

Broadband light enhancement and polarization dependent coupling in Si₃N₄ slot waveguides.

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In the beginning of the years 2000, “optical quantum computing” (OQC) [1] has emerged as a new promising platform to demonstrate the power of the quantum computing idea and to build prototypical quantum computers radically outperforming classical digital computers. OQC is appealing because it requires only single-photon (SP) sources, linear optical elements and SP detectors. At visible wavelengths, Si avalanche photodiodes (APDs) reach detection efficiencies as high as 80%. Nowadays, the major technological obstacle for on chip optical quantum computing is the lack of efficient sources of indistinguishable photons at wavelengths compatible with Si APDs.

In this work, we study the possibility to integrate triggered solid-state SP emitters directly on a photonic chip. We specifically investigate photonic chips made of silicon nitride (Si₃N₄) because this material has a larger refractive index than silica ($n = 2$), while being highly transparent in the visible and near-infrared range. In addition, Si₃N₄ devices and circuits can be realized on a SOI chip using standard CMOS compatible processing technology. Most importantly, the technology offers the possibility to embed alien solid-state single-photon emitters (such as colloidal quantum dots or diamond nanoparticles) inside the Si₃N₄ host. The ability to control SP emission depends critically on the understanding of the coupling of the emitters to their environment. Photonic structures on the wavelength and sub-wavelength scale can strongly modify quantum yield, emission rates, polarization and radiation patterns [2][3]. Hence, we investigate the light emission properties of an electrical dipole emitter inside 3-dimensional Si₃N₄ slot waveguides and evaluate the spontaneous emission enhancement (F_p) and polarization dependance of the waveguide coupling ratio (β). This study allows to select an optimal waveguide design, achieving an efficient integrated SP source with a high degree of polarization.

For rectangular strip waveguides, no significant Purcell enhancement is found (Purcell factors ranging between 0.7 and 1.3 for all dipole polarizations). The coupling of the light to the waveguide is nevertheless high. For instance, for a 220×280 nm hanging strip waveguide, we find a 61% coupling efficiency for a central emission wavelength of 650 nm and a randomly oriented dipole moment. The polarization of the emitted photons can be better controlled by embedding the QD into a thin SiO₂ layer in the center of the Si₃N₄ waveguide (see inset of Fig. 1a). FDTD simulations show a significant Purcell enhancement of spontaneous emission in the polarization orthogonal to the SiO₂ layer (F_z up to 3).

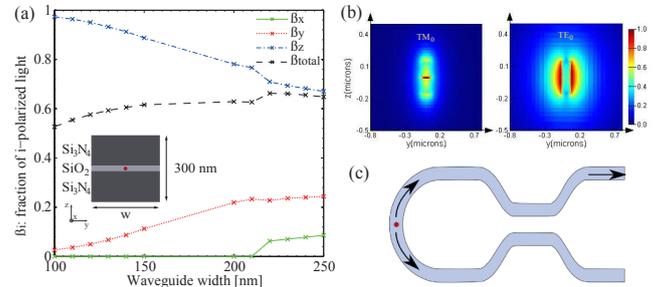


FIG. 1. (a) Total coupling and corresponding polarization fractions for a SP emitter embedded in Si₃N₄ waveguide with a thin SiO₂ layer. (b) Mode profiles of guided modes in H300×W120 waveguide structure shown in a). (c) SP self-interference makes it possible to collect all the emission in one output arm.

For an otherwise isotropic emitter, the probability to emit an i-polarized photon is equal to $p_i = F_i / (\sum_i F_i)$. Fig. 1a shows the total coupling and corresponding degree of polarization in a (300 nm×w) Si₃N₄ waveguide with a 20-nm SiO₂ layer as a function of w. For w = 120 nm, we find that 74% of the emitted photons have a polarization orthogonal to the SiO₂ layer, 7% in the direction orthogonal to the waveguide, and 19% in the remaining direction. The emitted photons have an overall probability as high as 58% to be coupled into a guided mode (see Fig. 1a). The photons emitted with a polarization orthogonal to the waveguide are not guided at all. Among the guided photons, 95% have a polarization orthogonal to the SiO₂ layer and only 5% have the complementary polarization.

Replacing the SiO₂ layer with air, results in even higher Purcell factors (F_z up to 14) and hence an even higher degree of polarization (98%) and total coupling (59%) can be achieved. This shows that strongly polarized photons can be coupled to waveguides with high efficiency, even at room temperature. Although, a photon emitted in a waveguide is in a superposition of two opposite propagation directions, a directional emission can be easily obtained using reflectors at one end of the waveguide or by placing the emitting QD in a Sagnac loop as shown in Fig. 1c.

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