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Observation of Strong Coupling between a Single Quantum Dot and an L4/3 Photonic Crystal Nanocavity

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Abstract

We for the first time demonstrate strong coupling between a single quantum dot and a GaAs-based L4/3-type photonic crystal nanocavity, which supports a very-high *Q* factor together with an extremely small mode volume. In stark contrast to a leading platform using an H0-type nanocavity, its field distribution has the electric field maximum within the host dielectric material, thereby being more suitable for enhancing strong coupling with a single quantum dot embedded therein. We experimentally investigate a fabricated L4/3 cavity by photoluminescence measurements and observe a high quality factor of 33,000. We confirm that the quantum dot-nanocavity system is in strong coupling regime through measuring a clear vacuum Rabi splitting of ~ 87 μeV at the resonance.

1. Introduction

Photonic crystal (PhC) nanocavities are one of the best platforms to study strong coupling with quantum dots (QDs), because of their small mode volumes (V) and high quality (Q) factors. Since the first observation of strong coupling by measuring vacuum Rabi splitting (VRS)[1], strongly coupled QD-cavity systems have been used to study intriguing phenomena in cavity quantum electrodynamics (CQED)[2] and to develop diverse quantum information processing devices[3]. For pursuing better device performances and exploring novel physics, it is desirable to realize a higher coupling constant g ($\propto V^{-1/2}$) and a lower cavity decay rate κ ($\propto 1/Q$), which make the CQED system more coherent.

In our previous work, we have demonstrated a very large g of over 160 μeV using an H0-type PhC nanocavity that possesses a high Q and a near-diffraction-limited V[4]. Meanwhile, the electric field maxima of the fundamental mode of the H0 nanocavity are located inside the airholes, hindering maximizing its coupling to a QD and hence degrading the maximum achievable g. Recently, Minkov *et al.,* proposed a novel cavity design, L4/3-type PhC nanocavity, which supports a high design Q factor and a small V comparable with those of the H0 nanocavity[5]. Importantly, its field maximum is located at the cavity center filled with the host dielectric material. These properties are promising to largely improve g while keeping κ low, potentially enabling the access to hitherto-unexplored QD-CQED physics.

In this study, we for the first time demonstrate strong coupling between a single QD and an L4/3 PhC nanocavity, which is designed to support a high design Q factor over 8 million while keeping a very small V close to the diffraction limit. The designed nanocavity was fabricated into a GaAs slab embedding InAs QDs and was investigated by micro-photoluminescence (μPL) measurements. We observed a high experimental Q factor of 33,000, which enables the observation of a clear VRS of ~ 87 μeV.

2. Cavity design

First, we discuss the design basic of an L4/3 PhC cavity. We start from a L3-type PhC nanocavity, consisting of three missing airholes in a triangle-lattice PhC. We then add four airholes with equal intervals to defined the L4/3 cavity, as schematically shown in Fig. 1(a). These additional holes play an important role in squeezing the electric field distribution into the cavity center, leading to a largely reduced V compared to that of the original L3 design. We set the PhC lattice constant (a), airhole radius and slab thickness to be 260nm, 61 nm and 130nm, respectively. We then introduced airhole shifts (sx and sy) to improve Q factor. Figure 1(b) shows the details of the shifts of airhole positions. By employing 11 shift parameters reported in [5], we obtained a calculate Q factor of ~8 million, while keeping a small V of $0.32(\lambda/n)^3$ (resonant wavelength of λ = 970 nm, slab refractive index n = 3.46). Figure 1(c) shows an electric field distribution of the fundamental cavity mode calculated by the finite difference time domain method.

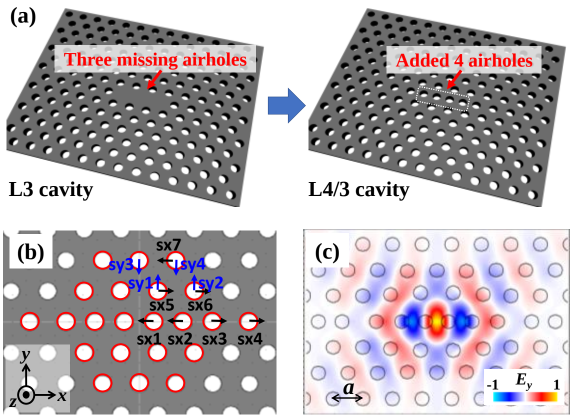

Fig. 1 (a) Schematic illustration of the L3 (left) and L4/3 (right) nanocavity. (b) Details of the airhole shifts. The shifted airholes are marked in red. Black and blue arrows show the directions of the shifts. In the actual design, we applied symmetric shifts with respect to the mirror plane across the cavity center (white lines). (c) Simulated cavity mode profile (E_y) of the investigated cavity mode.

Table 1 shows a summary of key parameters comparing the L4/3 nanocavity with other conventional PhC nanocavity designs. The Q values for all the cavities are over millions. The Vs of the L4/3 and H0 nanocavity are about 3~4 times smaller than those of the heterostructure-type and L3-type cavity. The maximum coupling constants (g_{max}s) are also about two times higher for the L4/3 and H0 design. Meanwhile, as we mentioned earlier, it is difficult for the H0 nanocavity to achieve the maximum coupling with a QD, while the L4/3 can do it by placing the QD at the cavity center (Fig.2 (b)). Overall, the L4/3 nanocavity is advantageous for realizing a higher g with keeping a high Q factor.

Table I. Comparison of the L4/3 nanocavity with other PhC nanocavity structures. All the Qs are theoretical values and are on the order of millions. g_{max}s are estimated via the relationship of $g \propto V^{-1/2}$ and are normalized to that of the heterostructure cavity.

Cavity type	$V\,(\lambda/n)^3$	$Q\,(\times10^6)$	g_{max}
L4/3 (this work)	0.32	8	2.1
H0[6]	0.25	1	2.4
L3[6]	0.95	4.2	1.2
Heterostructure[7]	1.4	130	1

3. Sample preparation and optical measurement

By using standard semiconductor nanofabrication processes, we patterned the designed cavity into a 130nm-thick GaAs slab, grown on a 1 µm-thick AlGaAs sacrificial layer. The slab contains a single layer of low-density InAs QDs at the middle. Figure 2(a) shows a scanning electron microscope (SEM) image of a fabricated cavity.

We performed μPL measurements in order to characterize the fabricated sample. The sample was kept at 5 K in a liquid helium flow cryostat and pumped by an 808 nm continuous wave laser. The PL signal was collected by an objective lens and resolved by a spectrometer equipped with a Si CCD detector. Figure 2(b) shows a PL spectrum of the fundamental cavity mode recorded under an excitation power of 16 nW. We fitted the spectrum by a Voigt function with fixing its Gaussian part that represents our spectrometer resolution of 21 μeV. From the fitting, we obtained a high Q factor of 33,000 (corresponding $\kappa = 40\ \mu$eV).

We then investigated coupling properties between a QD and the cavity mode with changing cavity mode wavelength using a Xe Gas condensation technique[8]. Figure 2(c) displays a color map of PL spectra. When the cavity mode crosses the QD emission line at 937.36 nm, we observed a clear anti-crossing, which indicates the system is in strong coupling regime. Figure 2(d) shows a vacuum Rabi spectrum with a splitting of ~87 μeV obtained under the QD-cavity resonance condition. The additional center peak originates form the bare cavity emission[2]. From the splitting and κ, we extracted a g of 45 μeV using the following equation: $g = \sqrt{(\mathrm{VRS}/2)^2 + (\kappa/4)^2}$. Here we neglected the minor influence of QD spontaneous emission decay. The obtained g is much smaller than that previously reported using a H0 nanocavity [4]. This could be due to a large displacement of the QD position from the cavity field maximum. We believe that it is possible to obtain a higher g in the future, using a precise QD position detection technique in conjunction with active QD position alignment methods[2,9].

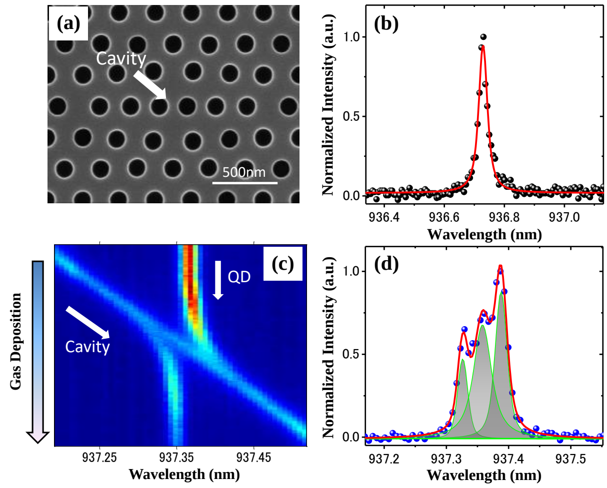

Fig. 2 (a) Top view SEM image of a fabricated cavity. White arrow indicates the cavity center. (b) Measured PL spectrum of the investigated cavity mode under a far detuned condition. Red line is a fitting curve with a Voigt peak function. (c) Color map of PL spectra. (d) Vacuum Rabi spectrum taken under the QD-cavity resonance condition. Colored solid lines denote fitting curves.

4. Conclusions

We observed strong coupling between a single QD and an L4/3-type PhC nanocavity. The cavity supports a high design Q factor of ~ 8 million while maintaining a very small V of ~ 0.32 $(\lambda/n)^3$. We experimentally evaluated the fundamental cavity mode by μPL experiments and obtained a high Q factor of 33,000. At the QD-cavity resonance, we observed a clear VRS of ~ 87 μeV, corresponding to an experimental g of 45 μeV. These results will be a great step to realize a QD-nanocavity coupled system with a much larger g and a small κ, opening up the way to explore diverse QD-CQED applications.

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References

[1] T. Yoshie *et al.*, Nature **432** (2004) 200.
[2] K. Hennessy *et al.*, Nature **445** (2007) 896.
[3] A. Faraon *et al.*, Nat. Phys. **4** (2008) 859.
[4] Y. Ota *et al.*, Appl. Phys. Lett. **112** (2018) 93101.
[5] M. Minkov *et al.*, Appl. Phys. Lett. **111** (2017) 131104.
[6] M. Minkov *et al.*, Sci. Rep. **4** (2014) 5124.
[7] T. Asano *et al.*, Opt. Express **25** (2017) 1769.
[8] S. Mosor *et al.*, Appl. Phys. Lett. **87** (2005) 1.
[9] K. Kuruma *et al.*, Appl. Phys. Lett. **109** (2016) 71110.