Dielectric Dipole Nanoantenna Design for highly Directional Emission from SiV Color Centers

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***Abstract*—We present a novel nanoantenna design investigated using COMSOL Multiphysics, featuring a nanodiamond silicon-vacancy (SiV) center embedded within a polyvinyl alcohol (PVA) layer sandwiched between titanium dioxide (TiO_2) cylinders. Simulation results reveal a 32-fold enhancement in emission at the 738 nm zero-phonon line (ZPL), along with approximately 70 percent collection efficiency in the upward direction, demonstrating strong potential for integrated photonic applications.**

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

I. Introduction

In this era of emerging quantum optical technology, there is a high demand for bright, deterministic, room-temperature single-photon sources with near-unity quantum efficiency (QE) and a collection efficiency (CE) of $\geq$67 percent [1], [2]. Traditional platforms such as photonic cavities, plasmonic nano resonators, and hyperbolic metamaterials suffer intrinsic plasmonic losses that degrade both QE and CE [3], [4]. Here, we propose an all-dielectric Mie-resonant dipole nanoantenna to boost spontaneous emission from a nanodiamond based SiV center at 738 nm ZPL [5]. Our geometry comprises two TiO_2 cylinders coupled with a PVA layer that houses the dipole emitter. The wavelength scale cylinder acts as mie resonator, after interacting with dipole radiation, supports multipolar Mie resonance modes likes electric and magnetic dipole mode (ED and MD) and quadrupolar mode (EQ and MQ) respectively [6]. These resonances reshape the local density of optical states (LDOS) , directly governing the dipole's spontaneous decay rate [7], [8]. Formally, the LDOS at frequency ω and position r is given by

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

Here, $\hat{d}$ is the unit vector specifying the direction of the transition dipole moment, **E** is the total electric field at the emitter, comprising its direct emission plus the fields scattered and reflected by the surrounding structure [7]. Here, we investigate how electromagnetic Mie-scattering modes of a TiO_2 coupled-dipolar antenna enhances the decay rates and the directionality of radiation from the SiV single color center embedded within the structure.

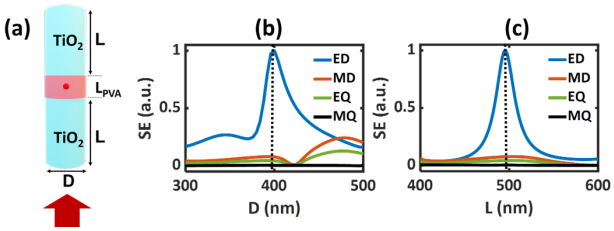

Fig. 1. (a) The schematic of TiO_2 coupled dipole nanoantenna. (b) and (c) The Scattering efficiency (SE) as a function of the diameter (D) and length (L) of the TiO_2 cylinder with maximum SE at D: 400 nm and L: 496 nm respectively.

II. Materials and Methods

Simulations were performed using COMSOL RF module with a perfectly matched layer (PML) / scattering boundary (SBC) condition applied on the calculation domain with minimum and maximum mesh sizes of 1 nm and $\frac{\lambda}{7}$, respectively. The optical constants of TiO2 were taken from [10]. The permittivity of PVA is taken from [11] and the diamond from [12].

A. Scattering efficiency calculation

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

B. Relative decay rate calculation

The SiV center was modeled as a point dipole. Relative decay rate was computed as $\Gamma_{rel} = \gamma/\gamma_0 = P/P_0$ [11], where P is the power emitted by point dipole when embedded in nanoantenna and P_0 is the power due to the emission of point dipole in the vacuum.

III. Results and Discussion

Using the COMSOL RF module, we designed an all-dielectric TiO_2 nanoantenna (D = 400 nm, L = 496 nm; Fig. 1. The 2D electric field profile shows a strong field confinement at the PVA center under plane wave excitation (Fig. 2(a)). PVA layer's spectral response shows a strong electric-dipole (ED) resonance at 738 nm (Fig. 2(b)), coinciding with the SiV emission—so it acts as a resonant cavity. At the cavity center,

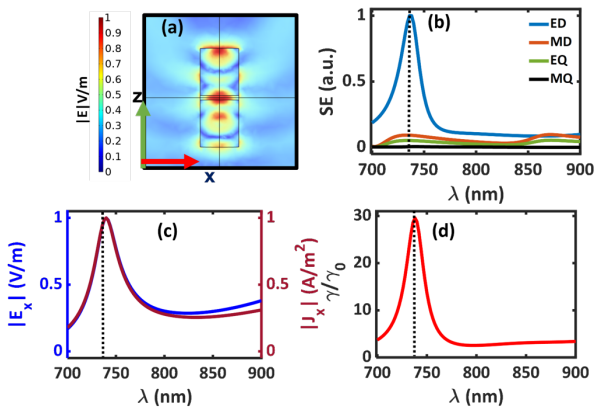

Fig. 2. (a) 2D electric field profile under plane wave excitation in the x–z plane, showing maximum field confinement near the PVA center. (b) PVA layer's spectral response exhibiting a strong electric dipole (ED) resonance at 738 nm. (c) E_x and J_x spectra at the center of the PVA cavity resonant at λ: 738 nm. (d) Relative decay rate spectrum of the SiV center within the PVA cavity.

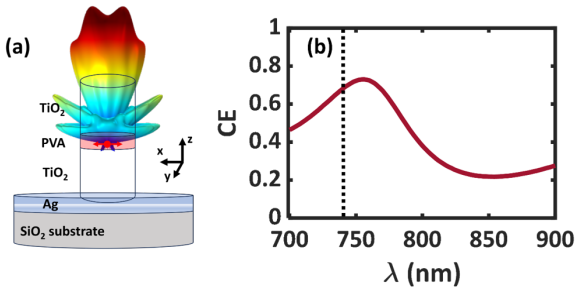

Fig. 3. (a) represents the schematic of the Dipolar antenna with silver reflector and directional 3D far field radiation profile. (b) The CE spectrum of the SiV center dipole radiation directed upward.

both E_x and J_x peak at 738 nm (Fig. 2(c)), boosting the LDOS and increasing the emitter's decay rate by 32 times (Fig. 2(d)). We further investigate the effect of two coupled TiO_2 cylindrical antennas on the radiation pattern of an embedded color center. A nearby dipole emitter placed at the cavity center excites multipolar Mie moments in the antennas, which emit into the far field and interfere with the emitter's radiation. When the electric and magnetic dipole contributions (ED and MD) are balanced, the structure achieves highly directional vertical emission, as shown in Fig. 3(a). For SiV emission, a collection efficiency of approximately 70 percent is achieved in the vertical direction (Fig. 3(b)).

IV. Conclusion and Future Work

In this work, we explored how multipolar Mie scattering moments influence the local density of states (LDOS), thereby controlling both the decay rate and far-field radiation pattern of a dipole emitter embedded in a nanoantenna. The observed enhancement in emission rate and directionality of single photons positions our design as a promising platform for advancing quantum photonics research in the near future.

V. Acknowledgements

We acknowledge the UGC MHRD, INDIA, for SRF.

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