A Review of "On-Chip Quantum Optics with Quantum Dot Microcavities"

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April 29, 2014

Abstract

The authors demonstrate that a "whispering gallery mode" microlaser can be fabricated from a QD-micropillar and used to perform integrated quantum optics experiments. The WGM microlaser was used to make a measurement of the Purcell factor of surrounding QD-micropillars . This result has important implications for the future of nanophotonics due to the increasing need for complex nanophotonic structures.

1 Introduction

If you stand along the wall of the dome in St. Paul's Cathedral, you might hear the whispers of someone on the other side of the dome as if they were standing next to you. This phenomenon was explained by Lord Rayleigh in 1878, who called these sound waves "whispering gallery waves." A whispering gallery wave, or what we now call a whispering gallery mode (WGM), is a wave that travels along a curved surface due to total internal reflection. An important property of WGMs is their high Q-factors, which allows them to store large amounts of energy with low losses.

Much research has been devoted to observing cavity quantum electrodynamics (cQED) in small cavities, but early observations on these small cavities were performed with external lasers. With increasingly demanding experiments on these microcavities, a desire arose for complex nanophotonic devices. The authors present a novel approach to this problem by integrating a WGM-microlaser into the device on which the experiment will be performed.

In the experiment performed by the authors, a WGM laser was fabricated from a quantum dot (QD) micropillar and used to excite surrounding (smaller) QD-micropillars . This WGM-microlaser induced photoluminescence (PL) in the surrounding QD-micropillars , which provided an indirect means for observing the resonant coupling of the WGM-microlaser to the QD-micropillars .

2 Theory

2.1 Origin of whispering gallery modes

Whispering gallery modes are solutions of the wave equation in a 2-dimensional disk geometry. The boundary conditions that give rise to the whispering gallery modes require that the index of refraction inside the cylinder be higher than the index of refraction outside the cylinder in order for total internal reflection to occur, and that the waves are allowed to extend outside the disk. The eigenmodes of this geometry are complex, meaning that the modes are lossy.

The electric field is a Bessel function of the first kind inside the disk, and a Hankel function of the first kind outside the disk, requiring that, in general,

(a) m=4, N=1 (b) m=15, N=1

Figure 1: Not all disk-modes are whispering gallery modes. Whispering gallery modes are localized to the wall of the disk, thus 1b is a WGM, while 1a is not. It is apparent that localization along the disk wall increases with m. The green line illustrates the m reflections a ray in the disk would undergo for a given mode.

the eigenmodes be solved for numerically. The eigenmodes are indexed by two integers, m and N, which determine the azimuthal and radial wave numbers. Depictions of two solutions are shown in Fig. (1). Comparing Fig. 1a and Fig. 1b illustrates the general result that whispering gallery modes are solutions for which $m >> 1$ and $N = 1$. It is also apparent that solutions with large m do not extend as far outside the disk, and thus have higher Q-factors[2].

By their very nature, the modes inside the disk are lossy, which is what allows the use of a QD-impregnated disk as a lasing medium (the leakage from the disk being the laser light).

2.2 Design considerations

A WGM-microlaser is very sensitive to the gain characteristics of the active layer, or lasing medium[1]. When studying the coupling of the WGM-microlaser to the peripheral QD-micropillars , it is important to prevent the stimulation of undesired laser modes.

2.3 Cavity QED

The spontaneous emission of an atom is influenced by the density of photon states into which the photon is emitted. The density of photon states is in turn influenced by the properties of the surrounding space. Thus, the spontaneous emission of an atom can be influenced by the properties of the

space surrounding the atom, called the cavity. Indeed, it can be shown that the photon density of states is proportional to the Q-factor of the cavity.

An atom is at resonance with the surrounding cavity when one of the transitions of the atom coincides with a mode of the cavity. The strength of the interaction between the atom and the cavity is determined by three parameters: κ, the photon decay rate of the cavity, γ, the non-resonant decay rate, and g_0, the atom-photon coupling parameter. The atom-photon coupling parameter can be thought of as the coupling of the atom to the vacuum field.

The coupling of the atom to the cavity can be classified as weak coupling or strong coupling based on the relative size of g_0 compared to the largest of κ or γ. Strong coupling is defined by $g_0 \gg \kappa, \gamma$, and weak coupling is defined by $g_0 \ll \kappa, \gamma$.

The effect of the cavity can be quantified by comparing the spontaneous emission rate of the atom in free space to the spontaneous emission rate in the cavity. This was first done by E.M. Purcell in 1946, and from his analysis we get the Purcell factor, F_P, which is the ratio of radiative lifetime in free space to radiative lifetime in the cavity.

$$F_P = \frac{\tau_R^{\text{free}}}{\tau_R^{\text{cav}}} = \frac{3Q(\lambda/n)^3}{4\pi^2 V_0}$$

3 Experiment

3.1 Construction

The WGM-microlaser was constructed as a Fabry-Perot microcavity with diameter 6μm, and an active layer constructed of InGaAs QDs. The central micropillar was surrounded by five smaller QD-micropillars of diameter 1.6-2.5μm located 20μm radially from the central pillar. The WGM-microlaser is contacted with an Au pad and anular masks are placed over the peripheral QD-micropillars in order to isolate the output of the micropillars from the light of the WGM-microlaser .

3.2 Design verification

The WGM-microlaser emits at 1.431eV with an injection current of 16μA (threshold 8μA) at 15K. The WGM-microlaser was used to resonantly ex-

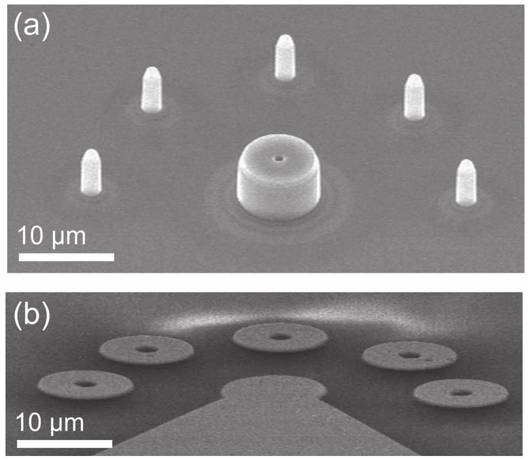

Figure 2: SEM images of the device (a) before, and (b) after contacting and masking.

cite the peripheral micropillars. Since the WGM-microlaser cannot be tuned externally, emission of the WGM-microlaser and the p-shell energy of the QD-micropillars were tuned by varying the temperature. The coupling between the laser and the QDs was measured in a photoluminescence-excitation experiment via the output of the QD-micropillars .

The emission of the QDs showed maximum intensity at 43K with laser energy 1.4290eV. This resonant behavior was separately confirmed via PLE measurements at 40K, 45K, and 50K with a tunable Ti:sapphire laser. The resonant behavior is most significant at excitation energies between 1.4280eV and 1.4295eV.

3.3 Results

The Purcell factor measurement was carried out by measuring the integrated intensity of the QD emission as a function of the detuning and fitting to a known function. The measured Purcell factor was $F_P = 4.1 \pm 0.6$, which was much lower than the expected value of $F_P \sim 15$. The authors explain this discrepancy as a result of non-ideal spatial coupling of the statistically grown QD to the WGM-microlaser .

4 Conclusion

The measurement of the Purcell factor is clear evidence that an integrated WGM-microlaser can be useful in nanophotonic devices. However, a far more useful result would be an integrated microlaser with directionality so as to (in this context) selectively excite a particular QD-micropillar . The authors look ahead to experiments in which they contact the peripheral QD-micropillars and tune the emission/absorption of the QDs via the confined quantum Starck effect.

References

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