Designing metamaterial antennae for improving the efficiency of single centers in diamond

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Abstract

Problem

Enhance emission properties of color centers in diamond by using bullseye patterned metamaterial.

Scope of work

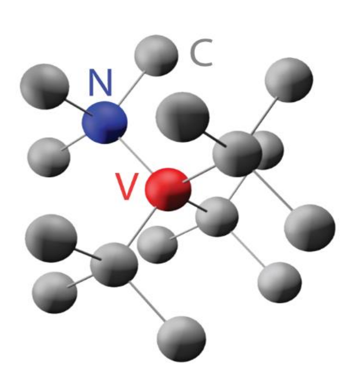
Optimize the geometrical parameters of the outcoupling structure using finite element method.

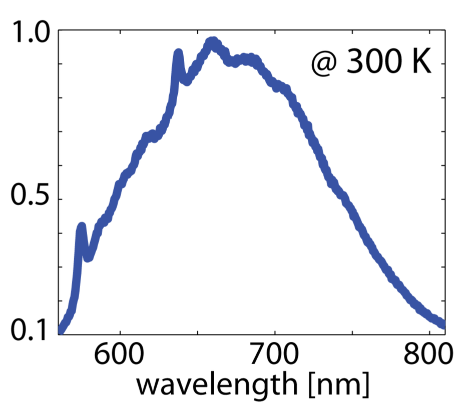
Results

Collected emission power using the bullseye outcoupler can increase by a factor of 9 compared to unpatterned metamaterial.

Introduction

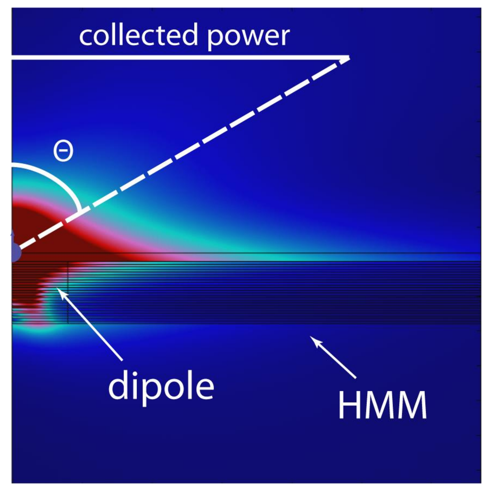
Nitrogen-vacancy (NV) centers in diamond are promising crystalline defects for applications in quantum information technologies and sensing [1]:





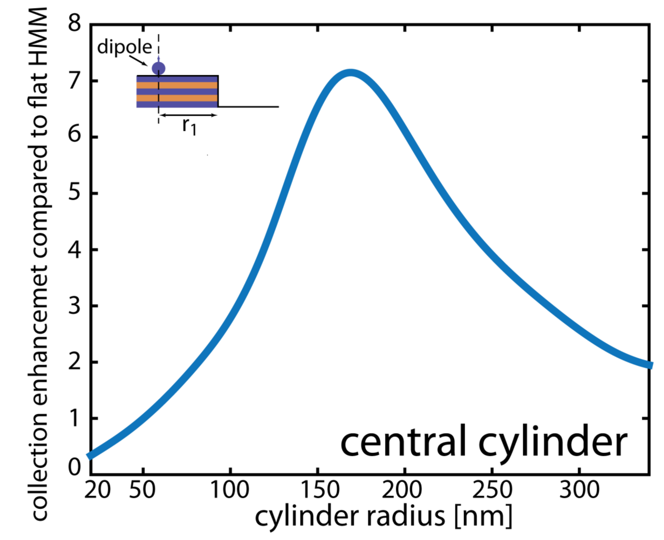
NV center can act as a spin-based quantum memory unit. It possesses a spin coherence time at room temperature in the millisecond range, which allows to perform many logical operations. The spin state can be initialized and read out optically. For higher operation speed and implementation of various algorithms, it is vitally important to efficiently collect the NV center emission. The broadband character of the emission makes this task particularly challenging.

Metamaterials with hyperbolic dispersion (HMM) can provide large photonic density of states (PDOS) in a broad wavelength range [2,3] and enhance the emission rate. For planar HMM, most of the power gets absorbed inside the material and is lost irreversibly.

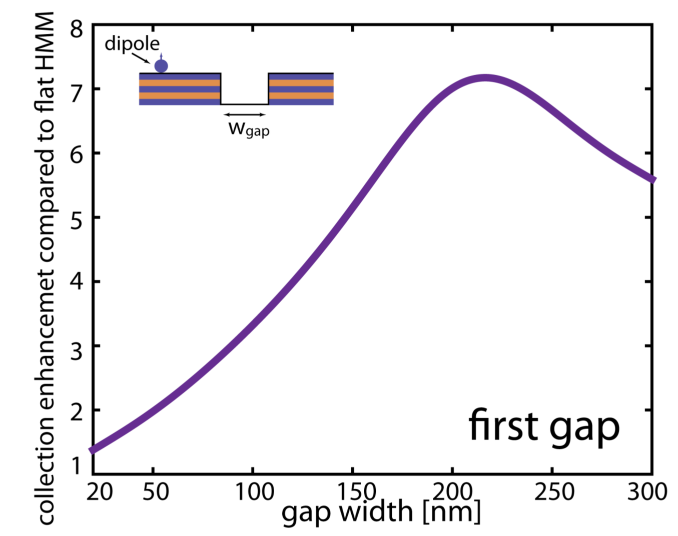


A bullseye pattern around a single NV center allows to scatter the modes away from the metamaterial, which must increase the collected power.

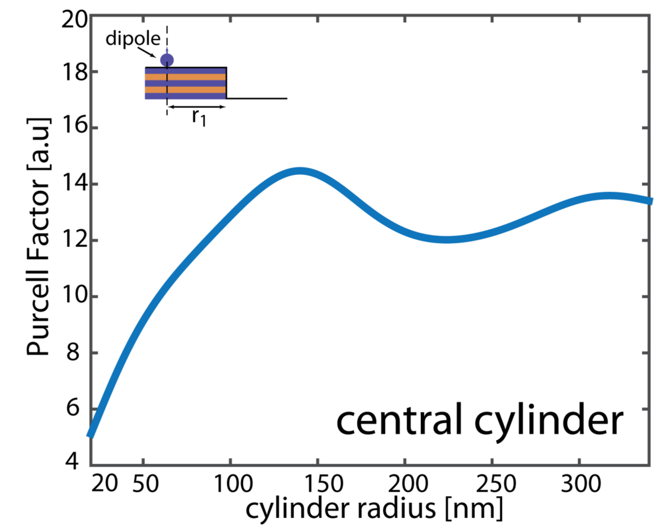
Optimization of outcoupler parameters



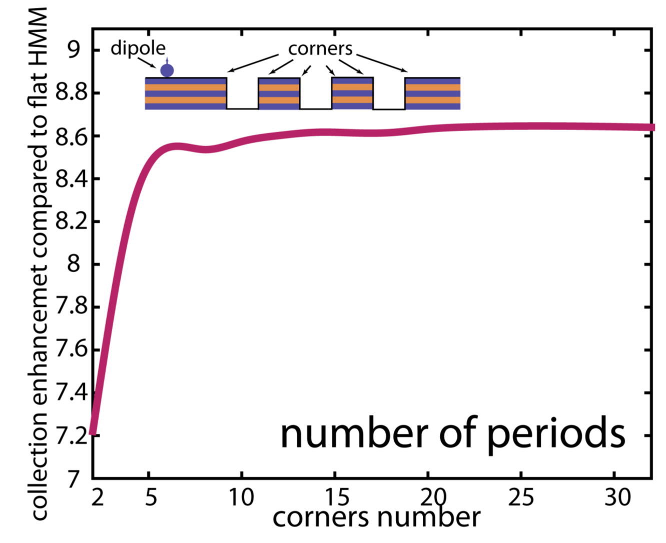
Single cylinder at the center of the structure allows to outcouple most of the radiated power.



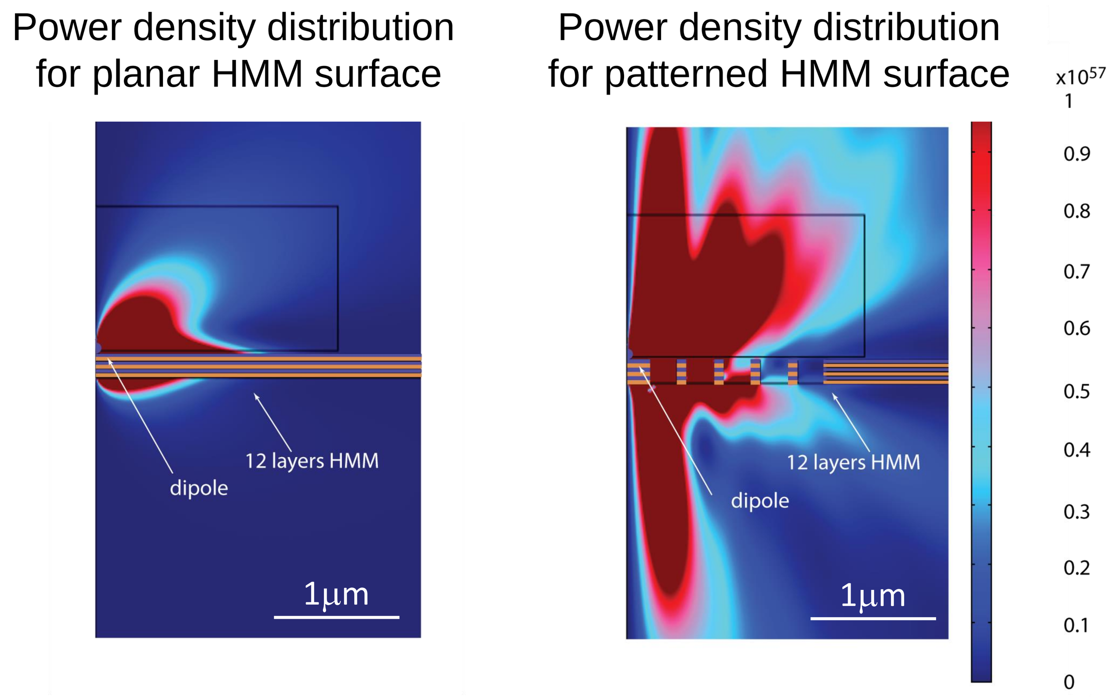
An additional corner leads to more outcoupling.



Cylinder size smaller than 150 nm does not support some of the propagating modes.



Outcoupling saturates with 4 rings or more.

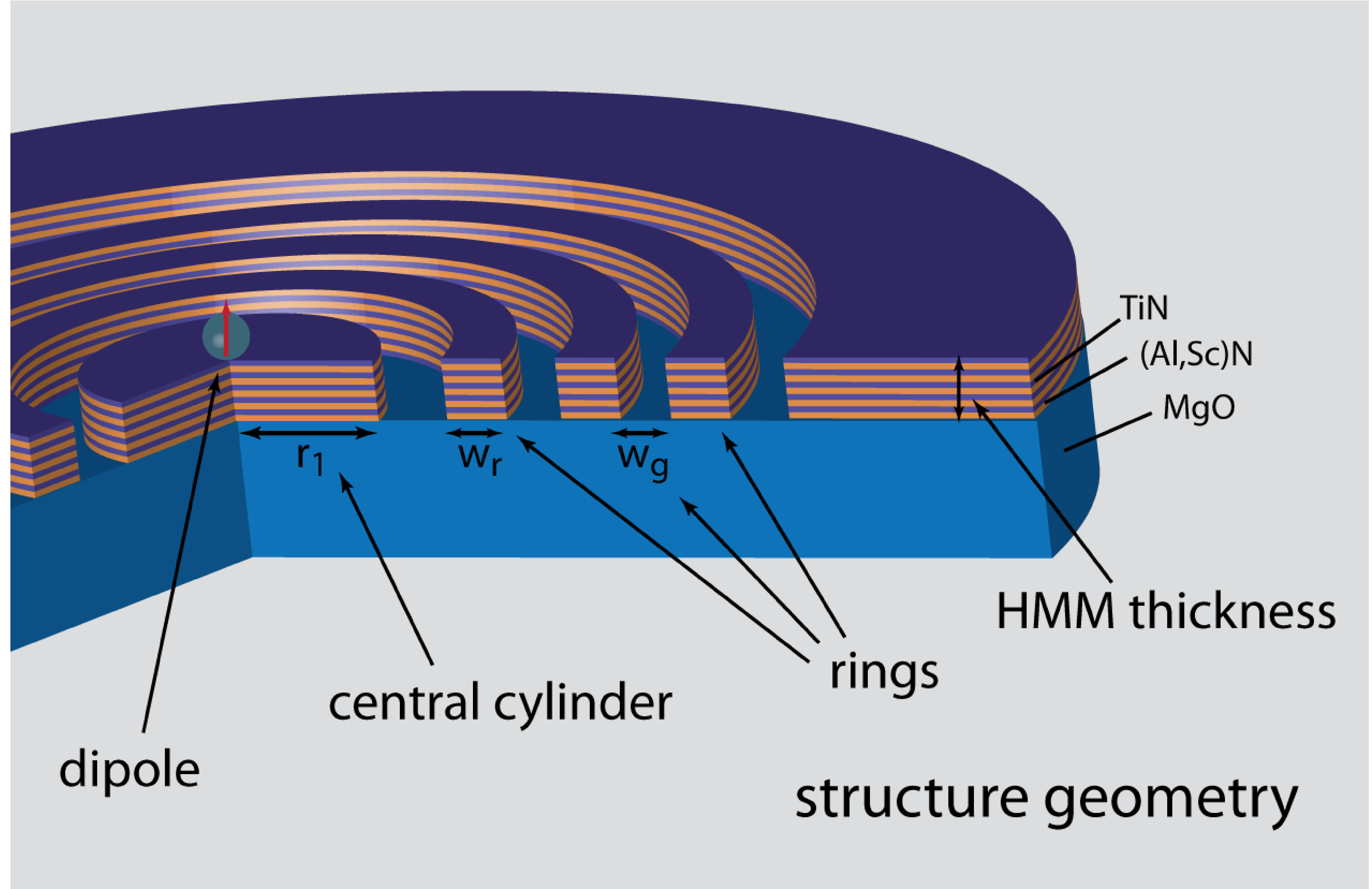


The corners of the bullseye structure outcouple the metamaterial propagating modes in the vertical direction.

Parameter	Optimized value
Central cylinder radius r_1	160 nm
Gap width w_g	230 nm
Rings width w_r	60 nm
Rings number N	4
Layers number	12 pairs
Top layer	TiN
Dipole position	At the top of the surface

Methods

The concentric circle pattern was simulated using a finite element method to find the optimal geometric parameters. A 2D axisymmetric model was created in COMSOL software. Based on the emission spectrum, wavelength of 680 nm was chosen for study.



Conclusion

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- Use of the optimized pattern increases radiated into a 60° angle power by a factor of 9.
- Corners of the structure are instrumental to achieve better outcoupling.
- A bullseye grating with 2 rings is suggested for fabrication as it will guarantee near optimal performance.

Future plans

- Finish optimization of the structure making it aperiodic
- Further optimize structure to avoid losses to substrate
- Experimentally demonstrate the outcoupling

References

[1] Doherty et al., Phys. Rep. 528, 1 (2013);
[2] Jacob et al., Appl. Phys. B, 100, 1, (2010);
[3] Shalaginov et al., LPR, 9 (2015)

Acknowledgements

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