A novel high-efficiency single-mode quantum dot single photon source

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Abstract

We present a novel single-mode single photon source exploiting the emission of a semiconductor quantum dot (QD) located inside a photonic wire. Besides an excellent coupling (>95%) of QD spontaneous emission to the fundamental guided mode [1], we show that a single photon collection efficiency above 80% within a 0.5 numerical aperture can be achieved using a bottom Bragg mirror and a tapering of the nanowire tip. Because this photon collection strategy does not exploit the Purcell effect, it could also be efficiently applied to broadband single photon emitters such as F-centers in diamond.

Introduction

The development of efficient solid-state sources of single photons (S4Ps) is a major challenge in the context of quantum communications, quantum information processing and metrology. Future practical S4Ps will implement a stable solid-state emitter able to emit photons one by one, such as a F-center [1] or a semiconductor quantum dot (QD) [2-7]. Various single photon collection strategies have been developed to increase the S4P efficiency and/or ensure a single mode operation [5]. By placing a semiconductor quantum dot (QD) in a pillar microcavity, single mode operation [3-4] and an efficiency around 40% have been demonstrated [6-7]. Though successful, this approach has several drawbacks, related to the implementation of a high-Q microcavity. Firstly, it cannot be applied to spectrally broad emitters, such as a QD at 300K or F-centers. Secondly, the properties of high-Q cavities, and especially their far-field radiation diagram, display a great sensitivity on structural imperfections. In the case of state-of-the-art single-mode S4Ps based on a single QD in a pillar microcavity, the efficiency is limited by the scattering induced by the roughness of the etched micropillar sidewalls [5]. A novel strategy towards highly efficient single mode S4Ps based on the insertion of the emitter in a single mode photonic wire (PW) has recently been proposed [8]. Optimally designed cylindrical photonic wires funnel indeed most of the emitter's spontaneous emission (SE), of the order of ~95%, into their fundamental guided mode. A single photon collection efficiency of the order of 17% by a 0.5 numerical aperture (NA) optics has been measured in a preliminary experiment, conducted on a single InAs QD located inside a vertical GaAs PW on a GaAs substrate [8].

In this geometry, the photon collection efficiency is limited by the photon escape toward the substrate at the bottom of the PW, and by the large angular divergence of the emission form the PW tip. On the basis of numerical simulations, we show that a single photon collection efficiency above 80% within a NA=0.5 can be achieved, using a bottom Bragg mirror and a tapering of the PW tip. Because this photon collection strategy does not rely on a high-Q optical system, it could be used to build a single-mode S4P starting from a broadband emitter, such as an F center in diamond.

Motivation

The overall efficiency of the PW S4P is influenced by two parameters. The first one is the fraction β of spontaneous emission coupling to the fundamental guided mode and the second is the collection efficiency γ, defined here as the power detected by the collection optics over that of the guided mode.

We first investigate the standard PW sketched in Fig. 1(a). A QD is positioned at the centre of a GaAs cylinder, and by choosing a radius $R_{pw} \sim c/\omega$, a $\beta \sim 1$ is obtained for this PW [8]. The emitted power is illustrated in the far field emission diagrams of Fig. 1(b), for the two polarizations $\phi = 0$ and $\phi = \pi/2$. The figure reveals that for $\omega R_{pw}/c = 0.5625$ and 6 light is mainly emitted within an angle of 30° from the axis, whereas the emission profiles for $\omega R_{pw}/c = 1$ and 2 are much broader. To facilitate the analysis, we have computed the total transmission into free space as well as the collection efficiency γ of a lens with NA equal to 0.8 in Fig. 1(c). We see that for small or large R_{pw}, γ is above 60 %. By contrast, γ is only ~ 25 % for radius values that maximize the SE coupling factor β ($R_{pw} \sim c/\omega$).

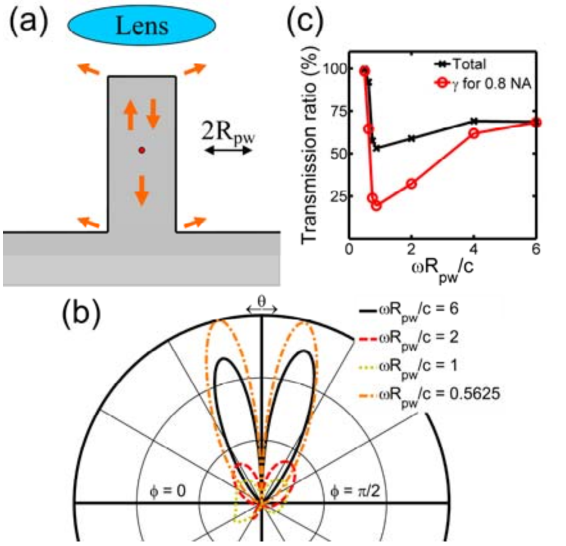

Figure 1: Standard photonic wire geometry (a). Corresponding far field radiation pattern (b) and total free space transmission and collection efficiency as function of R_{pw}.

Also, only 50 % of the photons are coupled to the forward propagating mode. The other half couples to the downward propagating mode and is lost in the substrate. The result is that the total efficiency for this standard PW design with a 0.8 NA lens is 12 %.

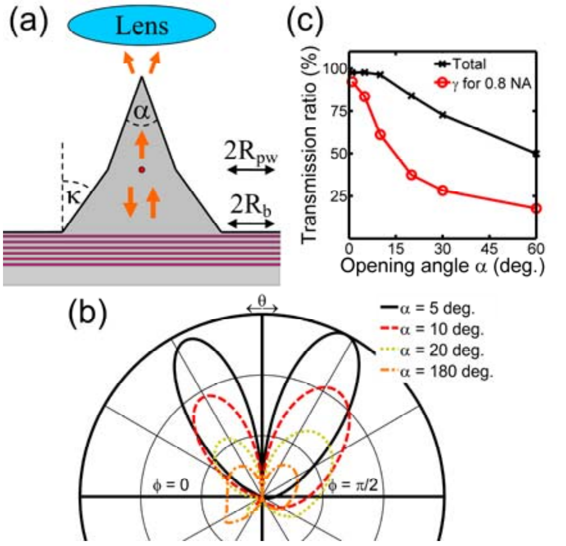

Figure 2: Photonic wire geometry with tapers and Bragg reflector (a). Corresponding far field radiation pattern (b) and total free space transmission and collection efficiency as function of opening angle α.

Now we consider the geometry sketched in Fig. 2(a). This PW features taperings above and below the position of the QD and a distributed Bragg reflector with 20 periods of $\lambda/4$ GaAs/AlAs layers in the substrate. Fixing $\omega R_{pw}/c = 1$, we study the collection efficiency as function of taper opening angle α. The corresponding emission diagrams and the total emission and collection efficiency as function of α are given in Fig. 2(b,c). For large opening angles, the collection efficiency is not improved by the taper, but we observe that when α approaches 0, γ increases dramatically, reaching 87 % for $\alpha = 1°$. This high collection efficiency can be attributed to two beneficial effects. First an adiabatic mode expansion eliminates the reflection at the semiconductor-air interface and second the guided mode is expanded such that the divergence of the output beam is reduced [9].

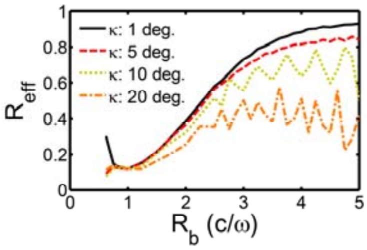

Figure 3: Reflection of the fundamental guided mode as function of R_b and side wall angle κ.

As in the standard PW, half of the photons are coupled to the downwards propagating mode, so that the introduction of a bottom mirror is compulsory. For small diameter PWs ($R_{pw} < c/\omega$) however, Bragg mirrors display small reflection coefficients, be they integrated within the PW or below the PW as in Fig 2(a). We therefore propose to enlarge adiabatically the foot of the PW in order to get a sufficiently high reflectivity by a bottom Bragg mirror as sketched in figure 2(a). Fig. 3 displays the modal reflection R_{eff} of the downwards propagating fundamental guided mode by the Bragg mirror, as a function of the side wall angle κ and of the PW bottom radius R_b. We observe that by choosing a large R_b and a small κ, reflection coefficients well above 0.8 can be obtained.

Assuming $\beta=0.95$, $\gamma=0.9$, $R_{eff} = 0.85$ and that half the photons are coupled to the backwards propagating mode, a total efficiency of 0.95 *(0.5 + 0.5*0.85)*0.9 = 80 % is obtained.

Conclusions

To conclude, high-efficiency (>80%) single-mode S4Ps can be build by embedding a single photon emitter inside an engineered photonic wire.

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