Controlling Spontaneous Emission in SiC Pillar Metasurface with Color Centers

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***Abstract*—Using COMSOL RF Module, we fabricate a periodic Silicon carbide (SiC) pillar lattice embedded with Silicon vacancy (SiV) centers emitting at 862 nm. Engineered pillar geometry and spacing induce coherent Mie resonances, enhancing the local optical density of states. We achieve over fifteen-fold increase in SiV spontaneous decay rate via resonant field confinement and inter-pillar coupling, demonstrating a route to boost solid-state quantum emitter performance.**

***Index Terms*—Mie resonances, single photon, decay rate.**

I. Introduction

Metasurfaces are ultrathin nanostructures engineered to manipulate electromagnetic waves via resonant interactions with electric and magnetic fields [1], [2]. Silicon carbide (SiC) has gained attention in metasurface design due to its robust optical properties and ability to host color centers such as silicon vacancies (SiV), which act as stable single-photon sources at 862 nm [3]. In this work, we fabricate a periodic array of SiC nanopillars, each embedded with a SiV center. These wavelength-scale pillars act as Mie resonators, where dipole emission excites multipolar charges and current distributions that support Mie resonances [4]. The interference of these multipolar modes enhances the local optical density of states (LDOS), enabling control over spontaneous emission [5]. We further analyze how the geometry and environment influence scattering efficiency through individual multipole contributions, providing insights into emitter–metasurface coupling mechanisms [6]. The total scattering efficiency (SE) of different multiples is expressed as [4]. In a periodic SiC–pillar array, inter-pillar coupling of Mie resonances boosts the overall scattering efficiency [7]. The coherent superposition of these multipolar modes increases the local density of optical states (LDOS), directly governing the dipole's spontaneous decay rate [8]. Formally, the LDOS at frequency ω and position r is given by

$$\rho(\omega, r) = \sum_{k,\sigma} |\hat{d} \cdot \mathbf{E}_{k,\sigma}(r)|^2 \delta(\omega - \omega_{k,\sigma}). \tag{1}$$

Here, $\hat{d}$ is the unit vector specifying the direction of the transition dipole moment, $\mathbf{E}$ is the total electric field at the emitter, comprising its direct emission plus the fields scattered and reflected by the surrounding periodic pillar [9]. Thus, by tailoring Mie-scattering modes with periodicity, one can precisely tune the local field at the source and, hence, the emitter's decay dynamics.

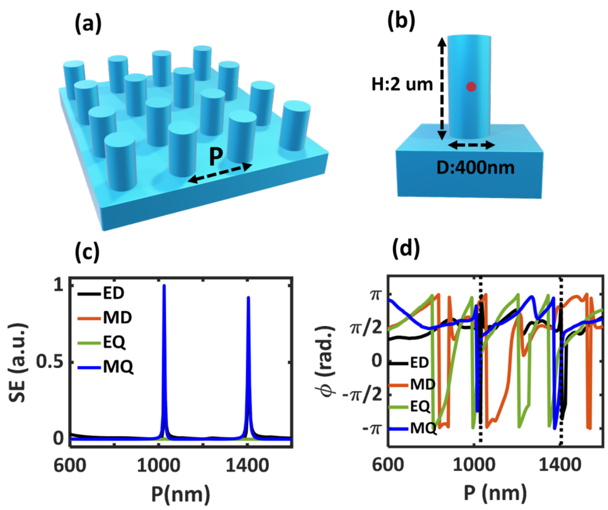

Fig. 1. (a) and (b) are schematics of SiC pillar lattice and unit cell embedded with dipole emitter, respectively. (c) and (d) Mie resonance response and corresponding phases as a function of the periodicity of the Pillar, respectively.

II. Materials and Methods

Simulations were performed using COMSOL RF module with periodic boundary and scattering boundary condition applied on the domain of unit cell to generate a periodic array of pillars, with mesh sizes between 1 nm and $\lambda/7$. SiC optical constants were taken from Singh et al. [10].

A. Scattering efficiency calculation

SE was calculated semi-analytically by integrating electric fields inside the nanopillars using custom code that is already programmed by us inside COMSOL.

B. Relative decay rate calculation

The SiV center was modeled as a point dipole. Relative decay rate was computed as $\Gamma_{rel} = \gamma/\gamma_\infty = P/P_\infty$ [11], where P is the power emitted by point dipole when embedded in SiC pillars lattice and P_∞ is the power due to the emission of point dipole in the bulk SiC.

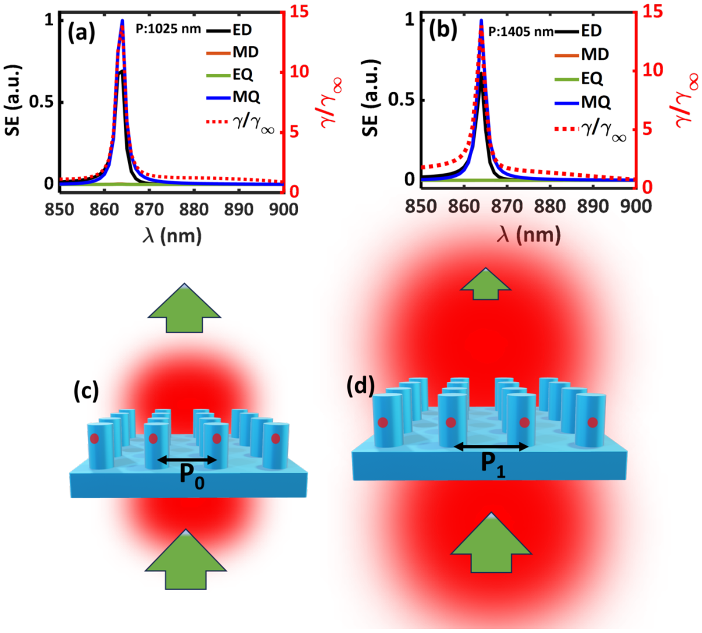

Fig. 2. (a) and (b) The spectral response of Mie-scattering moments together SiV relative decay rate in the SiC pillar lattice as a function of wavelength for P_1 resonant values respectively under point dipole excitation. (c) and (d) The schematic representation of tuning the SiV emission with the lattice periodicity, P_0 (off-resonant) and P_1 (resonant) respectively.

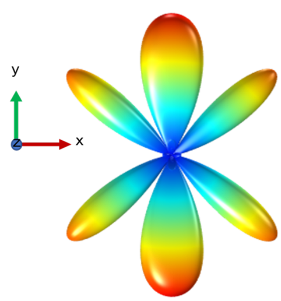

Fig. 3. represents the 2D far-field emission spectra confined in the x-y plane only.

III. Results and Discussion

We have computationally optimized the meta-surface using a commercial Comsol Multiphysics RF module to achieve the optimum dimension of the pillar lattice shown in schematic Fig. 1. (a) and (b). The optimization of the meta-surface is done using a plane wave having excitation wavelength λ_{exc} : 862 nm moving in $\pm$ z direction with electric field aligned in the + x direction. Finally by fixing the optimized values of the pillars, the periodicity (pillars to pillars distance), P of the metasurface is optimized from P:600 nm to P:1600 nm shown in Fig. 1 (c). The maximum value in SE is observed for electric dipole (ED) and magnetic quadrupole (MQ) at periodicity of P:1025 nm and P:1405 nm respectively, with ED and MQ being in phase at this resonant periodicity P_1 Fig. 1 (d). Finally, we obtained SE and relative decay rate as a function of the wavelength for the resonant Periodicity P_1 over the spectral ranges from 850 nm to 900 nm shown in Fig. 2 (a) and (b). It is observed that both the ED and MQ are well resonant around the 862 nm wavelength. Thus, their coherent superposition results in increasing the total electric field E at the source position and hence the local density of optical states (LDOS) (refers to Eq 1). This led to an enhancement of almost 15 times in the relative decay rate of the color center embedded in the SiC pillars. Further, we get a less bright SiV emission when interaction among Pillars being out of phase that is at P_0 and a very bright emission at P_1 when interaction being in phase shown in Fig. 2 (c) and (d) respectively.

IV. Conclusion and Future Work

By tuning the metasurface periodicity, we selectively excite the electric dipole and magnetic quadrupole Mie resonances, which modulate the LDOS and enhance the emitter's decay rate by 15-fold, promising for quantum technological applications. However, the far-field emission remains largely non-directional (Fig. 3), indicating that control over the relative phases of these Mie modes is required to achieve directional emission.

V. ACKNOWLEDGEMENTS

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