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# Design of electrically driven single-photon source based on intra-cavity contacted microcavity with oxide-confined optical apertures emitting at 1.3 $\mu$ m

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Abstract. We propose a hybrid microcavity design of a 1.3  $\mu$ m range electrically driven singlephoton source (SPS) consisting of two high-contrast dielectric distributed Bragg reflectors which surround a 3 $\lambda$ -thick semiconductor cavity with two intra-cavity contact layers and four 40-nmthick oxide-confined apertures. According to 3D finite-difference time-domain modelling, the overall photon-extraction efficiency of ~74% and the Purcell factor of ~13 can be obtained by properly adjusting the position of oxide-confined apertures relative to the electric field of the fundamental optical mode. The studied SPS design also demonstrates a coupling efficiency of up to 13% within numerical aperture 0.12 in contrast to ~5% reached for a conventional semiconductor micropillar.

In recent years, much attention has been paid to the development of true quantum–light sources with nonclassical statistics based on single InGaAs semiconductor quantum dots (QD) as photon emitters. This research is motivated by applications in secure communication and quantum information technology which has become very popular trend of research in nanophotonics [1]. One of the key parameters for the design optimization of single-photon source (SPS) are high photon extraction efficiency and high single-mode fiber coupling efficiency as well as a high Purcell factor. Using single InGaAs QDs emitting in the short wavelength around 900 nm and optical excitation scheme, photon extraction efficiencies up to 65% (NA=0.42) was reported for SPS based on solid GaP immersion lens under optical excitation [2], 72% (NA=0.75) for SPS based on photonic nanowires under optical excitation [3], 74% (NA=0.42) (and corresponding Purcell factor of ~5.8) for semiconductor micropillar under optical excitation [4], 85% (NA=0.65) for SPS based on circular Bragg gratings [5]. Recently, the photon-extraction efficiencies up to 61% (NA=0.4) and the Purcell factor up to 3.2 have been experimentally reached for an electrically driven semiconductor micropillar [6].

At the same time, InGaAs QD-based SPSs emitting in the 1.3  $\mu$ m wavelength range still suffer from low efficiency. Photon extraction efficiencies up to 10% (NA=0.4) were reported for SPSs based on a half-vertical microcavity with semiconductor microlens under optical excitation [7] and 36% (NA=0.7) (and corresponding Purcell factor of ~4.4) for SPS based on photonic crystal cavity [8]. According to Journal of Physics: Conference Series

the theoretical work [9], the photon–extraction efficiencies can be increased up to 95% (NA=0.8) with the Purcell factor close to 30 for the 1.3 µm optically pumped SPS based on the hybrid circular Bragg gratings. However the development of the 1.3 µm electrically driven QD-based SPSs is a more difficult task as compared to the short-wavelength range QD-based SPSs due to higher free-carrier absorption loss. The most straightforward solution is to use a vertical microcavity with carrier injection through nand p-type intra-cavity layers (hereinafter referred to as IC layers), which have modulated doping profiles (the heavily doped layers are located at the node of the longitudinal standing-wave pattern) to reduce optical losses caused by free carrier absorption. More recently, we proposed the 1.3 µm electrically driven SPS design based on the passive cavity concept and circular Bragg grating [10], which potentially promises an overall photon–extraction efficiency of  $\sim 83\%$  with the Purcell factor of  $\sim 5$  as well as the efficiency of photon coupling to a single-mode fiber (NA=0.12, core diameter ~8.2 µm) up to 11% versus  $\sim 6\%$  for a conventional semiconductor micropillar [11]. However, the formation of a circular Bragg grating in a multilayer dielectric structure is technologically challenging despite some robustness of the proposed design. The insertion of the oxide-confined apertures into the intra-cavity contacted vertical microcavity is a simpler way to improve the outcoupling efficiency [12]. In this work, we present detailed results of numeric optical modeling for an electrically driven O-band SPSs based on intra-cavity contacted vertical microcavity with multiple oxide-confined optical apertures.

The 3-D finite-difference time-domain (FDTD) method was applied for the comprehensive investigation of the impact the microcavity design on the photon extraction efficiency, far-field pattern as well as Purcell effect. The single InGaAs QD is modeled by a dipole source with an in-plane dipole moment linearly polarized along the X-axis, which is placed in the antinode of the electric field to excite the microcavity response at its resonance frequency corresponding to the fundamental optical mode HE11. The overall photon–extraction efficiency as well as sidewall and bottom leakages are evaluated as the ratio of the number of photons passing through the corresponding planes of a probe box surrounding the microcavity (indicated by the green dashed line in Fig. 1a, Fig. 2a, Fig. 3a and Fig. 5a) to the total number of photon–extraction efficiency to the desired aperture angle is estimated from the far-field pattern. The photon–extraction efficiency to the desired aperture angle to the total number of photons generated by the dipole. The near–to–far–field transform was used to find the far-field pattern as the ratio of the number of photons emitted to this aperture angle to the total number of photons generated by the dipole. The details of numeric model can be found in the work [11].

A distinctive feature of intra-cavity contacted microcavity design is the requirement to form a micropillar only in the upper DBR (hereinafter referred to as a half-micropillar), otherwise the injection of carriers cannot be realized. Figure 1 shows modeling results for a circular half-micropillar with a diameter of 2  $\mu$ m consisting the bottom dielectric DBRs based on 6 pairs of  $\lambda$ /4-thick CaF<sub>2</sub>/ $\alpha$ -Si layers, semiconductor cavity with top and bottom GaAs-based IC layers and single QD in between, and top dielectric DBRs based on 3 pairs of  $\lambda$ /4-thick CaF<sub>2</sub>/ $\alpha$ -Si layers. The high-contrast dielectric DBR allow to suppress the undesired bottom leakage to 1%. However the weaker lateral optical confinement results in the huge sidewall leakage of about 52%, which in turn limit the overall photon–extraction efficiency to 47%. The light scattering at the edge of the half–pillar leads to a complex far-filed pattern, and the photon–extraction efficiency within NA=0.12 is less than 3%.



**Figure 1.** Numerical results for a 1.3  $\mu$ m range hybrid half-pillar based on semiconductor cavity with IC layers and dielectric DBRs: (a) refractive index profile in X-Z plane, (b) and (c) on-resonance electric field intensity distribution in X-Z and Y-Z planes, (d) far-field pattern (the circle grid with a step of 10°).

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The key point is to increase the microcavity thickness to  $3\lambda$  and insert four abrupt oxide-confined apertures with diameter of ~2 µm (fabricated by the wet selective oxidation of AlGaAs aperture layers). Such an aperture in the AlGaO oxide layer makes it possible not only to restrict carrier injection into a single QD, but also to ensure strong optical confinement. Since the actual position of the AlGaAs aperture layers relative to the electric field of the fundamental optical mode in the  $3\lambda$ -cavity also impact on the resonance wavelength of the investigated half-pillar, the thickness of the semiconductor cavity was adjusted so that the resonance wavelength remained at about 1.3 µm. On the one hand, the oxide-confined apertures placed at a node of the electric field of the fundamental optical mode slightly affect the lateral distribution the electromagnetic field in the cavity as well as far-filed pattern (see Fig. 2). As a result, the side emission is still strongly enhanced (~44%), and the overall photon–extraction efficiency does not exceed ~56%, while the photon–extraction efficiency within NA = 0.12 increases up to 5%. The small value of the Q–factor (~300) caused by a weaker lateral optical confinement limits the Purcell factor at about 2.5.



**Figure 2.** Numerical results for a 1.3  $\mu$ m range hybrid half-pillar based on semiconductor 3 $\lambda$ -cavity with IC layers, oxide–confined apertures placed at node and dielectric DBRs: (a) refractive index profile in X-Z plane and standing-wave pattern of the electric field on inset, (b) and (c) on-resonance electric field intensity distribution in X-Z and Y-Z planes, (d) far–field pattern (the circle grid with a step of 10°).

On the other hand, the oxide–confined apertures placed at an antinode of the electric field of the fundamental optical mode provide strong lateral optical confinement, which in turn leads to enhancement of the Q–factor and the Purcell factor up to 3300 and 20, respectively (see Fig. 3). However the light scattering at the semiconductor–oxide boundary leads to not only the strong divergence of the emission, but also keeps the sidewall leakage at level of 44% and, therefore, limits the overall photon–extraction efficiency to ~54%.



**Figure 3.** Numerical results for a 1.3  $\mu$ m range hybrid half-pillar based on semiconductor 3 $\lambda$ -cavity with IC layers, oxide–confined apertures placed at antinode and dielectric DBRs: (a) refractive index profile in X-Z plane and standing-wave pattern of the electric field on inset, (b) and (c) on-resonance electric field intensity distribution in X-Z and Y-Z planes, (d) far–field pattern (the circle grid with a step of 10°).

Nevertheless, as it follows from the modeling results presented in Fig. 4, it is possible to reach a compromise by tuning the longitudinal position of oxide–confined apertures in the cavity (aperture position  $\Delta d_{ap}$ ), when the overall photon–extraction efficiency can be enhanced up to ~74% due to a partial suppression of the side emission (~25%). A decrease in the optical mode volume resulting from

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the reduction of the semiconductor cavity thickness makes it possible to simultaneously maintain the Purcell factor as high as 13. In addition, a significant redistribution of the electromagnetic pattern in the microcavity provides a narrowing of the emission divergence in the far-field pattern in this case and allows to increase the photon–extraction efficiency within NA=0.12 up to ~13% (see Fig. 5), which is 2-3 times higher than that for the conventional semiconductor micropillar. Noteworthy, the photon extraction efficiency of the hybrid passive cavity-based half-micropillar with the circular Bragg grating [11] is even comparable with the maximum theoretically achievable outcoupling efficiency into the high aperture single-mode fiber (NA=0.42, core diameter ~2.5 µm) of the optically pumped SPS based on the half-vertical microcavity with semiconductor microlens [13-14]. However it is still lower than the record outcoupling efficiency into available single-mode fibers predicted for optically pumped SPSs based on the hybrid circular Bragg gratings: up to 56% for SMF28 fiber (NA=0.12, core diameter ~8.2  $\mu$ m) and 76% for 980HP fiber (NA=0.2, core diameter ~3.6  $\mu$ m) [9]. Note that the photon-extraction efficiency into low-NA collection optics and outcoupling efficiency into single-mode fibers can be further enhanced (up to the aforementioned record level) using the tapered oxide-confined optical apertures, which can significantly reduce the resonator's sidewall leakage, as this approach eliminates the light scattering at the edge of the half-pillar (one can use a planar microcavity structure) while maintaining a high Purcell factor.

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**Figure 4.** Numerical results for a 1.3 µm range hybrid half-pillar based on semiconductor  $3\lambda$ -cavity with IC layers, oxide–confined apertures and dielectric DBRs: (a) overall photon–extraction efficiency *PEE* and sidewall leakage *SWL* as a function of aperture offset  $\Delta d_{ap}$ , (b) photon–extraction efficiency *PEE* within NA=0.12 and Purcell factor  $F_p$  as a function of aperture offset  $\Delta d_{ap}$ . All oxide–confined apertures are shifted in Z-direction simultaneously relative to the electric field of the fundamental optical mode from the antinodes to the nodes.



**Figure 5.** Numerical results for a 1.3  $\mu$ m range hybrid half-pillar based on semiconductor 3 $\lambda$ -cavity with IC layers, oxide–confined apertures placed at optimum position and dielectric DBRs: (a) refractive index profile in X-Z plane and standing-wave pattern of the electric field on inset, (b) and (c) on-resonance electric field intensity distribution in X-Z and Y-Z planes, (d) far–field pattern (the circle grid with a step of 10°).

Using in-situ electron beam lithography combined with cryo-cathodoluminescence spectroscopy [15] or in-situ far-field optical lithography combined with cryo-photoluminescence spectroscopy [16] for spatially and spectrally pre-selection and the deterministic insertion of a target single QDs to electrically-driven SPSs is a rather complicated and challenging task, therefore, we analyzed the impact of the relative position of the QD in the cavity and the microcavity center on the characteristics of the proposed SPS. Although the lateral dipole displacement from the microcavity symmetry axis does not affect the Q-factor, the calculations revealed a drop in the Purcell factor caused by an increase in the mode volume (see Fig. 6.a). According to Fig. 6.b, an increase in the lateral dipole-to-cavity displacement also leads to a drop in the overall efficiency due to an increase in the sidewall leakage. Nevertheless, the lateral dipole-to-cavity displacement by  $\pm 0.2 \,\mu$ m in the studied microcavity results in a decrease in the overall photon–extraction efficiency and the Purcell factor by less than 20%.



**Figure 6.** Numerical results for a 1.3 µm range hybrid half-pillar shown in Figure 5: (a) mode volume  $V_m$  and relative change in the Purcell factor  $\Delta F_p$  as a function of the lateral dipole-to-cavity displacement  $\Delta L_{dp}$ , (b) change in the overall photon–extraction efficiency  $\Delta PEE$  and change in the sidewall leakage  $\Delta SWL$  as a function of the lateral dipole-to-cavity displacement  $\Delta L_{dp}$ .

In conclusion, we have carried out 3D FDTD modeling of photon–extraction efficiency from intracavity contacted hybrid microcavity with multiple oxide-confined apertures, which can potentially be used for the realization of 1.3  $\mu$ m bright electrically driven QD–based SPSs. By adjusting the position of oxide-confined apertures relative to the electric field of the fundamental optical mode, the overall photon-extraction efficiency of about 74% and the Purcell factor of about 13 can be achieved. The photon extraction efficiency within NA=0.12 reaches ~13% versus ~5% for a conventional semiconductor micropillar. The presented SPS design enables one to eliminate the negative effect of nonradiative carrier recombination or light scattering on the etched sidewalls and demonstrates high tolerance against lateral dipole-to-cavity displacement. Further improvements can be obtained by using the taper oxide-confined optical apertures.

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### References

- [1] Michler P Quantum Dots for Quantum Information Technologies, Springer 2017
- [2] Chen Y et al. 2018 Nature Communications 9, 2994
- [3] Claudon J et al. 2010 Nature Photonics 4, 174
- [4] Unsleber S et al. 2016 Optics Express 24, 8539
- [5] Liu J et al. 2019 Nature nanotechnology 14, 586
- [6] Schlehahn A et al. 2016 APL Photonics 1, 011301

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- [7] Srocka N et al. 2018 AIP Advances 8, 085205
- [8] Kim J–H et al. 2016 *Optica* **3**, 577
- [9] Rickert L et al. 2019 Optics Express 27, 36824
- [10] Blokhin S A et al 2020 J. Phys.: Conf. Ser. 1697 012179
- [11] Blokhin S A et al. 2021 Optics Express 29, 6582
- [12] Blokhin S A et al. 2021 Technical Physics Letters 47, 231
- [13] Schneider P-I et al. 2018 Optics Express 26, 8479
- [14] Zołnacz K et al. 2019 Optics Express 27, 26772
- [15] Gschrey M et al. 2015 Nature Communications 6, 7662
- [16] Nowak A K et al. 2014 Nature Communications 5, 3240