Optical analog of valley Hall effect of 2D excitons in hyperbolic metamaterial: supplement

Sriram Guddala,1 Mandeep Khatoniar,1,2 Nicholas Yama,1 Wenxiao Liu,3,4 Girish S. Agarwal,3 and Vinod M. Menon1,2,∗

1Department of Physics, City College of New York, City University of New York, New York 10031, USA
2Department of Physics, The Graduate Center, City University of New York, New York 10016, USA
3Institute for Quantum Science and Engineering, and Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas 77843, USA
4Current Affiliation: Shaanxi Province Key Laboratory for Quantum Information and Quantum Optoelectronic Devices, and Department of Applied Physics, Xi’an Jiaotong University, Xi’an 710049, China
∗Corresponding author: vmenon@ccny.cuny.edu

This supplement published with The Optical Society on 11 January 2021 by The Authors under the terms of the Creative Commons Attribution 4.0 License in the format provided by the authors and unedited. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

Supplement DOI: https://doi.org/10.6084/m9.figshare.13322987

Parent Article DOI: https://doi.org/10.1364/OPTICA.404063
Effective medium parameters of HMM

A hyperbolic metamaterial (HMM) \(^{1,2}\) was designed with two sheeted hyperbolic iso-frequency dispersion for optical frequency range by using effective medium theory analytical calculations. The thicknesses of Ag and Al\(_2\)O\(_3\) layers were optimized to be 10 nm with 50% filling fraction of metal and dielectric layers. A schematic of the HMM medium is shown in Fig. 1b. The refractive index of Al\(_2\)O\(_3\) is considered as 1.67 from our reflection measurements and refractive index of Ag taken as dispersive from the earlier report of Palik\(^3\). The simulated HMM with these optimized parameters is found to show an entirely anisotropic dielectric permittivity for optical frequency range as shown in Fig. S1(a), namely, the electromagnetic waves with polarization in the plane of the layers experience the permittivity \(\varepsilon_{//} = \varepsilon_x = \varepsilon_y < 0\) and at the same time, the waves with perpendicular polarization are governed by the permittivity, \(\varepsilon_\perp = \varepsilon_z > 0\), called two sheeted hyperbolic metamaterial\(^4,5\). These hyperbolic metamaterials are well known to show large wave-vector modes with TM polarization.

Photoluminescence spectrum of a WS\(_2\) monolayer on the HMM surface was obtained for the wavelength of excitation of 470 nm, as shown in Fig. S1 (black line). The emission spectrum shows exciton resonance at 620 nm and spectrally overlaps with the hyperbolic dispersion region of the HMM in the visible region.
Fig. S1. Dielectric constant of the HMM medium calculated from effective medium theory. The inset shows the respective Type-I (two sheeted) and Type-II (One sheeted) hyperbolic isofrequency dispersion of the spectral regions. Black line is WS$_2$ monolayer emission spectrum with exciton resonance at 620nm.
Optical Characterization:

Optical image of the WS₂ monolayer transferred to the HMM surface. The dotted line bounded area is the WS₂ monolayer used for this study.

White light reflection spectrum of the HMM shows broad band reflection with transmission below the 500 nm. The high reflectivity spectral region from 500 nm to higher wavelengths indicate the hyperbolic dispersion for the 50% filling fraction of metallic Ag and dielectric Al₂O₃.

Fig. S2. a) Optical image of the monolayer WS₂ monolayer transferred on the HMM surface. b) White light reflection spectrum of seven period HMM collected by using 50x magnification microscope objective with 0.8 NA. TMM simulations for a linear dipole at the top surface shows symmetric mode dispersion for both c) seven period HMM and d) one-unit cell HMM samples.
COMSOL simulations for one-unit HMM with chiral dipole emission:

Finite element method based COMSOL simulations were performed for the one-unit cell HMM with chiral dipole assumed in the $xy$ plane. Unidirectional SPP modes propagation in the one-unit HMM similar to the seven period HMM SPP modes can be seen in the below figures. The right ($\sigma^-$) and left ($\sigma^+$) handed circular polarizations show asymmetric intensity distribution similar to the case of seven period HMM, however, it is very obvious that the contrast between $+k_z$ and $-k_z$ directions relatively less in comparison to the seven period HMM in Fig. 2 of the main text.

Fig. S3. 2D Simulation of $H_z$ magnetic field intensity distribution for one period HMM. The phase maps indicate very less asymmetric intensity mode profile for a) left ($\sigma^+$) and b) right ($\sigma^-$) handed circular polarizations.
Helicity resolved measurements of WS$_2$

Schematic of Experimental set up:

Fig. S4(a): Optical analogue of Valley Hall effect in HMM integrated with WS$_2$ monolayer is measured by using back focal plane imaging in the transmission mode.

Fig. S4(b). Bare WS$_2$ monolayer helicity measurements for a) left ($\sigma^+$) and b) right ($\sigma^-$) handed circular polarization excitations.
**Helicity resolved Optical Valley Hall effect measurements**

HMM with monolayer WS$_2$ excited with 620 nm. Full $k$-space images for helicity resolved angles were recorded. (a) and (b) corresponding to $\sigma^-$ excitation, similarly (c) and (d) are for opposite $\sigma^+$ excitation.

![k-space images](image)

Fig. S5. Helicity resolved $k$-space images of the HMM with WS$_2$ monolayer for left ($\sigma^-$) and right ($\sigma^+$) handed circular polarization excitations. For $\sigma^-$ excitation: a) dominant $\sigma^-$ and b) poor $\sigma^+$ emission. Similarly, for $\sigma^+$ excitation: c) poor $\sigma^-$ and d) dominant $\sigma^+$ emission.
One-unit HMM sample, a silver thin film with Al₂O₃ layer capping (one period HMM) and monolayer WS₂ transferred to the surface is excited with 620 nm. Full k-space images for helicity resolved angles were recorded. (a) and (b) corresponding to $\sigma^-$ excitation, similarly (c) and (d) are for opposite $\sigma^+$ excitation.

Fig. S6. Helicity resolved k-space images of the one period HMM with WS₂ monolayer for left ($\sigma^-$) and right ($\sigma^+$) handed circular polarization excitations. For $\sigma^-$ excitation: a) dominant $\sigma^-$ and b) poor $\sigma^+$ emission. Similarly, for $\sigma^+$ excitation: c) poor $\sigma^-$ and d) dominant $\sigma^+$ emission.
Verification of laser scattering to high- $k$ wavevectors:

The samples were excited with 10X objective with 0.25 NA. It is obvious that the laser cannot scatter to the high $k$-wavevectors. However, the excitation laser wavelength of 620 nm leakage to the high-$k$ mode is verified by moving the $k$-space image edge to the slit entrance of the spectrometer (Figure S7). The collected PL does not show any signature of laser peak at 620 nm. This indicates that there is no possibility of incident laser driving the asymmetric mode profile of the high-$k$ modes. The observed effect is strictly dependent on the near field interaction of circular dipole emission to the high $k$-wavevector SPP modes of HMM.

Fig. S7. Left: $k$-space image edge through the entrance slit of the spectrometer. Right: Measured PL intensity.