Field-based design of a resonant dielectric antenna for coherent spin-photon interfaces

Abstract

Proposal: Field-based design for dielectric antenna to interface diamond color centers with Gaussian propagating far-field.

In effect, Gaussian propagating far-field is the prerequisite for good spin-photon interfaces. What is a field-based design?

Result: Efficient Spin-photon interface with a Purcell factor exceeding 400 and and 93% mode overlap to a 0.4 NA far-field Gaussian mode. Robust to fabrication noise, such as fabrication imperfections, variations in the dimensions of the dielectric perturbations.

Enables: efficient free-space interface for closely packed arrays of quantum memories for multiplexed quantum repeaters, arrayed quantum sensors, and modular quantum computers.

What are closely packed arrays of quantum memories?

What are multiplexed quantum repeaters?

What are arrayed quantum sensors?
What are modular quantum computers?

Introduction

Goal of quantum optics: efficient interface between a free-space propagating field and a quantum emitter dipole.

Challenge: Although NV centers in diamond are leading candidates, high-cooperativity interfaces are still a challenge to realize.

Photonic interface goal: a high Purcell factor and directional emission, jointly optimizing spectral and spatial collection.

Approach taken in the paper: Starting from the radiation field of an emitter in a 2D dielectric slab and then adding perturbations to transfer the desired output. Then, optimizing the power transfer through cavity Purcell factor.

Is power transfer through cavity Purcell factor is something different than adding the perturbations? Or did they just mention it separately to emphasize on the term Purcell factor.

Field-based design: introduces a novel 3D transfer matrix approach which extends the 1D transfer matrix approach, used in dielectric mirror design.

What is field-based design? What is the transfer matrix approach?

The goal is to go from a dipole in a dielectric membrane to a dielectric antenna with a back reflector through the process of field-based design and matching the atomic dipole emission to a targeted free space propagating mode.

The starting structure:

- NV center with the zero-phonon emission line at $\lambda{\sim}637\ nm$.
  What is the zero-phonon emission line?
- Slab thickness is $150\ nm\ (\lambda\backslash 2n)$. $n = 2.4$ is the dielectric constant of diamond.

Summarized Result:

- Purcell factor of 420

- 93% mode overlap within an NA = 0.4
- 99% collection efficiency within an NA = 0.5
- Spin-photon interface efficiency can improve ≥ 300 times.

What is the difference between the mode overlap and the collection efficiency?

Metallic antennas suffer from Ohmic loss and quenching, which dielectric antennas do not.

What is Ohmic loss and quenching?

We can alleviate the surface charge and the spin noise by placing the closest etched surface more than one wavelength away from the dipole emitter.

Antenna Design

We shall define some figures of merit.

Spin-photon interface efficiency $\eta = \eta_1 \times \eta_2$

η_1: Spin-antenna interface efficiency

η_2: Antenna efficiency

$$\eta_1 = \frac{\eta_0 \times F_p}{\eta_0 \times F_p + 1 - \eta_0}$$

η_0: Radiation efficiency in the ZPL

F_p: Purcell factor, increasing the spontaneous emission rate of the ZPL

Antenna far-field, $\vec{E}_{far} = E_r\,\vec{r} + E_\theta\,\vec{\theta} + E_\phi\,\vec{\phi}$, calculated on a hemisphere surface located at $r_0 = 1m$ away.

Expectation is $E_r = 0$ because the electric field is perpendicular to the direction of propagation.

$$\vec{E}_{far}(r_0, \theta, \phi, t) = C_{far} \exp[-i\left(\omega t - \frac{2\pi r_0}{\lambda}\right)]\ \vec{e}_{far}(\theta, \phi)$$

C_{far}: far-field amplitude

$\vec{e}_{far}(\theta, \phi)$: the dimensionless normalized vector. $\vec{e}_{far}$ captures the polarization and the angular profile of the far-field. Mathematically, its total solid angle integral captures the fraction of the total power going into the $+z$-direction.

Antenna efficiency, $\eta_2 = \left| \int_0^{2\pi} \int_0^{\pi} \vec{e}_{far}(\theta, \phi) \cdot \vec{e}_{tar}(\theta, \phi) \sin\theta \, d\theta d\phi \right|^2$, the mode overlap between the antenna far-field and the target field.

The target far-field used in the paper, $\vec{e}_{tar}(\theta, \phi) = 2.10 \times \exp(-\frac{\tan^2\theta}{0.4^2})\ \vec{y}$

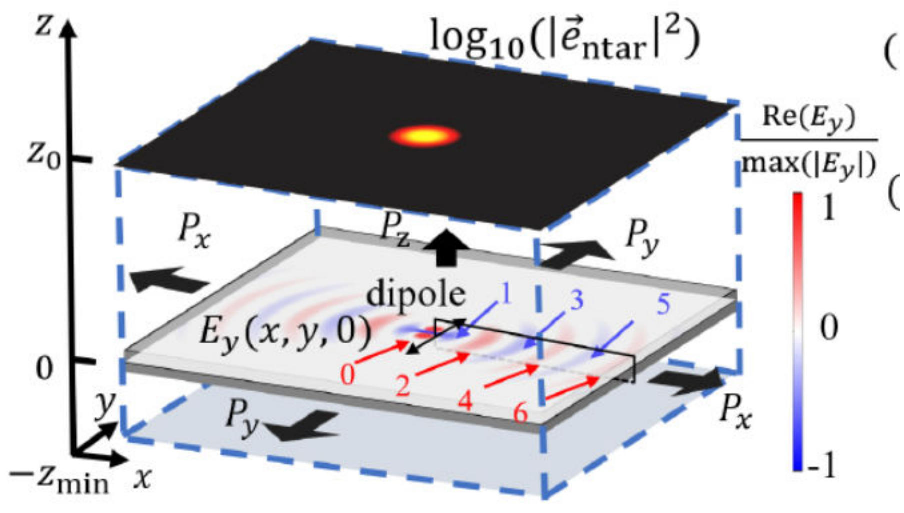
What is the logic behind selecting the polarization to be in the y-direction?

The paper also mentions some higher-order correction of the target far-field, which I think is not much important here.

In the design mentioned in the paper, this overlap integral is added as a figure of merit. It also estimates the single-mode fiber collection efficiency, important for quantum photonic applications.

The design procedure is summarized here below:

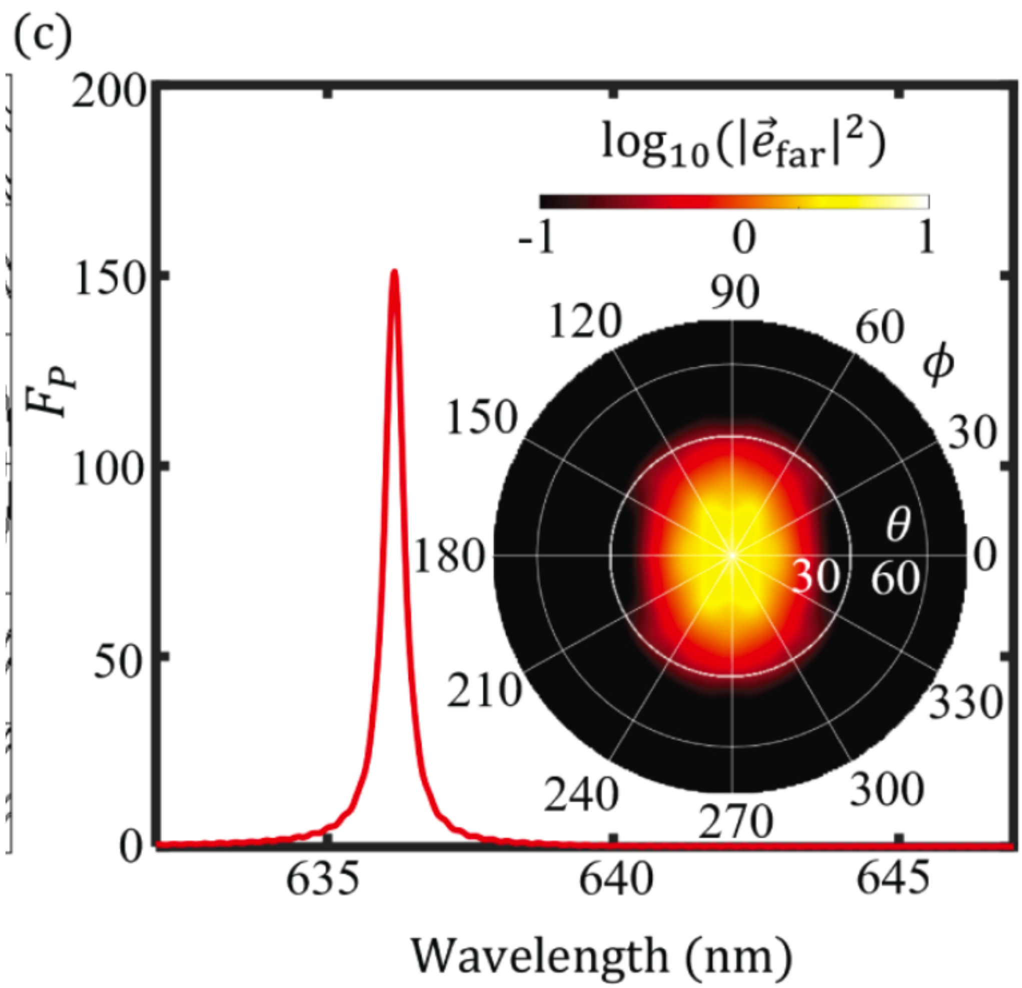
1. Calculate the field profile of a y-oriented dipole in the diamond membrane, which is 150 nm thick. The thickness can be changed to target a different resonant wavelength. n^{th} phase front is defined as the points with $n\pi$-phase difference from the dipole.



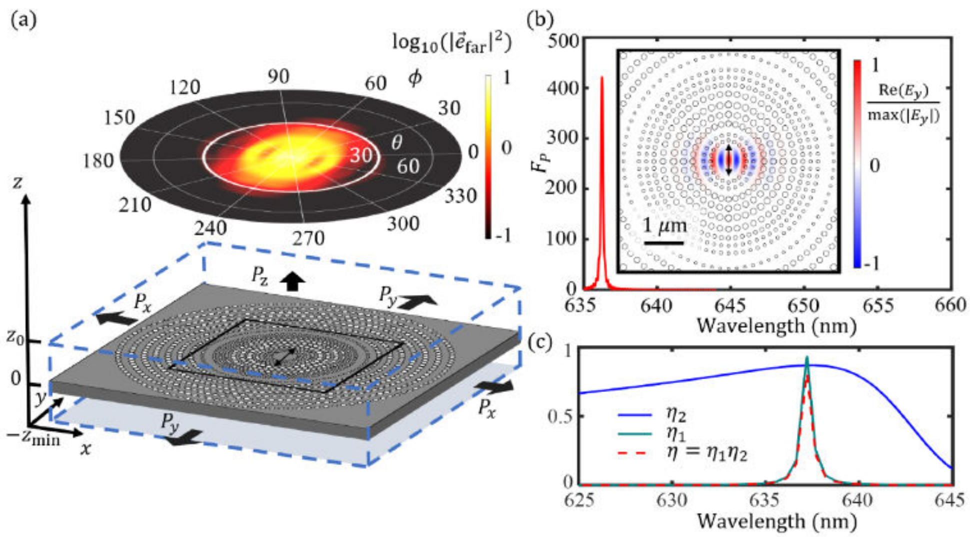
Dielectric perturbations are added along the phase fronts.

2. *Something related to the field-based design which does not concern me right now.*
3. *Something related to field-based design which does not concern me now.*
4. Mode overlap is maximized to optimize the parameters. *What is the optimization procedure?*
5. Using the results from 4 as the initial guess, we optimize the structure to maximize η calculated from FDTD simulations using gradient descent.
6. Add the destructive interference slots. *Does not matter right now, maybe related to the topics of the antenna design.*

Simulation Results



So far, the structure used slots as the etching geometry. At this point, the authors decided to replace them with holes. The holes have a minimum diameter of 70 nm.



For the optimized structure,

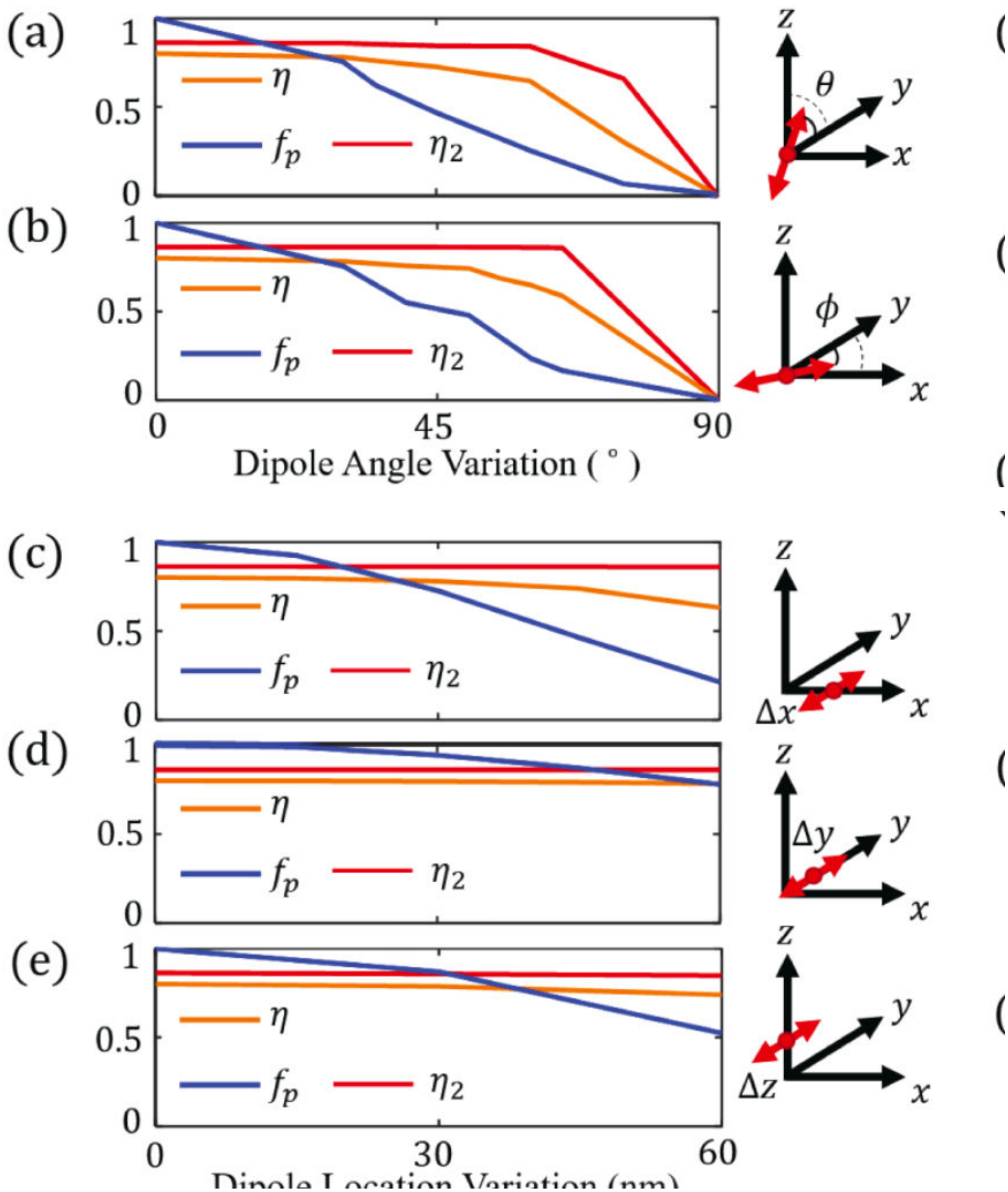
- η is 81%.
- Purcell factor is 420.
- Q factor is 4400, ($\eta_1 = 93\%$)
- Mode overlap, $\eta_2 = 87\%$.

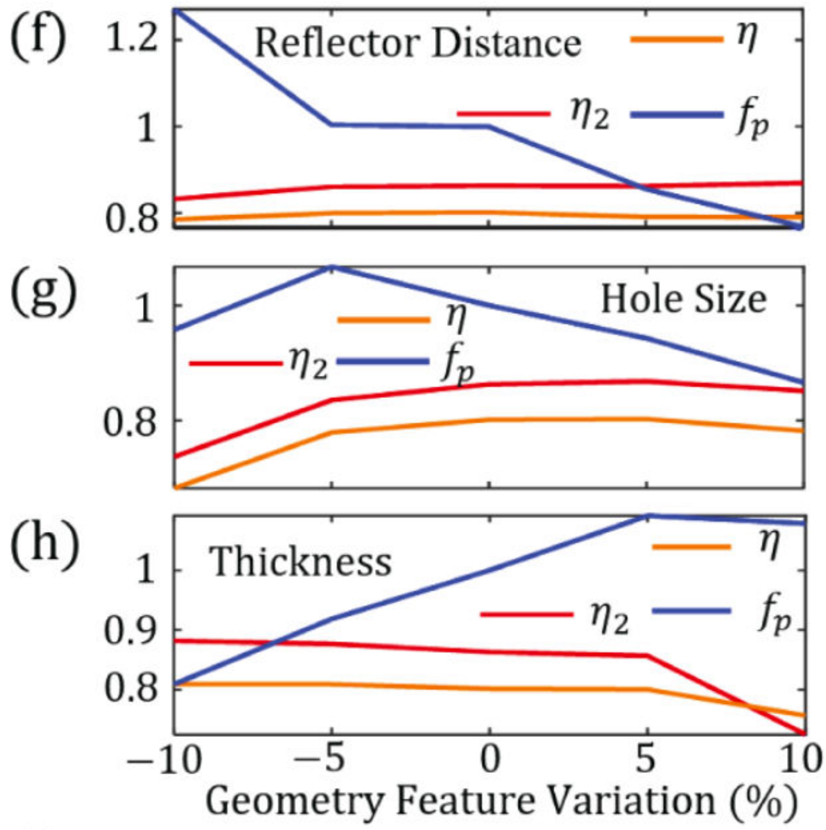
In the structure, the closest perturbation is more than λ/n_d away from the emitter dipole, which can alleviate the surface-charge noise.

This paper seems to have discussed bullseye cavity performance, keeping here for future reference.

The small NA collection can provide lower magnification for a larger field of view to examine more quantum emitters and have a longer working distance between the objective lens and the cryogenic stage.

Sensitivity Analysis

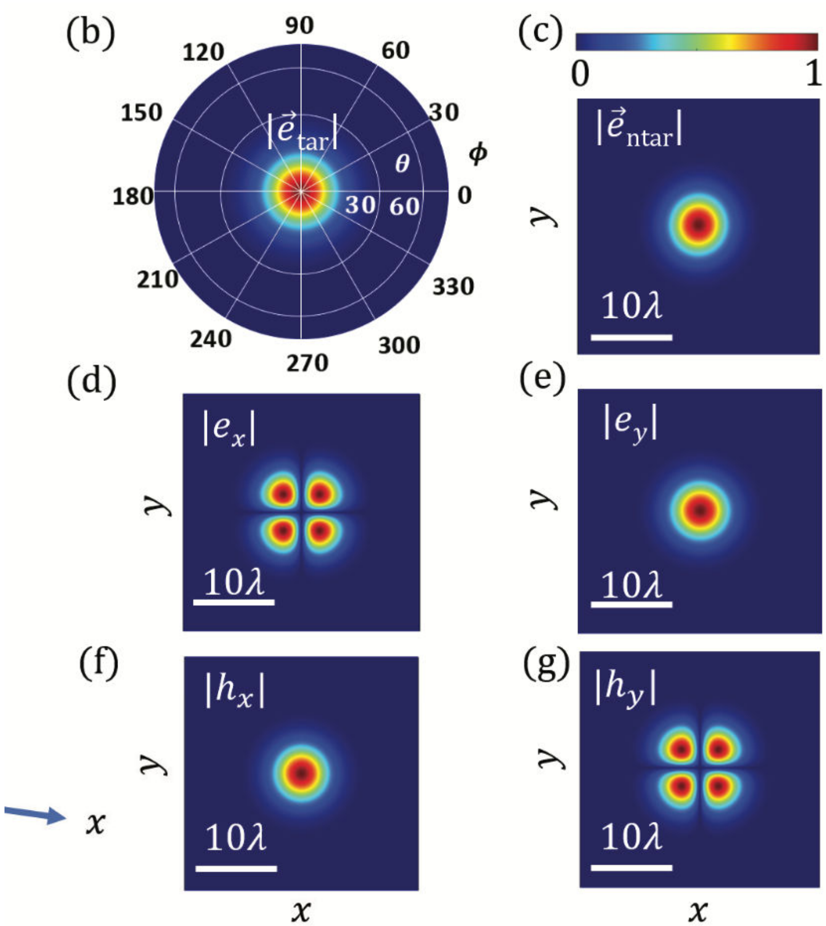




Different fabrication imperfections may affect the device performance, which can be overcome with parameter sweeps, and tolerance optimized design.

Supplemental Information

Far-Field to Near-field



This picture proves that we should expect something similar from our FDTD simulation.

Antenna Design for GaAs Quantum Dot

Bullseye antennas in $GaAs$ membrane with SiO_2/Au back reflector.

In the new design:

- Purcell factor = 316
- Mode overlap of 93% with Gaussian far-field of NA = 0.4.

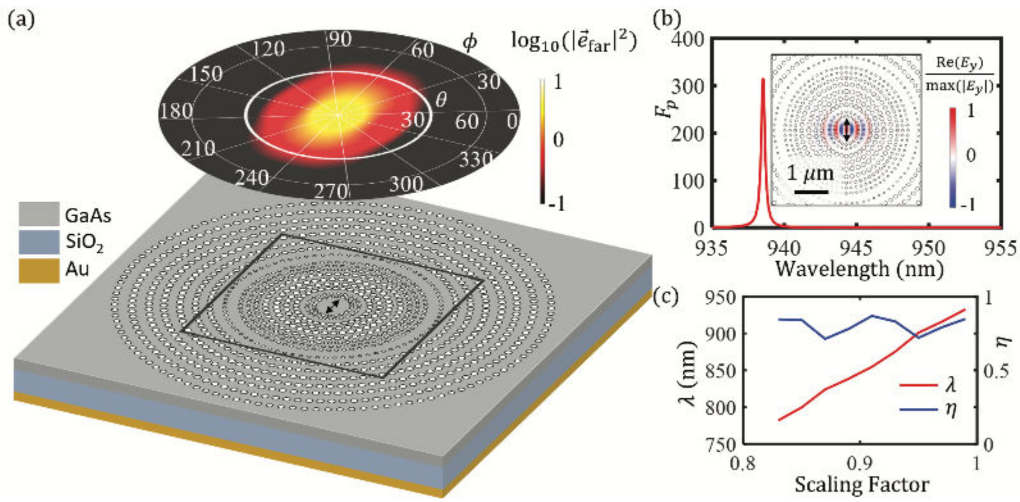


Fig. S6 (a) Illustration of the GaAs dielectric antenna structure, along with a plot of $\log_{10}(|\vec{e}_{\text{far}}|^2)$