High quality factor Er^{3+}-activated dielectric microcavity fabricated by rf sputtering

A. Chiasera[a)]
CNR-IFN, Istituto di Fotonica e Nanotecnologie, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

R. Belli
Dipartimento di Fisica, Università di Trento, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

S. N. B. Bhaktha and A. Chiappini
CNR-IFN, Istituto di Fotonica e Nanotecnologie, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy and Dipartimento di Fisica, Università di Trento, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

M. Ferrari and Y. Jestin
CNR-IFN, Istituto di Fotonica e Nanotecnologie, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

E. Moser
Dipartimento di Fisica, Università di Trento, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

G. C. Righini
CNR, Department of Materials and Devices, via dei Taurini 19, 00185 Roma, Italy

C. Tosello
Dipartimento di Fisica, Università di Trento, CSMFO Group, via Sommarive 14, 38050 Povo, Trento, Italy

(Received 21 July 2006; accepted 8 September 2006; published online 26 October 2006)

The authors report on one-dimensional dielectric photonic crystals activated by Er^{3+} ion and fabricated by rf-sputtering deposition. The cavity was constituted by an Er^{3+}-doped SiO_2 active layer inserted between two Bragg reflectors consisting of six pairs of SiO_2/TiO_2 layers. Near infrared transmittance spectra evidence the presence of a stop band from 1350 to 1850 nm and a cavity resonance centered at 1537 nm. Intensity enhancement and narrowing of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission band of Er^{3+} ion, due to the cavity effect, were observed. A cavity quality factor of 171 was achieved. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2364841]

The recent developments of optically confined structures have opened new possibilities in the field of both basic and applied physics, in a large area covering information communication technologies, health and biology, structural engineering, and environment monitoring systems. As far as telecommunications are concerned, Er^{3+}-activated glasses have become one of the key materials in photonic systems because of their relevance for the development of optical amplifiers. The short-term goal is to develop appropriate material systems and devices to exploit at the best the luminescence properties of erbium. Er^{3+}-activated confined structures at different scales thus offer interesting solutions. The last decade has seen a remarkable increase in the experimental efforts to control and enhance emission properties of emitters by tailoring the dielectric surrounding of the source. With this aim, several approaches, using nanocomposite materials[1] or specific geometries, such as planar interfaces,[2] photonic crystals,[3] solid state planar microcavities,[4,5] dielectric nanospheres,[6] and spherical microresonators,[7] have been proposed. Among these systems, planar microcavity resonators, also called one-dimensional (1D) photonic crystals, are the simplest photonic band-gap device exploitable to manage the spontaneous emission rate of an excited atom in the weak-coupling regime where the cavity decay time is much shorter than the atom-cavity mode interaction time.[4,5,8,9] As far as Er^{3+} ions are concerned, Vradenberg *et al.*[4] reported on an Er^{3+}-doped SiO_2 active region sandwiched between two distributed Bragg reflectors (DBRs) composed of Si/SiO_2 quarter-wave layers. Upon 980 nm excitation, the peak intensity at 1535 nm was enhanced by nearly 60, compared to the no-cavity yield at the corresponding wavelength, and the full width at half maximum (FWHM) was about 10 nm.

Fabrication of planar microcavities using oxide-based dielectric materials is of particular interest because it is possible to obtain devices transparent in the UV-visible-near infrared region and suitable for application in environments that see elevated temperature, corrosion, and radiation.[10,11] Several techniques have been employed to fabricate Fabry-Pérot dielectric microcavities where deposition of thin and smooth dielectric layers that constitute DBRs is mandatory to achieve a high quality factor (Q). Literature presents results obtained by using electron-beam evaporation,[12] sol-gel,[5,10] ion plating,[9] and sputtering[11,13] processes.

In this letter we report on an Er^{3+}-codoped all-dielectric microcavity fabricated by rf sputtering (RFS) and operating at 1544 nm. The microcavity consists of a SiO_2 half-wave

[a)]Electronic mail: achiaser@science.unitn.it

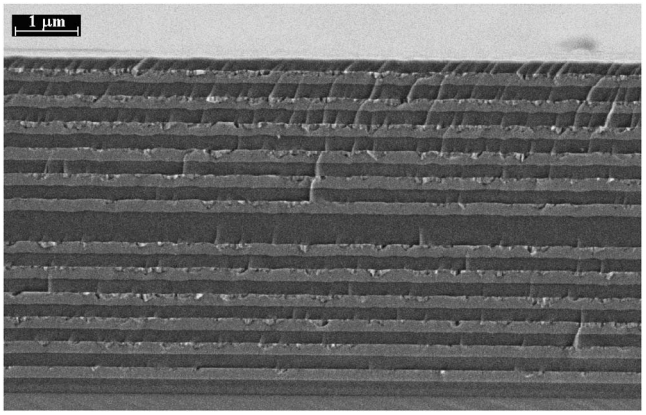

FIG. 1. Cross section image of the sample performed with the scanning electron microscopy. The bright and the dark areas are TiO_2 and SiO_2 layers, respectively.

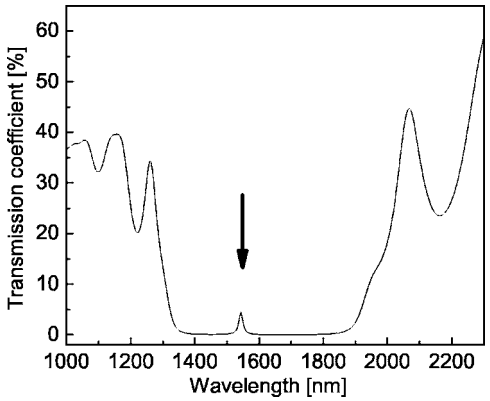

FIG. 2. Transmittance spectrum of the cavity with six doublet Bragg mirror. The stop band lies from 1350 to 1850 nm. The cavity resonance corresponds to the sharp maximum at the center of the transmission window. The incident light is not polarized.

layer inserted between two Bragg reflectors constituted by a stack of six pairs of alternated SiO_2 and TiO_2 quarter-wave layers. Each SiO_2 layer is activated with 0.3 at. % of Er^{3+} ions, as measured by energy dispersive spectroscopy using a Noran Instruments mod. Voyager apparatus. The refractive indices at 1542 nm of the silica and titania layers, measured by *m*-line spectroscopy on the single films, were 1.444 ± 0.002 and 2.30 ± 0.02, respectively. To increase the reflection coefficient of the DBRs, the index contrast between the two materials has to be as large as possible, and TiO_2 and SiO_2 have been chosen.[5,10] The samples were deposited on silicon and silica substrates. The sample deposited on silicon was employed for scanning electron microscopy (SEM) measurements. The sample deposited on silica substrate was employed for transmittance and photoluminescence (PL) measurements. In order to improve the adhesion of the films, the substrates were cleaned inside the RFS deposition chamber by removing some atomic layers just before the deposition procedure: in this presputtering stage the face of the substrates is exposed to the plasma for 10 min. Sputtering deposition of the films was performed by sputtering alternatively a 4 in. titania target and a 4 in. silica target on which metallic erbium pieces were placed. The deposition time necessary to reach the appropriate thicknesses of the Bragg grating layers was 14 min 15 s for the titania target and was 11 min 15 s for the silica target. The deposition time necessary to reach the appropriate thickness of the silica defect layer, to obtain a cavity resonance centered at 1.5 μm, was 25 min. The residual pressure, before deposition, was about 2×10^{-7} mbar. During the deposition process the substrates were not heated. The sputtering occurred with an Ar pressure of 5×10^{-3} mbar; the applied rf power was 150 W, with reflected powers of 16 and 0 W for silica and titania targets, respectively.

A SEM image of the cross section of the cavity is shown in Fig. 1. The dark regions correspond to the SiO_2 layers and the bright ones to the TiO_2 layers. It is possible to identify the defect layer and the two Bragg reflectors. The SEM image allowed us to measure thicknesses of 210 ± 5 and 195 ± 5 nm for the silica and titania layers, respectively, of the Bragg mirrors, and a thickness of 490 ± 5 nm for the SiO_2 defect layer.

The transmittance spectrum of the cavity, obtained by using a Varian-Carry spectrophotometer, is shown in Fig. 2. The spectral reflection range, i.e., the stop band, lies from 1350 to 1850 nm. A sharp peak in the transmittance spectrum appears at 1544 nm (see the arrow in Fig. 2). It corresponds to the cavity resonance wavelength related to the half-wave layer inserted between the Bragg mirrors.

Figure 3 compares the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ PL spectrum of the cavity activated by Er^{3+} ions and the PL spectrum of the single Er^{3+}-doped SiO_2 active layer, without Bragg mirrors. Both the cavity and no-cavity structures were excited with the 514 nm line of an Ar+ion laser with an excitation power of 100 mW. The luminescence was dispersed by a 320 mm single-grating monochromator with a resolution of 1 nm. The light was detected using a Hamamatsu photomultiplier tube and standard lock-in technique. The details about the experimental setup were reported in a previous paper.[14] For this analysis, the samples are fixed on a rotating holder. The PL from the cavity and from the Er^{3+}-doped single SiO_2 layer was detected at 5° from the normal on the samples, with a solid angle of 10^{-1} s. The erbium emission from the no-cavity single SiO_2 active layer is centered at 1538 nm with a FWHM of 28 nm and exhibits the characteristic shape of erbium ion emission in silica glass.[15] The cavity resonance is strongly dependent on the detection angle;[10] for a detection angle of 5°, the cavity resonance corresponds to the maximum of the erbium PL of the no-cavity SiO_2 active layer. The peak luminescence intensity of Er^{3+} ions is enhanced by a factor of 90, compared to the no-cavity yield at

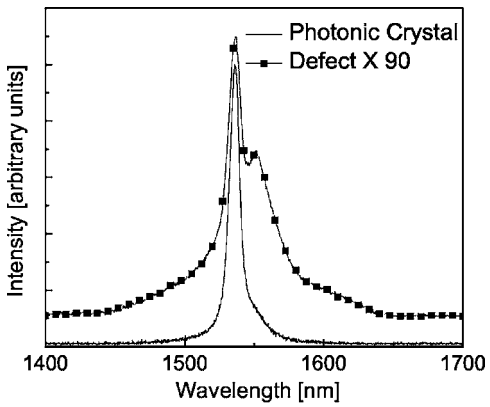

FIG. 3. $^4I_{13/2}\rightarrow{}^4I_{15/2}$ photoluminescence spectra of the cavity activated by Er^{3+} ion (1D photonic crystal) and of the single Er^{3+}-doped SiO_2 active layer without Bragg mirrors (defect). The light is recorded at 5° from the normal on the samples upon excitation at 514.5 nm.

the corresponding wavelength. The Er^{3+} $^4I_{13/2} \rightarrow {}^4I_{15/2}$ PL line shape is strongly modified by the cavity, and the Er^{3+} emission is enhanced when the wavelength corresponds to the cavity resonant mode and weakened for the other emission wavelengths. A sharp line is observed for PL spectrum from the cavity, as shown in Fig. 3. The FWHM is 9 nm, corresponding to a quality factor of the cavity, Q, equal to 171, assuming that no photon reabsorption occurs.[5,9]

In summary, we fabricated via the rf-sputtering technique an Er^{3+}-activated microcavity with a quality factor of 171 using Er^{3+}-doped SiO_2 and TiO_2 thin films. The transmittance spectrum shows a cavity resonance centered at 1538 nm with a stop band from 1350 to 1850 nm. Er^{3+} luminescence enhancement of 90 times, due to the cavity effect, was observed. We can affirm that rf sputtering is a suitable technique to fabricate all-dielectric erbium-activated microcavities operating at 1.5 μm.

The authors acknowledge the financial support of MIUR-FIRB RBNE012N3X-005, PAT (2004–2006) FAPVU, and ITPAR (2003–2006).

[1]V. K. Tikhomirov, D. Furniss, A. B. Seddon, I. M. Reaney, M. Beggiora, M. Ferrari, M. Montagna, and R. Rolli, Appl. Phys. Lett. **81**, 1937 (2002).
[2]E. Snoeks, A. Lagendijk, and A. Polman, Phys. Rev. Lett. **74**, 2459 (1995).
[3]J. Kalkman, E. de Bres, A. Polman, Y. Jun, D. J. Norris, D. C. 't Hart, J. P. Hoogenboom, and A. van Blaaderen, J. Appl. Phys. **95**, 2297 (2004).
[4]A. M. Vredenberg, N. E. Hunt, E. F. Schubert, D. C. Jacobson, J. M. Poate, and G. J. Zydzik, Phys. Rev. Lett. **71**, 517 (1993).
[5]J. Bellessa, S. Rabaste, J. C. Plenet, J. Dumas, J. Mugnier, and O. Marty, Appl. Phys. Lett. **79**, 2142 (2001).
[6]H. Schniepp and V. Sandoghdar, Phys. Rev. Lett. **89**, 257403 (2002).
[7]L. Yang, T. Carmon, B. Min, S. M. Spillane, and K. J. Vahala, Appl. Phys. Lett. **86**, 091114 (2005).
[8]L. Zhou and G. Li, Opt. Commun. **230**, 347 (2004).
[9]H. Rigneault, C. Amra, S. Robert, C. Begon, F. Lamarque, B. Jacquier, P. Moretti, A. M. Jurdyc, and A. Belarouci, Opt. Mater. (Amsterdam, Neth.) **11**, 167 (1999).
[10]K. M. Chen, A. W. Sparks, H.-C. Luan, D. R. Lim, K. Wada, and L. C. Kimerling, Appl. Phys. Lett. **75**, 3805 (1999).
[11]S. F. Chichibu, T. Ohmori, N. Shibata, and T. Koyama, Appl. Phys. Lett. **88**, 161914 (2006).
[12]L. Persano, P. Del Carro, E. Mele, R. Cingolani, D. Pisignano, M. Zavelani-Rossi, S. Longhi, and G. Lanzani, Appl. Phys. Lett. **88**, 121110 (2006).
[13]P. Kelkar, V. Kozlov, H. Jeon, A. Nurmikko, C. C. Chu, D. C. Grillo, J. Han, C. G. Hua, and R. L. Gunshor, Phys. Rev. B **52**, R5491 (1995).
[14]A. Chiasera, C. Tosello, E. Moser, M. Montagna, R. Belli, R. R. Gonçalves, G. C. Righini, S. Pelli, A. Chiappini, L. Zampedri, and M. Ferrari, J. Non-Cryst. Solids **322**, 289 (2003).
[15]W. J. Miniscalco, J. Lightwave Technol. **9**, 234 (1991).