Dispersive coupling between MoSe$_2$ and a zero-dimensional integrated nanocavity

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Abstract: We demonstrate dispersive coupling between the neutral exciton in monolayer MoSe$_2$ and a zero-dimensional, small mode volume nanocavity with an estimated exciton-cavity coupling of $\sim 4.3$ meV and a cooperativity of $C \sim 3.4$. OCIS codes: (140.3945) Microcavities, (240.5420) Polaritons

Atomically thin van der Waals (vdW) materials coupled with nanophotonic structures have recently emerged as a promising platform for hybrid integrated photonics due to their easy integration onto a substrate via vdW forces without concern for lattice matching. In particular, the large excitonic binding energy of transition metal dichalcogenides (TMDs) presents an excellent opportunity to study the quantum light-matter interaction in large-scale photonic systems. The first step towards such a quantum system is to demonstrate a coherent interaction between a small mode volume cavity and TMD excitons. To that end, several research groups have observed exciton-polaritons, the manifestation of a coherent interaction between a TMD excitonic transition and a photonic mode. Most of these polaritonic modes have been shown to arise from the strong coupling between two-dimensional (2D) delocalized excitons and bound photonic modes, either obtained with planar microcavities between distributed Bragg reflector (DBR) mirrors or as guided resonances in planar waveguides. Since these photonic modes are spatially extended in 2D, it would be difficult to realize strong polariton-polariton nonlinearities that are inversely proportional to the confinement area $A$, an important requirement for photonic quantum simulators and strongly correlated photonic devices. While exciton-polaritons in fiber-DBR cavities can be confined to a small mode volume, such structures emit light out-of-plane which precludes a straightforward means to couple neighboring cavities.

We fabricated an on-chip integrated zero-dimensional photonic crystal (PhC) cavity [3] consisting of a 220 nm thick and 779 nm wide silicon nitride film on silicon oxide substrate (Fig. 1(a)) with cross-polarized grating couplers for optimal transmission measurements. The center region of the PhC cavity, where the light is confined, consists of 10 tapering elliptical holes, and 20 Bragg mirror holes to further improve the quality factor of the nanocavity (Fig. 1(b)). The monolayer material was integrated on the nanophotonic device via a high-precision local transfer method [4] to eliminate bulk material (Fig. 1(c) and 1(d)).

Fig. 1: a) Optical image of the monolayer MoSe$_2$ (not visible) integrated onto the PhC cavity (orange box) with the grating couplers for transmission measurements (green - excitation, red - collection). Scale bar is 10 µm. b) Electric field intensity simulated at the center of the SiN nanobeam cavity by 3D-FDTD at the cavity mode resonance frequency, showing wavelength scale field confinement. c) False color SEM image of the monolayer MoSe$_2$ integrated onto the PhC cavity. (MoSe$_2$ - gold, SiN - purple, SiO$_2$ - teal). d) False color SEM image of the monolayer MoSe$_2$ integrated onto the PhC cavity with deposited gold to prevent charging. The obstruction of the PhC cavity holes is made explicit. Red arrows indicate the cavity center.
Fig. 2: a) Representative transmission spectra of the PhC cavity cavity without an integrated flake of monolayer MoSe$_2$ at 100 K to 200 K in 20 K increments. b) Representative transmission spectra of the PhC cavity cavity with an integrated flake of monolayer MoSe$_2$ at 80 K to 200 K in 20 K increments. b) Dispersive shift of the cavity resonance in transmission.

Compared to temperature dependent spectra of the PhC cavity without an integrated monolayer (Fig. 2(a)), we observed a dispersive shift in the cavity transmission spectrum as the exciton is temperature-tuned near the cavity resonance (Fig. 2(b)). The exciton-cavity coupling can be fit to an approximate equation for the shift in cavity resonance as a function of the exciton-cavity detuning [5]. The extracted exciton-cavity coupling is found to be $\bar{h}_g \approx 4.3$ meV for an estimated cooperativity $C = 4g^2/(\kappa_0\gamma_0) \sim 3.4$, in which $\hbar\gamma_0 = 5.77$ meV is the measured intrinsic broadening of the TMD exciton, and $\hbar\kappa_0 = 3.8$ meV is the bare photonic mode linewidth measured without the TMD material. While our experiment probes the coupled system in a dispersive regime, it provides a straightforward path to achieve the strong light-matter coupling regime at 4 K, with an anticipated cooperativity of $C \sim 380$ for this material platform.

References

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