High Q whispering gallery modes in GaAs/AlAs pillar microcavities


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Abstract: We report the observation of whispering gallery modes (WGM) in high quality GaAs/AlAs pillar microcavities defined by electron-beam lithography and electron cyclotron resonance reactive ion etching. Photoluminescence experiments, conducted using InAs quantum dots as an internal probe, reveal a remarkably simple WGM spectrum, consisting of a single series of TE modes. For diameters ranging from 3 to 4 μm, Q-factors in excess of 15 000 were measured, allowing for WGM lasing. Noticeably, sub-micron diameter micropillars also display high Qs (∼1000), close to the limit set by intrinsic radiative losses. These results open the way to the development of original microlasers and improved quantum-dot single photon sources.

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1. Introduction

GaAs/AlAs pillar microcavities have been extensively studied over the last twenty years in view of a better control of light-matter interaction processes in semiconductors and related applications in optoelectronics. Original and highly efficient devices such as vertical-cavity surface emitting microlasers [1, 2] or ultrafast optical photonic switches [2, 3] have been developed using micropillars as an essential building-block. Early theoretical studies revealed also their potential for the control of spontaneous emission of a semiconductor active medium [4, 5]. This idea could be fully exploited by combining micropillars and quantum dots [6]. Benefiting from the atom-like properties of QDs, numerous quantum optics experiments have been performed, and noticeably the demonstration of the Purcell effect [7, 8, 9, 10] and of single-QD vacuum Rabi oscillation [11]. These microcavity effects are, or will be, exploited in novel photonic devices, such as single mode QD single photon sources [8, 9, 10] or photonic switches operating on the single photon level [12]. In all these achievements, the three-dimensional confinement of the resonant cavity mode results from a combination of wave guiding along the pillar axis and reflection back and forth by the Bragg reflectors. In this paper, we show that micropillar can also sustain high quality factor (high-$Q$) whispering gallery modes (WGM), which are more commonly observed in semiconductor microdisks [13, 14, 15, 16, 17]. We have observed and studied these modes by microphotoluminescence, using an ensemble of self-assembled quantum dots as an internal light source. We have precisely identified these modes by modeling of the structure using the effective index method [18], which proved to be particularly well adapted to the present photon confinement geometry. One should note at this point that the observation of WGMs in micropillars has been recently reported by Astratov et al [19]. In their work, they have used a different experimental geometry and a 3D finite difference time domain (FDTD) modeling. Practical assets of the pillar geometry, as well as the coexistence of conventional pillar modes and WGMs, open appealing opportunities in the fields of microlasers and single photon sources.

2. Principle of experiments

2.1. Sample description

The inner structure of the GaAs/AlAs micropillars under study can be seen on Fig. 1(a), which shows a scanning electron microscopy (SEM) image of a half-pillar prepared by focused ion beam-etching in a Strata 400 dual-beam system (FEI Compagny). Pillars were fabricated from an epitaxial planar cavity grown by molecular beam epitaxy and consist of a 290nm thick GaAs spacer corresponding to a $1.175 \left( \frac{\lambda}{n} \right)$ cavity [20], sandwiched between two distributed Bragg reflectors (DBR) with 17 and 27 AlAs/GaAs periods for the top and bottom mirrors. Neglecting other loss mechanisms, the DBR reflectances imply an intrinsic quality factor of about 4400 for the planar structure. The GaAs cavity contains three layers of self-assembled InAs QDs. Two of them are located 10nm away from the center of the cavity and the third one is situated 20nm away from the bottom DBR. The QD arrays, which combine broadband inhomogeneous emission and low absorption, are ideal light sources to probe the resonant modes of semiconductor...
The planar cavity was then processed into pillars having various diameters, ranging from 0.5 μm to 4.15 μm. A 100 nm thick Ni hard mask is first defined using electron beam lithography and a standard lift-off procedure. Reactive ion etching is then performed using a Ar-Cl₂ plasma prepared using electron cyclotron resonance (ECR). After etching, part of the Ni mask remained on top of the pillars, which proved to be useful for most optical studies. Coupled to SEM imaging, focused ion beam (FIB) etching is a powerful tool to investigate the precise geometry of micropillars. A careful study of Fig. 1(a) shows that the ECR etched sidewalls present a small but finite 1.5° deviation from a vertical line. Moreover, zooming in on the pillar sidewall reveals the presence of a 90 nm thick oxide skin which is probably formed during the ECR etching. In a real structure, the diameter of the cavity layer cannot be estimated directly from the size of the hard mask, or by imaging a tilted micropillar by SEM. As a consequence, the precise determination of the active semiconducting lateral dimensions requires a FIB investigation.

For some micropillars, the residual Ni mask has been removed using FIB etching, special care being taken to avoid any degradation of the pillar sidewalls. The spatially resolved etching shown in Fig. 1(c) was performed on a disk having a diameter slightly smaller than the top facet diameter. Under these conditions, the low sidewall roughness of the sample is preserved, which is essential for the observation of WGM. Moreover, the Ga ions current was chosen to be sufficiently low so that the etching development can be monitored by successive SEM images. This enables to stop the process just after completion of the top GaAs surface cleaning.

2.2. Experimental setup

The samples were mounted in a variable-temperature liquid helium flow cryostat of a microphotoluminescence (μPL) set-up. Optical excitation is delivered by a continuous wave Ti:sapphire laser focused on the sample with a microscope objective (NA=0.4), which also collects the luminescence signal emitted by the pillar. The excitation energy is 1.6 eV, and the focused spot size is a few μm in diameter. Unlike Ref. [19], in our experiments, excitation and collection are...
performed in the pillar axis direction. Thus, for pillars covered by a top Ni mask, optical excitation reaches the QDs through the structure sidewalls. The luminescence signal is dispersed by a 1-m spectrometer equipped with a liquid nitrogen-cooled charge coupled-device camera. Two gratings, with 600 and 1800 lines/mm are available on the spectrometer. Unless otherwise mentioned, measurements are performed using the 600 lines/mm grating leading to a spectral resolution of 0.1 nm.

3. Experimental results

3.1. Whispering gallery resonances and free spectral range

Figure 2(a) presents the $\mu$PL spectrum of a 4.15 $\mu$m diameter pillar without the Ni top mask. On its high-energy side, it displays the standard resonant modes of the micropillar, where the spectral positions are consistent with the structure geometry. These modes appear on top of a broadband signal corresponding to the emission of the QD array into the continuum of non-resonant modes of the micropillar. Remarkably, three regularly spaced modes also emerge from this background on the low energy side of the spectrum. Figure 2(b) shows the $\mu$PL spectrum for the same pillar, obtained before removing the opaque Ni top mask. In such a case, the QD emission cannot exit any more from the micropillar through its top facet, but only through its sidewalls or bottom side. For our experimental configuration, this results in a suppression of the standard pillar modes in the $\mu$PL spectrum, as well as in a reduction of the intensity of the broadband QD emission. Instead, six well defined "non-standard" modes are now observed, due to a strong improvement of the mode to background contrast [21]. The three lower energy modes correspond precisely to the ones observed in Fig. 2(a), indicating that these are unaffected by the presence of the top metallic mask. Various pillars, with diameters ranging from 0.75 to 4.15 $\mu$m, were studied. A comb-like structure is observed in all cases for these modes.
with a free spectral range (FSR) that increases regularly when the pillar diameter decreases, as shown in Fig. 3. These experimental features strongly suggest that these modes are in fact WGMs. We will show below that this is actually the case, and that their formation results from a combination of a waveguiding effect by the high-index GaAs cavity layer with a quasi-total internal reflection at the etched sidewalls of the micropillars. This conclusion is firmly supported by the agreement of the experimentally determined WGM energies (and FSR) with the results of a simple theoretical model.

3.2. Theoretical modeling

In this paragraph, we present a simple calculation of the micropillar WGM energies. In an air suspended GaAs microdisk, the WGMs are strongly confined by the air - GaAs refractive index difference in the disk plane and in the vertical direction, as well. Therefore, an accurate description of WGMs requires a full three-dimensional calculation. For instance, FSRs differing by as much as ten per cent are obtained for approximate 2D models and more accurate 3D FDTD [22]. By contrast, micropillars present a weak vertical refractive index contrast between the core GaAs cavity and the DBR structures. It is then possible to decouple the vertical and the in-plane description of the WGMs, and to use the effective index method (EIM) [18]. As said before, the infinite planar cavity is a waveguide for light propagating in the GaAs central zone. The guided modes, indexed by their polarization (TE or TM, with respectively 

\[ n_z \text{ (TE)} = 3.693 - 1.052 \times E + 0.610 \times E^2 \quad \text{and} \quad n_z (TM) = 3.626 - 0.980 \times E + 0.582 \times E^2, \]

over the relevant energy domain \( 1.2 - 1.4 \text{ eV} \). These relations include low temperature correction and the spectral dispersions of GaAs and AlAs refractive indexes [23]. The EIM model reduces the calculation of the WGMs to a two-dimensional problem. Assuming a cylindrical geometry for the micropillars, reflection at the pillar sidewalls does not induce any TE-TM mode coupling. Following Little and Chu, we simplify the search of the WGM energies by neglecting the radiation field outside the structure, and assuming an exponential decay of the electromagnetic field outside the pillar [24]. Matching the continuous electromagnetic components inside and outside the pillar leads to in the following boundary equation:

\[ x J_{m+1}(x) = (m + \eta x \sqrt{n_e^2 - 1}) J_m(x). \]

Here, the reduced variable \( x = (E n_e d)/(2 \hbar c) \) is proportional to the mode energy \( E \). \( J_m \) is the Bessel function of the first kind; \( \eta = n_e \) for a TE mode and \( 1/n_e \) for a TM one. \( d, \hbar \) and \( c \) are the pillar diameter, the reduced Planck constant and the speed of light in vacuum, respectively. For a given azimuthal number \( m \), Eq. (1) displays a set of solutions, indexed by the radial index \( n_r \).

Analysis of the experimental spectra shows they are dominated by a single TE mode family, characterized by the lowest possible radial index \( n_r = 1 \). To proceed in the analysis, one should note that the WGM energies are, unlike FSRs, very sensitive to changes of the pillar diameter. Thus, special care was taken in its precise experimental determination. The pillar diameter was obtained by etching the structure along one diameter with a FIB and measuring it via high resolution Scanning Electron Microscope (SEM) images. The values given in this paper correspond to the lateral dimension of the central GaAs cavity layer. The calculation carried out in the previous paragraph agrees with the experimental peak position within a 10 meV error range, corresponding to a residual 30 nm uncertainty on the diameter. This error range, smaller
than half of the FSR, renders our study precise enough to identify the azimuthal index of the modes [Fig. 2]. Moreover, the experimental variation of FSR with the diameter is quantitatively understood for a large 0.95 – 4.15 μm diameter range [Fig. 3], with no free parameter. One should recall at this point that the FSR is slightly dependent on the energy window under consideration, due to the dispersion of the GaAs and AlAs refractive indices. In order to build Fig. 3, both experimental and calculated FSR correspond to the energy difference between the $m$ and $m+1$ WGMs around 1.3 eV. The excellent agreement between theory and experiment unambiguously confirms the WGM nature of the observed modes and the validity of the EIM model for accurately describing WGMs in micropillars.

Unlike conventional GaAs microdisks on a pedestal (eg. Ref. [16]), the micropillar WGM spectra do not show clearly any TM modes. As shown by Cortez et al [25], the dipole of the fundamental optical transition of InAs/GaAs QDs is randomly oriented in the plane of the sample. Therefore, one does not expect pure TM modes to couple to the QDs under weak pumping conditions. In our work, as well as in Ref. [19], the PL spectra are dominated by the TE$_{1,1,m}$ family. This suggests that WGMs in micropillars are pure TE or TM modes in excellent approximation, due to the relatively weak vertical confinement. By contrast, WGMs modes in suspended microdisks are only "quasi-TE" or "quasi-TM" modes, due to the strong vertical confinement. "Quasi-TM" modes have an electric field component within the microdisk plane, which enables a coupling of the QDs to the WGMs.

3.3. Mode volume

We applied the EIM method to evaluate the components $\{E, H\}$ of the electromagnetic field for the modes TE$_{1,1,m}$. As an example, Fig. 4(b) and 4(c) illustrate the field distribution in a 2 μm diameter pillar. The spatial field confinement is characterized by the effective modal volume $V_{\text{eff}}$:

$$V_{\text{eff}} = \frac{\int_{V} n^2(r) |E(r)|^2 \, d^3r}{\max[n(r)^2 |E(r)|^2]},$$

(2)

A plot of the calculated $V_{\text{eff}}$ versus the reduced pillar diameter $d/\lambda$ is shown in Fig. 4(d). In the 1 – 5 μm diameter range, the scaling of $V_{\text{eff}}$ with the pillar diameter is well reproduced by the power law $V_{\text{eff}} = 5.8(d/\lambda)^{1.3}$, where $V_{\text{eff}}$ is measured in ($\lambda/n$)$^3$ units. For the sake of comparison, the modal volume of the fundamental standard pillar mode, as well as the modal
Fig. 4. WGM structure calculated within the EIM model. (a): Intensity profile of the TE₁ mode guided along the GaAs cavity in an infinite planar cavity. (b) and (c): Field distribution of the TE₁,₁₇ mode in a 2 µm diameter pillar. (b) is a map of the radial and vertical distribution of the field intensity along one pillar diameter. (c) shows the amplitude of the radial component of E in the GaAs plane (z = 0). (d): Effective volume $V_{\text{eff}}$ of the TE₁,₁₇ modes versus the reduced diameter $d/\lambda$ calculated within the EIM approach. $m$ is chosen so that the mode energy is around 1.3 eV. The solid red line is power law fit. For comparison, the mode volume of the fundamental standard pillar mode and the mode volume of TE₁,₁₇ WGMs in air-suspended GaAs microdisks are also shown.

The volume of TE₁,₁₇ WGMs sustained by a GaAs microdisk surrounded by air are shown. They scale respectively as $5(d/\lambda)^2$ [26] and $2.7(d/\lambda)^{1.3}$. The last expression is obtained from a fit of FDTD calculations for a GaAs microdisk [27] whose thickness is close to the one of the GaAs cavity in our micropillars. Considering pillars having diameters larger than 4 µm, pillar WGMs display a significantly better spatial confinement, with a mode volume two times smaller than the one for the fundamental standard pillar mode. As mentioned by Astratov et al [19], this makes them appealing candidates for cavity quantum electrodynamics experiments. However, this advantage gradually vanishes when the diameter is reduced: around a 1 µm diameter, the mode volumes become comparable.

As mentioned before, compared to GaAs microdisks surrounded by air, micropillars display a lower vertical refractive index contrast. As a consequence, a significant part (~30%) of the mode total energy is stored in the two Bragg structures, outside the central GaAs cavity. The vertical confinement length in micropillars is close to the GaAs spacer thickness, whereas it is roughly two times smaller for air-suspended GaAs microdisks. Interestingly, the weaker confinement of WGMs in pillars is balanced out by the easier fabrication of small diameter ($d < 1$ µm) cavities in the pillar geometry. Other opportunities related to this geometry will be discussed in more detail in the last part of this paper.
3.4. Quality factor

For pillars having diameters in the $3 - 4 \mu$m range, experimental $Q$s are well above 10 000 [Fig. 5]. Under low excitation conditions however, lower $Q$ values are observed, limited to around 4 000 by the modal absorption of the QD arrays. As a consequence of the bleaching of the QD absorption and of the onset of the QD gain, we observe a strong increase of $Q$ as a function of increasing excitation power. This effect is depicted in Fig. 6. In order to get a reliable measurement of the bare cavity $Q$, we also study the integrated PL intensity of the WGM and of the background emission of the QDs as a function of excitation power. The particular mode studied in Fig. 6 lases under strong pumping conditions, as revealed by the superlinear dependence of the WGM emission, together with a clear saturation of the background QD emission. Although the detailed discussion of WGM lasing in these pillars is beyond the scope of this paper, the lasing threshold gives an estimate of the transparency threshold of the QDs which are coupled to the mode. For the particular mode under study, we deduce from this study a bare cavity $Q$ equal to 15 000. Quite remarkably, much higher $Q$s, larger than 20 000, are measured for higher pumping levels due to the onset of the QD gain.

The observation of high-$Q$ WGMs in micropillars is a novel proof of the very significant improvement of the smoothness of micropillar sidewalls which is obtained using RIE-ECR etching. Record $Q$s as high as 170 000 for large diameters and 50 000 for a $2 \mu$m diameter have recently been observed for the standard modes of GaAs/AlAs micropillars etched by RIE-ECR [28]. In the low diameter limit, $Q$s are limited by scattering by sidewall roughness for WGMs just as it occurs for standard modes [28, 29]. Observing and studying WGMs provides however a novel insight into this issue, because they correspond to a transverse propagation of the photons, unlike standard pillar modes for which photons propagate along the pillar axis. The $Q$s of standard modes are sensitive to longitudinal variations of the pillar diameter, whereas WGMs are not. By contrast, WGMs probe deviations from a perfect circular pillar section.

In the small diameter limit, we have estimated the bare-cavity $Q$ of numerous WGMs, both lasing or non-lasing. Generally, we focused on modes lying on the low energy side of the QDs distribution. When lasing properties were not investigated, we chose modes as detuned as possible...
Fig. 6. Lasing in a 3.65 μm pillar and determination of the bare cavity $Q$-factor. The TE$_{1.1.34}$ mode under study is centered at 1.307 eV. Under high excitation power, above 95 mW, the μPL integrated signal reveals a clear lasing behavior. The bare cavity $Q$-factor, around 15 000, is estimated at the power corresponding to the lasing threshold.

Fig. 7. WGM $Q$-factors versus diameter for small pillars (black squares). The solid red line corresponds to $Q_{rad}$, the $Q$-factor limited by intrinsic radiative losses, calculated within the EIM approach. In the sub-micron range, the WGM $Q$-factor seems most likely limited by intrinsic radiation losses rather than by additional extrinsic losses. Reducing the diameter down to the sub-micron range is obviously simpler for the micropillar geometry than for standard microdisks on a pedestal. Therefore, micropillars offer a unique opportunity to explore this regime.
of radiation-loss limited $Q$, which has not yet been achieved for WGMs in silica or semiconductor based optical microcavities. As a first step, we have measured in this work a $Q$-factor of about 900 for a pillar with a 750 nm diameter [Fig. 5].

Borselli et al have investigated Rayleigh scattering induced by a small distributed surface roughness into detail [17]. Such a scattering not only degrades the WGMs $Q$-factor but also induces a systematic splitting of all WGMs, which results from a coupling between two counterpropagating modes with opposite azimuthal indexes $m$. We observed splittings in some $\mu$PL spectra [Fig. 5], but in most cases, this splitting only affects a given WGM whereas the other WGMs remain unsplit. A similar experimental signature was observed for suspended GaAs microdisk having comparable quality factors [16]. These splittings are most likely due to scattering by some localized defects on the pillar circumference. Further improvement of the lithography and etching steps might therefore lead to an improvement the $Q_s$ of these WGMs, and, eventually, bring them even closer to the ultimate limit set by radiative losses.

4. Prospective applications

The observation of WGMs in pillar microcavities opens interesting prospective applications. In the long term, one might for instance develop microlasers sustaining both laterally-emitting and vertically-emitting lasing modes, even being able to switch from lateral to vertical emission and vice-versa on demand. In the short term however, a significant improvement of WGM lasers and single photon sources could be achieved as discussed in this section.

4.1. WGM microlasers based on the pillar geometry

Let us first consider standard microdisk lasers, supported by a pedestal [Fig. 8(a)]. By virtue of their geometry, these devices suffer from poor heat sinking [15, 31] and inefficient carrier injection under electrical pumping. After optimization of their design and fabrication process, continuous wave operation at 300K has been observed for both optical and electrical pumping.
schemes [14, 31, 32]. In spite of this success, over-heating is still a major issue for these devices, as shown by the large difference between pumping thresholds observed under CW or pulsed operation [32]. By contrast, a WGM laser based on the pillar geometry (without Bragg mirrors), sketched in Fig. 8(b), would benefit from an improved heat sinking and a more efficient electrical pumping of the peripheral active medium, at the expense of some increase (∼ × 2) of the effective mode volume of the WGMs. Further improvement of the threshold current under electrical injection could be obtained through a preferential current injection in the peripheral region of the GaAs spacer layer. This could for instance be achieved by drilling a hole within the top cladding layer, as shown in Fig. 8(c).

Finally, inserting Bragg mirrors in the structure, as in our experiment, could also improve the spontaneous emission coupling factor $\beta$ and thus lasing characteristics. To illustrate this point, let us consider a WGM mode with a $\lambda_{WGM}$ wavelength. The vertical structure in Fig. 8(d) is made of a 0.75$\lambda_{WGM}/n$ GaAs spacer layer in order to avoid any standard pillar resonance around $\lambda_{WGM}$. The spacer is surrounded by two quarter-wavelength Bragg mirror designed for a wavelength $\lambda_{DBR}$ such that the WGM lies on the high energy side of the Bragg stop band under normal incidence (parallel to the pillar axis, corresponding to $i = 0$ in Fig. 8(d)). Such a structure inhibits the QD spontaneous emission for all angles of incidence between 0 and 23°, for both TE and TM modes. Considering the corresponding solid angle, this would reduce by around 20% the QD spontaneous rate into leaky modes.

4.2. Advanced SPS exploiting the coexistence of WGMs and PMs

Amazingly enough, devices exploiting the standard modes of the micropillars, such as single-mode QD single photon sources (QD-SPS) [8, 9, 10], can also benefit from the formation of WGMs. QD-SPS exploit the Purcell effect to channel the spontaneous emission of the QD preferentially into a single cavity mode. Although a ”nearly” single mode behavior -including polarization control- could be obtained using this approach [8], the single photon collection efficiency $\varepsilon$ is still at most around 40% for such QD-SPS [33]. This non-ideal efficiency ($\varepsilon < 1$) results mostly from imperfections of the micropillars. In order to get a sufficiently strong Purcell effect, one has to implement micropillars with a high $Q$ ($\sim 1000$ to $10000$) and a small volume (1 – 3 μm diameter). In such microcavities, optical scattering by the roughness of the etched sidewalls opens a novel escape path for the confined photons. This effect degrades $Q$ and broadens the far-field emission pattern of the micropillar. Taking this effect into account, one can simply write the SPS efficiency as [34, 35]:

$$\varepsilon = \beta \frac{Q}{Q_{int}} = \frac{F}{F + \gamma Q_{int}},$$

where $F$ is the Purcell-enhanced SE rate into the cavity mode, $\gamma \sim 1$ the SE rate into the continuum of non-resonant modes of the micropillar (both rates being normalized by the QD SE rate in bulk GaAs), $Q_{int}$ the quality factor of an ideal micropillar and $\beta$ the SE coupling factor.

In the quest for high efficiency QD-SPS, strongly decreasing $\gamma$ would be of major interest. It would indeed allow, for a given desired value of $\beta$, the use cavity modes with lower Purcell factors and lower $Q$s, which are less sensitive to extrinsic loss mechanisms, and the achievement of a higher SPS efficiency according to Eq. (3).

Forming high-$Q$ WGMs is an attractive route towards this goal. To illustrate this point, we present in Fig. 9 two schematic views of the density of modes per unit volume seen by a QD located within a distance $\lambda/n$ from the pillar sidewall, for a pillar cavity either sustaining or not high-$Q$ WGMs. We assume here that there is no accidental degeneracy between WGMs and standard pillar modes. The formation of high-$Q$ WGMs entails a decrease of the background density of modes seen by the QD (blue dashed horizontal line in Fig. 9 (a) and (b)), and
Fig. 9. Density of state in a micropillar cavity seen by a quantum dot localized near the sidewall of the GaAs cavity. The QD resonance frequency is tuned on the fundamental standard pillar mode (PM). Compared to a pillar sustaining low-$Q$ WGMs (a), the existence of high-$Q$ WGMs (b) significantly reduces the density of leaky modes seen by the QD, the effect being maximum for a QD at a WGM antinode.

therefore of $\gamma$. Qualitatively, the easiest way of demonstrating such effect is by continuously reducing $Q$ for the WGMs in Fig. 9(b). When the WGM linewith becomes comparable to the FSR, these modes cannot be resolved anymore; they become simply part of the background density of modes seen by the QD in Fig. 9(a).

In order to study the magnitude of this effect, let us evaluate the total density of modes seen by the QD in Fig. 9(a), and the average density of modes related to the TE$_{1,1,m}$ family of WGMs. For standard micropillars, QDs that are out of resonance with pillar modes exhibit a radiative lifetime which is comparable to their lifetime in a bulk GaAs matrix [7, 36]. Therefore, $\rho_{\text{tot}}$, the background density of modes per unit volume and unit wavelength in Fig. 9(a) can be approximated by its value in bulk GaAs. Taking into account the in-plane orientation of the QD dipole moment [25], we obtain:

$$\rho_{\text{tot}}(\lambda) = \frac{2}{3} \times \frac{8\pi}{\lambda^3} \left( \frac{n}{\lambda} \right)^3.$$  \hspace{1cm} (4)

On the other hand, for large pillars with $d \gg (\lambda/n)$, the FSR of the TE$_{1,1,m}$ WGM family is roughly: $\Delta \lambda = \lambda^2/(n\pi d)$. Assuming that the QD sits at an antinode of the WGMs, the relevant normalization volume is their effective volume, which scales for these modes as $V_{\text{eff}} = a(d/\lambda)^{1.3}(\lambda/n)^3$ (see paragraph 3.3). Therefore, the contribution of the single TE$_{1,1,m}$ WGMs family to the background of modes in Fig. 9(a) can be estimated as

$$\rho_{\text{WGM}}(\lambda) = \frac{2}{\Delta \lambda V_{\text{eff}}} = \frac{2\pi n}{a} \left( \frac{\lambda}{d} \right)^{0.3} \left( \frac{n}{\lambda} \right)^3,$$  \hspace{1cm} (5)

corresponding to the relative contribution

$$\frac{\rho_{\text{WGM}}(\lambda)}{\rho_{\text{tot}}(\lambda)} = \frac{3n}{8a} \left( \frac{\lambda}{d} \right)^{0.3}.$$  \hspace{1cm} (6)

For a 2 $\mu$m diameter pillar, $\rho_{\text{WGM}}$ is then 20% of the total density of leaky modes. From
these simple considerations, we can conclude qualitatively that forming high-$Q$ WGMs reduces significantly the background density of modes seen by the QD.

This result might be further improved by using asymmetric QDs displaying a very high linear polarization degree, such as those recently observed by Favero et al. [37] in very dilute InAs/GaAs QD arrays. Considering that for such QDs the dipole moment lies only along one direction, the density of modes seen by the emitter in the bulk, $\rho_{\text{tot}}$, is divided by an additional factor 2. Provided the QD dipole moment is aligned with the local polarization of the WGM (i.e. the pillar radius), the $\text{TE}_{1,1,m}$ WGM modes account for about 40% of $\rho_{\text{tot}}$ in the low-$Q$ case [Fig. 9(a)].

Coming back to the application of this "reduction of the background density of modes" to QD-SPS, one sees that the QD should be located close to both the antinode of the standard pillar mode of interest -so as to get a strong Purcell effect-, and to the antinode of the $\text{TE}_{1,1,m}$ WGMs. For SPS using the fundamental standard pillar mode, this could be achieved in small diameter micropillars ($d < 1 \mu\text{m}$). However, we can also imagine to use higher-order pillar modes to get a better spatial overlap with the $\text{TE}_{1,1,m}$ WGMs. To conclude, micropillars supporting high-$Q$ WGMs look very promising for developing high efficiency QD-SPS. Detailed calculations of the local density of states seen by the QD as a function of its position in the micropillar will be conducted to optimize the design of such devices, and to estimate quantitatively their efficiency.

5. Conclusion

To conclude, we have observed WGMs in high quality GaAs/AlAs pillar microcavities containing a QD active medium. Unlike standard microdisks, their emission spectra is dominated by the single $\text{TE}_{1,1,m}$ family. Due to the relatively weak vertical confinement of the field, an accurate description of WGM energies can be obtained from a simple effective index model. Thanks to the smooth sidewalls achieved by means of the optimized ECR etching process, $Q$-factors as high as 15000 were observed, allowing for WGM lasing. The micropillar geometry opens a path towards the development of ultra-small cavities sustaining WGMs. As a first step, a 750 nm diameter cavity has been fabricated, showing a $Q$-factor near 1000 which is close to the intrinsic radiative limit. Finally, various original applications of such WGM micropillar structures have been proposed.

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