Directing monolayer tungsten disulfide photoluminescence using a bent-plasmonic nanowire on a mirror cavity

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Abstract Designing directional optical antennas without compromising the field enhancement requires specially designed optical cavities. Herein, we report on the experimental observations of directional photoluminescence emission from a monolayer tungsten disulfide using a bent-plasmonic nanowire on a mirror cavity. The geometry provides field enhancement and directivity to photoluminescence by sandwiching the monolayer between an extended cavity formed by dropcasting bent-silver nanowire on a gold mirror. We image the photoluminescence emission wavevectors using Fourier plane imaging technique. The cavity outcouples the emission in a narrow range of wavevectors with a radial and azimuthal spreading of only $11.0^\circ$ and $25.1^\circ$, respectively. Furthermore, we performed three-dimensional finite difference time domain-based numerical calculations to corroborate and understand the experimental results. We envisage that the results presented here will be readily harnessed for on-chip coupling applications and in designing inelastic optical antennas.

Controlling and manipulating spontaneous emission is a principal indispensable task in nanophotonics [1–4]. The emergence of cavity electrodynamics has provided an excellent framework to study and manipulate spontaneous emission [5–7]. Molecular fluorescence coupled to micro- and nano-cavities has been widely studied from fundamental point of view as well as for application purposes [8–10]. Of late, studying spontaneous emission from emitters confined in plasmonic cavity has gained relevance. Specifically, plasmonic cavities formed using mirror substrates have gained special attention because of ease of preparation and very intense electric field inside the cavity formed between the structure and its image across the mirror substrate [9,11,12].

To this end, various cavities have been utilized for field enhancement by placing nanoparticle [11], nanocube [13], and nanowire [9,14] on mirror. Out of these, nanowires not only provide enhancement but also direct the light from molecules placed between the nanowire and mirror [9,15]. Furthermore, bending the nanowire has shown to enhance the directionality of the secondary emission from molecules placed on the nanowire [16] or in the gap between the nanowire and mirror cavity [17]. The gap between the particle–image particle can be controlled by placing either molecular monolayer or two-dimensional materials of finite thickness [9,11,17].

Recently, two-dimensional transition metal dichalcogenides (TMDs) have emerged as new quantum emitters with high exciton binding energy, which lead to well-pronounced optical transitions [18–21]. The direct bandgap of monolayers of TMDs makes them suitable for switching and optoelectronics devices [19,22]. Well-defined molecular orientation and dipole moment of a monolayer of TMDs make it more suitable candidate to study quantum cavity electrodynamics [23–25]. TMDs show other unique optical properties such as strong spin–orbit interaction, [26,27] valley polarization [28–30], second harmonic generation [31–33], and chiral Raman [34]. Plasmonic and dielectric cavities coupled to TMDs have been utilized for strong coupling [12,35–37], photoluminescence enhancement [38–40], tailoring the emission [13], trion enhancement [41], and chiral routing of Raman [42] and photoluminescence [43]. Motivated by coupling TMDs to mirror based plasmonic cavities, we study a bent-plasmonic nanowire on a mirror cavity with a monolayer of WS\textsubscript{2} placed in the cavity. We show that the cavity can direct the WS\textsubscript{2} photoluminescence (PL) emission to a very narrow range.
of wavevectors when the emission is collected from the kink region, upon excitation of the nanowire end. Using Fourier plane imaging [44–47], we image the PL emission wavevectors, and corroborate and understand the experimental findings using three-dimensional finite difference time domain-based numerical calculations.

Figure 1 shows the schematic of the experiment configuration. A monolayer of WS$_2$ was sandwiched between a gold mirror and a bent-silver nanowire thus confining the monolayer in an extended cavity. One end of the nanowire was excited using a focused laser source of wavelength 532 nm with polarization along the length of the nanowire. Propagating surface plasmon polaritons (SPPs) outcouple from the kink part of the nanowire, exciting the cavity enhanced monolayer photoluminescence (PL) of WS$_2$. The fundamental SPPs along the nanowire and incoming laser source at the nanowire end also excite the cavity-assisted PL emission from the WS$_2$. This PL emission also couples to the nanowire SPPs because of near-field coupling and outcouples from the kink part of the nanowire. The emission from the kink of B-NWoM cavity was collected using spatial filtering and was routed to the spectrometer for spectroscopy or EMCCD for Fourier plane imaging.

A detailed optical setup is shown in Fig. 2a. The sample was excited using a high numerical aperture 100x, 0.95 NA objective lens. The backscattered light was collected using the same lens. The 532 nm laser light was expanded using a set of two lenses L1 and L2. M1 is a mirror to direct the laser into the microscope. The polarization of the incoming laser was controlled by a λ/2 waveplate in the path. BS1 and BS2 are beam splitters to simultaneously excite the sample with laser and its visualization using white light. Lens L3 was used to loosely focus white light on the sample plane. A set of two edge filters and one notch filter were used to reject the elastically scattered light for PL spectroscopy and Fourier plane imaging. Lens L4 was used to recreate the real image for spatial filtering. Lens L5 was used to image the Fourier plane on the camera or CCD, whereas lens L7 was used to switch from real to Fourier plane. Mirror M2 and Lens L6 were used to route light towards the spectrometer and to focus the light onto the spectrometer, respectively.

Figure 2b shows the optical characterization of the monolayer WS$_2$. Monolayer WS$_2$ was grown using atmospheric pressure chemical vapor deposition at 300 nm SiO$_2$-coated silicon wafer following the procedures given in references [48,49]. Gold mirror was prepared by depositing 160 nm gold on a glass cover slip using thermal vapor deposition. Monolayer WS$_2$ was then transferred to the gold mirror by wet transfer method using polystyrene support film [50]. After the transfer, WS$_2$ layers were characterized by PL and Raman spectroscopy. Figure 2b shows the optical characterization of the monolayer WS$_2$. High PL intensity confirms that the sample probed was a monolayer. In the Raman spectrum, the intensity of the E$_{1g}^1$ is much higher than A$_{1g}$ and the peaks E$_{2g}^1$ and A$_{1g}$ are positioned at 351 cm$^{-1}$ and 417 cm$^{-1}$, respectively, which matches with the reported Raman spectra for monolayer WS$_2$ [51,52].

Silver nanowires (AgNWs) of average diameter 350 nm were synthesized using polyol process [53]. The nanowires were sonicated for 30 s to bend the nanowires [54]. Post-bending the AgNWs were dropcasted on the WS$_2$ transferred gold mirror. This leads to the placement of the monolayer WS$_2$ in the cavity formed between the bent nanowire and mirror (B-NWoM cavity). The optical images of the monolayer WS$_2$ placed in

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**Fig. 1** Schematic representation of the experimental configuration. A monolayer of WS$_2$ is grown and transferred onto the top of a gold mirror. A bent-silver nanowire was dropcasted on a gold mirror, thus forming a bent nanowire on a mirror (B-NWoM) cavity with the monolayer inside the cavity. One end of the nanowire was excited using a high numerical aperture objective lens, and the emission from the kink region was spatially filtered for spectroscopy and Fourier plane imaging. The emission from the kink is directional in nature and covers a very narrow range of angles.
Fig. 2 Optical imaging and PL spectroscopy. a Schematic of the experimental setup used to probe the Fourier plane imaging of WS$_2$ PL from B-NWoM cavity. b Raman spectroscopy of the WS$_2$ layer confirming the monolayer. c Optical imaging of B-NWoM cavity. (i) Bright-field image of a ~350 nm-thick bent nanowire placed on a gold mirror of thickness 160 nm with a monolayer of WS$_2$ inside the gap. (ii) Elastic scattering image of the same bent nanowire when one end of the nanowire was excited with a 532 nm laser. d WS$_2$ PL spectrum collected from the kink part [shown as white circle in Fig. 2c(ii)] of the bent nanowire upon excitation of one end of the bent nanowire (black curve), and spectrum collected only from the WS$_2$ monolayer placed on the gold mirror (blue curve).

the B-NWoM cavity are shown in Fig. 2c. The bright-field image shows a bent-silver nanowire of thickness approximately 350 nm placed on a gold mirror. One end of the nanowire was excited using a focused laser source of wavelength 532 nm with polarization along the length of the nanowire to efficiently excite the propagating nanowire SPPs [55]. The light outcoupled from the kink portion of the nanowire was spatially filtered for spectroscopy and Fourier plane imaging. Spectral signature collected from only the kink portion of the B-NWoM cavity shows a modulated spectrum as compared to the spectrum collected from the WS$_2$ monolayer placed only on the gold mirror (Fig. 2d). This modulation can be attributed to exciton-to-trion conversion caused by coupling of surface plasmon polaritons [15,41].

Figure 3a shows the schematic to visualize the directionality of the emission. The emission from the sample plane was collected using the objective lens, which forms the Fourier plane at its back aperture. To image the Fourier plane, it was recreated onto the camera, using a combination of tube lens and Bertrand lens. Pin hole in the path was placed to selectively collect the emission from the kink part of the B-NWoM cavity using spatial filtering.

Figure 3b shows the schematic to understand the projection of the emission direction from the sample plane to the Fourier plane. Every point on the hemisphere represents a direction, and can be written in terms of radial and azimuthal angles $\theta$ and $\phi$. The bent nanowire, placed in the $x-y$ plane, emits the light in direction $\theta_{em}$ and $\phi_{em}$ as shown by red arrows. Fourier plane is the two-dimensional projection of the emission in radial ($\theta$) and azimuthal angles ($\phi$). The directionality of the emission can be quantified from the spread in $\theta_{em}$ and $\phi_{em}$. Black curve shows the maximum angle ($\theta_{NA}$) corresponding to the numerical aperture of the objective lens.

To study the angular distribution of WS$_2$ PL emission spectrum from the kink portion of B-NWoM cavity, we performed Fourier plane imaging on the WS$_2$ PL emission. Figure 4a shows the Fourier plane image of the PL emission collected from the kink portion of the B-NWoM cavity using spatial filtering technique. The emission is confined to a narrow range of wavevectors and is directed towards the higher $k_x/k_0$ and $k_y/k_0$. On the other hand, the Fourier plane imaging performed on the PL emission from the distal end of the nanowire without the bending shows that the emission is directed towards higher angles and the majority of the emission is along the nanowire length (Fig. 4b). For comparison, the Fourier plane image of off-cavity emission from only the monolayer WS$_2$ on a gold mirror is shown in Fig. 4c. The emission is isotropic in nature and covers a large
**Fig. 3** Schematics to visualize the Fourier plane imaging.  
(a) Experimental configuration to image the Fourier plane using objective lens. 4f Configuration was used to reimagine the Fourier plane from the back aperture of the objective lens to the camera.  
(b) The emission direction from the sample plane is marked as a point on the hemisphere. θ and φ are the radials and azimuthal coordinates in the Fourier plane.  
Schematic showing the direction emission in real plane (red curve) and Fourier plane is the two-dimensional projection of the emission. Black curve shows the maximum angle corresponding to the numerical aperture of the objective lens.

**Fig. 4** Fourier plane imaging of WS$_2$ PL emission.  
(a) Fourier plane image of PL emission from the kink portion of B-NWoM cavity upon excitation of one end of nanowire after rejecting elastic scattering light.  
(b) Fourier plane image of PL emission from the distal end of a nanowire placed on a mirror cavity (NWoM cavity) upon excitation of one end of nanowire after rejecting elastic scattering light.  
(c) Fourier plane imaging of WS$_2$ PL emission from a monolayer of WS$_2$ placed on a mirror.  
(d) Intensity cross-cuts along the red dotted line in (a), blue dotted line in (b), and black dotted line in (c).  
(e) Intensity profile of azimuthal angles (φ) for θ corresponding to maximum intensity in the Fourier plane images (a–c).
Fig. 5 FDTD-based numerical calculations to understand the directional PL emission from the B-NWoM cavity. 

- Component-wise magnitude of near-field electric field in the B-NWoM cavity upon excitation of one end of nanowire with a focused Gaussian laser source of 532 nm. Calculated Fourier plane images of the emission from the kink portion of B-NWoM cavity, upon excitation of nanowire end by a dipole oscillating along x axis (d), y axis (e), z axis (f), and an incoherent sum of emission from all three dipoles (g). The dipoles are oscillating at a wavelength of 620 nm, which is near the maxima of monolayer WS\(_2\) PL range of angles. The intensity cross-cuts along the red, blue, and black dashed lines in Fig. 4a–c are shown in Fig. 4d. The emission in the case of B-NWoM is very narrow in radial angles with a full width at half maxima of 11.0°. The intensity profiles of azimuthal angles (\(\phi\)) for \(\theta\) corresponding to maximum intensity in the Fourier plane images Fig. 4a–c are shown in Fig. 4e. Along with the confinement in radial angles, the emission is also confined in terms of azimuthal angles in the case of B-NWoM cavity with a full width at half maxima of 25.1° and 31.7°, respectively. Because of the finite reflection from the nanowire end the emission is also directed towards the \(-k_y/k_0\) direction which decreases the forward to backward ratio of emission [55] (Fig. 4d). On the other hand, the kink portion of the bent nanowire does not reflect the emission in the backward direction and outcouples the maximum of the mission in one direction only. This makes the B-NWoM cavity an excellent geometry for directing TMDs emission to a narrow range of angles.

To corroborate and understand the experimental results, we performed finite difference time domain-based numerical calculations in Lumerical Software. The bent nanowire was modelled by combining two cylindrical silver rods of length 6 \(\mu\)m. The radius of the cylinder was 125 nm, and to make the kink portion, the radius was made to be 110 nm. The thickness of the gold mirror was set to be 100 nm. A 5 nm gap is set between the mirror and nanowire to account for the molecular monolayer thickness and the PVP coating on the nanowire [56]. Figure 5a–c shows the component-wise near-field electric field in the cavity upon illumination of one end of the nanowire using a high numerical aperture objective lens. The polarization of the incoming laser was set along the x axis, which is along the length of the nanowire for efficient excitation of the propagating nanowire SPPs. The \(E_z\) field is much more enhanced in the cavity as compared to the \(E_x\) and \(E_y\) field. The large electric field present in the gap enhances the emission from the WS\(_2\) monolayer. To see how the molecular orientation affects the far-field emission wavevectors, we excited the cavity by placing dipoles oscillating in different orientations at a wavelength of 620 nm at one of the ends of the bent nanowire. A two-dimensional monitor was placed near the kink part of the B-NWoM cavity and the near-field was projected to the far-field using the in-built feature in Lumerical software. Figure 5d–f shows the Fourier plane images when the nanowire end was excited by dipoles oscillating along the \(z\), \(y\), and \(x\) axis, respectively. Figure 5g shows the Fourier plane image of the incoherent addition of the emission from the \(x\), \(y\), and \(z\) oriented dipoles. In all the four cases, the emission is directional in nature and the result matches well with the experimentally obtained Fourier plane image. This suggests that both in-plane and out-of-plane exciton emission outcouple from the cavity in the same manner which makes it difficult to distinguish their individual contribution.
To conclude we show how a bent-silver nanowire placed on a gold mirror can direct monolayer WS$_2$ PL which is otherwise isotropic in nature. The emission is confined to a narrow range of angles with a full width at half maxima in radial and azimuthal angles of 11.0$^\circ$ and 25.1$^\circ$, respectively. Furthermore, using finite difference time domain-based numerical calculations, we understood the effect of dipole orientation on the radiation pattern of PL emission. We believe that the results presented here will be extrapolated to direct enhanced Raman signal from TMDs and to design on-chip directional optical sources using various other class of TMDs.

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References

1. L. Novotny, N. van Hulst, Antennas for light. Nat. Photon. 5, 83–90 (2011)
2. D. Wang, W. Zhu, M.D. Best, J.P. Camden, K.B. Crozier, Directional Raman scattering from single molecules in the feed gaps of optical antennas. Nano Lett. 13, 2194–2198 (2013)
3. D. Vercruysse, Y. Sonnefraud, N. Verellen, F.B. Fuchs, G. Di Martino, L. Lagae, V.V. Moshchalkov, S.A. Maier, P. Van Dorpe, Unidirectional side scattering of light by a single-element nanoantenna. Nano Lett. 13, 3843–3849 (2013)
4. S. Khatua, P.M.R. Paulo, H. Yuan, A. Gupta, P. Zijlstra, M. Orrit, Resonant plasmonic enhancement of single-molecule fluorescence by individual gold nanorods. ACS Nano 8, 4440–4449 (2014)
5. M. Kowalewski, S. Mukamel, Manipulating molecules with quantum light. Proc. Natl. Acad. Sci. 114, 3278–3280 (2017)
6. E.M. Purcell, Spontaneous Emission Probabilities at Radio Frequencies (Springer, In Confined Electrons and Photons, 1995), pp. 839–839
7. J.A. Hutchison, T. Schwartz, C. Genet, E. Devaux, T.W. Ebbesen, Modifying chemical landscapes by coupling to vacuum fields. Angew. Chem. Int. Ed. 51, 1592–1596 (2012)
8. O.S. Ojambati, R. Chikkaraddy, W.D. Deacon, M. Horton, D. Kos, V.A. Turek, U.F. Keyser, J.J. Baumberg, Quantum electrodynamicst at room temperature coupling a single vibrating molecule with a plasmonic nanocavity. Nat. Commun. 10, 1049 (2019)
9. A.B. Vasista, H. Jog, T. Heilpern, M.E. Sykes, S. Tiwari, D.K. Sharma, S.K. Chaubey, G.P. Wiederrecht, S.K. Gray, G.V.P. Kumar, Differential wavevector distribution of surface-enhanced Raman scattering and fluorescence in a film-coupled plasmonic nanowire cavity. Nano Lett. 18, 650–655 (2018)
10. D. Byrne, C. McDonagh, In situ generation of plasmonic cavities for high sensitivity fluorophore and biomolecule detection. Nanoscale 10, 18555–18564 (2018)
11. R. Chikkaraddy, B. de Nijs, F. Benz, S.J. Barrow, O.A. Scherman, E. Rosta, A. Demetriadou, P. Fox, O. Hess, J.J. Baumberg, Single-molecule strong coupling at room temperature in plasmonic nanocavities. Nature 535, 127–130 (2016)
12. M.-E. Kleemann et al., Strong-coupling of WSe2 in ultra-compact plasmonic nanocavities at room temperature. Nat. Commun. 8, 1296 (2017)
13. J. Huang, G.M. Akselrod, T. Ming, J. Kong, M.H. Mikkelson, Tailored emission spectrum of 2D semiconductors using plasmonic nanocavities. ACS Photon. 5, 552–558 (2018)
14. K.J. Russell, T.-L. Liu, S. Cui, E.L. Hu, Large spontaneous emission enhancement in plasmonic nanocavities. Nat. Photon. 6, 459–462 (2012)
15. S.K. Chaubey, G.M. A. D. Paul, S. Tiwari, A. Rahman, G.V.P. Kumar, Directional emission from tungsten disulfide monolayer coupled to plasmonic nanowire-on-mirror cavity. Adv. Photon. Res. 2, 2100002 (2021)
16. Y. Wang, C. Li, G. Duan, L. Wang, L. Yu, Directional modulation of fluorescence by nanowire-based optical traveling wave antennas. Adv. Opt. Mater. 7, 1801362 (2019)
17. S. Tiwari, A.B. Vasista, D. Paul, S.K. Chaubey, G.V.P. Kumar, Beaming elastic and SERS emission from bent-plasmonic nanowire on a mirror cavity. J. Phys. Chem. Lett. 12, 6589–6595 (2021)
18. K.F. Mak, C. Lee, J. Hone, J. Shan, T.F. Heinz, Atomically thin MoS$_2$: a new direct-gap semiconductor. Phys. Rev. Lett. 105, 136805 (2010)
19. K. He, N. Kumar, L. Zhao, Z. Wang, K.F. Mak, H. Zhao, J. Shan, Tightly bound excitons in monolayer WSe$_2$. Phys. Rev. Lett. 113, 026803 (2014)
20. A. Splendiani, L. Sun, Y. Zhang, T. Li, J. Kim, C.-Y. Chim, G. Galli, F. Wang, Emerging photoluminescence in monolayer MoS$_2$. Nano Lett. 10, 1271–1275 (2010)
21. Q.H. Wang, K. Kalantar-Zadeh, A. Kis, J.N. Coleman, M.S. Strano, Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. Nat. Nanotechnol. 7, 699–712 (2012)
22. K. Roy, M. Padmanabhan, S. Goswami, T.P. Sai, G. Ramalingam, S. Raghavan, A. Ghosh, Graphene-MoS$_2$ hybrid structures for multifunctional photoreponsive memory devices. Nat. Nanotechnol. 8, 826–830 (2013)
23. J.A. Schuller, S. Karaveli, T.-L. Liu, J. Hone, R. Zia, Orientation of luminescent excitons in layered nanomaterials. Nat. Nanotechnol. 8, 271–276 (2013)
24. X.-X. Zhang et al., Magnetic brightening and control of dark excitons in monolayer WSe$_2$. Nat. Nanotechnol. 12, 883–888 (2017)
25. G. Wang et al., In-plane propagation of light in transition metal dichalcogenide monolayers: optical selection rules. Phys. Rev. Lett. 119, 047401 (2017)
26. Z.Y. Zhu, Y.C. Cheng, U. Schwingenschl¨ ogl, Giant spin-orbit-induced spin splitting in two-dimensional transition-metal dichalcogenide semiconductors. Phys. Rev. B 84, 153402 (2011)
27. B.T. Zhou, K. Taguchi, Y. Kawaguchi, Y. Tanaka, K.T. Law, Spin-orbit coupling induced valley hall effects in transition-metal dichalcogenides. Commun. Phys. 2, 26 (2019)
28. K.F. Mak, K. He, J. Shan, T.F. Heinz, Control of valley polarization in monolayer MoS2 by optical helicity. Nat. Nanotechnol. 7, 494–498 (2012)
29. H. Zeng, J. Dai, W. Yao, D. Xiao, X. Cui, Valley polarization in MoS2 monolayers by optical pumping. Nat. Nanotechnol. 7, 490–493 (2012)
30. D. Xiao, G.-B. Liu, W. Feng, X. Xu, W. Yao, Coupled spin and valley physics in monolayers of MoS2 and other group-Vi dichalcogenides. Phys. Rev. Lett. 108, 196802 (2012)
31. W.-T. Hsu, Z.-A. Zhao, L.-J. Li, C.-H. Chen, M.-H. Chiu, P.-S. Chang, Y.-C. Chou, W.-H. Chang, Second harmonic generation from artificially stacked transition metal dichalcogenide twisted bilayers. ACS Nano 8, 2951–2958 (2014)
32. L.M. Malard, T.V. Alencar, A.P.M. Barboza, K.F. Mak, A.M. De Paula, Observation of intense second harmonic generation from MoS2 atomic crystals. Phys. Rev. B 87, 201401 (2013)
33. Y. Li, Y. Rao, K.F. Mak, Y. You, S. Wang, C.R. Dean, T.F. Heinz, Probing symmetry properties of few-layer MoS2 and H-Bn by optical second-harmonic generation. Nano Lett. 13, 3329–3333 (2013)
34. S.-Y. Chen, C. Zheng, M.S. Fuhrer, J. Yan, Helicity-resolved Raman scattering of MoS2, MoSe2, WS2, and WSe2 atomic layers. Nano Lett. 15, 2526–2532 (2015)
35. M. Stührenberg, B. Munkhbat, D.G. Baranov, J. Cuadra, A.B. Yankovich, T.J. Antosiewicz, E. Olsson, T. Shegai, Strong light-matter coupling between plasmons in individual gold bi-pyramids and excitons in mono- and multilayer WSe2. Nano Lett. 18, 5938–5945 (2018)
36. B. Chakraborty, J. Gu, Z. Sun, M. Khatomiar, R. Bushati, A.L. Boehmeke, R. Koots, V.M. Menon, Control of strong light-matter interaction in monolayer WS2 through electric field gating. Nano Lett. 18, 6455–6460 (2018)
37. B. Munkhbat, A. Canales, B. Küçüköz, D.G. Baranov, T.O. Shegai, Tunable self-assembled Casimir microcavities and polaritons. Nature 597, 214–219 (2021)
38. S. Butun, S. Tongay, K. Aydin, Enhanced light emission from large-area monolayer MoS2 using plasmonic nanodisc arrays. Nano Lett. 15, 2700–2704 (2015)
39. H.S. Lee, M.S. Kim, Y. Jin, G.H. Han, Y.H. Lee, J. Kim, Selective amplification of the primary exciton in a MoS2 monolayer. Phys. Rev. Lett. 115, 226801 (2015)
40. A.D. Johnson, F. Cheng, Y. Tsai, C.-K. Shih, Giant enhancement of defect-bound exciton luminescence and suppression of band-edge luminescence in monolayer WSe2-Ag plasmonic hybrid structures. Nano Lett. 17, 4317–4322 (2017)
41. J. Shi et al., Enhanced trion emission and carrier dynamics in monolayer WS2 coupled with plasmonic nanocavity. Adv. Opt. Mater. 8, 2001147 (2020)
42. Q. Guo, T. Fu, J. Tang, D. Pan, S. Zhang, H. Xu, Routing a chiral Raman signal based on spin-orbit interaction of light. Phys. Rev. Lett. 123, 183903 (2019)
43. S.-H. Gong, F. Alpeggiani, B. Sciacca, E.C. Garnett, L. Kuipers, Nanoscale chiral valley-phonon interface through optical spin-orbit coupling. Science 359, 443–447 (2018)
