InGaAsP/InP Micropillar Cavities for 1.55 μm Quantum-Dot Single Photon Sources

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Abstract Micropillar cavities containing 1.55 μm quantum dots are required for silica-fiber based quantum information processing. The straight way is to construct micropillars consisting of InGaAsP/InP distributed Bragg reflectors. We perform a systematic study mainly on optical properties correlated to the micropillar diameter. As expected, the mode wavelength increases with extending micropillar diameter and tends to saturate at 1.55 μm for the diameter larger than 2.0 μm. Able to be as high as 10⁴, the quality factor, however, is almost independent of pillar diameter, which may be the result of the small refractive index contrast. The Purcell factor reaches highest (>130) at pillar diameter of ~0.6 μm, suggesting that these cavities could serve as efficient 1.55 μm single photon sources. The output efficiency increases with extending diameter, and is acceptably good at small diameters. Although not easy in fabrication technique, this cavity provides monolithic scheme for constructing 1.55 μm single photon sources.

1. Introduction
For the purpose of quantum communication over silica-fiber-based networks, InAs/InP quantum dots (QDs) are promising as single photon sources (SPSs) [1]. However, the spontaneous lifetime of InAs/InP QDs is so long (T₁ ~ 1.2 ns) that the demanding GHz emission is not available. A QD SPS also needs to emit highly identical single-photon pulse trains, but the photon indistinguishability of an InAs/InP QD is still bad due to the big gap between the excitonic coherence time (T₂ typically ~100 ps) and the spontaneous lifetime. These two problems can be resolved by introducing InAs/InP QDs into micropillar cavities possessing high Purcell factors F_p. Like the micropillar cavities for InAs/GaAs QDs [2], the straight way to construct an efficient cavity containing InAs/InP QDs might be using a pillar composed of InP-lattice-matched distributed Bragg reflectors (DBRs), but there has been neither experimental nor theoretical trials on this system. In this work, we are going to study and design InGaAsP/InP DBR micropillar cavities for 1.55 μm telecommunication band SPSs.

2. Model and method
The micropillar cavity is a cylinder standing on a semi-infinite InP substrate, as shown in Fig. 1(a). It consists of disk-shaped (in XY plane) periodic InGaAsP/InP pairs coaxially along Z direction on the
top and bottom side of an InGaAsP spacer layer. The InGaAsP/InP periodic structures are the DBRs taking the role of reflecting light towards the spacer. The bottom DBR has more pairs of InGaAsP/InP layers than the top DBRs so that there is less useless leakage to the bottom. The thickness of each InP(InGaAsP) layer in DBRs is set as $t_{1(2)} = \lambda_B/(4n_{1(2)})$, where $\lambda_B$ is the Bragg wavelength around 1.55 μm and $n_{1(2)}$ is the refractive index of InP(InGaAsP). The spacer layer is one wavelength thick in conventional micropillar cavities, or replaced by tapered DBRs in tapered-DBR cavities. Here “taper” means adiabatically deducing the layer thicknesses as the DBR extends towards the cavity center (new spacer) [2]. The layer thicknesses in the tapered DBRs linearly decrease as $t_{1i} = t_1(1-\rho(2i-1))$ for InP and $t_{2i} = t_2(1-2\rho i)$ for InGaAsP, where $i$ is the taper segment number and $\rho$ the tapering slope of layer thickness, in other words, the decreased fraction per tapered layer. In between the tapered DBRs is an InGaAsP spacer layer with thickness $t_0 = t_1(1-2\rho N)$, where $N$ is the total segment number in one tapered DBR. It’s worth noting that the spacer here is much thinner than that without tapered DBRs. The InGaAsP layers are lattice-matching to the InP substrate and have an energy gap larger than the photon energy of 1.3 μm wavelength, so that they are extremely transparent for ~1.55 μm photons. A photon emission source, representative of an InAs QD, is inserted in the spacer.

By using finite-difference-time-domain method, the optical properties of this conventional micropillar cavity are simulated with the optical constants of the materials cited or deduced from Ref. [3]. Once a polarized impulse is launched from the photon emission source, the time evolution of the light intensity can be obtained at monitors set in the spacer layer. A Fourier transform gives a spectrum of the electric field intensity, showing some peaks representing the cavity modes. By setting the light source as a narrow-band emission around a mode wavelength $\lambda$, we obtain the intensity decay with time $t$ and the steady state distribution, i.e. the mode profile. The quality factor $Q$ can be obtained by fitting the exponential light intensity envelope to $\exp(-2\pi ct/Q\lambda)$, where $c$ is the light velocity in vacuum.

Fig. 1. (a) Schematic cross section of the InGaAsP/InP micropillar cavity without tapered DBRs; (b) Distribution profile of the $x$-polarized electric field $E_x$ of the fundamental mode.

3. Simulation and Results
The result of the simulation of this InGaAsP/InP micropillar cavity is as follows. At first, there does exist the fundamental mode peaked near 1.55 μm for both conventional and tapered cavities as expected. The $x$-polarized electric field $E_x$ of the fundamental mode is depicted in Fig. 1(b). It is
demonstrated that the profile is highly symmetric and well confined around the spacer layer, which suggests the cavity can be of a good quality.

Massive simulations were performed to obtain the optical characteristics of the fundamental modes with the pillar diameter $D$ varying from 2.5 to 0.4 $\mu$m. Figure 2(a) shows the mode wavelength $\lambda$ as a function of pillar diameter $D$ for conventional and tapered-DBR cavities. At first, $\lambda$ exhibits a bit blueshift at big $D$ with respect to the designed Bragg wavelength $\lambda_B = 1.55$ $\mu$m, and tends to saturate at $\lambda_B$ for $D > 2$ $\mu$m. As $D$ decreases, the blueshift increases at a faster rate. It’s noticeable that the blueshift behavior is independent with whether the tapered DBRs are employed or not, and similar to our previous study on conventional Si/SiO$_2$ micropillar cavities [4] as well as other micropillar cavities with a low index contrast [5], although the total thicknesses of different DBR layers vary a lot (from ~10 to ~30 $\mu$m). The $\lambda$ trend along with $D$ variation can be interpreted by waveguide dispersion that a smaller $D$ brings about more localized geometrical confinement of an optical mode. As a consequence, a smaller $D$ results in a shorter mode wavelength [5].

The quality factor $Q$ as a function of micropillar diameter $D$ with different numbers of DBRs is shown in Fig. 2(b). The $Q$ factor looks more stable than the other micropillars such as GaAs/AlAs [7] and Si/SiO$_2$/InP [4]. In detail, it tends to saturate at big $D$ and at small $D$. The saturation for $Q$ happens at $D$ close to 0.6 $\mu$m instead of a big value $D > 2$ $\mu$m like in Si/SiO$_2$/InP case [4]. The positive correlation between $Q$ and $D$ derives from the fact that as $D$ decreases, $\lambda$ strongly deviates from $\lambda_B$ and the effective incident angle of light on the DBRs increases [6]. A strong $Q$ oscillation with respect to $D$, which has been demonstrated in previous conventional [2,8] and hybrid [4] micropillar cavities, is hardly observed here. This implies these modes are rather pure, i.e., almost not coupled with the high-order propagating Bloch modes. Physically, this property is related to the small refractive index contrast (~0.2), which makes the cavity more like a waveguide. Anyway, this property benefits to practical applications since one can get good emission linewidth without paying special attention to the cavity size.

A high quality factor $Q$ is the basic and extremely important requirement for an effective cavity SPS. Since the refractive index contrast between InP and InGaAsP is so poor (~0.2), a large number of DBRs would be needed for enough reactivity to get high $Q$. It’s necessary to examine how $Q$ changes with respect to the numbers of DBR pairs as the thickness of each InP(InGaAsP) layer of the conventional DBR remains at $t(2) = \lambda_B/(4n(2))$. Also demonstrated in Fig. 2(b), the quality factor $Q$ increases remarkably as the DBR increases from 16/28 to 40/70 pairs. In detail, on a cavity with 16/28 pairs of top/bottom DBR layers and pillar height ~10 $\mu$m, the $Q$ factor is found to be about 250 for $D > 0.6$ $\mu$m. Such a poor quality factor results from the fact that the inadequate DBR pairs can’t confine the mode profile efficiently. 30/50 pairs of DBR layers with pillar height ~20 $\mu$m lead to $Q$ factor ~1900 for $D > 0.6$ $\mu$m. 40/70 pairs of DBR layers with pillar height ~30 $\mu$m bring about $Q$ factor up to 6000 for $D > 0.6$ $\mu$m. When tapered DBRs are introduced to the spacer, the $Q$ factor enhancement is more significant. For example, when the spacer of the cavity with 30/50 pairs of DBR layers is replaced by tapered DBRs with tapering segment $N = 3$ and tapering slope $\rho = 0.02$, the $Q$ factor reaches ~2200 for $D > 0.8$ $\mu$m, about 16% enhancement obtained with merely ~5% pillar height increased. As well, the replacement of tapered DBR for the spacer of the cavity with 40/70 pairs of conventional DBR layers results in ~20% and ~35% $Q$ enhancement with only ~4% and ~8% pillar height increase for $N = 3$, $\rho = 0.02$ and $N = 6$, $\rho = 0.02$, respectively, consistent with Ref. [7]. It is worth stressing that it is possible to get a $Q$ factor as high as 10$^4$ on a InGaAsP/InP micropillar cavity.

A small mode volume

$$V = \frac{\int \varepsilon(r) |\mathbf{E}(r)|^2 \, dr}{\varepsilon_0 E_m^2}$$

(1)

where $\varepsilon$ is the relative dielectric constant, $\mathbf{E}$ the electric field of the light at the position $\mathbf{r}$, and $\varepsilon_0$ and $E_m$ the corresponding values at the point of the maximum light intensity, is always desired for micropillar cavity SPSs since it brings about the capability of separating a single QD resonant with the
cavity mode and miniaturizing and integrating the quantum devices. It’s thus necessary to check the change of mode volume $V$ against $D$ in the unit of $(\lambda/n)^3$, which is demonstrated in Fig. 2(c), where $n$ is the effective refractive index. It’s natural that $V$ monotonically increases with extended $D$ in all cases as expected, and is mainly positively correlated with the micropillar height. The introduction of tapered DBRs to the spacer, on the contrary, helps little on the reduction of $V$, which exhibits the same behavior as that in previous Si/SiO$_2$ pillar cavities [9].

$$V = \frac{3Q\lambda^3}{4\pi^2n^3} \quad (2)$$

with the cavity size, as shown in Fig. 2(d). Besides, high Purcell factors reduce the spontaneous emission lifetimes of the QDs and may thus increase the operation frequency from MHz to GHz and result in highly identical single-photon pulse trains as well. Here $F_p$ achieves the peak value at $D = 0.6$ μm for all pillar cavities with or without tapered DBRs. $F_p$ decreases rapidly as $D$ deviates away from where the maximum $F_p$ locates. Specifically, for the cavity with 16/28 pairs of DBR layers, $F_p$ remains below 5 for $D \geq 0.8$ μm. On a cavity with non-tapered 30/50 pairs of DBR layers, there occurs an $F_p$ more than 20 as the diameter is below 1 μm, and the maximum $F_p$ of ~35 is obtained at $D = 0.6$ μm. $F_p$
becomes smaller at larger diameters because the mode volume is getting larger while the \( Q \) factor remains. When the spacer is replaced by 3 segments of tapered DBRs with tapering slope \( \rho = 0.02 \), \( F_p \) goes about 20\% higher for all diameters.

More significantly, a cavity with non-tapered 40/70 DBR pairs exhibits \( F_p \) from 20 to more than 100. This happens with the pillar diameter being less than 2 \( \mu \)m. Besides, the cavities with 40/70 DBR pairs together with tapered DBRs possess higher \( F_p \) than those of non-tapered cavities at the same pillar diameters. More segments of tapered DBRs brings about higher \( F_p \), e.g., 6 segments of tapered DBRs lead to \( F_p \) enhancement of \( \sim 15\% \) compared to that of 3 segments of tapered DBRs. Although the highest \( F_p \) here is high enough for the microcavity to enter a strong coupling regime [9], it’s still a practical index that higher \( F_p \) is preferred, which corresponds to \( D < 1 \) \( \mu \)m for micropillar cavities with 30/50 DBRs and \( D < 1.8 \) \( \mu \)m for cavities with 40/70 DBRs.

Apart from the above parameters, the output efficiency is another figure of merit that affects the quality of the micropillar cavity. Since the QD SPS usually operates under cryogenic temperatures, bad efficiency would give rise to amount of heat generation and thus fierce degradation of the SPS performance. Figure 3 depicts the relationship between the output efficiency \( \omega \) and the pillar diameter \( D \). Here \( \omega \) is expressed as

\[
\omega = \frac{P_{\text{top}}}{(P_{\text{top}} + P_{\text{bottom}} + P_{\text{lateral}})}
\]

where \( P_{\text{top}} \) represents the direct emergent power flux through the top, \( P_{\text{bottom}} \) and \( P_{\text{lateral}} \) are the power flux leakage through the bottom layers and lateral sidewalls, respectively. The output efficiency increases rapidly from a few percent to several tens of percent at extending pillar diameter at small \( D \), and tends to be stable at \( D > 2 \) \( \mu \)m. In detail, \( \omega \) tends to saturate at \( \sim 73\% \) for cavities with 30/50 pairs of DBRs and \( \sim 85\% \) for cavities with 40/70 pairs of DBRs. The bad efficiency at small \( D \) is mainly caused by poor lateral confinement of the mode profile. The bottom leakage, however, dominates the power loss at large \( D \). It’s noted that the replacement of the spacer by tapered DBRs doesn’t make any contribution to \( \omega \), unlike those cases to \( Q \) and \( F_p \). On the other hand, the micropillar diameter mismatch at highest \( F_p \) and best \( \omega \) suggests that a tradeoff would be made according to practical use.

![Fig. 3. The output efficiency as a function of the diameters of InGaAsP/InP micropillar cavities.](image)

4. Discussion
With the simulated quality, the above cavity can be considered to be used as a QD SPS. The best single photon generation rate is inversely proportional to the spontaneous lifetime \( T_1 \) of the QD
excitons. As such, our cavity with $F_P > 10$ could increase the operation frequency from several hundred MHz into GHz band. For photon indistinguishability, there should be a coherence time $T_2$ comparable or longer than $2T_1$, so a microcavity with $F_P > 2T_1/T_2 \sim 20$ would be required. Obviously, it could be expected that highly indistinguishable 1.55 μm single photons could be produced using the present micropillar cavities by tuning the Bragg wavelength and the tapering slope of tapered DBRs [4]. Furthermore, the best quality also satisfies the strong coupling condition $Q/V^{1/2} > 2200$ [9], so even a coherent SPS at 1.55 μm is also producible by using the present InGaAsP/InP micropillar cavities. Finally, when high output efficiency is considered on account of operation stability, a tradeoff needs to be made since the correlated $D$ for the highest $\omega$ deviates a bit from that for the best $F_P$. For example, output efficiency of $\sim 50\%$ is possible while the Purcell factor remains as high as $\sim 90$ with pillar diameter of $\sim 0.8 \mu m$.

The previous 1.55 μm micropillar cavities may be realized by a hybrid fabrication process. Consisting of epitaxially available semiconductor structure, the present cavity provides a monolithic scheme for 1.55 μm QD SPS. Of course, a necessarily 20-30 μm pillar height looks a challenging task, which needs a great effort in fabrication technique.

5. Conclusion

InGaAsP/InP micropillar cavities are studied as candidates for 1.55 μm QD-SPSs. The design condition for efficient SPS is found to be: DBR pairs more than 30/50, tapered DBRs, and pillar diameter less than a specific value, e.g., 1 μm for cavities with 30/50 DBRs and 1.8 μm for cavities with 40/70 DBRs. If the output efficiency is of priority, the pillar diameter can deviate a bit as a tradeoff. Although not technically easy, this monolithic cavity may be producible in the near future.

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