

Triangular Silicon Carbide Nanophotonic Devices for Quantum Simulators

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Abstract: We explore applications of silicon carbide photonics in quantum simulation. We design a low-loss triangular photonic crystal molecule with embedded color centers, and explore the formation of hybridized light-matter states in this system. © 2021 The Author(s)

1. Introduction

Nanophotonic cavity arrays operating in cavity Quantum Electrodynamics (cQED) regimes were proposed for quantum simulation of Mott insulators and Fractional Quantum Hall effect about a decade ago [1]. However, the pursuit of their experimental realization with quantum dots encountered limitations due to high emitter inhomogeneities. More recently, color centers in wide band gap materials emerged as nearly-identical quantum emitters [2] with demonstrations of cavity integration. It has been hypothesized that multi-emitter-cavity systems could reach strong cQED interactions needed to form hybridized states of light and matter [3], also known as polaritons. We extend this multi-emitter cQED study to design and simulate a photonic crystal molecule with embedded multiple color centers as a step toward the realization of polariton physics simulator in SiC coupled cavity arrays [4]. We focus on the triangular device geometry, which is one of the leading nanofabrication choices to efficiently integrate color centers in bulk substrates with photonic devices [5]. This approach allows for a high-performing and wafer-scale arbitrary substrate integration. We use Finite-Difference Time-Domain (FDTD) method for optical resonance design and use open quantum system modeling to analyze the formation of hybridized light-matter states.

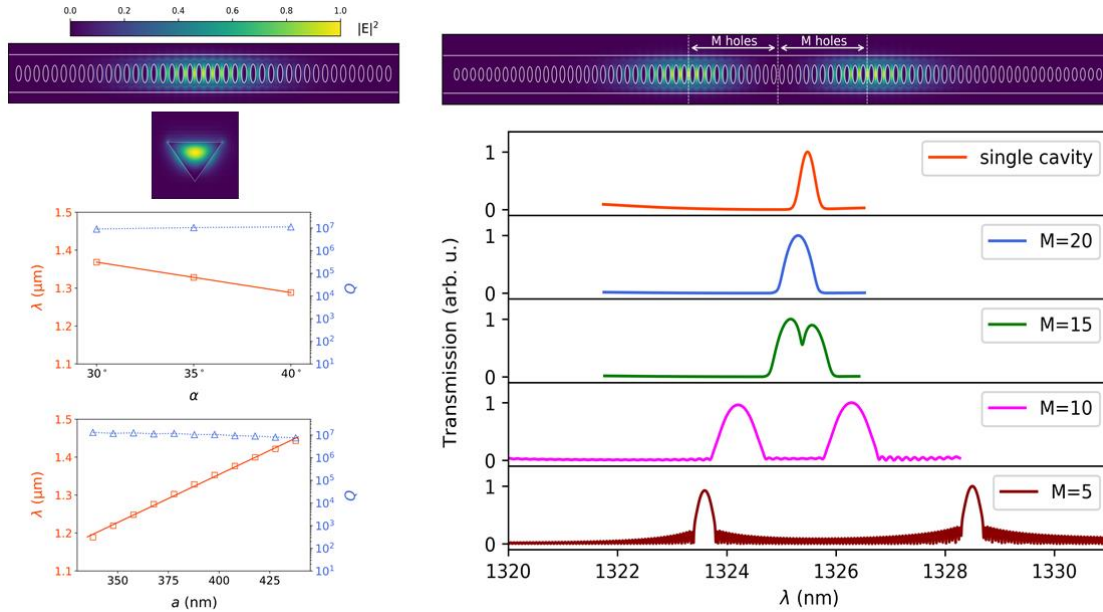


Figure 1 (left) The resonant mode profile, wavelength, and quality factor dependence on the geometry parameters of a single triangular nanobeam cavity. (right) Photonic crystal molecule resonance profile and transmission spectra for variable number of holes at the cavity-cavity interface.

2. FDTD modeling of triangular cross-section photonic molecule in SiC

We model a triangular nanobeam photonic crystal cavity using Lumerical FDTD package, and optimized it for the near infrared resonances corresponding to the 4H-SiC nitrogen-vacancy emission: $\lambda = 1324 \text{ nm}$, $Q \sim 1.05 \times 10^7$, $V \sim 2 \times (\lambda/n)^3$. When the triangle half-angle α is increased, the resonant wavelength of the fundamental mode decreases while the Q -factor and mode volume remain almost constant ($< 10\%$ variation). Tuning the lattice constant a across a

range of 100 nm shifts the resonant wavelength between 1200 nm to 1500 nm, keeping the Q-factor and mode volume remain almost intact, as shown in Figure 1 (left).

The silicon carbide photonic crystal molecule was designed by stacking two triangular nanobeam photonic crystal cavities next to each other with a reduced number of holes at the interface ($M < 30$). The coupling between the two cavities causes the resonant mode splitting. As shown in Figure 1 (right), we observe that with a reduction of the separation between the two cavities (decreasing M), the resonant wavelength splitting in the transmission spectra increases, indicating an increasing coupling strength.

3. Open quantum systems modeling

To model light and matter interaction in the photonic crystal molecule hosting multiple color centers, we solve the quantum master equation driven by the Tavis-Cummings-Hubbard Hamiltonian. We simulate a system of two coupled cavities with two emitters each. As the polariton peak splitting in the strong coupling regime is directly proportional to the coupling strength J between the two cavities, we extract J values by fitting a two-peak Lorentzian to the transmission spectrum of a photonic crystal molecule shown in Figure 1. As the modeled transmission spectra in Figure 2 show, the photonic molecule with low and high hopping rates J exhibit the cavity protected peak splitting as long as the inhomogeneous broadening is lower than the collective emitter-cavity coupling rate [4].

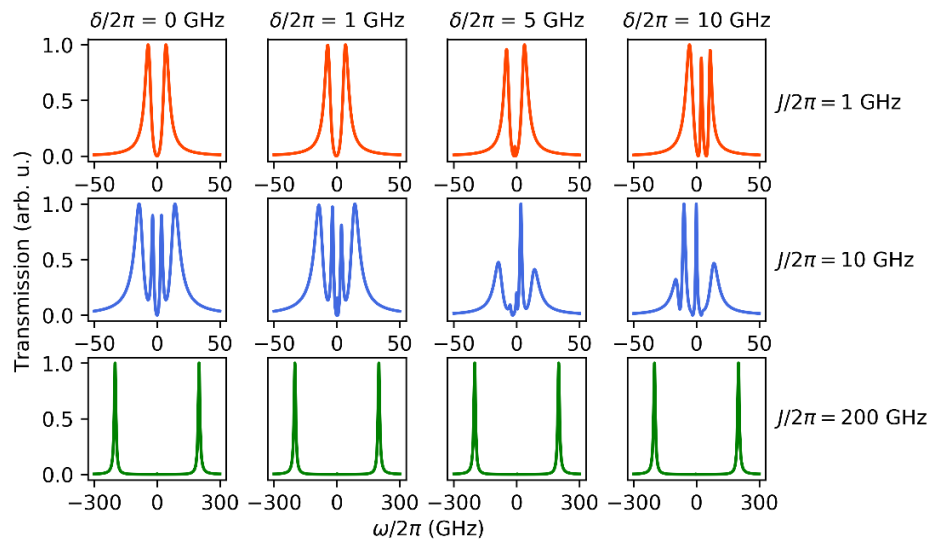


Figure 2 Open quantum system modeling of the transmission in a system of two coupled cavities hosting two non-identical emitters each for variable cavity hopping rates J and emitter frequency distribution δ , for parameters $\{g, \kappa, \gamma\}/2\pi = \{5, 10, 0.17\}$ GHz.

4. Conclusion

We show that silicon carbide photonic devices compatible with the state-of-the-art lithographic processing in low-strain substrates with nearly-identical color centers, could create polaritonic states in the cavity-protection regime of cQED. Our results are obtained on a proof-of-principle system of two coupled cavities hosting two emitters each, and can be generalized to larger coupled cavity arrays for applications in photonic quantum simulation.

5. References

- [1] Hartmann *et al.*, "Quantum many-body phenomena in coupled cavity arrays." *Laser & Photonics Reviews* **2**(6), 527-556 (2008).
- [2] Norman *et al.*, "Novel color center platforms enabling fundamental scientific discovery." *InfoMat* **1**–24 (2020).
- [3] Radulaski *et al.*, "Photon blockade in two-emitter-cavity systems." *Physical Review A* **96**(1), 011801 (2017).
- [4] Majety *et al.*, "Quantum photonics in triangular-cross-section nanodevices in silicon carbide." arXiv preprint arXiv:2012.02350 (2020).
- [5] Burek *et al.*, "Free-standing mechanical and photonic nanostructures in single-crystal diamond." *Nano letters* **12**(12), 6084-6089 (2012).