Cavity-based Diamond Spin-Photon Interface in Photonic Integrated Circuits

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Abstract: We demonstrate heterogeneous integration of solid-state nanophotonic cavities into a scalable photonic platform as an efficient optical interface for quantum memories based on diamond color centers. © 2023 The Author(s)

1. Introduction

A central challenge to constructing a quantum network is to efficiently distribute entanglement across distant nodes. One promising approach entails using atomic memories that communicate with one another via photonic qubits [1] in a repeater-based network. Among the explored memory candidates, solid-state quantum emitters prove promising due to their scalability and ease of integration into matured photonic platforms. In particular, group-IV color centers in diamond such as the SiV^- centers have exhibited excellent optical and spin properties that enabled memory-enhanced quantum communication [2]. However, to further scale up a quantum network repeater node likely requires intertwining the merits of matured photonic integrated circuits (PICs) and solid-state defects via heterogeneous integration. PIC platforms such as silicon nitride (SiN) contain optical waveguides that are phase-stable, critical for any interferometry-based protocols. Moreover, on-chip components such as microwave striplines, electrodes, directional couplers, Mach-Zehnder interferometer arrays enable full spin control and optical routing essential for interference. By performing Bell state measurement via two-photon interference, one can then build up local entanglement to construct a scalable repeater node [3].

2. Diamond Cavities

In this work, we design photonic crystal cavities which support a fundamental TE mode at ~619 nm, corresponding to the emission wavelength of the SnV^- centers in diamond. The defect mode (i.e. the cavity mode) in the photonic bandgap is introduced by applying a periodicity modulation based on a Gaussian distribution. FDTD simulation calculates a quality factor Q of 3×10^6 with a mode volume V of $\sim 0.8(\lambda/n)^3$ (Fig. 1(a)). Leveraging the quasi-isotropic etching technique detailed in Ref. [4], we fabricate these air-clad nanophotonic cavities out of bulk diamond, shown in the scanning electron micrograph in Fig. 1(b). Using a home-built cross-polarized confocal setup, we characterize our diamond cavities by exciting them with a broadband supercontinuum light source and measuring the spectrum of the reflected signal [5]. We observe an average quality factor of about 1500, whose discrepancy from the simulated Q likely stems from surface roughness and perturbations to the device geometry resulting from fabrication.

In a 4 K cryostat, we further demonstrate coupling between the SnV^- centers and the diamond cavities by in-situ gas tuning in which Ar gas is deposited onto the devices to red-shift the cavity resonance wavelength. By resonantly exciting the emitters with $\sim$ 500 ps pulses and measuring their spontaneous emission rates, we are able to observe a decrease in the SnV^- centers' lifetimes as we reduce their absolute detuning with the cavity resonance. Fig. 1(c) illustrates a lifetime reduction by a factor of $\sim$ 7 for one example SnV^-, limited by the precision in controlling the cavity-emitter detuning Δ. Among the studied emitter-cavity systems, we observe Purcell enhancement factors exceeding 10.

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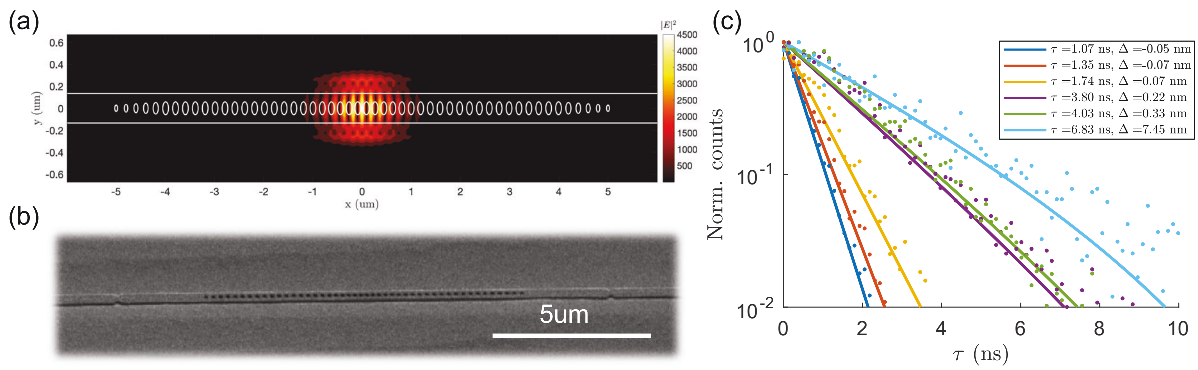

Fig. 1. Diamond device fabrication and measurements. (a) FDTD simulation of the fundamental TE mode of an air-clad diamond photonic crystal cavity. (b) SEM image of a fabricated diamond cavity. (c) Lifetime measurements of a coupled SnV^- to a diamond nanocavity at 4 K. Δ represents the detuning between the cavity resonance and the SnV^-'s emission.

3. Integration into a Photonic Platform

Subsequently, we transfer diamond cavities onto custom SiN PICs based on the platform described in Ref. [6], as shown in Fig. 2(a). The diamond waveguides adjacent to the photonic crystal cavities are adiabatically coupled to SiN waveguides, which are then coupled to an optical fiber array. By exciting the cavities with a supercontinuum light source from the top (free-space) and collecting from the optical fiber, we observe Fano lineshapes indicative of cavity resonances in the spectra. Similarly, we can excite the cavities' modes through the fiber array and observe their resonances by collecting from free-space, as shown in Fig. 2(b).

Our preliminary results showcase the SiN PIC as an effective optical interposer. Furthermore, on-chip microwave striplines and directional couplers allow for the possibility of performing spin-dependent reflectivity and interference between neighboring cavities, crucial for constructing local entanglement within a repeater node. We believe this heterogeneous quantum photonic platform is a promising *scalable* architecture for near-term quantum network applications.

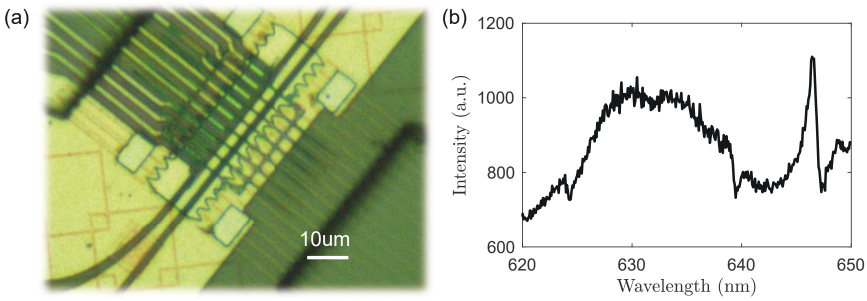

Fig. 2. Integration into SiN PIC. (a) An optical image of heterogeneously integrated diamond devices adiabatically coupled to the underlying nitride waveguides. (b) Example cavity transmission spectrum through waveguide excitation (via an optical fiber array) and free-space collection of the cavity mode.

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