.53 μm was determined for the co-doped PSWG after the thermal treatments. Photoluminescence (PL) of Er was measured at room temperature by using Argon laser excitation at 488 nm. Optical loss measurements at 1.55 μm were investigated by measuring the light streak scattered out of the upper surface of the PSWG. The "on/off" gain at 1.53 μm of co-doped waveguide has been also measured for a 0.5 cm length samples at 980 nm pumping.

## 2. Sample preparation and experimental arrangements

Porous silicon layers were elaborated by anodic etching of $P^+$ type wafer using (1 0 0) oriented Si substrates. The resistivity

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of the wafer was 4–6 mΩ cm. The anodization was performed in a (HF 50%, $C_2H_5OH$, $H_2O$: 2:2:1) electrolyte. Two-step anodization process was performed. At first, current density of 50 mA/cm$^2$ was applied to obtain a guiding layer with a 3 μm-thickness. Then, the current density was raised up to 80 mA/cm$^2$ to form the cladding layer with a 5 μm-thickness.

In order to dope the as-prepared porous silicon layers, Er or Er–Yb were electrochemically deposited onto the PSWG at a constant current density of 0.1 mA/cm$^2$ for 10 min. For the Er–Yb codopage, the [Yb]/[Er] concentration rate was equal to 3 in the electrolyte solution.

Thermal treatments of the obtained PSWG were performed using a three-step process. First, the porous structure was stabilized by a pre-oxidation at a low temperature (300 °C) in wet $O_2$, then the PSWG was oxidized at 900 °C in wet $O_2$. Lastly, the temperature was raised up 1000 °C in a $N_2$ gas to diffuse and activate the rare earth ions.

In order to estimate the Er and Yb concentration in the layers, SEM observations coupled with EDX analysis were performed on the sample cross-section. The error is estimated at 0.25 at.% by taking into consideration the concentration variation between the different analysed zones. The reflectance spectra of the porous layers after thermal treatments were obtained by a Lambda 900 Perkin-Elmer beam spectrometer equipped with a specular reflectance module with a 6° fixed angle. The parameters (refractive index and thickness of porous layer) associated with transfer matrix formalism are adjusted to fit the experimental spectra by using the Bruggeman model [13]. The absolute errors are equal to ±0.01 and ±5 nm, respectively, for refractive index and thickness. The infrared photoluminescence (IR-PL) of the samples was obtained from $Ar^+$ laser excitation at 488 nm. The pump power was equal to 125 mW over a circular area of ∼1 mm in diameter and the laser beam was mechanically chopped. The luminescence signal was analysed by a Jobin–Yvon monochromator and it was detected by an InGaAs photodiode. Optical losses were measured by studying the scattered light from the surface of the waveguide [14,15]. Laser light was coupled into the waveguide by a single-mode fiber. The intensity of the scattered light was recorded with a digital camera placed on the top of the surface sample. Transverse scanning along the light propagation direction enabled the 2D light intensity distribution of the guided modes to be obtained. The curve of light intensity as a function of $z$-propagation distance was obtained by integrating the data along each sampling transverse line. The light intensity decreases exponentially with the $z$-propagation distance. In this study, the attenuation values were averaged from several measurements performed on several places of the sample. The first 1–2 mm length from the input facet of the obtained photograph were not considered to improve the signal to noise ratio and also to avoid taking the multiple scattering at the injection point into account.

The "on/off" optical gain ($G_{on/off}$) measurements were measured using a 0.5 cm length co-doped planar PSWG. A 980 nm beam, emitted from laser diode and coupled into a single mode fibre, was used as the pump. The pump and the signal beam at 1.53 μm, emitted from a laser diode (Agilent 81680A) were combined by a 980/1530 nm wavelength multiplexer, and were

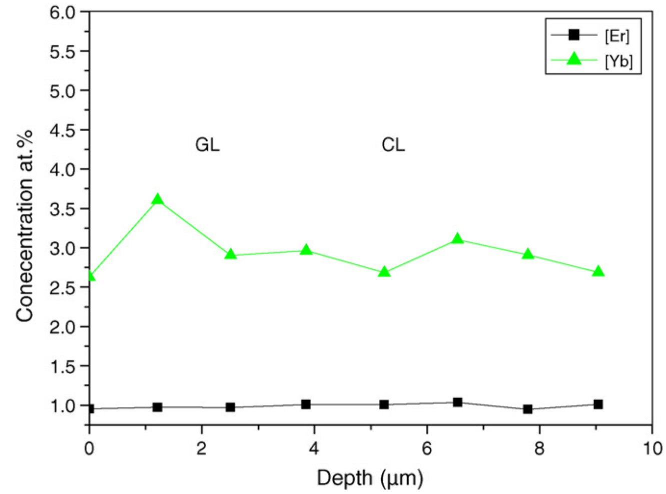


Fig. 1. Er and Yb concentration profiles as a function of porous silicon waveguides depth (GL: guiding layer and CL: cladding layer) obtained by (EDX) analysis.

then coupled into the PSWG with a microlensed optical fiber. The output light from the waveguide was focused with a microscope objective in a Jobin–Yvon monochromator and detected by a camera (InGaAs). By keeping the input signal power (100 μW) constant, for each pumping power, the intensity of the signal power coupled out of the WG was measured when the pump laser was off ($I_0$) and on ($I_1$). Curves of the "on/off" gain (dB/cm), defined as $10/l \log(I_1/I_0)$ where $l$ is equal to 0.5 cm long, were recorded as a function of the pump power. Then the internal gain is deduced by subtracting the losses performed on the co-doped waveguide [16].

## 3. Results and discussion

By EDX analysis performed in different regions of the PSWG, the profiles of Er and Yb have been determined for different samples. The Er and Yb profiles are reported in Fig. 1. They reveal that the Er and Yb distribution are very homogenous in depth. The value of Er concentration in the guiding layer (GL) is of about 1 at.% which corresponds approximately to $1.1 \times 10^{20}$ cm$^{-3}$. Similarly, the Yb concentration is nearly constant GL. The value of Yb concentration is equal to $3.5 \times 10^{20}$ cm$^{-3}$, three times important than Er concentration as expected regarding the [Yb]/[Er] concentration rate in the electrolyte solution.

Refractive index measurements were performed on single layer corresponding to low and high current density (50 or 80 mA/cm$^2$) for undoped and co-doped waveguides. The results are reported in Table 1. After thermal treatments, the refractive

Table 1
Refractive index of guiding and cladding layers at 1.53 μm of undoped and codoping PSWG after thermal treatments

| | Current density (mA/cm$^2$) | PSWG | Co-doped PSWG |
|---|---|---|---|
| GL | 50 | 1.31 | 1.35 |
| CL | 80 | 1.23 | 1.32 |

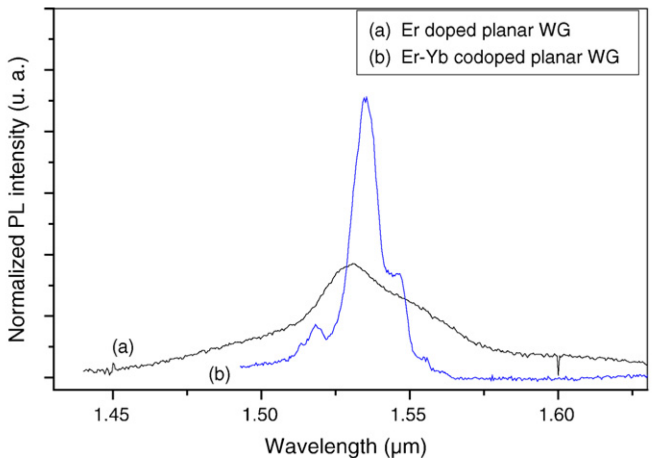


Fig. 2. Room temperature photoluminescence spectra relative to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of $Er^{3+}$ for erbium doped porous silicon waveguide (a) and Er–Yb co-doped porous silicon waveguide (b) after thermal treatments with excitation pump powers at 488 nm.

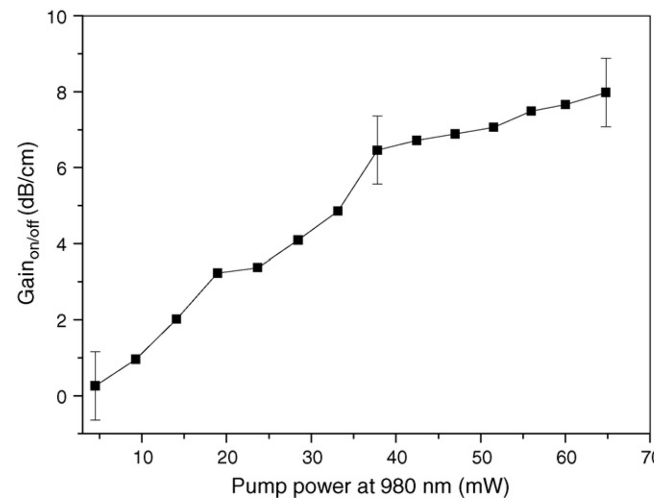


Fig. 3. Measurement of the "On/Off" Gain at 1.53 μm for a 0.5 cm long Er–Yb co-doped planar PSWG as a function of 980 nm pump power, the input signal power is equal to100 μW.

index of each layer decreases and has a lower value than the one of silica [17]. So, the oxidized layers remain porous. In addition, the index contrast still exits but decreases and is equal to 0.08. After codoping, we notice that the refractive index increases due to the Er and Yb presence. For example, the refractive index of undoped oxidized porous layer fabricated by 50 mA/cm$^2$ and co-doped layers are respectively equal to 1.31 and 1.35. The same values for co-doped PSWG were determined for the Er doped waveguides [18]. This increase of refractive index reveals that the Er and Yb incorporation into the porous layer is effective in accordance with EDX results. These values were also verified on planar waveguides elaborated with the same conditions than those of single-layers. Moreover, after thermal treatments, the thickness of the layer increases of about 25% due to the transformation of silicon into silica, which leads to a volumic expansion [19].

The photoluminescence (PL) spectra of Er–Yb co-doped PSWG and Er doped PSWG were compared in Fig. 2. The $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition centered at 1.53 μm was observed in the two cases for waveguides. Indeed, the intensity of PL of Er–Yb co-doped PSWG is nearly three times as stronger as Er doped PSWG. The absorption cross-section of Er is relatively small and therefore could not lead to an enhanced emission. This can be ameliorated by the introduction of Yb as a sensitizer. The greater absorption cross-section of Yb, coupled with efficient resonant energy transfer between the $^2F_{5/2}$ level of Yb and the $^4I_{11/2}$ level of Er, can significantly enhance emission at 1.53 μm at room temperature. The excitation of Er ions occurs mainly via energy transfer from the Yb ($^2F_{5/2}$) to the Er ($^4I_{11/2}$) state when it is pumped at 488 nm. After the selective excitation of the Yb ($^2F_{5/2}$) state, it can relax radiatively to the $^2F_{7/2}$ ground state, producing luminescence in the 920–1100 nm range, or transfer to the $^4I_{11/2}$ level of Er ion via the cross relaxation process.

Optical loss measurements performed on the doped and co-doped porous silicon planar waveguides at 1.55 μm were measured. The value of loss was equal to 1.1 dB/cm for the Er doped-PSWG and 2.1 dB/cm for the Er–Yb co-doped ones; while, for undoped waveguides the loss was equal to 0.7 dB/cm [18]. This loss in the doped PSWG can be explained principally by surface scattering which plays a significant role at these wavelengths [18,20]. In fact, the optical losses depend on the interface roughness between the layers (interface scattering) and nanostructure scattering inside each layer (volume scattering). Moreover, the presence of Er increases the absorption at 1.53 μm.

The $G_{on/off}$ was measured while varying the 980 nm-pump power in the range from 5 to 70 mW (always measured at the end of the in-couling fibre). The plot is shown in Fig. 3, which refers to a planar PSWG with 0.5 cm length. At low pump powers, the Er is not excited to the upper level and most of the signal is absorbed. By increasing the pump power, the excited Yb concentration is increased because the higher absorption cross-section which limits the propagation of the pump through the waveguide. However, the enhancement of the output signal from the PSWG is due to the increased of the excited Er because of the energy transfer from Yb to Er. Confirmed by PL, the result indicates that the presence of Yb is effective and we can try to increase the excited Er ions. As a result we obtain a maximum for the $G_{on/off}$ of $7.9 \pm 0.9$ dB/cm at a 65 mW pump power. By subtracting the losses performed on the co-doped waveguide, the internal gain is equal to 5.8 dB/cm at this pump power. This value is higher than the 0.56 dB/cm reported in ref. [2] for silicon rich silica waveguide containing Er ions, because that emission cross-section at 1.53 μm and absorption cross-section at 980 nm are increased with the presence of Yb and therefore the internal gain is more significant. To our knowledge, this is the highest internal optical gain per unit length reported in the literature for Er–Yb co-doped porous silicon planar waveguide at such pump power values.

## 4. Conclusion

We have fabricated a porous silicon planar waveguide and Er–Yb were introduced by the electrochemically method. The incorporation of Er and Yb were determined by EDX analysis and the refractive indexes of cladding and guiding layers were measured. Strong PL was observed at 1.53 μm and we have concluded that the PL enhancement was the result of the energy transfer from the excited states of Yb to that of Er. An internal optical gain of 5.8 dB/cm was measured at 1.53 μm for PSWG of 0.5 cm in-length and a pump power of 65 mW.

## References


[1] B.C. Hwang, S. Jiang, T. Luo, J. Watson, S. Honkanen, Y. Hu, F. Smektala, J. Lucas, N. Peyghambarian, Electron. Lett. 35 (12) (1999) 1007.

[2] D. Navarro-Urrios, M. Melchiorri, N. Daldosso, L. Pavesi, C. Garcıa, P. Pellegrino, B. Garrido, G. Pucker, F. Gourbilleau, R. Rizk, J. Lumin. 121 (2006) 249–255.

[3] J.F. Philipps, T. Töpfer, H. Ebendorff-Heidepriem, D. Ehrt, R. Sauerbrey, Appl. Phys. B 74 (3) (2002) 233.

[4] Huang Lihui, Liu Xingren, Xu Wu, Chen Baojiu, Lin Jiuling, J Appl. Phys. 90 (2001) 5550.

[5] V. Filippov, P. Pershukevich, V. Homenko, V. Bondarenko, M. Balucani, A. Ferrarri, Phys. Chem. Appl. Nanostruct. 58 (1997).

[6] V.V. Filippov, P.P. Pershukevich, V.V. Kuznetsova, V.S. Homenko, J. Lumin. 99 (2002) 185.

[7] Y.H. Xie, E.A. Fitzgerald, Y.J. Mii, J. Appl. Phys. 70 (1991) 3223.

[8] J.L. Benton, D.J. Eaglesham, A. Almonte, P.H. Citrin, M.A. Marcus, D.L. Adler, D.C. Jacobson, J.M. Poate, Mater. Res. Soc. Symp. Proc. 298 (1993) 447.

[9] H. Ennen, G. Pomrenke, A. Axmann, K. Eisele, W. Haydl, J. Schneider, Appl. Phys. Lett. 46 (1985) 381.

[10] G. Gu, Y.W. Du, T. Yu, Thin Solid Films 315 (1998) 263.

[11] T. Kimura, A. Yokoi, H. Horiguchi, R. Saito, T. Ikoma, A. Sato, Appl. Phys. Lett. 65 (1994) 983.

[12] A. Najar, J. Charrier, H. Ajlani, N. Lorraine, H. Elahouichet, M. Ouislati, L. Haji, J. Lumin. 121 (2006) 245.

[13] D.E. Aspnes, Thin Solid Films 89 (1982) 249.

[14] W. Teiss, Surf. Sci. Rep. 29 (1997) 91–192.

[15] Y. Okamura, S. Yoshinaka, S. Yamamoto, Appl. Opt. 22 (23) (1983) 3892.

[16] Y. Le Luyer, Ph.D., at INPG of Grenoble, 1997.

[17] J. Charrier, E. Le Gorju, L. Haji, M. Guendouz, J. Porous Mater. 7 (2000) 243–246.

[18] A. Najar, H. Ajlani, J. Charrier, N. Lorrain, S. Haesaert, M. Oueslati, L. Haji, Physica B 396 (1–2) (2007) 145.

[19] K. Barla, R. Herino, G. Bomchil, J. Appl. Phys. 59 (1986) 439.

[20] P. Pirasteh, J. Charrier, Y. Dumeige, S. Haesaert, P. Joubert, J. Appl. Phys. 101 (7) (2007) 083110.