Patterning metamaterials for fast and efficient single-photon sources

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Abstract

Problem

Enhance emission properties of color centers in diamond by use of a groove patterned metamaterial.

Scope of work

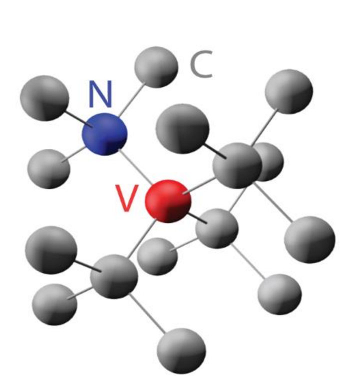
Optimize the geometrical parameters of the outcoupling structure using finite element method.

Results

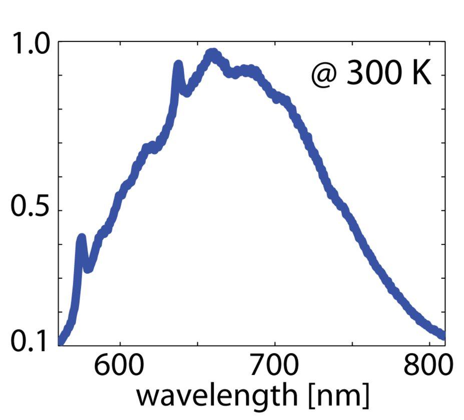
Collected emission power using the groove outcoupler can increase compared to planar structures of different materials for all studied wavelengths.

Introduction

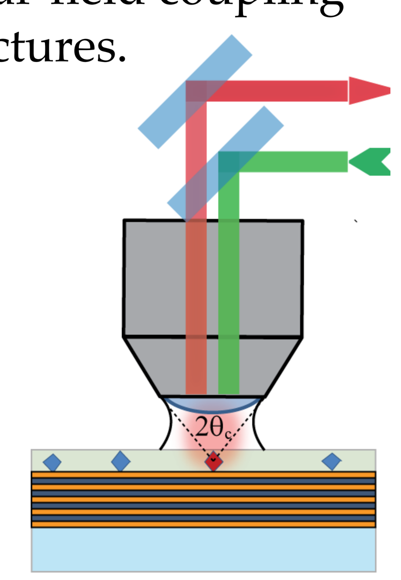
Solid state quantum emitters, promise to make fast on-demand single-photon sources an attainable reality.



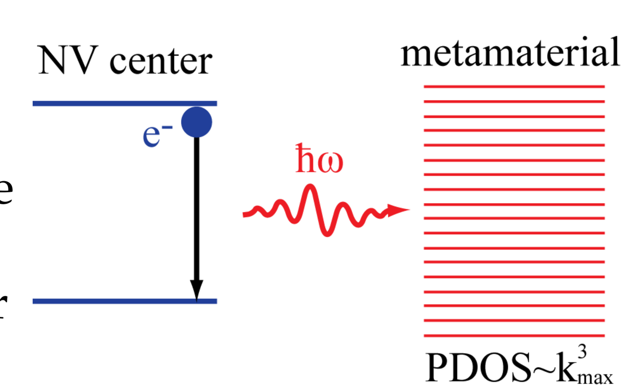
The improvement in photon emission and collection efficiencies for quantum emitters, such as nitrogen-vacancy (NV) centers in diamond, can be achieved by using near-field coupling to nanophotonic structures.



The broadband character of the emission makes this task particularly challenging for NV centers.



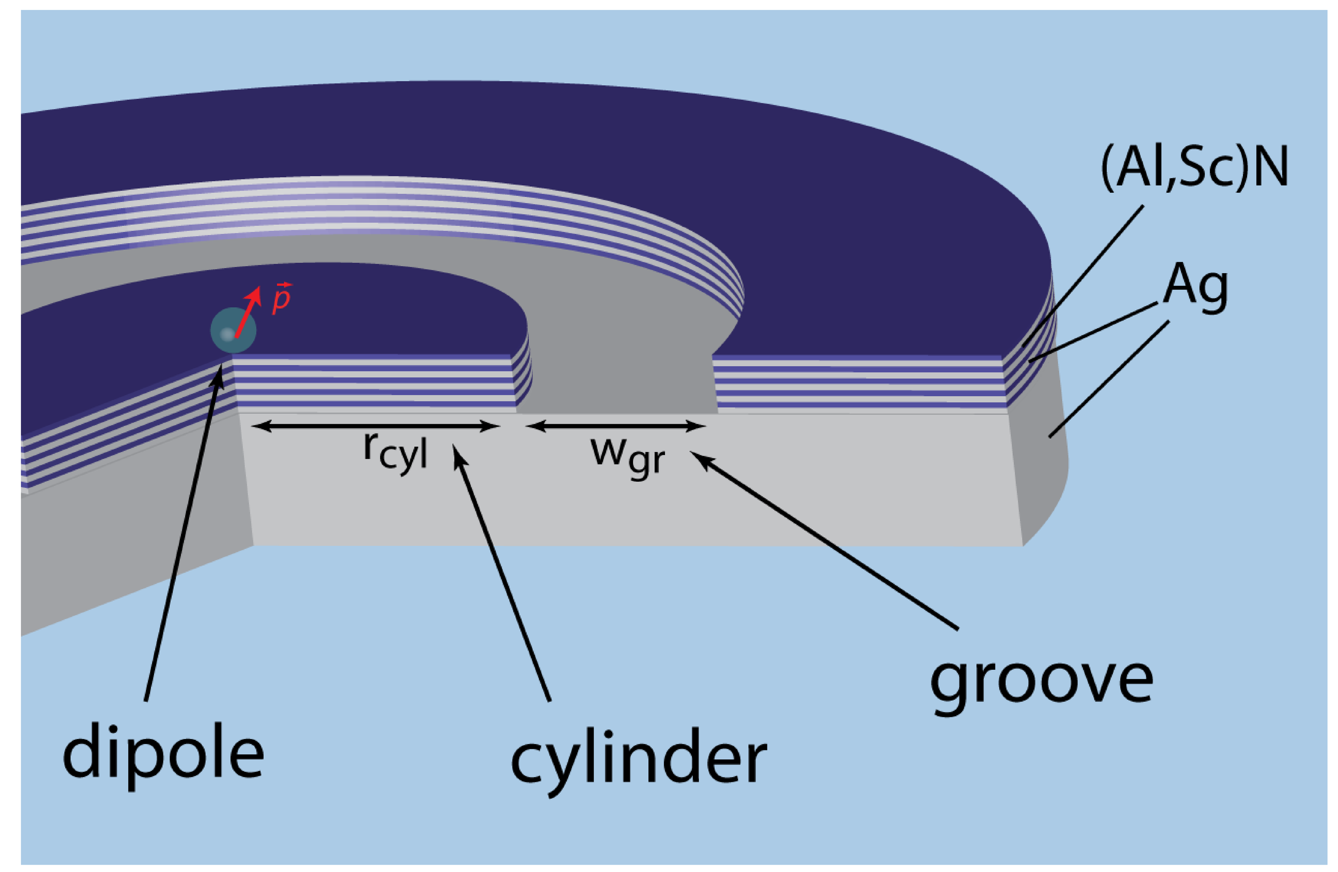
Metamaterials with hyperbolic dispersion (HMM) can provide large photonic density of states (PDOS) in a broad wavelength range [1,2] and enhance the emission rate. For planar HMM, most of the power gets absorbed inside the material and is lost irreversibly.



A groove pattern around a single NV center allows to scatter the modes away from the metamaterial, which must improve the objective coupling efficiency [3, 4].

Parameters optimization

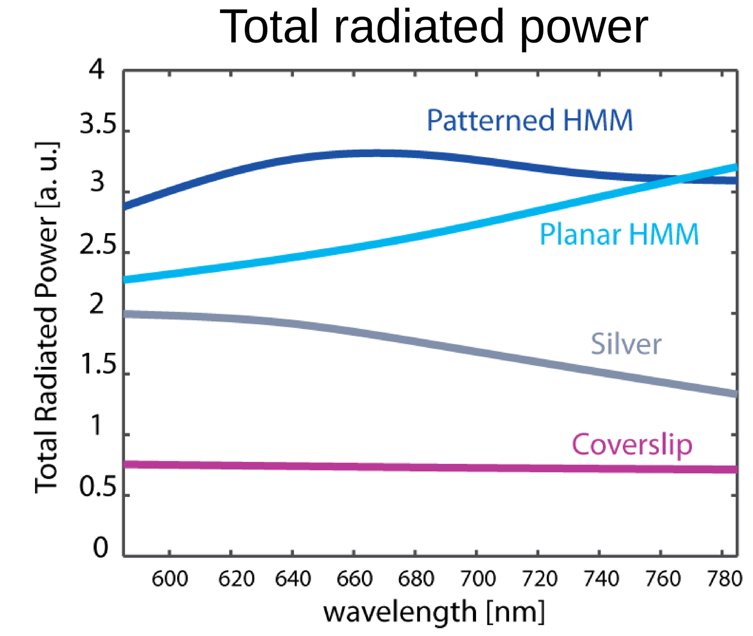
The groove pattern was simulated using a finite element method to find the optimal geometric parameters. A 2D axisymmetric and 3D models were created in COMSOL software. Based on the emission spectrum, wavelength of 685 nm was chosen for study.

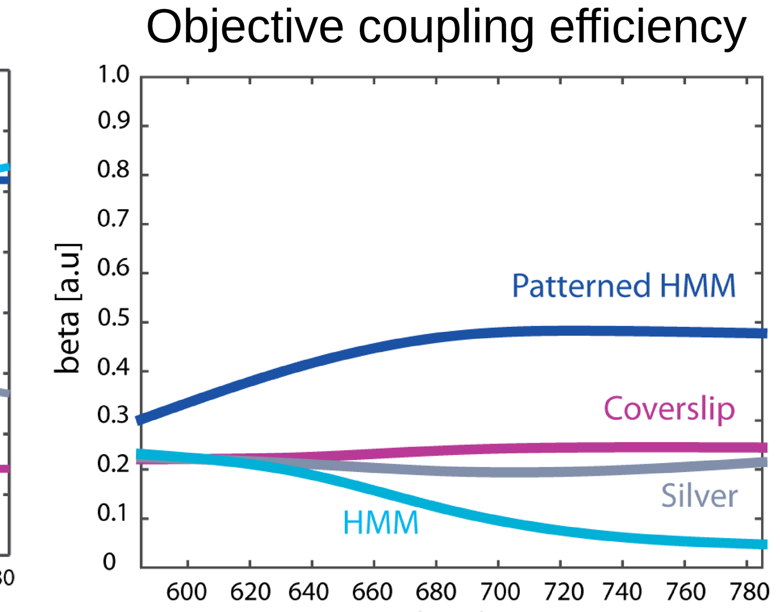


Optimized structure parameters

Parameter	Optimized value
Central cylinder radius r_{cyl}	100 nm
Groove width w_{gr}	350 nm
Layers number	8 pairs
Dipole position	At the top of the surface
Substrate	Silver

The structure was optimized in such way that the contribution of both orientations would be enhanced. The parameters include the fact that horizontally oriented dipole brings 2/3 of total power.



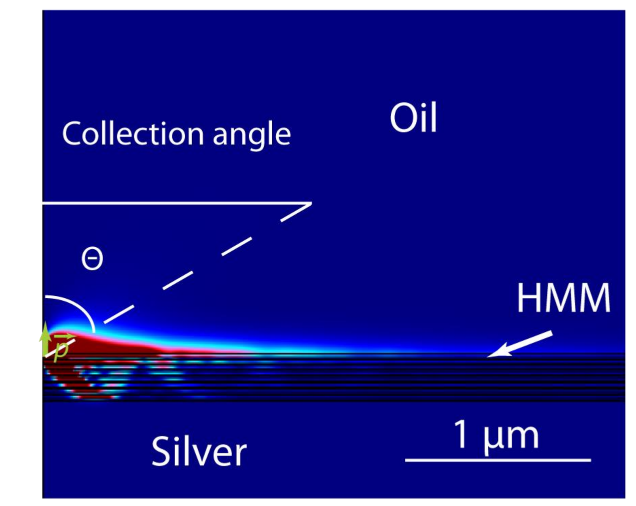


Broadband performance of patterned HMM compared to planar HMM, coverslip and silver.

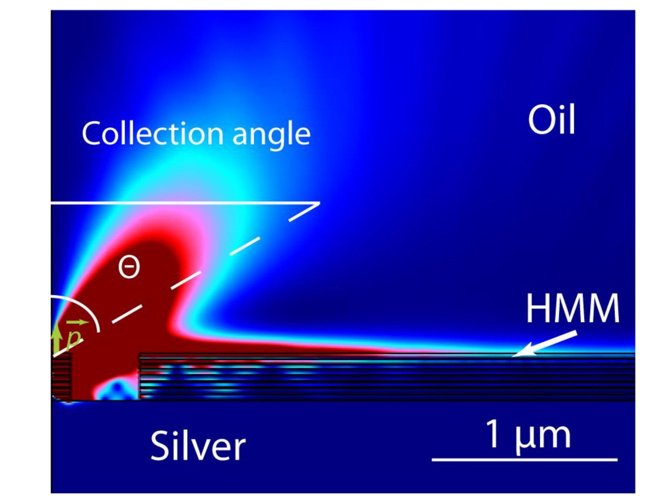
Even though the structure was optimized for the wavelength of 685 nm, it shows a good performance in the broadband range

Results

Power density distribution of vertically oriented dipole for planar and groove patterned HMM



Planar HMM



Patterned HMM

The corners of the structure outcouple the emission power carried by the metamaterial waves into free-space modes.

Emission enhancement compared to other samples

Samples	Total power enhancement	Collection efficiency
Coverslip	4.6	2.0
Ag	1.9	2.5
HMM	1.3	4.7

The designed structure allowed to increase both total radiated and collected power compared to other considered materials.

Conclusion

- Increased collected power by a factor of 6 compared to unpatterned metamaterial
- The structure proposes broadband behavior of emission enhancement at the wavelength range 685±100 nm

Future plans

- Compare the structure performance with other similar patterns
- Experimentally demonstrate structure performance

References

[1] Jacob et al., Appl. Phys. B, 100, 1, (2010);
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