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Compact QED system of single photon emitter coupled to silicon nitride nanobeam

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ABSTRACT

We discuss a compact QED system of Germanium Vacancy(GeV) centres coupled to high quality factor silicon nitride nanobeam Photonic crystal(PhC) cavities. Devices with a quality factor of 24,000 around the zero-phonon line of the GeV center in diamond are demonstrated with an efficient fiber-to-waveguide coupling platform. We also present a method for fiber-waveguide coupling that allows seamless transition of photons from optical fibers into photonics devices and vice versa. Our method uses conical tapered optical fibers (with a tapering angle of $\sim 4°$) that are coupled over $\sim 11\mu m$ to a silicon nitride (Si3N4) waveguide taper (with a tapering angle of $\sim 1°$) achieving upto $\sim 96\%$ coupling efficiency.

Keywords: Germanium vacancy centres, Photonic crystal, cavity QED, nanodiamond

1. INTRODUCTION

The novel researches in quantum information processing has increased the demands for a robust scalable platform to realize an efficient quantum interface between light and matter. The capability of such systems has played an important role for many applications ranging from optical sensing and metrology[1] to quantum information and quantum computation.[2] A Cavity QED system[3,4] is one of the most promising type of platforms which may involves a 2 or 3 energy level atomic system coupled to an optical resonator to allow a coherent energy exchange in form of photons. Photonic crystal (PhC) cavities have recently emerged as a scalable platform for efficient light-matter interactions due to their small mode volumes accompanied with high quality factors.[5–9] In this framework, Si3N4 offers advantages due to its wide band gap and compatibility with standard CMOS processes. In this report, we demonstrate nanobeam PhC cavities with a quality factor of about 24,000. The efficient technique for coupling of fiber and cavity is based on evanescent coupling from a suspended waveguide to a biconical fiber taper with an efficiency over 90%. Here, we employ the same principle using a single-sided optical fiber tip and demonstrate a coupling efficiency of 96%.[10]

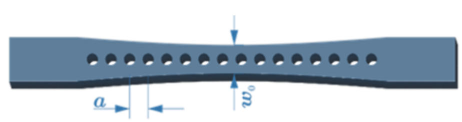

Figure 1. Sketch of Si3N4 nanobeam PhC cavity design adopted from Ahn et al.[11]

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2. FREE STANDING SILICON NITRIDE CAVITY

The device proposed by Ahn et al.[11,12] based on quadratic tapering method is used in which the nanobeam width is varied adiabatically while other parameters are unvaried, as depicted in Fig. 1. We focused on TE modes since the TM bandgap is absent. The parameters have been adjusted such that the simulated intrinsic quality factor reaches $\sim 10^6$ and the spacing between holes is set to match the resonant frequency with the target frequency around 602 nm, the zero-phonon line emission of the GeV color center in a diamond. Fabrication process of such cavities uses EBL and plasma etching technique.[13] See Fig. 2.

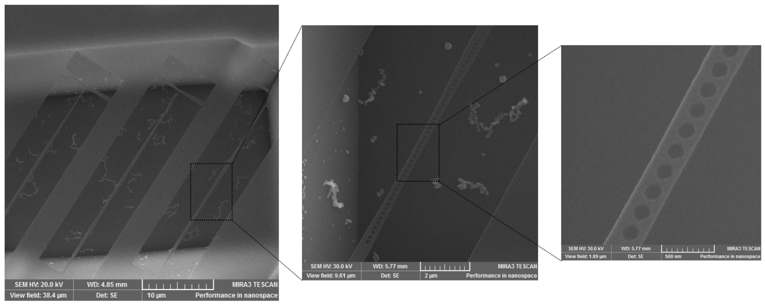

Figure 2. SEM images of Si3N4 nanobeam PhC cavities and free standing waveguide tapered at the end

For the quality factor measurement, a tunable laser was used and scanned around the TE fundamental mode, see Fig. 3(a). The experimentally measured quality factors is ranging from 18,000 to 24,000.

The light couples to the device using a single mode optical fiber tip that is coupled to the waveguide taper. This coupling technique is based on adiabatic transfer of an optical power between an optical fiber mode and a waveguide fundamental mode. The key idea is to change the effective refractive index of the target mode gently such that all the optical power are contained in the same mode profile. Therefore, the criterion of an adiabatic transfer is fulfilled if the change in the effective refractive index of the fundamental mode is less than the difference between effective refractive index of the fundamental mode and the nearest mode. This requires the tapering length to be longer than so-called beat length, the length over which the optical power could leak into a another mode.

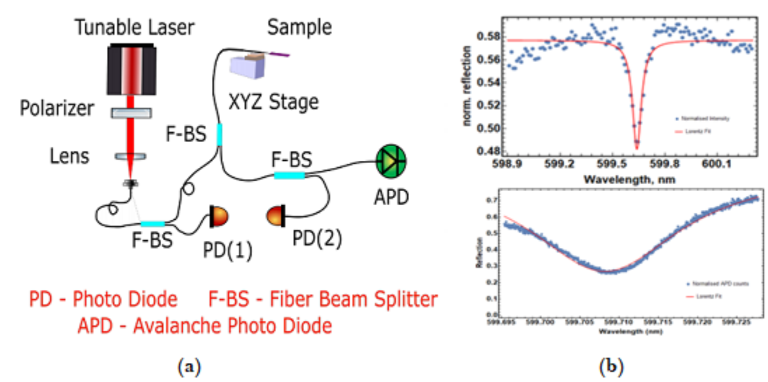

Figure 3. (a) Schematic quality factor measurement of the Si3N4 nanobeam PhC cavity. (b) upper: Spectrum measured using schematic shown in Fig 4(a) lower: scanned APD signal.

The beat length is given by $Z_b = \frac{\lambda}{\eta_{eff,1} - \eta_{eff,2}}$ and it corresponds to about $2\mu m$ and the waveguide is stretched over $10\mu m$ to ensure the stability of the optical fiber tip.

Chemical wet etching process to fabricate the conical optical fiber tip. A single mode fiber is dunked in hydrofluoric acid(HF) covered by an organic solvent (e.g. xylene) to provide a oil-water interface. About 2-3 cm fiber is stripped and the non-stripped fiber is clamped on a motorized stage to control the pulling up speed via a motor controller. The stripped fiber diameter continues to shrink gradually as it is pulled out of the HF solution. The height of the oil-water interface mainly depends on the fiber diameter and the surface tension difference between the acid and the organic solvent. The speed of pulling up the fiber is optimized so to achieve the desired angle dictated by the criterion of adiabatic transition of the fiber mode over the tapering region.

The coupling efficiency (μ_c) between optical fibers and suspended Si3N4 cavities is measured using a super-continuum laser which is launched into a dichroic mirror and then polarized before coupled into the fiber network where two photodetectors (PD1 and PD2) are used to record the ratio between the incoming and reflected optical power (γ) . See Fig 4. The optical fiber is placed on top of a 3-axis stage controlled precisely by a piezo controller. Next, we connect a retroreflector device to the incoming beam instead of the optical fiber. The resulting ratio of obtained from two photodetectors (η) is used to calculate the coupling efficiency given by $\mu_c^2 = \frac{\gamma}{\eta\mu_{Bragg}}$[13] , where μ_{Bragg} is the reflection of the cavity Bragg mirror which is assumed to be unity. For optical fibers with high power transmission, we routinely achieve a coupling efficiency $\mu c > 90\%$. The maximum coupling efficiency we have achieved is $\mu c = 96\% \pm 2\%$. The error bar reflects the fluctuations in the data collected by photodetectors which is averaged over a long period.

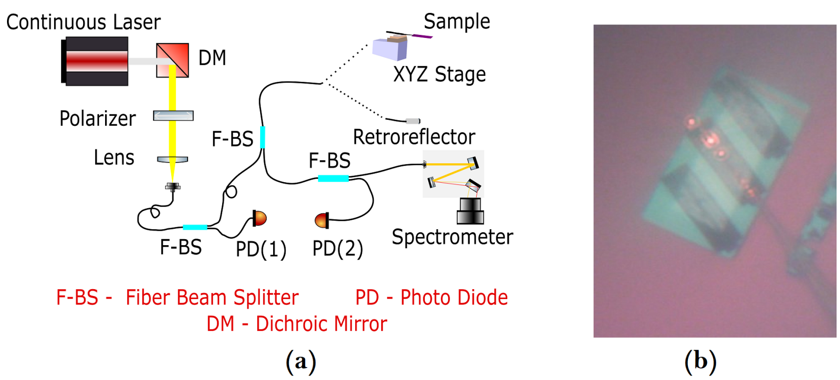

Figure 4. (a) Schematic optical characterization of the coupling between a Si3N4 nanobeam PhC cavity and an optical fiber. (b) Optical micrograph of a waveguide coupled to an optical fiber obtained from CCD camera. Reprinted from Fig 5.[13]

3. SUMMARY

Fabrication and characterization of nanobeam PhC cavities based on silicon nitride at visible wavelengths has been presented. We were able to demonstrate devices with quality factors higher than 10^4 by scanning laser around the cavity resonance. Specifically, we aim to integrate diamond color centers with silicon nitride photonics platform to realize an efficient light-matter interface.The technique presented here for coupling light from an optical fiber to on-chip suspended Si3N4 nanobeam PhC cavities achieving coupling efficiency upto 96% can be applied to similar platforms. A promising start for coupling cavity and single photon emitter is by placing emitter at point of maximum field inside cavity. In our case, we first position GeV nanodiamonds[14,15] of sizes about 10-15nm on Si3N4 mask substrate precisely and observing optical active ones under confocal and then carrying out the fabrication of cavity around the optically active nanodiamond.

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REFERENCES

[1] D. S. Simon, G. J. and Sergienko, A. V., [*Quantum Metrology, Imaging, and Communication*] (2017).

[2] Nielsen, M. A. and Chuang, I., [*Quantum computation and quantum information*] (2002).

[3] Cirac, J. I., Zoller, P., Kimble, H. J., and Mabuchi, H., "Quantum state transfer and entanglement distribution among distant nodes in a quantum network," *Phys. Rev. Lett.* **78**, 3221–3224 (Apr 1997).

[4] Imamoglu, A., Awschalom, D. D., Burkard, G., DiVincenzo, D. P., Loss, D., Sherwin, M., and Small, A., "Quantum information processing using quantum dot spins and cavity qed," *Phys. Rev. Lett.* **83**, 4204–4207 (Nov 1999).

[5] Hennessy, K., Badolato, A., Winger, M., Gerace, D., Atatüre, M., Gulde, S., Fält, S., Hu, E. L., and Imamoğlu, A., "Quantum nature of a strongly coupled single quantum dot–cavity system," *Nature* **445**, 896–899 (Feb 2007).

[6] Faraon, A., Santori, C., Huang, Z., Acosta, V. M., and Beausoleil, R. G., "Coupling of nitrogen-vacancy centers to photonic crystal cavities in monocrystalline diamond," *Phys. Rev. Lett.* **109**, 033604 (Jul 2012).

[7] Sipahigil, A., Evans, R. E., Sukachev, D. D., Burek, M. J., Borregaard, J., Bhaskar, M. K., Nguyen, C. T., Pacheco, J. L., Atikian, H. A., Meuwly, C., Camacho, R. M., Jelezko, F., Bielejec, E., Park, H., Lončar, M., and Lukin, M. D., "An integrated diamond nanophotonics platform for quantum-optical networks," *Science* **354**(6314), 847–850 (2016).

[8] Liu, X., Galfsky, T., Sun, Z., Xia, F., Lin, E.-c., Lee, Y.-H., Kéna-Cohen, S., and Menon, V. M., "Strong light–matter coupling in two-dimensional atomic crystals," *Nature Photonics* **9**, 30–34 (Jan 2015).

[9] Miura, R., Imamura, S., Ohta, R., Ishii, A., Liu, X., Shimada, T., Iwamoto, S., Arakawa, Y., and Kato, Y. K., "Ultralow mode-volume photonic crystal nanobeam cavities for high-efficiency coupling to individual carbon nanotube emitters," *Nature Communications* **5**, 5580 (Nov 2014).

[10] Tiecke, T. G., Nayak, K. P., Thompson, J. D., Peyronel, T., de Leon, N. P., Vuletić, V., and Lukin, M. D., "Efficient fiber-optical interface for nanophotonic devices," *Optica* **2**, 70–75 (Feb 2015).

[11] Ahn, B.-H., Kang, J.-H., Kim, M.-K., Song, J.-H., Min, B., Kim, K.-S., and Lee, Y.-H., "One-dimensional parabolic-beam photonic crystal laser," *Opt. Express* **18**, 5654–5660 (Mar 2010).

[12] Alajlan, A., Cojocaru, I., and Akimov, A. V., "Compact design of a gallium phosphide nanobeam cavity for coupling to diamond germanium-vacancy centers," *Opt. Mater. Express* **9**, 1678–1688 (Apr 2019).

[13] Abdulrahman Alajlan, Mohit Khurana, X. L. I. C. and Akimov, A. V., "Free-standing silicon nitride nanobeams with efficient fiber-chip interface for cavity qed," *https://arxiv.org/pdf/2006.13580.pdf* (2020).

[14] Ndukaife, J. C., Isaacoff, B. P., Shalaginov, M. Y., Bogdanov, S., Nnanna, A. G. A., Biteen, J. S., Segev, M., Shalaev, V. M., and Boltasseva, A., "Massive parallel positioning of nanodiamonds on nanophotonic structures," in [*Conference on Lasers and Electro-Optics*], *Conference on Lasers and Electro-Optics* , FTu3H.1, Optical Society of America (2017).

[15] Bolshedvorskii, S. V., Zeleneev, A. I., Vorobyov, V. V., Soshenko, V. V., Rubinas, O. R., Zhulikov, L. A., Pivovarov, P. A., Sorokin, V. N., Smolyaninov, A. N., Kulikova, L. F., Garanina, A. S., Lyapin, S. G., Agafonov, V. N., Uzbekov, R. E., Davydov, V. A., and Akimov, A. V., "Single silicon vacancy centers in 10 nm diamonds for quantum information applications," *ACS Applied Nano Materials* **2**(8), 4765–4772 (2019).