Efficient Collection and Detection of Color Center Emission in Triangular Nanophotonic Geometry of Silicon Carbide

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Abstract: Angle-etching fabrication produces state-of-the-art color center *triangular* nanophotonic devices. We uncover how the photonic band gap is formed in the triangular geometry and utilized for efficient detection from SiC waveguide into overlaid NbTiN detectors. © 2023 The Author(s)

Color centers in silicon carbide (SiC) are prominent candidates for applications in quantum repeaters, graph state generation, and quantum optical circuits due to their long spin coherence times, available spin-photon entanglement interfaces, addressable nuclear spins as well as NIR and telecom wavelength emissions [1]. For ensuring the pristine environment of the color centers, angle-etching method has been successfully implemented in diamond and SiC [1, 2] to generate refractive index contrast via optical isolation. The photonic devices produced by the angle-etching method results in a *triangular* cross-section.

We study electromagnetic propagation in triangular SiC photonics for efficient collection and detection of color center center emission. Focusing on nitrogen-vacancy (NV) center emission in 4H-SiC, we explore integration into an assymetric triangular waveguide that features a photonic crystal mirror (PCM) and is overlaid with a NbTiN superconducting nanowire single-photon detector (SNSPD), as shown in Fig. 1(a). We employ the Plane Wave Expansion (PWE) method to study the dispersion relations, verify the PCM reflectivity and subsequent photon detection by NbTiN SNSPD with Finite-Difference Time-Domain (FDTD) simulations.

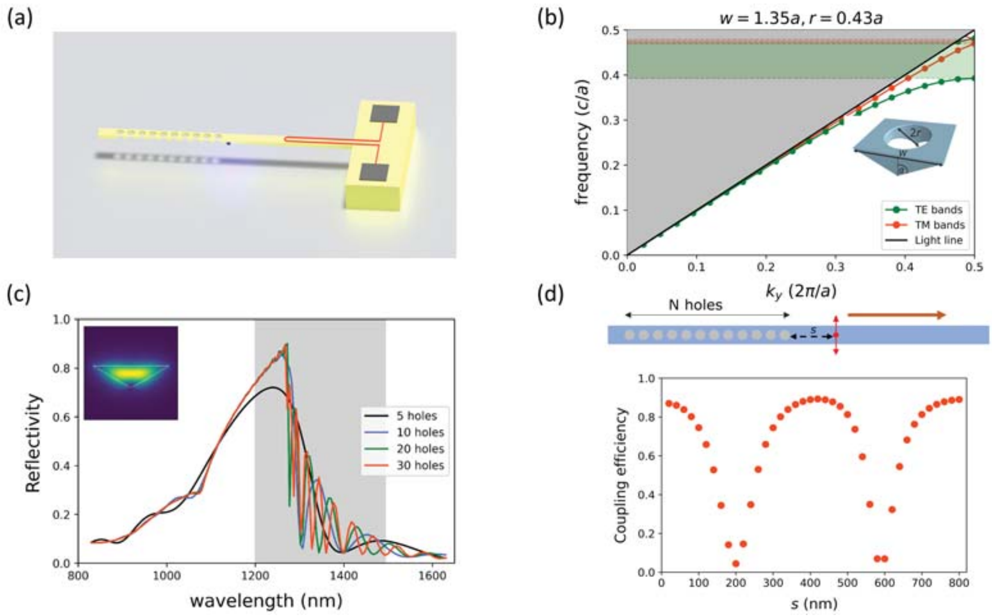

Fig. 1. (a) Illustration of a photonic crystal mirror (PCM) and an SNSPD (red) integrated with a triangular cross-section waveguide with an implanted color center (deep blue). (b) Dispersion relations in the 60° triangular cross-section PhC, where a is the lattice constant. (c) The FDTD reflectivity spectrum of the NV emission from PCM for the f-TE mode with a varying number of air holes. Grey regions indicate the band gap values calculated by the PWE method. Inset shows the f-TE mode profile (d) The interference pattern of the color center emission coupling efficiency into the f-TE mode as a function of the color center (red) distance (s) from the PCM.

An asymmetric waveguide terminated by a photonic crystal mirror (PCM) can overcome the dipole emitter coupling limit of 50% into a propagating mode of a waveguide. To design this functionality, we study how photonic band gap (PBG) is formed in a triangular photonic crystal (PhC) in SiC [3]. Our 1D PhC is constructed by inserting cylindrical air holes in the 60° angle-etched triangular waveguide. We choose this etch angle due to a realistic implantation depth (70 nm) as well as single mode propagation for NV center emission ($\sim$ 1230 nm) in SiC [2,4]. We employ MPB software for applying the PWE method to obtain the dispersion relations shown in Fig. 1(b). We observe that the transverse electric (TE) PBG is much larger than the transverse magnetic (TM) PBG. Our optimized design for NV center emission in single mode 60° triangular waveguide features width, hole radius and lattice constant parameters of $(w,r,a) = (800,213,533)$ nm. Using Lumerical FDTD, we verify the reflectivity of the NV emission optimized PCM [5] shown in Fig. 1(c). We then optimize the position of the color center (s) relative to the PCM which causes periodic interference of the light coupled into the f-TE mode. At the peak, the coupling into the waveguide is doubled compared to a symmetric waveguide case. Moreover, the high coupling condition is robust to the imprecision in the color center placement by $\pm$100 nm.

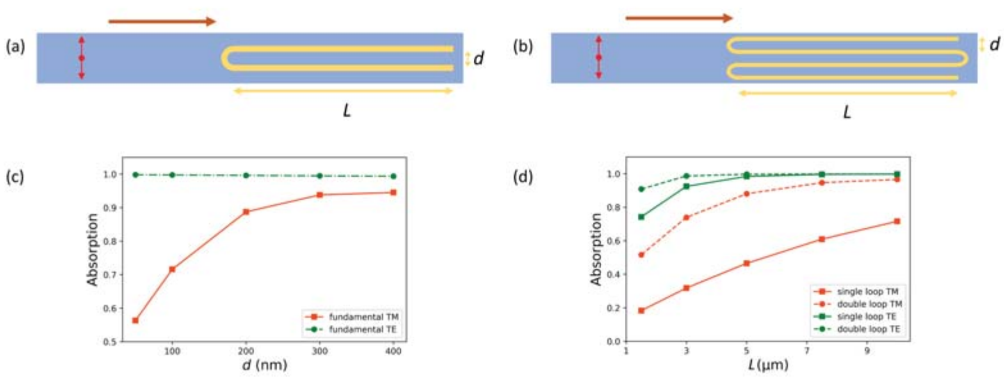

Fig. 2. (a) and (b) demonstrate the top view of a single loop and double loop NbTiN (yellow) respectively on a triangular cross-section SiC waveguide (blue). (c) Absorption of the f-TE and f-TM modes as a function of spacing between adjacent arms d (d) Absorption comparison of the f-TE and f-TM modes as a function of length L.

For efficient single-photon detection, we model meander shaped (single loop and double loop) NbTiN SNSPDs on triangular SiC waveguides, shown in Fig. 2(a)-(b), and calculate the absorption efficiency at 1230 nm with Lumerical FDTD [5]. Fig. 2(c) shows that for a single loop NbTiN with strip width 100 nm, thickness 6 nm, and length 100 μm, the absorption of the f-TM mode increases rapidly with the spacing between adjacent arms whereas the absorption of the f-TE mode remains constant. The absorption of the double loop with spacing d =100 nm is higher than the single loop, with a significant improvement in the f-TM mode absorption and identical detection efficiency for the f-TE and f-TM is observed at higher lengths, depicted in Fig. 2(d).

In conclusion, we explore the photonic band gap formation in triangular geometry of silicon carbide nanodevices and the relative positioning of the color center to a photonic crystal mirror that doubles the collection efficiency into a triangular waveguide. We then optimize the design of an overlaid NbTiN SNSPD for high collection of light propagated in the fundamental TE and TM modes. These results demonstrate highly efficient collection and detection of color center emission in triangular SiC devices for QIP applications.

References

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