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Spectroscopy of Er^{3+} in Zn-diffused $LiNbO_3$ waveguides

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Abstract

In this work, the spectroscopic properties of Er^{3+} ions in Zn-diffused lithium niobate waveguides are investigated. Experiments under CW excitation reveal that the dominant emissions of the Er^{3+} ions in the waveguide retain the polarisation characteristics observed in bulk samples. The temporal evolution of these emission bands has been also analysed, in this case under pulsed excitation. It has been found that Zn-diffusion does not induce appreciable changes in the lifetimes. Thus, the spectroscopic analysis indicates that the Zn-diffusion waveguide fabrication technique preserves the spectroscopic properties of the Er^{3+} ions, therefore being an adequate technique for photonic applications. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Waveguide; Lithium niobate; Er; Zn-diffusion

1. Introduction

$LiNbO_3$:Er^{3+} has become a key material in developing monolithic integrated photonic devices because of the combined properties of the host and the dopant. During the last decade a great number of integrated optoelectronic devices operating in the third window in waveguide configuration have been made on the basis of the well established Ti-diffusion fabrication technique [1].

Zn-diffusion from the vapor phase represents an alternative method to produce $LiNbO_3$ low-loss waveguides at substantially lower temperature than Ti-diffusion [2]. This reduction in the diffusion temperature represents an advantage in the fabrication of $LiNbO_3$ non-linear waveguides, because it allows the formation of waveguides over substrates in which periodically poled structures are previously defined [3].

From the point of view of integrated optoelectronic devices, it is necessary to investigate whether the spectroscopic properties of the active ions have been preserved by the fabrication procedure [4].

In this work, the optical properties (CW luminescence and lifetime measurements) of Er^{3+} ions in Zn-diffused $LiNbO_3$ waveguides are analysed. The obtained results indicate that the emission spectrum in the waveguide, obtained under CW excitation at 794 nm, is energetically coincident with that reported for bulk doped samples and retains its polarisation characteristics [5].

The different emission bands present a temporal evolution which in all cases can be fitted with a single exponential decay, and the values are only slightly reduced in comparison with those reported for bulk doped samples.

2. Experimental procedure

Commercially available $LiNbO_3$ z-cut wafers were doped near the surface by in-diffusion of an Er^{3+}-layer into the substrate [1,6]. This doping procedure induces a Gaussian active ion profile with a surface Er^{3+} concentration close to 0.3 mol% related to Nb ions (6.6×10^{19} ions cm^{-3}). After the local doping process the waveguide was fabricated by Zn-diffusion as reported elsewhere [2]. Waveguides fabricated with the same diffusion parameters, time and temperature, have been previously analysed by energy dispersive X-ray analysis (EDX) [7]. These analyses indicated that the concentration of Zn ions in the waveguide region is close to 5.0 mol% related to Nb ions (4.7×10^{21} ions cm^{-3}).

The spectroscopic characterisation of the Zn-diffused $LiNbO_3$:Er^{3+} waveguides has been performed under CW and pulsed excitation, by using an Ar-pumped Titanium-Sapphire laser (tuned at 794 nm) and the second harmonic of a Nd:YAG laser (532 nm), respectively. The excitation

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beam was coupled into the waveguide by using the end-fire coupling technique. The luminescence was collected at the other end, using a microscope objective, and then analysed through an ARC monochromator model SpectraPro 500-i. The fluorescence was detected by an InGaAs photodiode and a photomultiplier tube, for the infrared and visible radiation, respectively. In lifetime measurements, the signal was synchronously detected and averaged by a digital oscilloscope.

3. Results and discussion

Fig. 1(a) shows the pumping schemes used to perform the spectroscopic characterisation of the Er^{3+} ions in the Zn-diffused waveguide. After CW excitation at 794 nm ($^4I_{15/2}\rightarrow{}^4I_{9/2}$ absorption band) the Er^{3+} ions relax from the $^4I_{9/2}$ manifold to the $^4I_{11/2}$ multiplet mainly by non-radiative decay. From this level the Er^{3+} ions may relax directly to the ground state, giving luminescence at around 1.0 μm ($^4I_{11/2}\rightarrow{}^4I_{15/2}$ transition), or to the $^4I_{13/2}$ manifold. In $LiNbO_3$, this last relaxation ($^4I_{11/2}\rightarrow{}^4I_{13/2}$) is mostly non-radiative [5]. From the $^4I_{13/2}$ multiplet, the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ relaxation gives luminescence at 1.5 μm. Additionally, this pumping scheme generates up-conversion via excited state absorption [8], inducing population in the erbium upper levels. As a consequence, a green emission can be also detected associated with the radiative decay from the $^2H_{11/2}$ and $^4S_{3/2}$, thermally coupled manifolds, to the $^4I_{15/2}$ ground state.

The pulsed excitation at 532 nm ($^4I_{15/2}\rightarrow{}^2H_{11/2}$ absorption band) allows information to be obtained about dynamic aspects of the three dominant emission bands observed in $LiNbO_3$:Er^{3+}, because the decay from the $^4S_{3/2}$ erbium level is also partially non-radiative to the $^4I_{11/2}$ manifold.

Fig. 1(b) shows the infrared emissions, after CW excitation at 794 nm, in the Zn-diffused waveguide and in a $LiNbO_3$ bulk sample doped with similar Er^{3+} concentration, solid and dotted lines, respectively. As can be seen, the TE and TM guided emissions (σ and π polarised spectra, respectively) are energetically coincident with those obtained in the $LiNbO_3$:Er^{3+} bulk doped sample and retain the same polarisation characteristics. This fact is in good accordance with previous results reported for Zn-diffused $LiNbO_3$:Er^{3+}/Yb^{3+} waveguides, in which the co-dopants were incorporated to the lattice during the crystal growth process [9,10].

Fig. 2 shows the comparison between the lifetimes reported for bulk samples containing Er^{3+} solely [5] (solid circles) and those measured in the Zn-diffused waveguide after pulsed excitation at 532 nm, Er^{3+} and Zn dopants (open circles). As can be seen, while the $^4I_{13/2}$ lifetime is unperturbed, the $^4I_{11/2}$ and $^2H_{11/2}$:$^4S_{3/2}$ lifetimes appear slightly reduced in comparison with bulk doped samples

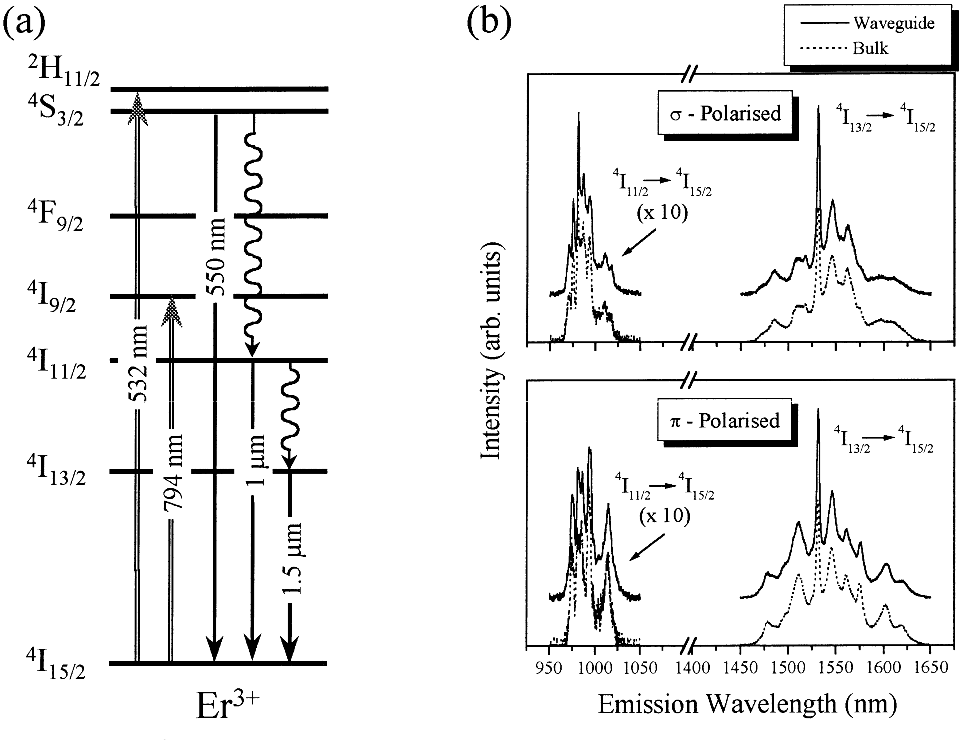

Fig. 1. (a) Energy level diagram of Er^{3+} ions in $LiNbO_3$ showing the pumping schemes used in this work and the dominant emission bands. (b) Comparison between the infrared emissions, at 1.0 and 1.5 μm, in the Zn-diffused waveguide (solid lines) and in a $LiNbO_3$ bulk sample doped with similar Er^{3+} concentration (dotted lines), after CW excitation at 794 nm, corresponding to TE and TM polarisation (σ and π polarised spectra, respectively).

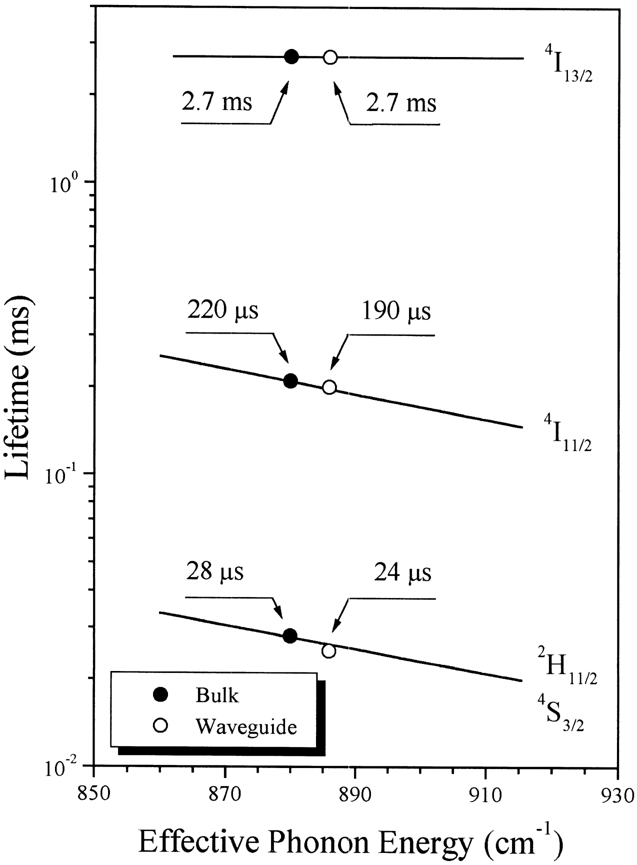

Fig. 2. Lifetimes for the $^4I_{13/2}$, $^4I_{11/2}$ and $^2H_{11/2}$:$^4S_{3/2}$ erbium excited multiplets reported for LiNbO$_3$:Er^{3+} bulk doped samples (solid circles) and in the Zn-diffused waveguides (open circles). The continuous lines represent the lifetimes as function of the effective phonon energy.

($\Delta\tau/\tau \approx 14\%$). This behavior indicates that these excited erbium manifolds are more sensitive to the environment.

The situation can be understood considering an increment in the non-radiative probabilities, which can be associated with local distortion of the Er^{3+} environment because of Zn incorporation causing an increase in the effective phonon energy (E_{ph}). The non-radiative contribution (W_{nr}) can be theoretically calculated as function of the effective phonon energy as [11]:

$$\left.\begin{aligned} W_{nr} &= \beta_{el} \exp[-\alpha(\Delta E - 2E_{ph})] \\ \log \beta_{el} &= \log \beta - 0.86\alpha E_{ph} \end{aligned}\right\} \qquad (1)$$

where β_{el} is an electronic factor, α and β are constants characteristic of the host (being in lithium niobate equal to 5.3×10^{-3} cm and 3×10^{11} s^{-1}, respectively [5]) and ΔE is the energy gap between the excited state and the next lower-lying level.

The total de-excitation probability (W_T), and therefore the experimental lifetime (τ_{exp}), can be evaluated as:

$$\tau_{exp}^{-1} = W_T = W_{rad} + W_{nr} \qquad (2)$$

where W_{rad} is the reciprocal of the radiative lifetime of the multiplet.

Fig. 2 represents the experimental lifetimes in the waveguide (open circles) and the calculated as a function of the effective phonon energy (continuous lines), according to Eqs. (1) and (2) where the radiative lifetimes have been taken from the literature [5]. Assuming an effective phonon energy slightly higher ($E_{ph} \approx 885$ cm^{-1}) than that reported for LiNbO$_3$ ($E_{ph} \approx 880$ cm^{-1}) [12], the lifetimes observed in the Zn-diffused LiNbO$_3$:Er^{3+} waveguide can be explained.

In conclusion Zn-diffusion is an adequate method for waveguide production in LiNbO$_3$ doped with Er^{3+} ions, in which the spectroscopic properties are preserved, and the fabrication technique induces only a slight reduction in the lifetime of the $^4I_{11/2}$ and $^2H_{11/2}$:$^4S_{3/2}$ multiplets. The method is therefore adequate for the fabrication of photonic devices based in this material.

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