

Strong Er^{3+} radiative emission enhancement by quasi-BIC modes coupling in all-dielectric slot nanoantenna arrays

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Abstract.

We have designed and realized all-dielectric lossless nanoantennas, in which a thin SiO_2 layer doped with erbium ions is placed inside slotted silicon nanopillars arranged in a square array. The modal analysis has evidenced that the slotted nanopillar array supports optical quasi-BIC resonances with ultra-high Q -factors (up to $Q \sim 10^9$), able to boost the electromagnetic local density of optical states in the optically active layer. Up to 3 orders of magnitude photoluminescence intensity increment and 2 orders of magnitude decay rate enhancement have been measured at room temperature when the Er^{3+} emission at about $\lambda = 1540$ nm couples with the quasi-BIC resonances. Furthermore, by tailoring the nanopillar aspect ratio, the slot geometry has been exploited to obtain selective enhancements of the electric or magnetic dipole contribution to Er^{3+} radiative transitions in the NIR, keeping the emitter quantum efficiency almost unitary. Finally, by computing the angularly resolved electromagnetic field enhancement inside the nanoslot, the nanoantenna directivity has been designed, proving that strong beaming effects can be obtained. Our findings have a direct impact on the development of bright and efficient photon sources operating at telecom wavelength that are of primary importance for quantum nanophotonic applications.

1 Introduction

The spontaneous emission rate of an emitter can be modified acting on its electric and magnetic local density of optical states (LDOS). Recently, all-dielectric high refractive index nanostructures have attracted increasing interest due to their unique optical properties (i.e., low absorption, optical magnetism, and multipolar responses) that can be exploited to enhance the optical properties of a nearby emitter without decreasing its quantum efficiency. However, the relatively modest Q -factors exhibited by electric and magnetic Mie resonances ($Q \sim 5$ -10) have limited the application of high-index nanoparticles in the enhancement of the LDOS. A possible way for obtaining orders of magnitude higher Q -factors in all-dielectric nanostructures is based on optical bound states in the continuum (BICs). Although true BIC can exist in structures that are infinitely extended at least in one direction, finite-size systems can support their analogue in the form of quasi-BICs, with the resonance quality factor that increases rapidly before reaching a maximum value limited by the finite-size effects. Despite the novelty of the field, quasi-BICs have already demonstrated their ability to outperform traditional photonic nanostructures for many photophysical processes usually limited either by losses or by low Q -factor resonances, such as second- and third-harmonic generation, light guiding, beam shaping, and sensing. Nonetheless, the realization of nanoantennas able to boost the emitter

optical properties through an efficient coupling with quasi-BIC modes remains still an open issue [1].

2 Results

In this framework, we propose a novel design for all-dielectric lossless nanoantennas, in which the combination of the nanoslot geometry [2] and the quasi-BIC modes can be exploited to boost the electromagnetic LDOS in the optically active region of the nanoantenna [3]. A sketch of the nanoantenna is shown in Fig. 1(a). The emitting layer, a 30 nm thick nanodisk of silica doped with erbium, is placed at half height of the high-index silicon nanopillars arranged in a square array on a silica substrate. The total nanopillar height is $h = 430$ nm, while the radius was varied in the range $r = 125$ -390 nm. We choose erbium ions in silica as the emitting medium since Er^{3+} can be seen as the ideal candidate for the development of novel photonic quantum sources operating at telecom wavelengths, due to the sharp room-temperature emission at $\lambda = 1540$ nm, that matches the silica minimum absorption window.

A strong modulation of the electric and magnetic dipole contribution to the Er^{3+} radiative transitions can be observed as a function of the nanopillar radius. The emitter magnetic branching ratio ($\eta_{MD} = \Gamma^{MD} / \Gamma^{tot}$, where $\Gamma^{tot} = \Gamma^{ED} + \Gamma^{MD}$) can be tailored from 10% to 90%, varying the nanostructure aspect ratio in the range $AR = 2r/h = 0.6$ -1.9. The obtained values are much higher than the ones achievable with planar dielectric films with similar slotted

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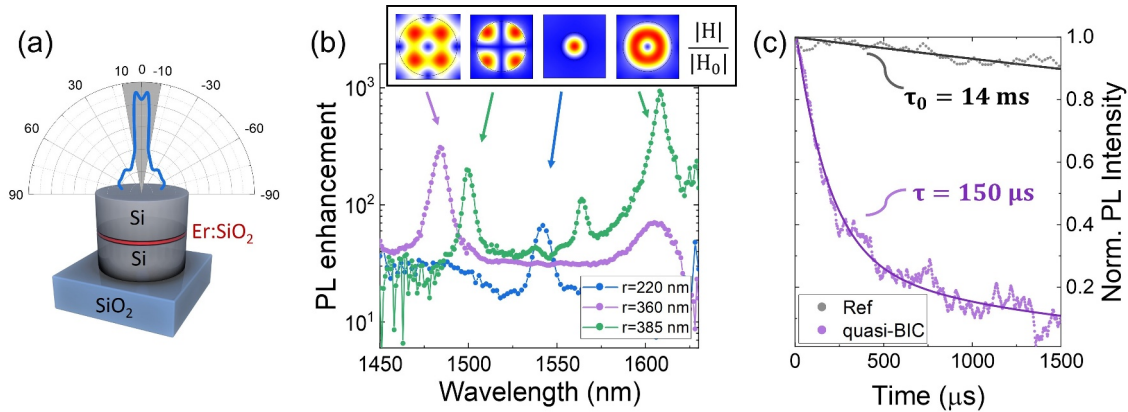


Figure 1. (a) Sketch of the all-dielectric nanoantenna and measured angular distribution of the Er³⁺ PL intensity at $\lambda = 1540$ nm for the sample with $r = 220$ nm. (b) The Er³⁺ PL intensity enhancement in logarithmic scale in the $\lambda = 1450$ –1650 nm wavelength range for slotted nanopillars with increasing radius. Upper panels report the magnetic field configuration ($|H|/|H_0|$) at quasi-BIC resonances. (c) Normalized PL temporal decay for the nanopillar with $r = 360$ nm (purple dots) and for the reference sample at $\lambda = 1540$ nm (grey dots). The continuous lines are the exponential fits.

structure and than the ones measured in for a rare-earth doped thin film deposited on top of a high-index nanopillar array [2]. Furthermore, ordered arrays of high-index slotted nanopillars arranged in a peculiar resonant configuration can support quasi-BIC resonances with huge Q -factors. Indeed, the eigenvalue analysis performed by FEM simulations evidenced that the proposed nanoantennas support electric and magnetic dipole and quadrupole quasi-BIC modes in the NIR spectral range with Q -factors up to $Q = 10^9$. The upper panel of Fig. 1(b) shows the simulated magnetic field distribution enhancement at the quasi-BIC resonances. These modes are characterized by an extremely narrow spectral width and a giant electromagnetic field enhancement inside the nanopillars and specifically in the region corresponding to the optically active layer. Fig. 1(b) reports the measured Er³⁺ PL intensity enhancement in logarithmic scale with respect to a 30 nm thick planar Si slot for a selected set of samples with quasi-BIC resonances in the Er³⁺ wavelength emission range. An almost perfect spectral agreement was found between FEM simulated resonances and measured PL peaks and up to 3 orders of magnitude Er³⁺ PL intensity increment with respect to the planar configuration have been measured at room temperature. This clearly shows that by coupling the Er³⁺ radiative emission at about $\lambda = 1540$ nm with quasi-BIC resonances, the photon emission from the nanoslot is strongly amplified. Moreover, Fig. 1(c) reports the normalized PL temporal decay for a reference sample (i.e., a 30 nm thick Er:SiO₂ film on the silica substrate, grey curve) and for the nanopillar array with $r = 360$ nm in correspondence to the quasi-BIC resonance (purple curve). The measured lifetime for the reference sample is $\tau_0 = 14.0 \pm 0.5$ ms (in good agreement with the values reported in the literature for Er-doped thin films on the SiO₂ substrate, proving the high quantum efficiency

of the deposited Er:SiO₂ layer, i.e., $\Gamma_{nr} \sim 0$ s⁻¹), while the Er³⁺ layer embedded in the nanoantenna exhibits a ~ 100 shorter lifetime $\tau = 150 \pm 10$ μ s. Decay rate measurements demonstrate that the proposed nanoantenna design can support a strong light-matter interaction inside the SiO₂ slot, especially when the emitter couples with quasi-BIC modes. At the resonance condition, indeed, a Purcell factor of two orders of magnitude has been measured at room temperature (i.e., $\Gamma/\Gamma_0 = \tau_0/\tau = 94$) for a lossless nanostructure (i.e., $Q.E. \sim 1$) [3].

Finally, by exploiting the reciprocity principle we were able also to design and control the emission directivity from the nanoslot, focusing more than 90% of the Er³⁺ emitted radiation at $\lambda = 1540$ nm in a lobe normal to the sample surface with an angular width of $\Delta\theta < 10^\circ$ (e.g., see the polar plot reported in Fig. 1(a)). This proves that not only decay rate enhancements but also strong beaming effects can be achieved when the coupling of Er³⁺ luminescence with high- Q modes is carefully designed. Our findings demonstrate that slotted nanopillars are highly promising candidates for the development of more efficient or novel light sources. For example, by decreasing the emitter concentration by roughly two orders of magnitude, bright, lossless and highly directional single-photon sources operating at telecom wavelength could be realized.

References

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