Enhancement of Light Emission in Silicon Photonic Crystal Slabs

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Abstract: Silicon-on-insulator photonic crystal waveguides with an active layer containing Er\(^{3+}\) ions displays strong enhancement of 1.54 \(\mu m\) emission at room temperature. A theory of photonic dispersion and spontaneous emission is discussed.

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1. Introduction

Achieving efficient light emission in Si-compatible systems is a long-standing goal of optoelectronics. Various routes have been explored including the use of silicon nanoclusters (nc) [1] and doping with Er ions. In particular, systems with Er-doped silicon nanoclusters are particularly promising as they show optical gain [2] and can be integrated in electrically driven devices. However, the problem of light extraction limits the external quantum efficiency.

Two-dimensional (2D) photonic crystals (PhCs) embedded in planar waveguides, also known as PhC slabs, can be used in order to tailor the propagation properties of light and to enhance vertical extraction efficiency as well as light-matter interaction [3,4]. In this work we realize silicon-on-insulator (SOI) PhC slabs containing a thin active layer with Er\(^{3+}\) ions and Si nc in the middle of the waveguide core. Strong enhancement of vertical emission at 1.54 \(\mu m\) is demonstrated [5]. The results are interpreted within a theoretical treatment of photonic mode dispersion, diffraction losses and spontaneous emission in PhC slabs.

2. Emission of light in active silicon-on-insulator photonic crystal slabs

Active SOI waveguides were fabricated by depositing a core on top of a 1.9 \(\mu m\) thick silicon dioxide layer thermally grown on a Si substrate. The core consists of Si(116 nm)/Si-nc:Er:SiO\(_2\)(19 nm)/Si(112 nm) and is realized by radio-frequency confocal magnetron sputtering. Subsequent annealing allows the separation of Si and SiO\(_2\) phases, the formation of Si nc, and the activation of Er\(^{3+}\) luminescence. 2D photonic crystals consisting of a triangular lattice of air holes were etched into the core. Several samples with lattice constant varying from \(a=1050\) nm to \(a=1250\) nm and hole radius \(r=0.33a\) were realized. The purpose of the design is to match the Er\(^{3+}\) emission line with a photonic mode at \(\theta=0^\circ\), i.e., at the \(\Gamma\) point of the 2D Brillouin zone.

Room-temperature photoluminescence (PL) and reflectance (R) spectra were measured at various angles \(\theta\) from 0° to 16°, with an angular resolution of \(\pm 2^\circ\). The PL was excited by a 532 nm laser line focused on the slab surface. Figure 1 shows PL spectra at \(\theta=0^\circ\) for two PhC samples and for the unpatterned SOI waveguide, as well as reflectance spectra. Vertical emission of Er\(^{3+}\) around 1.54 \(\mu m\) wavelength is strongly enhanced, especially for the \(a=1070\) nm sample for which the emission line is narrower. This effect occurs at the frequencies of quasi-guided photonic modes in the PhC crystal slabs, as is evident from the resonance features in reflectance curves which mark the excitation of such modes. Thus, out-of-plane diffraction at those frequencies is particularly efficient and acts to enhance the Er\(^{3+}\) luminescence in the vertical direction.

We have studied the angular dependence of the emission spectra and of the integrated intensities. The
maximum enhancement of emission occurs at \( \theta = 12^\circ \) for the \( a = 1070 \) nm sample and is about 150 (without normalizing to the reduced amount of active material, otherwise it becomes 250 after normalizing to the active Er\(^{3+}:\text{SiO}_x \) fraction). On the other hand, the PL intensity for the \( a = 1210 \) sample is largest at \( \theta = 0^\circ \) and it decreases as a function of angle. These features are related to the linewidths of the two modes, as discussed in the following.

3. Theory of photonic mode dispersion and spontaneous emission

In order to interpret the results and to describe the phenomena in a more general way, we follow two kinds of approaches: (a) a theory of photonic mode dispersion and diffraction losses in the PhC slab, based on the guided-mode expansion method \([6]\); (b) a calculation of angle-resolved emission spectra, based on a Fourier-modal method with a scattering matrix. Figure 2 shows photonic bands and emission spectra for the \( a = 1070 \) nm sample. The angular evolution of resonant features in emission spectra follows the photonic mode dispersion. Thus, the strict relation between enhanced emission and the presence of photonic modes close to the \( \Gamma \) point is established. It turns out that the \( a = 1070 \) nm sample has a mode at 0.8 eV which is forbidden at \( k = 0 \), i.e., uncoupled to the outgoing light. This mode has a vanishing linewidth at \( k = 0 \) and therefore it has a very high Q-factor. On the other hand, the \( a = 1210 \) sample has a mode at 0.8 eV which is allowed at \( k = 0 \), with an appreciable linewidth (of the order of the Er\(^{3+} \) emission linewidth, see Fig. 1) and a smaller Q-factor. These findings explain the experimental results and give guidelines to further optimize the emission enhancement.

We undertake systematic calculations of photonic mode dispersion and emission spectra for the SOI structure as well as for a self-standing membrane as a function of etching depth. In the case of a shallow etching, photonic bandgap effects are very small and the structure behaves as a diffraction grating. For deep etching, photonic crystal behaviour is recovered. The trends in the vertical emission enhancement as a function of various parameters are calculated. In general, it turn out that the distinction between forbidden and allowed modes at the G point is a crucial one for the physics of vertical emission in PhC slabs.

4. Conclusions

Strong enhancement of Er\(^{3+} \) emission at room temperature in SOI PhC slabs is demonstrated. A theory of photonic mode dispersion and angle-resolved emission is consistent with the results and it underlines the role of radiative coupling close to the \( \Gamma \) points. These findings are promising in view of integrating active functionalities in Si-compatible emitters, possibly with electric injection. Further investigations concern the role of the low-index slot layer for field confinement \([7]\) and the presence of a Purcell effect in the Er\(^{3+} \) lifetime.

5. References