Rare-earth doped selenides active waveguides for integrated mid-infrared sensing applications

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Mid-infrared (mid-IR) absorption spectroscopic techniques can provide inherent molecular selectivity and reach very low detection limits. They have therefore found applications in environmental, health or security domains. In parallel to the growing demand for the detection of traces molecules, the development of compact sensors is also urged to extend the operational range of these sensors to on-site measurements. Sophisticated on-chip mid-IR transducers [1] have been implemented using different integrated optical platforms (Si, Ge, SiNx, arsenides, chalcogenides…). However, despite the versatility of light sources spanning the whole mid-IR (synchrotron, globar, optical parametric oscillator, quantum/interband cascade laser (QCL/ICL) or supercontinuum sources), on-chip integration of mid-IR broadband light sources still remains a challenge. In particular, integrated broadband light sources and amplifiers operating in the 3-5 µm window would be of great interest as this spectral range overlaps an Earth's atmosphere transmission window and strong characteristic vibrational transitions displayed by chemical molecules such as hydrocarbons, carbon dioxide and carbon monoxide (Fig.1a).

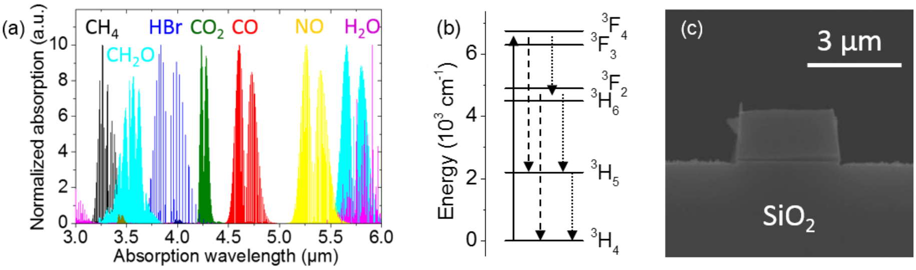

Fig. 1. a) Absorption bands of selected molecular species in the mid-IR range, b) Simplified low energy part of the energy level diagram of Pr^{3+} ions and c) Scanning electron microscope image of the processed waveguide after ICP-RIE.

Mid-IR lasers based on rare earth (RE) ions have already been demonstrated in fibers [2]. The transfer of these results in integrated technology is expected to have a tremendous impact on the development of mid-IR-lab-on-a-chip sensing applications. The transmission range of chalcogenides spans a large part of the mid-IR thanks to their low phonon energies. Efficient mid-IR waveguiding properties have also been demonstrated [3]. Praseodymium (Pr^{3+}) ions feature characteristic radiative transitions in the mid-IR under convenient pumping around 1.5 and 2 µm (Fig.1b).

In this paper, we report the optical design, fabrication and mid-IR optical characterizations of integrated active ridge waveguides based on praseodymium (Pr^{3+})-doped selenides.

RF magnetron sputtering was used to deposit a 1.7-µm thick Pr^{3+}-doped chalcogenides guiding layer based on the quaternary system composed of Ga, Ge, Sb and Se atoms on different cladding layers (thermally oxidized silicon and selenide-based materials). Refractive indices of doped films were measured by ellipsometry and values of 2.607 and 2.565 were, respectively, obtained at 1.55 µm and 4.70 µm. Ridge waveguides patterning was subsequently performed using i-line photolithography and fluorine-based RIE/ICP dry etching techniques.

Optical field distribution of the propagating modes and the corresponding effective indices were simulated, as a function of waveguide width and wavelength, using a commercial mode solver. At 1.55 µm, the waveguides were found multimode for widths larger than 0.3 µm. Single-mode operation at the propagating wavelength of 4.70 µm can be obtained for waveguide widths smaller than w=1.9 µm (h=1.7 µm). Fig. 2a shows the simulated intensity profile of the fundamental transverse electric (TE) mode propagating at the wavelength of 4.70 µm in a 1.7 × 1.5 μm^2 (height × width) ridge waveguide.

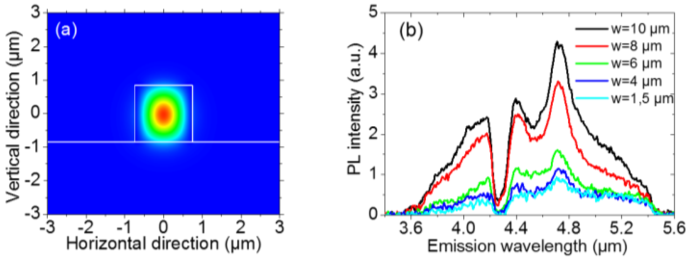

Fig. 2. a) Simulated TE fundamental mode at λ=4.70 µm for a 1.7 × 1.5 μm^2 ridge waveguide, b) Mid-IR PL spectra for different waveguide widths (h=1.7 µm).

Guided photoluminescence (PL) experiments were performed between 3.5 and 5.5 µm using a continuous wave excitation at 1.55 µm in co-propagative configuration. PL was investigated as a function of waveguide width (from 10 µm down to 1.5-µm wide) and pumping power (4-30 mW). Fig. 2b displays typical mid-IR PL spectrum recorded at room temperature in the 3.6-5.4 µm wavelength range. The dip in PL intensity located around 4.3 µm originates from the vibrational absorption of CO_2 from atmosphere and emphasizes the potential of these active waveguides for mid-IR spectroscopic sensing (Fig. 1a).

In conclusion, ridge waveguides were fabricated by RF magnetron sputtering and subsequent patterning using standard photolithographic steps. Geometrical dimensions (width and height) of the waveguides were adjusted to obtain single-mode propagation at mid-IR wavelengths. Under 1.55 µm optical excitation, guided broadband mid-IR emission above 4 µm is demonstrated from Pr^{3+}-doped selenides ridge waveguides. These results correspond to the longest wavelength emission ever recorded from RE-doped integrated waveguides and underscore the potential of RE-doped chalcogenides for the development of low-cost on-chip mid-IR amplifiers or lasers that could be used, in particular, for sensing applications.

References

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