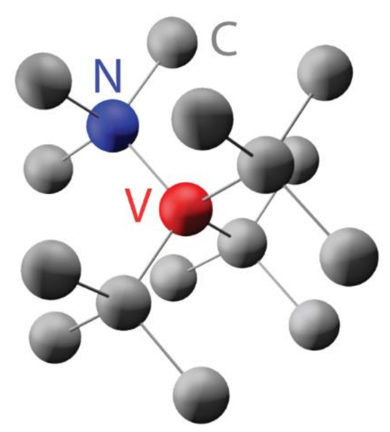
Enhancement of single-photon sources with metamaterials

M. Y. Shalaginov[1], V. V. Vorobyov[2], S. Bogdanov[1], A. S. Lagutchev[1], A. V. Kildishev[1], A. V. Akimov[2], A. Boltasseva[1], and V. M. Shalaev[1]

[1]School of Electrical & Computer Engineering & Birck Nanotechnology Center, Purdue University, West Lafayette, IN, USA; [2]Russian Quantum Center, Moscow, Russia

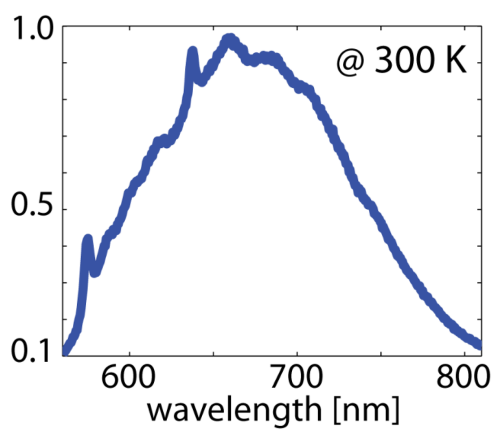
Atom-like centers in diamond



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

single-photon source
- photostable
- operates at room temperature
- broadband emission spectrum

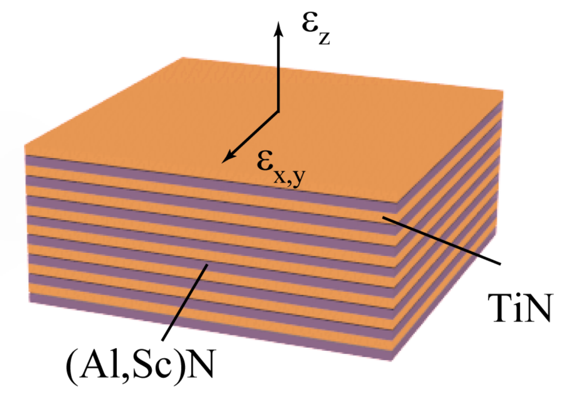
spin-based quantum memory unit
- long spin coherence time (~ms)
- can be read optically out



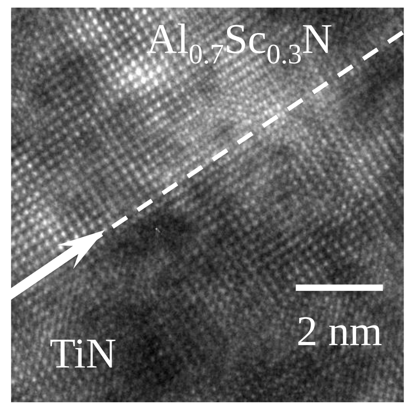
emission spectrum

Efficiency of the NV center as a quantum system can be substantially improved by enhancing its emission properties: rate and directionality.

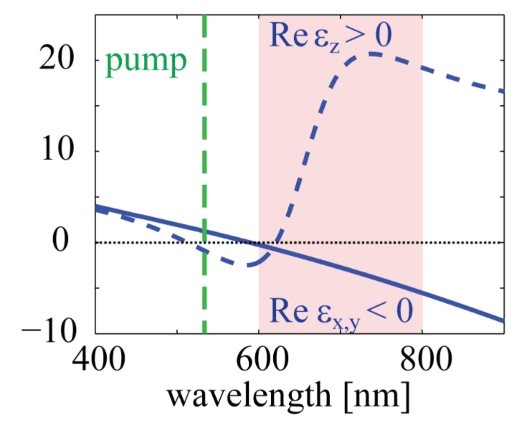
Metamaterial fabrication



multilayer stack: TiN – 8.5 nm, (Al,Sc)N – 6.3 nm; 20 layers



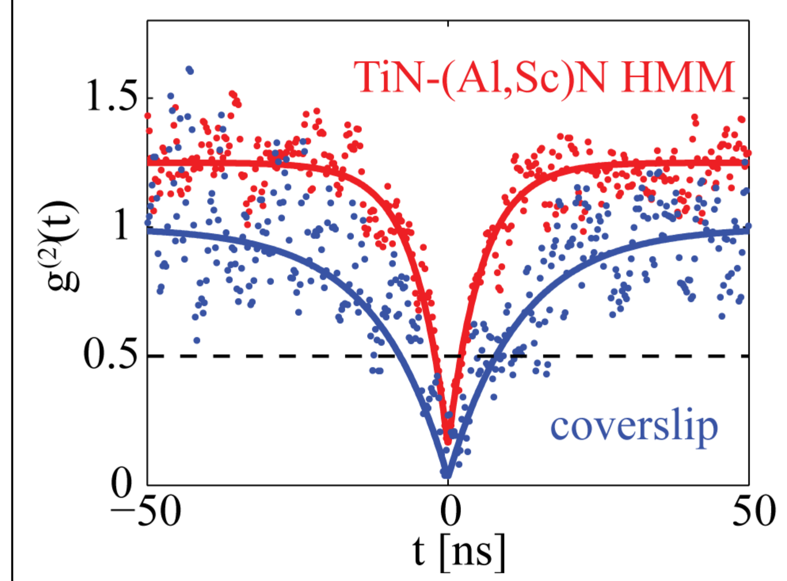
HR-TEM image of superlattice interface [3].



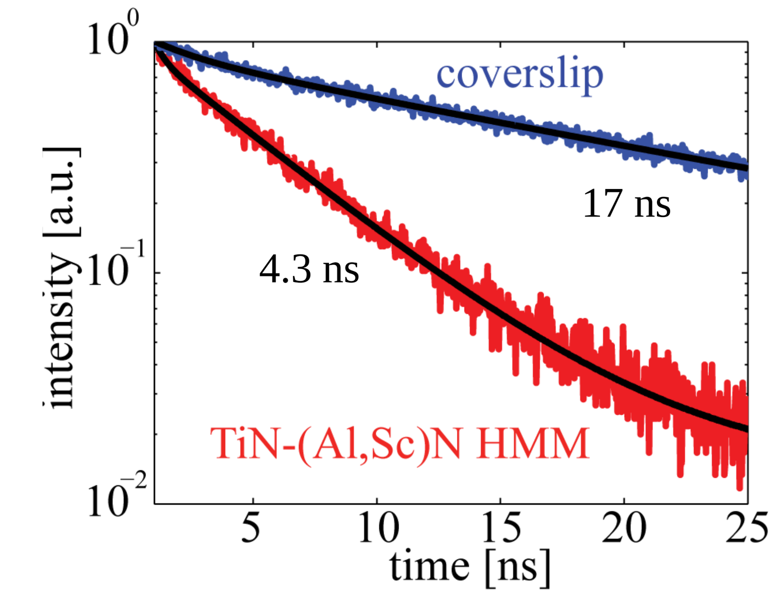
effective permittivites measured by spectroscopic ellipsometry

- possible to grow ultrathin epitaxial layers
- CMOS-compatible
- extreme thermal stability

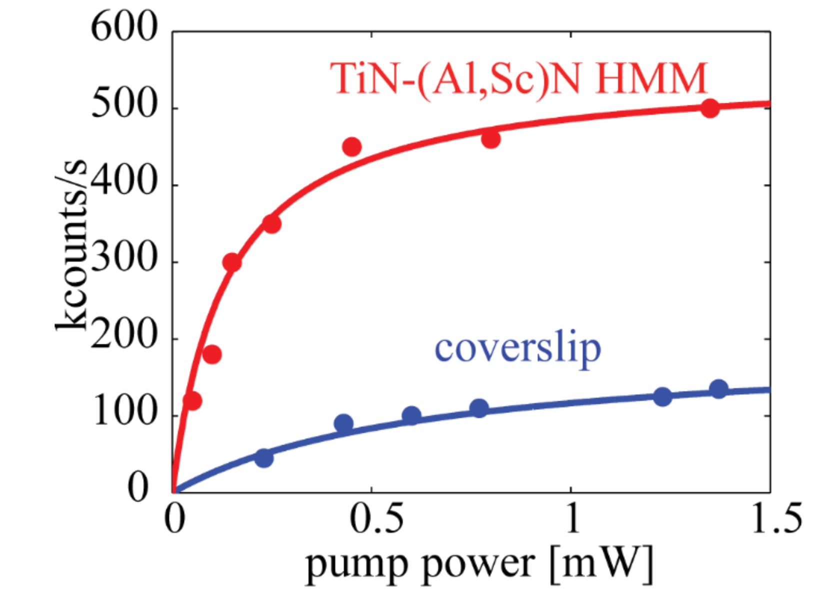
Observation of single-photon emission enhancement



Determined the single-photon nature of the emitters.

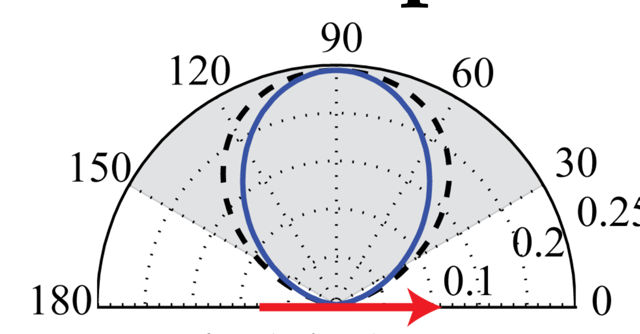


The average and largest decreases in lifetime are 4 and 11.4, respectively.

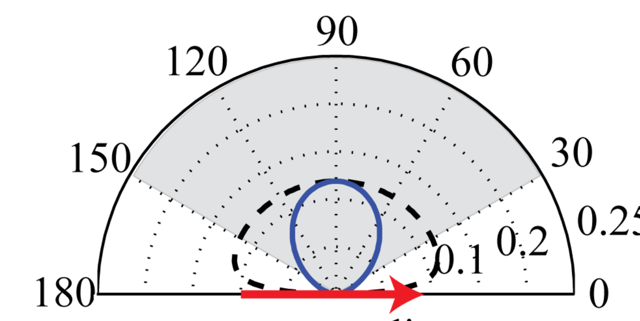


The average enhancements are 1.8 and 4.7.

Improvement in radiation pattern

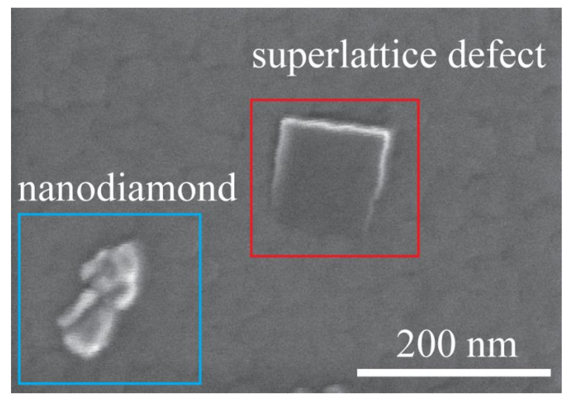


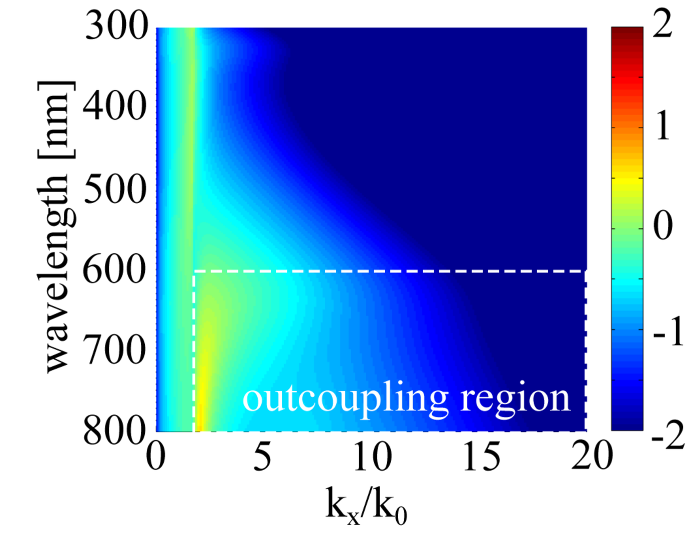
on TiN-(Al,Sc)N HMM



on coverslip

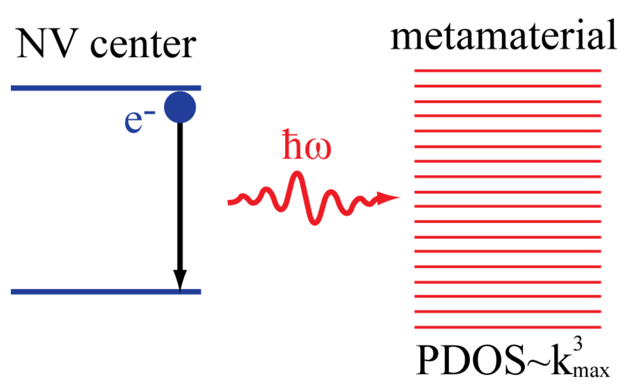
Outcoupling of high-k modes on surface defects





Superlattice defects with the size of ~50 nm can scatter into far-field the high-k modes with $k_x/k_0 \sim 20$. In FEM simulations, we showed that due to these defects on HMM the collected emission can be increased further.

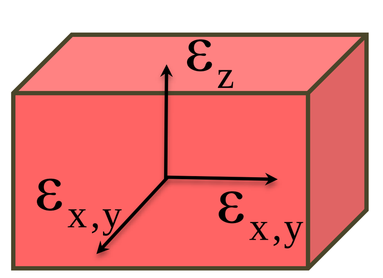
Broadband emission enhancement with hyperbolic metamaterials



Transition probability per unit of time from the state |i⟩ to a set of final states |f⟩ is given by (1st order perturbation)

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H'|i\rangle\right|^2 \times \text{PDOS}$$

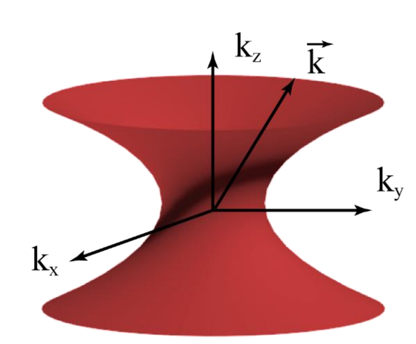
Metamaterials with hyperbolic dispersion (HMM) can provide large photonic density of states (PDOS) in a broad wavelength range [2] and enhance the emission rate.



uniaxial, extremely anisotropic medium

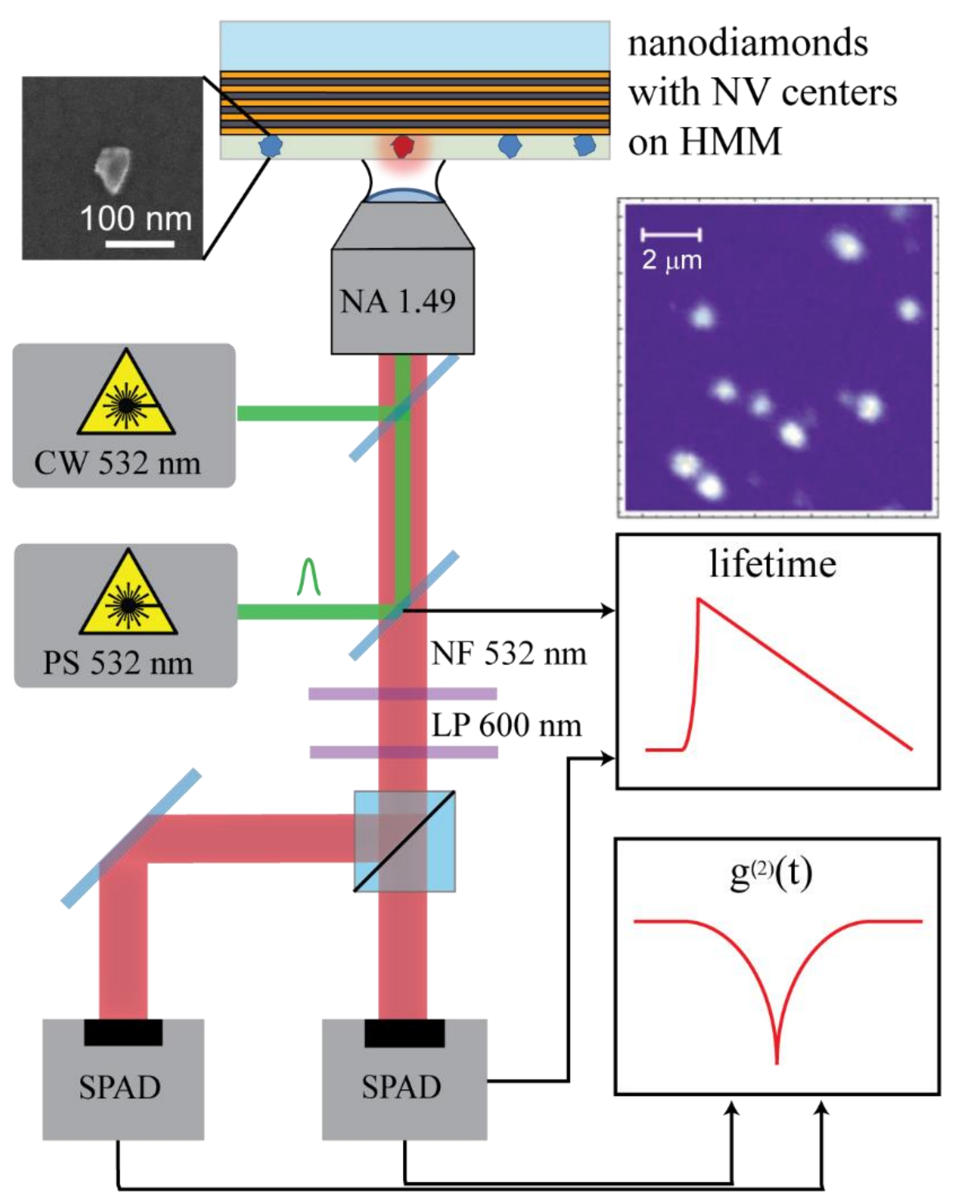
$$\frac{k_z^2}{\varepsilon_{x,y}} + \frac{k_{x,y}^2}{\varepsilon_z} = k_0^2$$

$$\varepsilon_{x,y} < 0,\ \varepsilon_z > 0$$



hyperbolic isofrequency surface

Setup to study emission properties



Conclusions

- Broadband enhancement of single-photon emission from NV centers in nanodiamonds using CMOS-compatible hyperbolic metamaterial;
- Up to 5 times more emission can be collected compared to coverslip substrate due to improved directionality and plasmons outcoupling by growth defects.

References

[1] Doherty et al., Phys. Rep. 528, 1 (2013); [2] Jacob et al., Appl. Phys. B, 100, 1, (2010)
[3] Naik et al., PNAS 111, 21 (2014); [4] Shalaginov et al., LPR 9, 1 (2015)

Acknowledgements

PURDUE UNIVERSITY Discovery Park
BIRCK NANOTECHNOLOGY CENTER