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Strong light-matter coupling in topological metasurfaces integrated with transition metal dichalcogenides

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Abstract. Strong light-matter interactions enable unique nonlinear and quantum phenomena at moderate light intensities. Within the last years, polaritonic metasurfaces emerged as a viable candidate for realization of such regimes. In particular, planar photonic structures integrated with 2D excitonic materials, such as transition metal dichalcogenides (TMD), can support exciton polaritons – half-light half-matter quasiparticles. Here, we explore topological exciton polaritons which are formed in a suitably engineered all-dielectric topological photonic metasurface coupled to TMD monolayers. We experimentally demonstrate the transition of topological charge from photonic to polaritonic bands with the onset of strong coupling regime and confirm the presence of one-way spin-polarized edge topological polaritons. The proposed system constitutes a promising platform for photonic/solid-state interfaces for valleytronics and spintronics.

1. Introduction

Topological photonics has undergone a tremendous growth in the past years as various platforms from microwave to optical spectral ranges were used for implementation of topological phases of light[1,2]. One of the recently emerged research directions in this field is aimed at expanding the concepts of topological photonics towards systems with strong light-matter interaction, which opens the possibilities for creation and control of exotic quasiparticle systems. In particular, integration of topological photonic structures with active media has led to creation of topological lasers[3], topological polaritonic phases[4], and highly nonlinear[5] topological photonic devices.

Topological polaritons, not unlike their non-topological counterparts, represent coupled light-matter excitation that emerge due to strong coupling between electromagnetic and solid-state degrees of freedom. However, they also exhibit a plethora of useful phenomena due to their topological origin. In particular, one-way spin-polarized transport, topological protection against scattering characteristic for topological phases combined with high nonlinearity arising from light-matter hybridization may enable the observation of topological solitons and modulation instability and generation of squeezed topological light[6,7]. Furthermore, topological systems coupled to excitonic TMD materials represent a promising interface between spin- and valley-degrees of freedom due to unique properties of TMD.

So far, topolaritonic systems were mostly limited to 1D systems, or 2D systems characterized by 1D topological invariants. The first topolaritonic system characterized by a 2D topological invariant was demonstrated in the work by S. Klembt et al.[8] in GaAs quantum well lattices for the case of broken time-reversal symmetry induced by magnetic field. Here, we realize topolaritonic spin-Hall phase that does not require magnetic field in a topological metasurface based on planar Si photonic structure strongly coupled to excitons in TMD monolayers. We experimentally demonstrate the transfer of topological charge from photonic to polaritonic mode and one-way propagation of the edge topological polaritons.

2. Results and discussion

The topological structure that we use here is shown in Fig. 1a. It represents a Si photonic metasurface with a honeycomb shrink-expand lattice design that is based on the one proposed for a topological quantum optical interface[9]. We adjusted this design to support leaky topological edge modes near the exciton frequency in $MoSe_2$ (1.65 eV at 7K). These samples were fabricated by patterning Silicon on Insulator (SOI) substrates with the use of e-beam lithography followed by reactive ion etching.

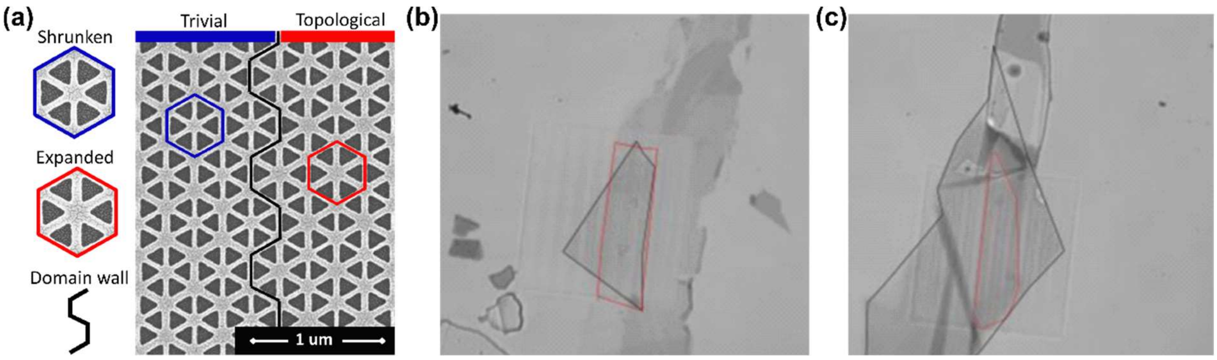

Figure 1. (a) SEM image of the domain wall (black line) between trivial and topological domains of an all-dielectric topological metasurface with hexagonal unit cells. (b,c) Optical images of topolaritonic metasurface with thin hBN layers (black) and $MoSe_2$ monolayer (red) transferred on top of the photonic topological metasurface with multiple domain walls.

To realize the transition to topological polariton regime, we transferred a MoSe2 monolayer on top of the metasurface together with a thin hBN layer. The latter enhanced the quality of the exciton and enabled the fine tuning of the spectral position of the photonic modes with respect to the exciton. Here, we study two samples with slightly different parameters of the metasurface unit cell (Fig. 1b,c) that provide different detuning of the lower topological band edge with respect to $MoSe_2$ exciton.

Leaky character of the metasurface modes allowed us to directly characterize the dispersion of photonic and polaritonic modes of the metasurfaces [10,11] using back focal (Fourier) plane imaging in our custom-built experimental setup. The setup was integrated with a closed-cycle helium cryostat and allows to capture the band diagrams in frequency-momentum space at temperatures down to 7K.

Fig. 2 shows the linearly polarized light reflectivity maps that illustrate the formation of topological polaritons with the onset of strong coupling regime with $MoSe_2$ exciton. We first studied the sample with a 10 nm hBN flake, but without the TMD monolayer. Fig. 2a,c reveal the topological band gap of the photonic lattice (~1.7-1.8 eV), with two gapless edge modes inside the bulk bandgap. These modes correspond to the spin-up and spin-down topological photonic edge states propagating along the domain wall in the opposite directions. The transfer of a $MoSe_2$ monolayer on top of hBN (Fig. 3b,d) leads to the appearance of the exciton in reflectivity maps crossing the lower photonic band of the topological metasurface approximately 0.07 eV below the band edge. These experimental spectra clearly reveal the anti-crossing behavior between the exciton and the photonic bands, manifesting the strong coupling regime and the formation of topological bulk states. Notably, Fig. 3b,d reveals that the edge modes asymptotically approach the newly formed polaritonic bulk band, which is indicative of the polaritonic nature of the edge states.

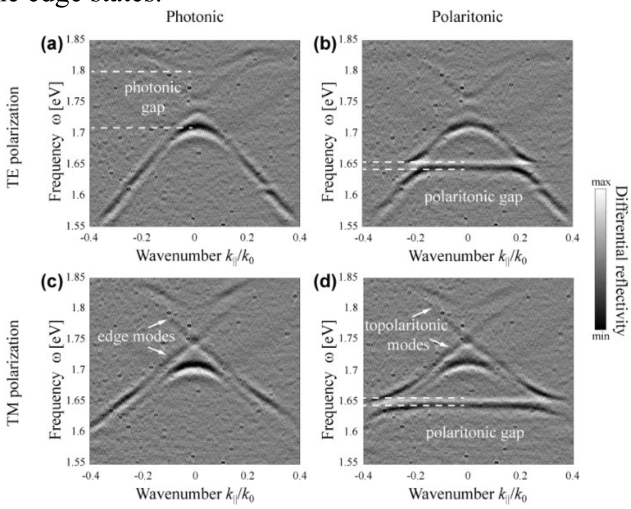

Figure 2. (a,c) Angle-resolved differential reflectivity measured from the vicinity of the domain wall of a metasurface with a 10nm hBN, but without MoSe2 for TE (a) and TM (c) polarized collection. (b,d) TE and TM polarized differential reflectivity maps of the domain wall with a MoSe2 monolayer on top hBN demonstrating strong coupling regime and the respective bulk and edge topolaritonic bands.

One of the most important properties of spin-Hall topological systems is the one-way spin-polarized character of their topological boundary states. While it was observed experimentally in photonic structures, a similar property should also emerge in spin-polarized topolaritonic boundary modes. Therefore, as a next step we measured the back focal plane reflectance spectra with left and right circularly polarized beams focused on the domain wall. The results shown in Figs. 3a,b that one of the edge modes is manifested in the reflectivity maps depending on the helicity of the incident light, which confirm the one-way nature of the edge topological polaritons.

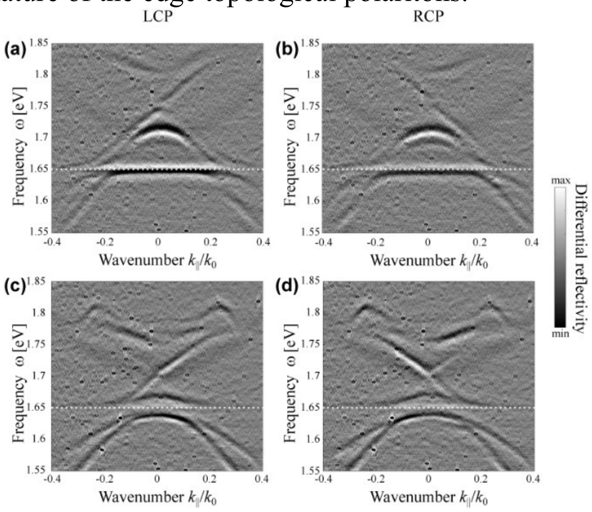

Figure 3. One-way propagation of edge topological polaritons in metasurfaces integrated with MoSe2: with exciton deep inside the photonic bulk mode (top row) and at its edge (bottom row). Differential reflectivity maps are shown for (a,c) left and (b,d) right circularly polarized light excitation.

We also performed the measurements on the second sample, with MoSe2 placed right on top of the metasurface and hBN transferred on top to provide larger overlap of photonic modes with TMD. The metasurface was scaled to ensure that the exciton resonance is aligned with the very edge of the lower energy photonic band at the Γ-point of the photonic Brillouin zone. The measured band diagrams for this sample, shown in Figs. 4c,d, once again reveal the formation of polaritonic bands; however, this sample demonstrates larger Rabi splitting between the polariton branches. Moreover, the topological edge modes in this case asymptotically approach the exciton frequency, which indicates their higher exciton fraction near the edge of the bulk band. As the data in Figs. 4c,d is measured for circularly polarized excitation, it also confirms the one-way propagation of the spin-polarized boundary states, with the forward and backward states that can be excited only with the circularly polarized light of proper helicity. We also note that even though MoSe2, as any other excitonic materials, is inherently absorbing, this absorption does not prevent the formation of the edge topological polaritonic modes and does not have a notable influence on the dispersion of the bulk photonic modes as can be seen in Figs. 2 and 3.

3. Conclusion

To conclude, we showed the formation of topological polaritonic phases with preserved time-reversal symmetry by engineering the strong coupling regime between silicon-based topological photonic metasurface and excitons in monolayers of transition metal dichalcogenides. We demonstrated experimentally the transfer of topological charge from photonic to polaritonic bulk modes and formation of one-way propagating spin-polarized edge topological polaritons. Through the combination of robustness of topological edge states and valley polarization in TMD, such platform holds great potential for future valleytronic and spintronic devices.

Acknowledgments

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