Metasurface Integrated Monolayer Exciton-polariton

Yueyang Chen1†, Shengnan Miao4†, Tianmeng Wang4†, Ding Zhong2, Abhi Saxena1, Colin Chow2, James Whitehead1, Dario Gerace6, Xiaodong Xu2,3, Su-Fei Shi4,5, Arka Majumdar1,2,*

1 Electrical and Computer Engineering, University of Washington, Seattle, WA 98199, USA
2 Department of Physics, University of Washington, Seattle, WA 98199, USA
3 Materials Science and Engineering, University of Washington, Seattle, WA 98199, USA
4 Department of Chemical and Biological Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
5 Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
6 Department of Physics, University of Pavia, Via Bassi 6, I-27100 Pavia, Italy

Abstract: We demonstrate a 2D exciton-polariton system by strongly coupling atomically thin tungsten diselenide monolayer to a silicon nitride metasurface. Our platform opens the door for the future development of exciton-polariton devices by advanced meta-optical engineering.

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Monolayer transition metal dichalcogenides (TMDs) have generated active research interest in recent years due to their strong light-matter interaction and unique optoelectronic properties. The strong excitonic response of the TMDs could be further enhanced by coupling the TMD monolayer to an optical cavity [1]. In the weak coupling regime, low-threshold nano-laser and cavity-enhanced light-emitting diodes have been demonstrated using TMD monolayer. In the strong coupling regime, TMD exciton-polaritons (EPs) have also been observed at room temperature. So far, most TMD-based EP devices are based on distributed Bragg reflector (DBR) cavity. The fabrication process of the DBR-sandwiched TMD platform is non-trivial since the encapsulation of the upper DBR layers often degrades the optical property of the monolayer TMD. Plasmonic cavities have also been explored, but they suffer from intrinsic absorption loss of metals.

In this paper, we demonstrated EPs in atomically thin tungsten diselenide (WSe2) strongly coupled to the guided mode resonances (GMR) in a silicon nitride (SiN) metasurface [2]. By performing energy-momentum spectroscopy on the WSe2-SiN metasurface, we measured the anti-crossing of the polariton dispersion both in the cavity reflection and photoluminescence. The EP dispersion measured in the experiment is also reproduced by our numerical simulation. Moreover, we showed that the Rabi splitting, the polariton dispersion and the far-field emission pattern could be tailored by subwavelength-scale engineering of the meta-atoms. Our platform thus opens the door for the future development of novel EP devices by advanced meta-optical engineering.

Figure 1: SiN metasurface supporting guided mode resonances: (a) The metasurface is made of SiN meta-atoms with holes arranged in a square lattice. (b) Simulated vs Experimentally measured angle-dependent reflection spectrum. (c) The optical microscope image of the SiN metasurface with hBN-capped WSe2 transferred (scale bar: 20 μm) (d) Simulated vs experimentally measured angle-dependent reflection spectrum. Anti-crossing is observed at kx ~ 2.4 μm⁻¹. (e) Fitting for the anti-crossing: a Rabi splitting value of the 18 meV is extracted. (f) PL emission also shows the anti-crossing.

Figure 1a shows the schematic of our platform. The metasurface is made of SiN with square lattice of holes. A WSe2 monolayer could be transferred directly on top for evanescent coupling. We first characterized the SiN metasurface
before the monolayer transfer. The right side of Figure 1b is the energy-momentum spectrum measured in experiment, which matches well with the simulation result shown at the left side. The simulation result is obtained via the rigorous coupled-wave analysis (RCWA) method (S4). There are two GMR modes shown in the spectrum: M1 has a linear dispersion and M2 has a parabolic shape. Two photonic modes come close at \( k_x = 0.6 \text{ \mu m}^{-1} \) and anti-cross due to the coupling between them.

We then transferred a hBN encapsulated WSe\(_2\) monolayer on top of the metasurface (figure 1c). We performed the optical measurement at 22K. As shown in Figure 1d, the GMR dispersion changed dramatically when coupled with WSe\(_2\) at the exciton wavelength (\( \sim 715\text{nm} \)). A clear anti-crossing is observed in the range from \( k_x = 1.5 \text{ \mu m}^{-1} \) to \( k_x = 3 \text{ \mu m}^{-1} \). We fitted the dispersion spectrum with a dispersive coupled-oscillator model to extract the interaction strength and dissipation rate of the system (figure 1e). From the fitting, we extracted \( \gamma_{\text{exc}} = 6.1 \text{ meV}, \gamma_{\text{cav}} = 8.3 \text{ meV} \) and \( g = 9.1 \text{ meV} \) and calculated the Rabi splitting as \( 18.2 \text{ meV} \) [2]. To further confirm the exciton-polariton physics, we have numerically calculated the dressed modes dispersion within a quantum theoretical approach based on guided-mode expansion [3]. We obtained an exciton-photon coupling energy \( g = 11.5 \text{ meV} \), in remarkably good agreement with the values above. Finally, we validated the experimental results by adding a monolayer of WSe\(_2\) on top of the SiN meta-atom in RCWA simulation. As shown in the left panels of Figure 1d and Figure 1f, our simulated reflection and absorption spectra show good agreement with the experimental reflection and PL spectra (right panels of Figure 1d and Figure 1f).

A unique property of our metasurface-based EP is the ability to engineer the Rabi splitting, the polariton dispersion and the far-field emission pattern by exploiting the large number of degrees of freedom offered by the nanopatterned photonic structures. Figure 2a shows the back focal plane image of the spatial distribution of the collected PL signal in experiment: the metasurface diffracts the polariton emission directionally along \( k_x \) and \( k_y \) axis. We also showed that in simulation, by tailoring the lattice period, it is possible to achieve a coherent coupling of the exciton to a ‘W-shaped’ dispersion (the white dash line in Figure 2b), with applications in the future study of momentum-space Josephson effect and micro-optical parametric oscillation. Besides, we showed that the light-matter coupling strength (g) could be tailored by the thickness of the metasurface. An optimal thickness of \( \sim 100\text{nm} \) is obtained via RCWA simulation (Figure 2c).

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