Photonic “hourglass” design for efficient quantum light emission

Østerkryger, Andreas Dyhl; Claudon, Julien; Gérard, Jean Michel; Gregersen, Niels

Published in: Optics Letters

Link to article, DOI: 10.1364/OL.44.002617

Publication date: 2019

Document Version: Peer reviewed version

Link back to DTU Orbit

A photonic "hourglass" design for efficient quantum light emission

Andreas Dyhl Osterkryger\textsuperscript{1}, Julien Claudon\textsuperscript{2}, Jean-Michel Gérard\textsuperscript{2}, and Niels Gregersen\textsuperscript{1,}\textsuperscript{*}

\textsuperscript{1}DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark
\textsuperscript{2}Univ. Grenoble Alpes, CEA, INAC, PHELIQS, “Nanophysique et semi-conducteurs” group, F-38000 Grenoble, France

*Corresponding author: ngre@fotonik.dtu.dk

We propose a novel "hourglass"-shaped design for highly efficient generation and collection of quantum light. The design features a quantum dot in a photonic nanowire sandwiched between tapered Bragg reflectors. For a Purcell factor of 9, the design features a spontaneous emission coupling of 0.993 to the cavity mode enabled by the strong dielectric screening of radiation modes. Thanks to a highly reflecting bottom mirror, we furthermore demonstrate a collection efficiency of 0.95 to a Gaussian profile. Finally, this photonic structure features a broad operation bandwidth, as large as 11 nm. © 2019 Optical Society of America

OCIS codes: (140.3300) Laser beam shaping; (140.3948) Microcavity devices; (250.5590) Quantum-well, -wire and -dot devices.

http://dx.doi.org/10.1364/ao.XX.XXXXXX

Within optical quantum information technology\textsuperscript{1}, a key component is the quantum light source capable of emitting single photons and entangled photon pairs (EPPs) on demand. For scalable information processing, the source must feature both near-unity extraction efficiency and photon indistinguishability. For several decades, spontaneous parametric down-conversion\textsuperscript{2} has been a workhorse for quantum light generation, however with an extraction efficiency of 0.66 combined with 0.985 photon indistinguishability\textsuperscript{9} has in recent years emerged as a promising platform for realizing deterministic single-photon generation\textsuperscript{4} and EPP sources\textsuperscript{5}. Today, the most successful design strategy for single-photon generation is based on a QD in a microcavity pillar\textsuperscript{6,7}, where Purcell enhancement is exploited to ensure high efficiency. Here, a photon collection efficiency \(\epsilon\) up to 0.79\textsuperscript{8} has been demonstrated, and more recently an \(\epsilon\) of 0.66 combined with 0.985 photon indistinguishability\textsuperscript{9} was reported. However, the micropillar design approach is inherently narrowband (bandwidth \(\Delta \lambda \sim 0.2\) nm), whereas EPP generation using the exciton-biexciton cascade requires a bandwidth of typically a few nm. While EPP generation from a double-pillar "molecule" geometry\textsuperscript{10} with an extraction efficiency \(\epsilon\) of 0.35 has been demonstrated, this design suffers from a highly non-Gaussian far-field emission pattern. An alternative design approach consists in placing the QD in a photonic nanowire, where a dielectric screening effect\textsuperscript{11} is employed to ensure high efficiency. In particular, no resonant effect is used and the design approach is thus broadband. Single-photon generation efficiency \(\epsilon\) up to 0.75 from "needle"\textsuperscript{12} and "trumpet" nanowires\textsuperscript{13–15} has been demonstrated as well as EPP generation\textsuperscript{16,17} with \(\epsilon\) of 0.15. However, obtaining high photon indistinguishability from photonic nanowires remains a challenge. Known decoherence mechanisms include fast excitation energy fluctuations due to an unstable electrostatic environment\textsuperscript{18} and well as interaction with phonons\textsuperscript{19} and discrete vibration modes of the nanowire\textsuperscript{20}. While resonant effects are not needed for high efficiency, it is nevertheless desirable to enhance the spontaneous emission (SE) rate to overcome\textsuperscript{19} these decoherence mechanisms and ensure high indistinguishability. To this purpose it was recently suggested to introduce weak cavity effects by implementing a distributed Bragg reflector (DBR) in the "trumpet" taper\textsuperscript{21}. Here the cavity consists of a bottom silica-gold mirror\textsuperscript{22} and the top DBR. A bottleneck of this design is the bottom metal mirror with reflectivity limited to \(\sim 0.91\textsuperscript{21–23}\). In particular, when the SE is Purcell enhanced in the presence of the DBR, this occurs at the cost of reduced efficiency due to increased light absorption in the metal.

To avoid this trade-off and to pave the way towards combined near-unity efficiency and indistinguishability, we propose in this Letter the "hourglass" design illustrated in Fig. 1(a). Its novelty consists of the combination of a top "trumpet" taper featuring a DBR\textsuperscript{21} and a bottom inverted "trumpet" taper featuring another DBR\textsuperscript{24} allowing for near-unity bottom mirror reflectivity. We will show that the "hourglass" may overcome the trade-offs of present design strategies both in terms of efficiency and indistinguishability\textsuperscript{25}. In the following, we first discuss the single-mode model used to analyze the performance of the "hourglass". Subsequently, we discuss the achievable reflectivity of the bottom DBR mirror. After having fixed a geometry, we then present calculations of the Purcell factor \(P_P\), the cavity coupling factor \(g\), the collection efficiency \(\epsilon\) and the bandwidth \(\Delta \lambda\). We will demonstrate that the "hourglass" allows for an \(\epsilon\) of 0.95 combined with a \(\Delta \lambda\) of 11 nm and an \(P_P\) of 9. Finally, we discuss strategies for further increasing the efficiency towards unity.

In this Letter, we consider a rotationally symmetric structure suitable for the EPP application. The radius at the position of the...
We present results both from exact calculations using a full waveguide mode for our design wavelength \( \lambda_0 = 925 \text{ nm} \) as discussed below. The cavity is formed by a QD-DBR height such that the radius of the first DBR layer is \( R_B = 150 \text{ nm} \). The black contour line indicates 0.98 reflectivity.

The implementation of a bottom mirror with near-unity reflectivity is crucial in the pursuit of quantum light sources for scalable quantum information processing.

We now present the calculated modal reflectivity \( R_{11}^B \) of the tapered DBR bottom mirror as function of the sidewall angle \( \theta \) and the number of DBR layer pairs in Fig. 2. Since the reflectivity of the DBR is significantly compromised for nanowire radii below \( \sim 0.15 \lambda_0 \) [22], we have chosen to place the first DBR pair at a QD-DBR height \( h_B \) corresponding to a radius \( R_B \) of 150 nm. We observe that a reflectivity above 0.98 is achievable for a sidewall angle \( \theta \) below 6°, and the general trend is that the reflectivity improves with decreasing angle and increasing number of layer pairs. Additionally, careful inspection reveals oscillations in the reflectivity as function of the sidewall angle. These oscillations are due to coupling between the fundamental mode and higher
order modes at the position of the first AlGaAs layer and could be suppressed by increasing \( R_b \) or by introducing an adiabatic DBR profile [29] with a gradually increasing AlGaAs layer thickness and/or a gradually decreasing AlGaAs refractive index.

A small sidewall angle \( \theta \) is required for adiabatic propagation [23] of the HE\(_{11} \) mode through the taper, and a large top radius \( R_{\text{top}} \) is needed to ensure a low out beam divergence [13–15] and a good coupling to a Gaussian mode in the far field. However, a large \( R_{\text{top}} \) and a small \( \theta \) lead to a large top taper height \( h_T \), whereas a compact device is preferential for the fabrication. There is thus a trade-off between high performance and choosing an \( h_T \) compatible with practical fabrication constraints.

In the following, we chose \( h_T = 15 \mu m \) and \( R_{\text{top}} = 1.2 \mu m \) corresponding to a \( \theta \) of 4.1°, which are parameters well compatible [15] with feasible fabrication. With this choice of parameters we compute a transmission \( \gamma \) of 0.975 to a Gaussian profile for the bare taper geometry, i.e. with no DBR in the top taper. Furthermore, we chose 40 layer pairs in the bottom DBR, which for \( R_b = 150 \) nm leads to a bottom reflectivity \( R_{11}^b \) of 0.987 - a remarkable improvement in reflectivity as compared to the dielectric-metal mirror. In the following, we investigate the influence of the number of layer pairs in the top DBR and of the QD-DBR separation \( h \). The maximum Purcell enhancement occurs when the QD is positioned at an antinode of the cavity mode, which is the case located at an antinode at the design wavelength of \( \lambda \) for the discrete values of \( h \) for which the total phase \( \arg(c_{11},c_{11}) \) describing a cavity roundtrip is zero. We note that increasing the number of DBR layer pairs from 4 to 40 modifies the total phase by less than 0.5°, which justifies our choice of identical top and bottom QD-DBR separation distances.

We present the computed Purcell enhancement \( F_p \), cavity coupling factor \( \beta_c \), collection efficiency \( \varepsilon \) and bandwidth \( \Delta \lambda \) of the Purcell enhancement in Fig. 3 as function of the number of top DBR layer pairs. The bandwidth is determined by computing the \( Q \) factor using the approach given in Ref. [30]. We present results for the first three separations \( h \) for which the emitter is located at an antinode at the design wavelength of \( \lambda_d = 925 \) nm. We observe that the Purcell factor increases slightly with larger separation \( h \). As the trumpet radius increases, the HE\(_{11} \) modal overlap at the GaAs/AlGaAs interfaces is improved, and this in turn leads to increased reflectivity [21] and Purcell enhancement. The cavity coupling factor \( \beta_c \) exceeds 0.97 even for a weakly reflecting DBR, which is a result of dielectric screening by the nanowire [11]. The collection efficiency \( \varepsilon \) is slightly improved with \( h \) due to the increase in Purcell enhancement, and it remains above ∼ 0.9 for up to 8 layer pairs thanks to the high reflectivity of the bottom DBR. As expected the bandwidth is largest for the shortest cavity, for which we observe a \( \Delta \lambda \) of 11 nm is obtained for 6 layer pairs. Fig. 3 includes results obtained from the single-mode model described above as well as from a full model taking into account interaction of the HE\(_{11} \) mode with radiation modes in the evaluation of the amplitude coefficients \( c_d \) and \( c_d \). Whereas the agreement for \( F_p \) and \( \Delta \lambda \) for two models is good, discrepancies are observed for \( \beta_c \) and \( \varepsilon \) which increase with reduced QD-DBR separation \( h \). This discrepancy originates from a modified \( c_d \) coefficient for the smaller cavities due to interaction with radiation modes. Whereas the single-mode model has provided remarkable agreement for simpler designs [23, 24], we conclude that full simulations are needed to predict the performance in the presence of significant cavity effects.

We now investigate the performance of an "hourglass" design featuring 40 (6) pairs in the bottom (top) DBR. The Purcell factor for this design is slightly larger than for the case with the silica-gold mirror [21] due to the increased reflectivity of the bottom DBR with a maximum \( F_p \) of ∼ 9 at the design wavelength and a corresponding \( \beta_c \) of 0.993. Furthermore, efficiencies \( \varepsilon \) of 0.95 and 0.965 are obtained for \( h = 202 \) and 554 nm respectively - significant improvements compared to the \( \varepsilon \) of 0.8 reported in Ref. [21]. While keeping the design wavelength \( \lambda_d = 925 \) nm fixed, we then present the cavity coupling factor \( \beta_c \) and the collection efficiency \( \varepsilon \) in Fig. 4 as function of emitter wavelength \( \lambda \) and QD-DBR separation distance \( h \). We observe that a \( \beta_c \) above 0.95 is obtained over a 36 nm range for the first resonance line highlighting the broadband nature of the design in terms of efficient coupling to the cavity mode. This leads to a collection efficiency above 0.88 over the same range for \( h = 202 \) nm. Similarly, Fig. 4 demonstrates the good tolerance of \( \beta_c \) and \( \varepsilon \) with respect to \( h \) thus ensuring feasibility in the fabrication. Finally, we note that, for \( h = 202 \) nm, the 0.95 collection efficiency to a Gaussian mode

![Fig. 3. Purcell enhancement \( F_p \) (a), cavity SE coupling factor \( \beta_c \) (b), collection efficiency \( \varepsilon \) (c) and bandwidth \( \Delta \lambda \) of the Purcell enhancement (d) as function of the number of DBR pairs in the top mirror computed for the first three resonant QD-DBR separation distances using the full model (solid curves) and the single-mode model (dashed curves).](image-url)

![Fig. 4. Cavity coupling factor \( \beta_c \) and collection efficiency \( \varepsilon \) as function of emission wavelength \( \lambda \) and QD-DBR separation distance \( h \) with \( \theta = 4.1^\circ \), \( R_{\text{Top}} = 1.2 \mu m \), \( h_T = 15 \mu m \) and 40 (6) layer pairs in the bottom (top) DBR.](image-url)
is combined with an 11 nm bandwidth, which makes the design attractive for the EPP application. The combination of the high Purcell factor with the broad spectral bandwidth is achieved thanks to a small cavity mode volume of \(\sim 0.7 (\lambda/n)^3\) [21].

Thus the "hourglass" design clearly has potential to outperform the micropillar geometry in the EPP application, and we now consider its strengths within the single-photon source application, where the micropillar geometry currently represents state-of-the-art. Here, the rotationally symmetric micropillar design suffers from lack of polarization control, which reduces its efficiency by a factor of 2 due to polarization filtering. An elliptical cross-section has been suggested [7] to establish polarization control, however it necessarily reduces the overlap to a Gaussian profile in the far field leading to a trade-off between degree of polarization and efficiency. On the other hand, the "hourglass" allows for an elliptical cross-section [31] at the position of the emitter combined with a rotationally symmetric top termination thus enabling for polarization control without compromising the far field pattern. Additionally, we note that the micropillar relies on Purcell enhancement to ensure high efficiency, and it is thus ultimately limited by a trade-off [25] between efficiency and indistinguishability in the presence of phonon-induced decoherence. Whereas calculations of the indistinguishability are beyond the scope of this Letter, we remark that the above trade-off is avoided in the "hourglass" design as high efficiency is obtained independently of the Purcell factor, which instead may be chosen to maximize the indistinguishability.

Whereas an exhaustive parameter optimization for the "hourglass" design is beyond the scope of this Letter, we finally now qualitatively point out strategies for increasing the efficiency further towards unity. Three main factors limit the collection efficiency of the present design: 1) A DBR operating in a low-diameter regime suffers from scattering [32] to higher order modes. As discussed above, this scattering can be suppressed using adiabatic engineering [29] of the layer thicknesses and of the refractive index profile. 2) The side wall angle \(\theta\) of 4.1° can be reduced further to increase \(\gamma\) for the bare taper. The price to pay is an increased top taper height \(h_T\). We have chosen a modest \(h_T\) of 15 \(\mu m\), however top tapers of almost twice this height [15] have already been demonstrated experimentally. 3) The maximum overlap between a HE_{11} mode in a GaAs nanowire (Bessel profile) and an optical fibre (Gaussian profile) is 0.985. This limitation, which also applies to the micropillar, can be overcome by butt-coupling the source to a tapered optical fiber.

In conclusion, we have proposed an "hourglass"-shaped design for a highly efficient source of quantum light. For a modest taper height compatible with fabrication, we show that an efficiency of 0.95 is achievable combined with an 11 nm bandwidth. The design does not rely on Purcell enhancement to achieve high efficiency, and the Purcell factor can be freely chosen e.g. to maximize the photon indistinguishability.

**Funding.** QuantERA ERA-NET Cofund (HYPER-U-P-S); Innovation Fund Denmark (7074-00048); Independent Research Fund Denmark (DFF-4181-00416); French National Research Agency (ANR-16-CE09-0010-01); CEA DRF Impulsion (SOUAPE).

**REFERENCES**
