Transition metal dichalcogenide photonic dimer nano-antenna with ultra-small gap

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In the past decade, transition metal dichalcogenides (TMDs) have drawn large scientific interest involving their integration with nano-photonic structures [1, 2]. However, the use of TMDs in these studies was limited to single and few-layer samples coupling to resonances and cavity modes in different material systems. Recently, TMDs have emerged as promising materials for fabrication of nano-photonic resonators due to their large refractive index and low absorption within a large portion of the visible spectrum. Another advantage of this material family is their compatibility with a wide variety of substrates owing to their van-der-Waals attractive forces. Recent reports have demonstrated WS_2 nano-disk Mie resonators where strong light-matter coupling [3] and second harmonic generation (SHG) enhancement [4] were observed. However, further uses for this material family within the nano-photonic field have been in short supply.

In our work we study the nano-photonic capability of TMDs by fabricating single (monomer) and double (dimer) nano-pillar antennas in a circular, square or novel zigzag-terminated hexagonal geometries with potentially atomically sharp edges and vertices. We probe the structures with dark field spectroscopy followed by second harmonic generation experiments, in which we induce polarization-dependent enhancement due to coupling with an anapole mode. In order to achieve ultra-small dimer gaps and rotate the relative orientation of individual nano-pillars, we introduce a post-fabrication atomic force microscopy (AFM) step, achieving gaps limited by our spatial resolution. The smallest dimer gap we measured (10±5 nm shown in middle inset of Fig. 1) confirms that we have reached the fabrication limit of focused ion beam milling, yet we provide a more precise and less damaging method for controlling the photonic properties of these structures.

Simulations of such nano-antennas yield electric field intensity enhancements of more than 10^3 at hotspots surrounding the edges of the fabricated hexagonal geometry. We calculate a Purcell factor as high as 157 for single photon emitters (SPEs) positioned within these hotspots (right image of Fig. 1). A route to the modulation of these values by varying the gap separation and relative rotations of the nano-pillars is also readily available. Optical trapping simulations for such small gaps result in attractive forces of >350 fN for colloidal quantum dots (QDs) (left image of Fig. 1) and > 70 fN for protein-like, polystyrene beads. These results surpass previous reports of dielectric nano-antennas by a factor of >83 for QDs [5] and >40 for PBs [6].

References

[1] Luo, Y. et al. *Nature Nanotechnology*, 13(2018), 1137-1142.

[2] Sortino, L. et al. *Nature Communications*, 10(2018).

[3] Verre, R. et al. *Nature Nanotechnology*, 14(2019), 679-683.

[4] Busschaert, S. et al. *ACS Photonics*, 7(2020), 2482-2488.

[5] Xu, Z. et al. *Optics Express*, 27(2019), 4034-4045.

[6] Xu, Z. et al. *ACS Photonics*, 5(2018), 4993-5001.

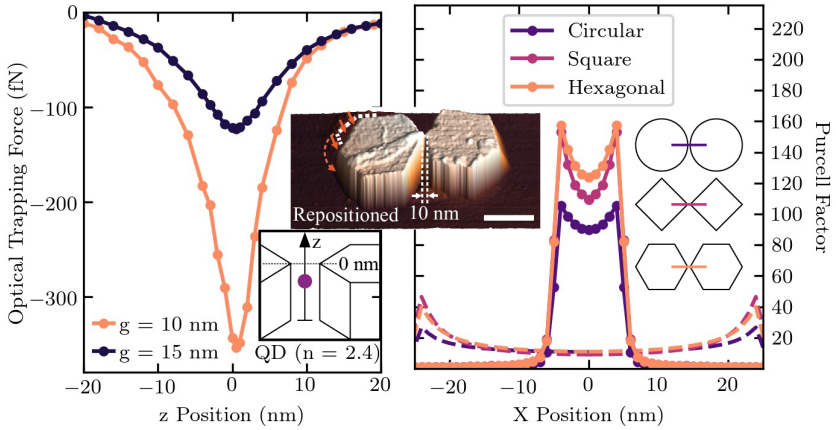

Figure 1: Simulations for a repositioned WS_2 hexagonal dimer nano-antenna. Left plot: Optical trapping force for a 10 nm QD translated across the z-axis in the middle of the dimer gap (g) for 10mW/μm pump intensity. Bottom right inset shows positions of QD. Right plot: Purcell factor for a SPE placed along the dimer axis 0.5 nm above the surface of nano-antennas with different geometries. Solid lines: g = 10 nm. Dashed lines: g = 50 nm. Right inset shows positions of SPE for different geometries. Inset middle: AFM scan of a repositioned WS_2 hexagonal dimer nano-antenna.