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Strong Purcell Enhancement in a “Nanopost” Single-Photon Source

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Abstract: We report on a simple nanopost single-photon source geometry based on a quantum dot in a mesa placed on a metal mirror. A remarkably large Purcell enhancement of 9 for the smallest structure is obtained. © 2020 The Author(s)

1. Introduction

Solid-state sources of quantum light are key building blocks in optical quantum information technology. Deterministic sources based on quantum dots in semiconductor microstructures have recently been demonstrated as efficient sources of highly indistinguishable single photons and entangled photon pairs. In these structures, Purcell enhancement of the spontaneous emission is beneficial for reducing the effects of phonon-induced decoherence and of spectral diffusion and thus enhancing the indistinguishability of the emitted photons. The champion single-photon source today is the micropillar structure [1-3], however its narrow-band operation requires spectral tuning capability and makes it unsuitable for emission of entangled photon pairs through the exciton-biexciton cascade. On the other hand, the photonic nanowire allows for broad bandwidth, where Purcell enhancement can be implemented [4] using a combination of metal mirrors and DBRs, however the fabrication of this hybrid design is quite complex.

In this work, we report on a simpler design, namely the “nanopost” single-photon source consisting of a quantum dot in a mesa placed on a silica-gold mirror as depicted in Fig. 1(a). Using an open-geometry Fourier modal method, we show that this design allows for the combination of remarkable Purcell enhancement. The highest Purcell enhancement is enabled by a coupling to radiation modes not accounted for using the standard single-mode Fabry-Perot model.

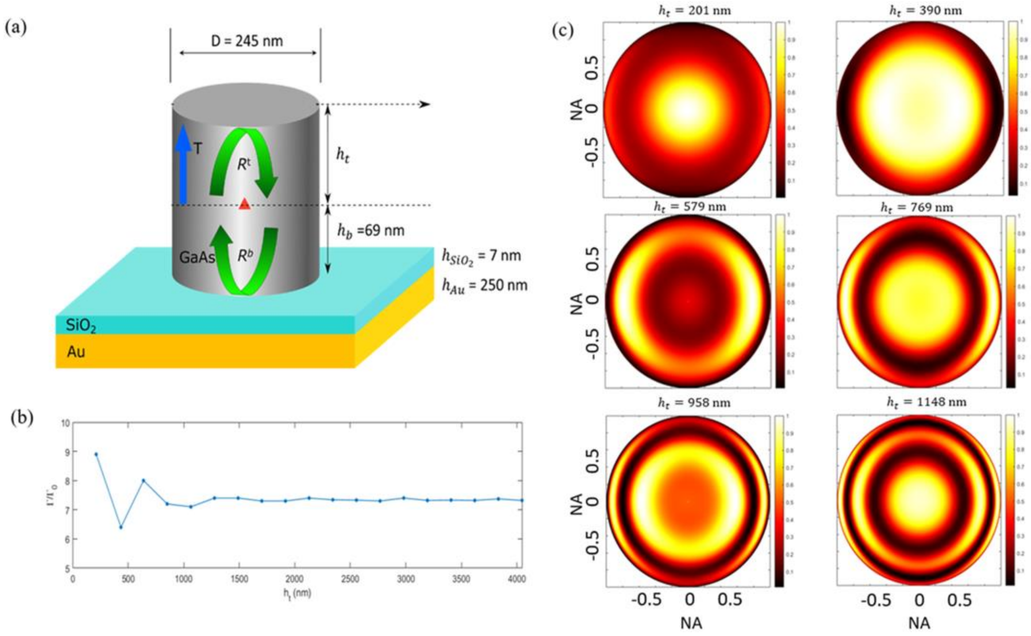

Fig. 1. (a) Nanopost on top of a silica-gold mirror with a dipole placed in an antinode of the cavity mode. (b) Purcell enhancement for the nanopost sketched in Fig. 1 (a) as function of the distance h_t between the dipole and the top facet. (c) Far-field patterns for the 6 smallest nanopost sizes with the dipole located in a field anti-node.

2. Results and discussions

We model the quantum dot as a classical dipole, which is placed in the first anti-node relative to the bottom mirror at $h_b = 69\ nm$. To fulfill the resonance condition, the distance between the dipole and the top facet, h_t, is chosen such that the resonance condition is fulfilled at the design wavelength leading to a set of discrete values for h_t. According to the standard Fabry-Perot model, as long as h_t takes such a value, the Purcell enhancement for the geometry in Fig. 1(a) should have no dependence on the height h_t. However, we observe in Fig. 1(b) that a Purcell enhancement of $\Gamma/\Gamma_0 \approx 9$ is achieved for smallest nanopost cavity, where Γ and Γ_0 are the total spontaneous emission rate and that into a bulk material, respectively. The enhanced Purcell effect for this geometry as compared to taller nanopost cavities is a consequence of a complex coupling at the bottom mirror and the top facet between the fundamental mode, radiation modes and evanescent modes. The HE11 mode reflectivity at the bottom mirror is 92 %, and thus 8 % of the power in the fundamental mode is transferred to the radiation and evanescent modes at the bottom mirror. However, for the smallest structure, the radiation and evanescent modes can couple back to the fundamental mode and thereby enhance the Q factor, and, in turn, the Purcell effect: Light coupled to the radiation modes at the bottom mirror is not simply lost, instead it propagates in the vertical direction and, for the shortest nanopost, is partly re-coupled back to the cavity mode at the top facet. Thus, a multi-mode model taking into the account the contribution from the radiation modes to the fundamental cavity mode is required to describe the physics. For higher values of h_t, oscillations are observed due to constructive and destructive interference from the radiation mode recoupling mechanism, until the Purcell factor converges towards its value predicted by the single-mode Fabry-Perot model.

The far-field emitted patterns of the 6 smallest nanopost sizes are shown in Fig. 1(c). Here we observe varying interference patterns as function of the distance between the dipole and the top facet, h_t. These rings are the consequence of constructive and destructive interference between the fundamental cavity mode and the back-scattered radiation modes discussed above. In addition to the light scattered into radiation modes at the bottom mirror, at the top facet 15 % of the intensity in the HE11 mode is backscattered into radiation modes, which is then reflected by the bottom mirror and will thus also be collected in the far-field domain.

3. Conclusion

In summary, we have performed numerical investigations of the Purcell enhancement and the far-field emission pattern in the simple “nanopost” single-photon source. An increased Purcell enhancement of 9 for the smallest nanopost geometry as compared to the larger geometries is demonstrated. This increased Purcell enhancement cannot be explained using a standard single-mode Fabry-Perot model and occurs due to recoupling of light scattered to radiation modes back into the cavity mode. In the far-field, the interaction between the backscattered radiation modes and the fundamental cavity mode is directly observable as interference rings in the far-field emission pattern.

4. Acknowledgements

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