Design optimization for bright electrically-driven quantum dot single-photon sources emitting in telecom O-band

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Abstract: A combination of advanced light engineering concepts enables a substantial improvement in photon extraction efficiency of micro–cavity–based single–photon sources in the telecom O–band at ~1.3 µm. We employ a broadband bottom distributed Bragg reflector (DBR) and a top DBR formed in a dielectric micropillar with an additional circular Bragg grating in the lateral plane. This device design includes a doped layer in pin–configuration to allow for electric carrier injection. It provides broadband (~8–10 nm) emission enhancement with an overall photon–extraction efficiency of ~83% into the upper hemisphere and photon–extraction efficiency of ~79% within numerical aperture NA=0.7. The efficiency of photon coupling to a single–mode fiber reaches 11% for SMF28 fiber (with NA=0.12), exceeds 22% for 980HP fiber (with NA=0.2) and reaches ~40% for HNA fiber (with NA=0.42) as demonstrated by 3D finite–difference time–domain modeling.

1. Introduction

Multiple advances have recently been made in the development of high–performance semiconductor optoelectronic light–emitting devices including diode lasers, light–emitting diodes or single-photon emitters [1–12]. This has led to substantial breakthroughs in reaching previously unavailable spectral regions [7], in improved thermal stability of emitting optical power or emission wavelength [4], in high power high brightness lasing [10–12], and in narrow or even single mode emission spectra in case of semiconductor lasers [5]. Beyond that, the steadily growing need in secure communication is the driving force for continuous development of quantum–light sources based on semiconductor quantum dots (QDs) for applications in photonic quantum technology, which has become a major branch of research in nanophotonics. The emitted single photons can be used as photonic qubits in quantum circuits and/or in long–distance quantum communication [13,14]. The important parameters for the design optimization of single–photon sources (SPSs) include a narrow far field to promote the in–coupling to optical fibers, as well as a high photon–extraction efficiency. A QD in a conventional planar semiconductor structure shows only a small (<2%) extraction efficiency, but broadband antennas made from dielectric or semiconductor materials can enhance the extracting photons from QDs significantly. For instance, monolithic microcavities patterned upon pre–selected QDs in combination with a bottom distributed Bragg reflector (DBR) allow for broadband enhancement of the photon–extraction
efficiency up to ∼29% under optical excitation [15]. An alternative approach using a solid GaP immersion lens with a low refractive index spacer layer makes it possible to increase the extraction efficiency of QD emission up to 65% under optical excitation by [16]. Photonic wires or trumpets can lead to an increase in extraction efficiency of QD emission up to ∼72%, again under optical excitation [17]. However, the fabrication of electrically driven SPSs remain challenging in the case of such broadband antennas. When embedding of single QDs into narrow–band micropillar cavities a photon–extraction efficiency up to ∼74% could be reached under optical excitation [18,19], and up to ∼61% under electrical excitation [20]. Recently, the development of QD SPSs based on circular Bragg gratings (CBG) has become very popular and enables photon–extraction efficiencies as high as 85% in experiment [21]. However, the CBG concept is not (directly) compatible with electrical carrier injection. We further note that most research on efficient QD–based SPS has been focused so far on the short wavelength range (GaAs QD emitting at ∼780 nm [21–23] or InGaAs QDs emitting at ∼900–960 nm [17–19,24–26] while quantum–light sources emitting in the telecom O–band at ∼1.3 µm still suffer from low photon–extraction efficiency. In fact, a micropillar cavity SPS based on InAs/GaAs double–sheet vertically coupled QDs demonstrated photon–extraction efficiency of 3.3% [27]. Deterministically fabricated microlens structures based on InGaAs/GaAs QDs showed photon extraction efficiencies of up to 10% (within a numerical aperture of 0.4) [28,29], and a photonic crystal cavity based on InAs/InP QDs resulted in an enhanced efficiency of 36% (within a numerical aperture of 0.7) [30]. Thus, there is a great need for bright 1.3 µm SPSs with narrow far field suitable for both single–mode fiber coupling and electrical excitation in order to advance real–world applications of such quantum devices, for example in fiber–based quantum communication. Interestingly, in a recent theoretical work the CBG concept was extended to the telecom wavelength O–band, which promises photon–extraction efficiencies up to 95% in optically pumped devices [31]. In the present paper, we carry out numeric modeling and optimization of different designs for electrically driven O–band SPSs. By combining the passive cavity concept and circular Bragg grating we propose a design which promises a photon–extraction efficiency of ∼83% under electrical pumping which is highly interesting in terms of real–world applications.

2. Semiconductor cavity–based micropillar

For device optimization we apply the three–dimensional (3D) finite–difference time–domain (FDTD) method. This allows us to address the influence of various microcavity design elements on the photon extraction efficiency. The used subwavelength meshes have a size of 20 nm in the vertical direction whereas a slightly larger size of 30 nm in the lateral direction suffices for smooth in–plane variations of the optical field. The perfectly matched layer (PML) method was used to implement radiative boundary conditions. The simulation region including the PMLs for each type of a microcavity exceeds the region visualized by approximately 30–50% in each direction. For simplicity we neglect free–carrier absorption in doped layers and use the refractive indices at room temperature for all materials. All microcavities are designed for 1.3 µm spectral range of the telecom O–band. The QD is modeled by a dipole source with an in–plane dipole moment linearly polarized along the X–axis and placed in the center of the active cavity (for example, see Fig. 1(a)). The FDTD method calculates the electromagnetic response of the structure at its resonance frequency in the time domain triggered by a short excitation pulse applied to the dipole. Assuming a broadband dipole source we calculate the actual mode spectrum of the microcavity by the Fourier transform of the microcavity response. By analysing the lateral distribution of the electromagnetic field inside the microcavity at the resonance frequencies, we identify the mode type in each case and select the resonance frequency corresponding to the fundamental mode HE_{11}. By calculating the energy flux passing through the top and the bottom planes of a probe box surrounding the microcavity (the green dashed line in Fig. 1(a)) we evaluate the part of light emitted from the top and the bottom of the cavity and compare this to the total energy
flux passing through a second, small probe box surrounding the dipole source in its vicinity. To find the far-field emission pattern we use the near-field results obtained by the FDTD method applying so-called near-to-far-field transforms. The overall photon-extraction efficiency (PEE) is defined as the ratio of the number of photons emitted to the top hemisphere (i.e. to the air) to the total number of photons generated by the dipole. The photon collection efficiency (PCE) in a given aperture angle is calculated as the ratio of the number of photons emitted to this aperture angle to the total number of photons emitted to the upper hemisphere. To compare various designs of microcavities we also calculated the value of the photon-extraction efficiency to the given aperture angle as a product of the PCE and PEE.

![Fig. 1. Numerical results for a telecom O-band range circular micro-pillar with a diameter of 2 µm based on a 2λ-cavity semiconductor structure: (a) refractive index profile, (b) and (c) on-resonance electric field intensity distribution in X–Z (b) and Y–Z (c) planes, (d) far-field pattern for the fundamental HE_{11} mode.](image)

As a reference structure for our advanced design to be discussed below, we consider an electrically driven SPS based on a single QD embedded in a circular semiconductor micro-pillar
microcavity with top and bottom semiconductor DBRs. For definiteness, we choose an experimentally realized electrically driven SPS, the micro–pillar diameter of \( \sim 2 \mu m \), in which a high photon–extraction efficiency with reasonably high Q–factor was achieved by standard nanofabrication technologies [20]. Figures 1(b) and 1(c) show cross–section images representing the modeled optical field. The microcavity consists of a \( 2\lambda \)–thick GaAs–cavity surrounded by p–type top and n–type bottom GaAs/AlAs DBRs (Fig. 1(a)) having 13 and 30 \( \lambda/4 \)–thick mirror pairs, respectively. Strong confinement of the electromagnetic field of the fundamental mode inside the circular micro–pillar is clearly seen. The microcavity Q–factor reaches 3000, and the Purcell factor exceeds 12 despite a rather thick cavity. The difference in the reflectivity of the top and bottom DBRs provides the light extraction from the top plane of the probe box up to 84\% with the sidewall leakage \( \sim 7\% \). Note that the spectral width at which the photon–extraction efficiency reaches 50\% of its maximum value (FWHM) is only about 1.5 nm. Light scattering at the pedestal of the circular micro–pillar leads to mode coupling between the fundamental and higher order lateral modes [32], which increases the undesired bottom leakage up to 9\%. The photon–collection efficiency within NA=0.7 reaches 93\% and the associated photon–extraction efficiency is 78\% within NA of 0.7. Such high extraction efficiency is comparable with state–of–the–art values of 74\% and 61\% obtained in the 930nm range for QD–based 1\( \lambda \)–thick microcavities in micropillars under optical [19] and electrical [20] excitation.

The development of bright electrically driven SPSs emitting at \( \sim 1.3 \mu m \) is a much stronger challenge as compared to the short–wavelength range counterparts due to huge free–carrier absorption in p–type doped layers [33,34]. Moreover, to ensure a reasonably low series resistance of the structure it is necessary to lower potential barriers at the interfaces between neighboring Ga\(_{1-x}\)Al\(_x\)As layers with different Al content in the DBRs. This is typically realized by intermediate layers with a graded alloy composition and a higher doping level, which reduces the DBR reflectivity and therefore reduces the Purcell factor. The most straightforward approach is to use a microcavity design with carrier injection through intra–cavity contact layers (IC layers) to minimize the mentioned absorption losses. It should be noted that using intra–cavity contact layers requires an increase of the microcavity thickness from \( \lambda \) to at least \( 2\lambda \), as one needs to open contact layers with a high precision while forming a mesa as well as to ensure suitable contacting of the IC layers and efficient spreading of the injection current.

Against this background we analyze a microcavity structure consisting of a \( 2\lambda \)–thick GaAs–cavity with n–type and p–type IC–layers surrounded by undoped top and bottom GaAs/AlAs DBRs (see Fig. 2(a)). The reflectivity of the top and bottom DBRs are the same as those in the previous structure with doped DBRs. To reduce the carrier injection area into the QD–based active region and improve the carrier injection efficiency into the single QD, a 40 nm–thick oxide–confined current aperture with a 2 \( \mu m \)–diameter was inserted into the cavity. Figures 2(b) and 2(c) show cross–section images representing the modeling results of the microcavity structure with IC–layers, where the micropillar with diameter of \( \sim 2 \mu m \) is formed only in the top DBR (hereafter referred to as half–micropillar) as the current path cannot be provided otherwise. The side emission is apparently strongly enhanced with some evidence of a complex mode structure due to a weaker lateral mode confinement, which in turn leads to a decrease in the Q–factor by more than 4.5 times and a drop in the Purcell factor to 3. In fact, the sidewall leakage increases to 48\%, while the bottom leakage is almost the same (\( \sim 11\% \)). The overall photon–extraction efficiency reduces from 84\% to 41\%, while the FWHM width increases to 3.5 nm. Moreover, the associated photon–collection efficiency within NA=0.7 changes from 93\% to 86\%. As a result, the photon–extraction efficiency within NA=0.7 decreases from 78\% to 35\% in this electrically–driven SPS.

It should be noted that thicker oxide–confined aperture layers promote strong lateral optical confinement. However, at the same time light scattering at the semiconductor–oxide boundary increases which affects negatively the photon–extraction efficiency. Besides that, thicker oxide
Fig. 2. Numerical results for a telecom O–band range circular half–micropillar with a diameter of 2 \( \mu \)m based on a \( 2\lambda \)–cavity semiconductor structure with IC–layers and oxide–confined aperture placed at an antinode of the electric field of the fundamental mode: (a) refractive index profile in X–Z plane and schematic view of envisioned contact layout (inset), (b) through (c) on–resonance electric field intensity distribution in X–Z (b) and Y–Z (c) planes, (d) far–field pattern for the fundamental mode HE\(_{11}\).

layers create stronger strain, which deteriorates the mechanical stability of the structure as well as the electronic structure of the QDs. It is possible to reach a compromise by using several oxide–confined apertures having a thickness of \(~40–70\) nm each, the approach being typically applied for VCSELs for the near–infrared spectral range. Interestingly, the oxide–confined aperture can also be used for the site–controlled integration of single QDs into SPSs with self–aligned current injection using the buried stressor growth concept [35]. To improve the photon–extraction efficiency, it is possible to insert two oxide–confined aperture layers, 60 nm thick each, at the antinodes of the electric field of the fundamental optical mode of the \( 2\lambda \)–micocavity. This design modification enhances the lateral optical confinement and leads
not only to an increase in Q–factor by 80% and an increase in Purcell factor to 5.5, but also
to a certain redistribution of the electromagnetic pattern in the microcavity. As a result, the
design containing two oxide–confined apertures leads to a moderate increase in photon–collection
efficiency for NA=0.7 up to 92% while the photon–extraction efficiency within NA=0.7 increases
up to a value of 45%.

3. Hybrid passive–cavity half–micropillar

In the following we introduce an improved device design to further enhance the photon–extraction
and collection efficiency of electrically driven QD SPSs in the telecom O–band. First, we
would like to note that the significant part of the sidewall leakage shown in Figs. 2(b) and
2(c) in the investigated microcavities is associated with the light emitted in–plane. Figure 3
shows the results of a 1D calculation of the optical modes in different planar microcavities. A
standard vertical 2λ–cavity semiconductor structure contains, apart from the vertical mode also a
waveguide mode (see, e.g., Fig. 3(a)) depending on the used cavity design. To solve this problem
of multi–mode operation the so–called passive cavity concept was proposed [3,36]. Recently, it
was demonstrated that the brightness of micro–LEDs emitting in the orange spectral range at
~610 nm can be enhanced up to ~95% with a narrow far–field pattern once the passive cavity
concept is employed [37].

Fig. 3. Calculated refractive index (black curves) and electric field strength profiles of
different modes for 2λ–cavity semiconductor structure with IC–layers (a) and hybrid passive
cavity structure (b) with IC layers and dielectric and oxidized DBRs. Blue curves: vertical
modes, green curves: waveguide modes, red curve: high–order waveguide (tilted) mode.

In the present paper the dielectric passive cavity based on SiO₂ layer is inserted below the
top dielectric DBR containing 7 pairs of λ/4–thick SiO₂/Ta₂O₅ layers and separated from the
semiconductor cavity with IC–layers and the active region by 1–period thick intermediate
dielectric DBR based on SiO₂/Ta₂O₅ layers (so–called hybrid passive cavity structure). To
reduce photon leakage caused by the light propagation at tilted angles in the bottom part of the
circular half–micropillar, the stop–band of the bottom DBR should be maximized. The selectively
oxidized DBR based on 6 pairs of λ/4 thick GaAs/AlGaO layers provides efficient light reflection
in a broad range light angles due to a huge refractive index step of approximately 1.8 between
GaAs and AlGaO layers. The semiconductor GaAs cavity is thinned down to approximately ~65
nm to increase the anti–waveguiding effect [38,39], while the thick matching AlGaO and SiO₂
layers were inserted to maximize interaction of the QD with the vertical optical mode of the
proposed microcavity structure. As it follows from Fig. 3(b), all modes of the planar waveguide
except one tilted mode are suppressed. However, in the frame of the simple planar structure
analysis, this tilted mode cannot be suppressed. Possibly the insertion of the oxide–confined
aperture near the active region and the ring trench pattern formed in the dielectric part (see
discussion below) can further prohibit the in–plane light propagation and redirect practically all emitted light in the vertical direction.

Figure 4 shows modeling results for a circular half–micropillar based on the proposed hybrid passive cavity structure with IC layers, the top dielectric and bottom oxidized DBRs and the oxide–confined aperture. The 20 nm–thick oxide–confined aperture was placed near the antinode to enhance the anti–waveguiding effect. The half–micropillar with a diameter of ∼2 µm is formed on top of the hybrid passive cavity structure’s dielectric part. As expected, the field intensity is mainly concentrated in the dielectric part, while light propagation in the direction towards the substrate is almost suppressed (the bottom leakage is ∼1%). However, the propagation of

![Figure 4](image-url)

**Fig. 4.** Numerical results for a telecom O–band range circular half–micropillar with a diameter of 2 µm based on hybrid passive cavity structure with IC layers, oxide–confined aperture and dielectric and oxidized DBRs: (a) refractive index profile in X–Z plane and schematic view of the envisioned contact layout (inset), (b) through (c) on–resonance electric field intensity distribution in X–Z (b) and Y–Z (c) planes, (d) far–field pattern for the fundamental mode HE$_{11}$.
the emitted light in the lateral plane is not fully prohibited. In addition, the significant part of emission still passes through the micropillar side, which results in a sidewall leakage of 34% of the total emission. Although the photon–collection efficiency within NA=0.7 reaches 94%, the photon–extraction efficiency of the circular half–pillar based on the hybrid passive cavity structure can be increased from 35% up to 61% (for NA=0.7) as compared to the circular half–micropillar based on the 2\(\lambda\)-cavity semiconductor structure with IC–layers structure. Nevertheless, the overall photon–extraction efficiency increases from 41% to 65%, while the FWHM increases up to 8 nm. Using of dielectric DBRs allows one to decrease the mode volume by a factor larger than 3 due to a reduced mode penetration depth in the DBRs as compared to semiconductor microcavities. However, a moderate value of the Q–factor (\(\sim570\)) caused by a weaker confinement of the mode in the lateral plane limits the Purcell factor to 5.5.

4. Circular Bragg grating microcavity half–micropillar

It is well known that the CBG cavity geometry, realized by a semiconductor microdisk surrounded by concentric semiconductor rings, enables efficient extraction of the emission of the light generated by a dipole placed in the center of the microdisk. The concentric rings of the CBG redirect the light trapped in guided modes mainly into the vertical direction and in the lateral direction back to the source of light, which leads to a strongly pronounced effect of the field confinement in the microcavity and to a high directionality of the light emission [31,40]. A first–order CBG acts as a mirror for in–plane guided modes, whereas a second–order CBG (with the period equal to the emission wavelength into the semiconductor slab) provides a first–order diffraction of the in–plane guided waves in the direction normal to the surface and thus enhances light extraction from microcavity [32,41]. Hence, an additional ring trench pattern creating the circular Bragg grating can provide the strong suppression of side emission in the hybrid passive cavity–based half–micropillar presented in the previous section.

The circular Bragg grating can be formed in the top dielectric part of the hybrid passive cavity structure by the etching of concentric trenches with a given period in the radial direction around

Fig. 5. Optimization of CBG microcavity geometry (gap width \(W\), ridge width \(L\), number of circular trenches \(N\)) for the hybrid passive cavity–based half–micropillar: (a) overall photon–extraction efficiency PEE and (b) photon–coupling efficiency PCE in NA=0.12 versus \(W\) at fixed \(L\) and \(N=4\), (c) far–field patterns for the fundamental mode HE\(_{11}\) at fixed \(L=550\) nm and \(N=4\), for different \(W\).
the half–micropillar having the diameter of ∼2 µm. As a major part of the light leaking through the side surfaces propagates at some tilt angles with respect to the surface plane, the second–order Bragg condition (where the period equals to the emission wavelength normalized by the effective refractive index in the high–index slab) was used in the FDTD modeling as a starting point in the procedure of the parameter optimization. Figure 5(a) illustrates the effects of varying the gap width (low–index grating region) and the ridge width (high–index grating region) on emission properties of the CBG microcavity half–micropillar structure. With reducing ridge width the modeling reveals a significant increase in overall photon–extraction efficiency (NA=1) up to a ridge width of 540 nm for which a maximum PEE of 83% for a gap width of 290 nm is observed.

![Fig. 6](image)

**Fig. 6.** Numerical results for a telecom range CBG microcavity half–micropillar based on hybrid passive cavity structure with IC layers, dielectric and oxidized DBRs and oxide–confined aperture: (a) refractive index profile in X–Z plane and schematic view of envisioned contact layout (inset), (b) through (c) on–resonance electric field intensity distribution in X–Z (b) and Y–Z (c) planes, (d) far–field pattern for the fundamental mode HE_{11}.
Indeed, Fig. 5(a) shows that for each fixed value of the ridge width there is a local maximum in the dependence of the overall photon–extraction efficiency versus gap width. Figure 6 displays modeling results for a CBG microcavity half–micropillar with a diameter of 2 µm based on the hybrid passive cavity structure with IC layers, the top dielectric and bottom oxidized DBRs and one oxide–confined aperture. The parameters of the CBG were chosen to reach maximum overall photon–extraction efficiency. As it follows from Fig. 5, the etching of the ring trench pattern with the gap width $W$ of $\sim$290 nm and the ridge width $L\sim$540 nm through the dielectric part enables one to block a portion of light propagating in the lateral direction and travelling away from the pillar side. According to Fig. 7(a), the effect increases upon a number $N$ of circular trenches and nearly saturates for 4 trenches. Moreover, the side emission in the CBG microcavity half–micropillar is also reduced to a fraction $\sim$16% of all emitted photons (see Fig. 7(a)), while the bottom leakage is almost prohibited ($\sim$1%). As a result, the overall photon–extraction efficiency reaches 83% while the FWHM width increases up to 10 nm in this electrically drivable device (see Fig. 7(b)). Due to such a remarkable change in the field distribution the photon–extraction efficiency within NA=0.7 rises up to 75% which includes also a fraction of the side emission directed towards the collection optics with the mentioned NA. It is interesting to note that using a CBG increases the mode volume by 10% leading to a reduction of the Purcell factor from 5.5 to 5.

5. Efficiency of photon coupling to an optical fiber

Apart from a high efficiency of photon collection using free–space optics which provides a large numerical aperture (up to NA=0.8), for real–world applications in photonic quantum technology it is worth considering the efficiency of photon collection to a standard single–mode fiber (SMF28) having a significantly smaller numerical aperture (NA=0.12). Recent research in this direction led to the development of fiber–coupled [42] and stand–alone [43] QD–SPSs in the 910–930 nm range and in the telecom O–band [44]. Moreover, single–mode fiber coupling has been achieved by 3D printed fiber–holders with and without integrated microoptics [45,46]. In this context it is worth considering the efficiency of photon coupling to a standard single–mode fiber having a significantly smaller numerical aperture of NA=0.12. It should be noted that, for a
circular micropillar with a diameter of 2 µm based on a 2λ–cavity semiconductor microcavity, the calculated value of the photon collection efficiency at NA=0.12 does not exceed 6% due to a strong divergence of the emission (see Fig. 1(d)), which actually limits the photon–extraction efficiency to the NA=0.12 at the level of 5%. Due to a partial redistribution of the electromagnetic field within the microcavity caused by oxide–confined apertures in a half–micropillar based on a 2λ–cavity semiconductor structure with IC–layers the photon collection efficiency to the NA=0.12 reaches 9%, which allows to keep the photon–extraction efficiency to the NA=0.12 at the level of 5% despite a smaller overall photon–extraction efficiency (see Fig. 2(d)). In case of a hybrid passive cavity–based half–micropillar the far field pattern has a rather complex structure, whereas a significant part of the emission is concentrated in the side lobes, and the photon collection efficiency to NA=0.12 drops down to 2%. As a result, the photon extraction efficiency to NA=0.12 does not exceed ~1% (see Fig. 4(d)).

Note that employing CBGs also allows one to significantly modify the near–field emission pattern, so nearly Gaussian transverse mode profile can be expected. In fact, results of the modeling of the photon collection efficiency within a narrow aperture angle as a function of the parameters of the CBGs presented in Fig. 5(b) show a significant increase in photon collection efficiency into NA=0.12 due to CBG design. However, the local maximum of the photon collection efficiency to NA=0.12 is shifted towards smaller gap width as compared to the plots of the overall photon–extraction efficiency given in Fig. 5(a). According to Fig. 5(c) this effect is caused by the narrowing of the far field pattern and by a decrease in emission intensity in the side lobes. Figure 8 shows modeling results for optimized CBG DBR microcavity half–micropillar with a diameter of 2 µm based on the hybrid passive cavity structure with the gap width of ~230 nm and the ridge width of 560 nm, parameters providing the narrowest emission divergence diagram. An increase in photon collection efficiency to NA=0.12 up to 11.5% has enabled to increase the photon–extraction efficiency to NA=0.12 up to 8% despite a drop in overall photon–extraction efficiency.

In contrast to a standard CBG design, the considered CBG microcavity half–micropillar is used to additionally reduce the sidewall leakage and to narrow the far–field emission pattern, and therefore should be less sensitive to technological imperfections such as fluctuations the CBG parameters. As it follows from Figs. 5(a) and 5(b), the dependence of the photon extraction efficiency and photon–coupling efficiency versus the CBG gap width calculated for different CBG ridge widths demonstrate a reasonable robustness of the effect, whereas, e.g., upon a 5% variation (change by ~30 nm) of the ridge width leads only to a moderate drop of the PEE (from ~83% to ~70%). A more stringent requirement arises for the photon–coupling efficiency to a single–mode fiber. Once the gap width is properly chosen (~290 nm), the PCE remains nearly unchanged upon a 2% variation of the ridge width. A more detailed analysis of the influence of fabrication imperfections on the properties of CBG microcavity half–micropillar based on hybrid passive cavity structure is a subject of an independent research and will be addressed elsewhere.

It should be noted that the considered CBG microcavity half–micropillar is a model structure to demonstrate the effect of PEE enhancement. Therefore, materials of the passive cavity and of both DBRs can further be optimized to increase the robustness of the effects versus fabrication imperfections. On the one hand, using dielectric DBRs with a high index contrast like those based on quarter–lambda layers of GaAs/AlGaO, Si/α–Si or CaF2/α–Si, will allow to reduce the thickness of the top DBR and, hence, the aspect ratio by a more than 2 times, keeping the photon–extraction efficiency at the level of 70–80%. On the other hand, using the third–order or fourth–order CBGs can further decrease the aspect ratio by 1.5–2 times while maintaining a narrow far–field emission pattern.

As shown in [31,42,47], the coupling efficiency of the extracted light to the fundamental mode of the single–mode fiber (so–called mode–coupling efficiency, MCE) depends on the degree of overlap between the near–field emission pattern of the investigated microcavity at the respective
Fig. 8. Telecom O–band range optimized CBG ($L=560\text{ nm}$ and $W=230\text{ nm}$) microcavity half–micropillar based on hybrid passive cavity structure with IC layers, dielectric and oxidized DBRs and oxide–confined aperture: (a) refractive index profile in X–Z plane and schematic view of envisioned contact scheme (inset), (b) through (c) on–resonance electric field intensity distribution in X–Z (b) and Y–Z (c) planes, (d) far–field pattern for the fundamental mode HE$_{11}$. 
distance and the Gaussian mode of the used single-mode fiber, the high coupling efficiency to the single-mode fiber can be achieved in the near-field coupling regime. However, a simple modeling of the field overlap does not yield a relevant behavior of the mode-coupling efficiency due to rather complex variation of the near field pattern upon distance from the surface of the CBG microcavity. Therefore, we have carried out an additional investigation of the direct (near-field) outcoupling of the emission from a microcavity to a telecom-wavelength single-mode fiber by means of 3D FDTD modeling. Figure 9(a) shows schematically the modeled object. Modeling was performed for three types of the SM fibers: SMF28 fiber with a core diameter of $d_{\text{core}} = 8.2 \, \mu m$ and refractive indices for core and cladding $n_{\text{core}} = 1.4537$ and $n_{\text{cladding}} = 1.447$; 980HP fiber, assuming $d_{\text{core}} = 3.6 \, \mu m$, $n_{\text{core}} = 1.46$ and $n_{\text{cladding}} = 1.447$ and HNA fiber [48], assuming $d_{\text{core}} = 2.5 \, \mu m$, $n_{\text{core}} = 1.5$ and $n_{\text{cladding}} = 1.44$. An air gap between the fiber tip and the microcavity top was considered and the symmetry axis of the microcavity was taken the same as that of the fiber. The model was first tested for a 1.3 $\mu m$ circular micro-pillar based on semiconductor $2\lambda$-cavity structure, having a broad and circularly symmetric emission far field pattern.

![Fig. 9. Direct coupling of the telecom O-band emission from microcavity to single-mode SMF28 fiber: (a) Fiber-coupling efficiency of light emitted at 1.3 $\mu m$ from a $2\lambda$-cavity based micropillar to SMF28 fiber as a function of the distance $F$ to the fiber tip calculated across the fiber core cross-section (red dots) and the entire fiber cross-section (black squares). Inset: schematic of the modeled object; (b) On-resonance electric field intensity distribution of the light emitted from the microcavity and coupled into SMF28 fiber.](image-url)
based on the fiber core cross-section area is underestimated. As a result, the value of MCE, which is the fraction of the power of the dipole emission, which is coupled to the fundamental mode of the single-mode fiber, can be calculated as a product of the fiber-coupling efficiency and the overall photon-extraction efficiency. For a 1.3 µm circular micropillar based on a semiconductor λc-cavity structure the value MCE does not exceed 6.5%, which correlates well with the estimations of the photon-extraction efficiency within NA=0.12 based on the far-field pattern.

Figures 10(a) through 10(c) address the coupling to the different single-mode fibers of the light emitted at 1.3 µm from a CBG microcavity half-micropillar based on a hybrid passive cavity structure, having a selectively oxidized bottom DBR, and a dielectric top DBR with a microcavity formed by CBG (as in Fig. 8(a)). The half-micropillar has a diameter 2 µm and the CBG was

Fig. 10. Coupling of the light emitted at 1.3 µm from a CBG microcavity half-micropillar based on a hybrid passive cavity structure into single-mode fibers: (a) through (c) on-resonant electric field intensity distributions for SMF28 (a), 980HP (b) and HNA (c) fibers. The fiber tip is placed 12 µm away from the top of the microcavity, d) Mode-coupling efficiency versus the distance between the microcavity top and the fiber tip D for different fiber types. Black squares: SMF28 fiber, red circles: 980HP fiber, green triangles: HNA fiber. Inset: on-resonant electric field intensity distributions for 980HP fiber at different D.
adjusted to improve the far–field light pattern (as in Fig. 8(d)), while the distance between the top of the CBG microcavity and the fiber tip is fixed, as an example, at 12 µm. Upon an increase in numerical aperture of the single–mode fiber, the characteristic size of the region decreases, in which coupling to the single–mode fiber occurs and the electromagnetic field outside the cavity has a noticeable intensity.

Figure 10(d) gives the comparison between different types of the fibers regarding the mode–coupling efficiency. Due to a narrower far field pattern the CBG microcavity half–micropillar based on a hybrid passive cavity structure allows to increase the photon–coupling efficiency up to 11% for SMF28 fiber which exceeds substantially the corresponding value of ∼6% for the classic micropillar. It should be noted that, contrary to [28,29], the mode–coupling efficiency for SMF28 fiber does not exceed 8.5% in the near–field coupling regime. However, fibers with a high NA reveal a significant increase in mode–coupling efficiency upon a decreasing distance between the microcavity top and the fiber tip D. Thus, mode–coupling efficiency exceeds 22% for 980HP fiber and reaches ∼40% for HNA fibers. Local minima at the distances 1.0–1.5 µm can be related not only to the interference in the cavity formed between fiber tip and top DBR, but also a significant redistribution of the electric field intensity for the fundamental mode HE11 once a CBG is introduced into a hybrid passive cavity–based half–micropillar (see inset of Fig. 10(d)). In this context it is interesting to note that the CBG microcavity half–micropillars show broadband photon–extraction efficiency with a width of up to 10 nm, while the circular 2λ–cavity micropillar shows a bandwidth of only about 1.5 nm. This broadband character of the CBG microcavity half–micropillars concept is very advantageous for application because it gives larger flexibility regarding the emission wavelength and avoids a need for spectral fine–tuning between the emitter and the photonic structures.

6. Summary

In summary, we have carried out 3D FDTD modeling of photon–extraction efficiency from different types of microcavity structures, which can potentially be used for the realization of ultra–bright electrically driven QD–based SPSs in the telecom O–band at 1.3 µm with real–world applications in quantum communication. The broad stop–band bottom DBRs blocks the light propagation practically at all tilted angles and can suppress the emission leakage below the active cavity. The hybrid passive cavity–based microcavity concept allows significant suppression of the sidewall emission as compared to classical semiconductor intra–cavity contacted microcavity. The radial trench pattern formed in the top DBR can potentially redirect upwards some part of the side emission and provides overall photon extraction efficiency of ∼83% combined with 8–10 nm wide broadband emission enhancement. The concept also demonstrates its advantage for the coupling to a standard single–mode fiber within numerical aperture 0.12, whereas the mode–coupling efficiency reaches 11% versus ∼6% for a conventional micropillar. The mode–coupling efficiency is higher for other types of the fiber. In fact, it exceeds 22% for 980HP fiber (with NA=0.2) and reaches ∼40% for HNA fiber (with NA=0.42). Moreover, the presented SPS concept enables one to etch the dielectric passive cavity region through without risking of nonradiative recombination of carriers on the etched sidewalls and thus demonstrating further advantage vs a conventional micropillar structure.

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