Emission control in quasi-bound states in the continuum and monolayer WS_2/Si_3N_4 hybrid metasurfaces

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Abstract: Si_3N_4 slotted disk metasurfaces with a high Q-factor have been designed and fabricated. Experimental measurements show enhanced emission from monolayer WS_2 – metasurface system. A Rabi splitting energy of 33.55 meV is achieved in the simulation.

All-dielectric metasurfaces supporting quasi-bound states in the continuum (q-BICs) provide a pathway to develop a new paradigm for trapping and confining resonant optical modes due to the high-quality factors (Q-factors) of q-BIC resonances. The low loss photonic metasurfaces offer broad spectral tunability and strongly enhanced near-fields for boosting both surface-driven and material-intrinsic processes in the field of nanophotonics [1]. The q-BIC resonance can be obtained by breaking the in-plane symmetry of the structure, and the ultrahigh Q-factor resonance modes in the q-BIC can be readily tuned by the degree of asymmetry [2,3].

In this paper we investigate a slotted disk metasurface design for strong coupling and emission control with monolayer WS_2. A range of q-BIC resonances (from 590 nm to 640 nm) are achieved from the low loss Si_3N_4 disk, where an asymmetric slot (air gap) is inserted in the disk. The asymmetric factor is tuned by changing the width and position of the slot. The slotted disk metasurface with q-BIC resonance in the range of the WS_2 exciton peak has been designed and fabricated. Lumerical finite-difference time-domain (FDTD) simulations of R and T, shown in Fig. 1(a), are used to calculate the absorbance from $A=1-R-T$ and, confirms negligible dissipation losses in the q-BIC mode. The magnetic field circulates (white arrows) inside the slotted disk in the y-z plane (Fig. 1(b)) as expected for the electric dipole (ED) resonance. Placing a PMMA layer on top of the metasurface effectively encloses it in a homogeneous refractive index environment, due to the comparable refractive indices of PMMA and fused silica. This optically homogeneous environment is required for accessing the strong coupling regime with the Si_3N_4 metasurface. The full-width-at-half-maximum (FWHM) of a PMMA/Si_3N_4/fused silica structure is shown in Fig. 1(c) as well as the corresponding Q factor. This structure design provides a Q-factor of 1230 but for different design parameters can yield values greater than 10^5. Simulations results show the slotted disk metasurfaces can be tuned to operate in the strong coupling regime at room temperature in a PMMA/WS_2/Si_3N_4 metasurface/fused silica hybrid system, with a Rabi splitting energy of 33.55 meV as shown in Fig. 1(d).

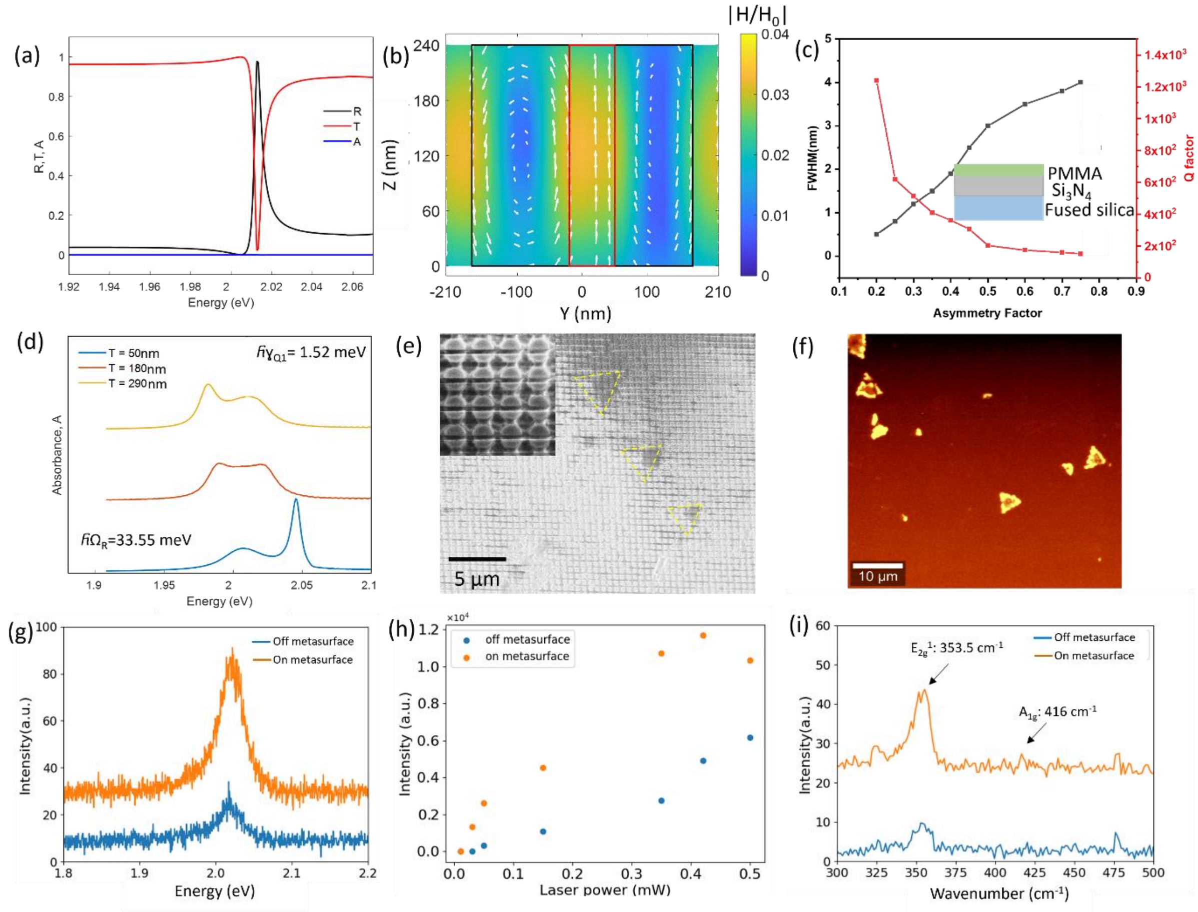

Figure 1. Reflectance R, transmittance T, and absorbance A spectra of the slotted disk q-BIC metasurface on the fused silica in air (a); the relative amplitude of the magnetic field |H/H0| in the y-z plane (b); The full width at half maximum (FWHM) and Q-factor of the PMMA/Si_3N_4/fused silica as a function of the asymmetry factor (c); The absorbance spectra of the hybrid PMMA/WS_2/Si_3N_4 structure are shown as a function of the thickness of the PMMA layer in nm (d); The SEM images of slotted Si_3N_4 disks and monolayer WS_2 (seen as triangles) (e); PL mapping of WS_2 on the metasurface (f); The PL intensity vs. energy of coupled WS_2 (on metasurface) and uncoupled WS_2 (off metasurface) (g); The laser power dependence of the PL emission for the coupled WS_2 (on metasurface) and uncoupled WS_2 (off metasurface) (h); The Raman scattering spectrum of coupled WS_2 (on metasurface and uncoupled WS_2 (off metasurface) (i).

The slotted Si_3N_4 disk metasurface was fabricated using electron beam lithography (EBL) followed by reactive ion etching (RIE). The structures (Si_3N_4/fused silica) shown in Fig. 1(e) have a radius of 170 nm, a height of 120 nm and a periodicity (x, y) of (400 nm, 420 nm), yielding a q-BIC resonance at 603 nm with a FWHM of 3.2 nm in air. The Si_3N_4 metasurface produces enhanced the light-matter interaction with a CVD grown monolayer WS_2, as seen in the PL mapping in the Fig. 1(f)), even in the absence of the top PMMA layer. Significant enhancement of both photoluminescence (PL) in Fig. 1(g) and Raman intensity has been observed for monolayer WS_2 coupled to a Si_3N_4 slotted disk metasurface (Si_3N_4/fused silica) without a top PMMA layer compared to monolayers on the fused silica substrate only. The PL emission from monolayer WS_2 integrated with the slotted disk metasurface exhibits a 2- to 6-fold increase over uncoupled WS_2 under varying excitation power in the Fig. 1(h). Similarly, WS_2 coupling to the q-BIC metasurface is evident through the pronounced enhancement of the Raman scattering intensity (Fig. 1(i)). Additionally, the coupled WS_2 exhibits an increased photoluminescence lifetime. Further results on WS_2/Si_3N_4 slotted disk metasurfaces for emission control will be discussed and presented.

Reference

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