Spectroscopy, Cooperative Upconversion and Optical Gain in Amorphous Al_2O_3:Yb^{3+} Waveguides on Silicon

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Abstract: Ridge waveguides in amorphous Al_2O_3:Yb^{3+} are produced by reactive co-sputtering and reactive-ion etching. Their spectroscopic properties, optical gain, and cooperative upconversion are studied and explained based on a model of distinct ion classes.

1. Introduction

Amorphous aluminum oxide (a-Al_2O_3) is a relevant material for rare-earth-doped waveguide (WG) amplifiers and lasers. One of its advantage is its compatibility with standard silicon (Si) wafer technology. Efficient laser operation was demonstrated using a-Al_2O_3:Yb^{3+} WGs: a monolithic distributed-Bragg-reflector channel (ridge) WG laser generated 47 mW of single-mode output at 1021 nm with a slope efficiency of 67% and excellent linewidth characteristics [1]. The spectroscopic properties of Yb^{3+} ions in a-Al_2O_3 have not been reported so far. Recently, it was shown for Er^{3+} and Tm^{3+} dopants in a-Al_2O_3 that an accurate description of their spectroscopic properties can be achieved with a model of distinct ion classes [2,3].

In the present work, we report on a detailed spectroscopic characterization of a-Al_2O_3:Yb^{3+} WGs, focusing in particular on cooperative upconversion (CU) and its effect on pump absorption and optical gain.

2. Fabrication of waveguides

Ytterbium-doped Al_2O_3 thin films were deposited on thermally oxidized 4-inch Si substrates by reactive co-sputtering from metallic sputtering targets (Al, Yb). The substrate holder was heated to 650°C. The sputtering power on the Yb target was varied between 16-33 W to adjust the dopant concentration N_{Yb}. N_{Yb} was determined by Rutherford Backscattering Spectroscopy and ranges from 1.33 to 6.55×10^{20} cm^{-3}. The deposition rate was 4-5 nm/min and the layer thickness was ~1 µm. The thin films were micro-structured by use of an inductively-coupled plasma reactive ion etch system. The etch depth was between 43 nm and 55 nm. The WG width was ~2 µm and their length was 0.4-0.5 cm.

3. Results and discussion

For Yb^{3+} ions in a-Al_2O_3, the maximum absorption cross-section σ_a is 2.5×10^{-20} cm^2 at 976 nm (zero-phonon line, ZPL); the FWHM of this line is 7.5 nm, see Fig. 1(a). Due to the quasi-three-level nature of the Yb^{3+} laser scheme, laser operation is achieved at wavelengths longer than the ZPL, where the stimulated-emission cross section is σ_e = 0.47×10^{-20} cm^2 at ~1030 nm. The crystal-field splitting of the Yb^{3+} ions is shown in Fig. 1(b). An increase of N_{Yb} from 1.33 to 6.55 × 10^{20} cm^{-3} results in a gradual shortening of the $^2F_{5/2}$ luminescence-decay time τ_{exp} from 708 µs to 311 µs, see Fig. 1(c).

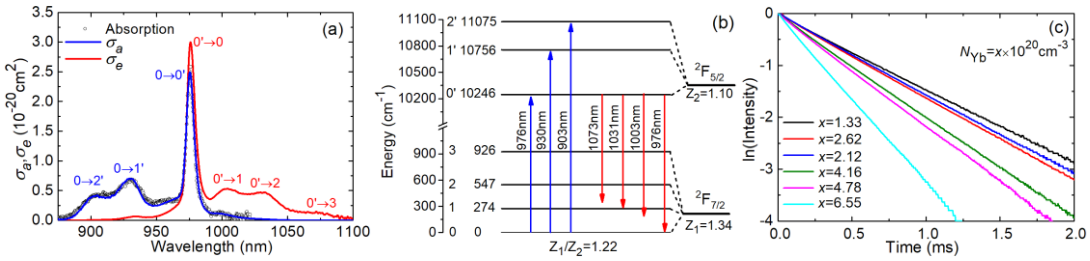

Fig. 1. (a) Absorption and stimulated-emission cross sections σ_a and σ_e, respectively, of Yb^{3+} in a-Al_2O_3: *red line* – σ_e spectrum calculated by the F-L method, *blue line* – σ_a spectrum calculated by the reciprocity method, *circles* – measured absorption spectrum. (b) Crystal-field splitting of the $^2F_{5/2}$ and $^2F_{7/2}$ multiplets. Z_1 and Z_2 are the partition functions. (c) Normalized luminescence-decay curves of Yb^{3+} measured at 1025 nm in a-Al_2O_3:Yb^{3+} with various Yb^{3+} concentrations.

Previously, the existence of quenched ions that exhibit a very short excited-state lifetime and do not emit photons was detected in a-Al_2O_3:Er^{3+} thin films by pump-absorption experiments [2]. Similar measurements are performed for Al_2O_3:Yb^{3+} WGs, see Fig. 2(a-b) for the min. and max. investigated N_{Yb}. With increasing launched pump power, absorption in the WGs saturates. With increasing N_{Yb}, the experimentally observed ground-state bleaching deviates from the curve calculated under the assumption that all ions are active (f_a = 1). This is due to an increasing fraction f_q of quenched ions. The fractions f_a and f_q versus Yb^{3+} concentration are displayed in Fig. 2(c). An increase of N_{Yb} from 1.33 to 6.55×10^{20} cm^{-3} results in an increase of f_q from 2% to 12%, following a nearly linear law.

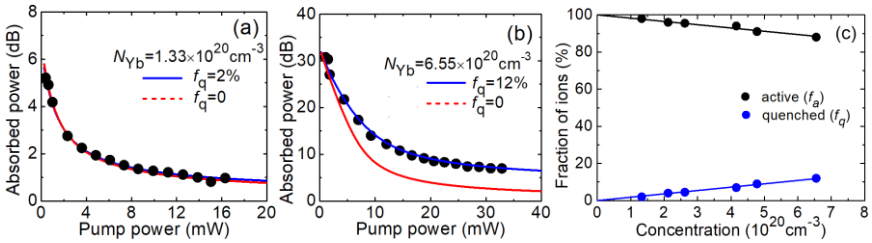

Fig. 2. Absorbed versus launched pump power for Al_2O_3:Yb^{3+} channel waveguides with (a) low and (b) high Yb^{3+} concentration N_{Yb} and a WG length of 0.5 cm. *Circles*: experimental data; *blue line*: their fit with the quenched-ion rate-equation model yielding the fraction f_q of quenched Yb^{3+} ions; *red line*: simulation for f_q = 0 (no quenched ions). (c) Fractions f_a of active and f_q of quenched Yb^{3+} ions in a-Al_2O_3 derived from the pump-absorption measurements and their linear fits.

Pumping of Al_2O_3:Yb^{3+} WGs at 976 nm results in a bright blue-green upconversion (UC) luminescence, see Fig. 3(a). It is assigned to emission from an excited state of Yb^{3+}-Yb^{3+} ion pairs having the energy of $2E(^2F_{5/2})$, as well as Er^{3+} impurities, see Fig. 3(b). To understand the Yb^{3+}-pair mechanism, we measured the intensities of near-IR and green luminescence as a function of pump power P. For UC processes, it is expressed by a power law, $I_{ucl} \sim P^n$. Figure 3(c) shows the slopes n for both emissions. To explain the observed dependences, we used a rate-equation model, based on the assumption that there exist two ion classes: (i) isolated Yb^{3+} ions and (ii) Yb^{3+}–Yb^{3+} ion pairs exhibiting CU. Good agreement with the experiment is observed when using this model for a fraction of ions forming pairs equal to the corresponding f_q value from the pump-absorption measurements. The CU micro-parameter is deduced. The model explains the pump bleaching and predicts the features of the green luminescence decay. We also show that the CU is responsible for slightly diminishing the optical gain in the Al_2O_3:Yb^{3+} WGs, see Fig. 3(d).

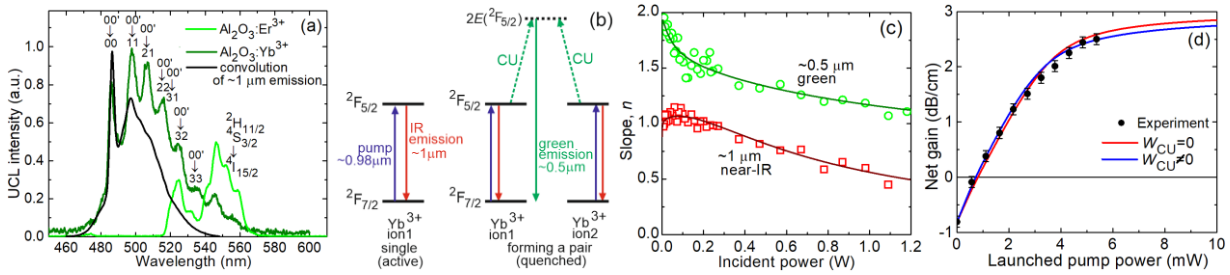

Fig. 3. (a) UC luminescence spectra for Al_2O_3:Yb^{3+} (*dark-green*) and Al_2O_3:Er^{3+} (*light-green*) WGs at λ_P = 976 nm; convolution of near-IR luminescence spectrum of Yb^{3+} (*black*). (b) Illustration of pump and de-excitation paths for the two classes of Yb^{3+} ions in a-Al_2O_3:Yb^{3+}. (c) Calculated slopes n of the dependences of near-IR and green emission intensities *vs*. incident power at 976 nm (*symbols*) and their theoretical values (*curves*). (d) Internal net optical gain in an Al_2O_3:Yb^{3+} WG for λ_P = 976 nm, λ_S = 1020.5 nm. *Symbols*: experiment, *curves*: numerical modeling. $N_{Yb} = 4.37 \times 10^{20}$ cm^{-3}.

4. Conclusions

The spectroscopic properties of Yb^{3+} ions in a-Al_2O_3 can be satisfactory described with a model comprising two ion classes, namely, (i) isolated ions exhibiting radiative relaxation leading to emission at ~1 μm, and (ii) ions forming Yb^{3+}-Yb^{3+} pairs, featuring a short-living excited-state with the energy of $2E(^2F_{5/2})$ and exhibiting CU. This has consequences for the pump absorption saturation and the optical gain in a-Al_2O_3:Yb^{3+} WGs. The proposed spectroscopic model is relevant for the design of WG amplifiers and narrow-linewidth lasers at ~1 μm.

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[3] P. Loiko, and M. Pollnau, "Stochastic model of energy-transfer processes among rare-earth ions. Example of Al_2O_3:Tm^{3+}," J. Phys. Chem. C **120**, 26480-26489 (2016).