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Valley-controlled directional coupling to plasmonic nanowire modes

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Abstract: The chiral interaction between transverse optical spin and circularly polarized emitters provides a novel way to manipulate spin information at the nanoscale. Here, we demonstrate the valley(spin)-dependent directional emission of transition metal chalcogenides (TMDs) into plasmonic eigenstates of a silver nanowire. Due to the spin-path locking of the plasmonic eigenstates, the emission from the two different valleys of TMDs material will couple to the guided modes propagating in opposite directions. The high valley polarization of TMDs and high density of the transverse optical spin of the plasmonic wire together offer a novel platform for a chiral network even at room temperature without any magnetic fields.

OCIS codes: (350.4238) Nanophotonics and photonic crystals; (130.5990) Integrated optics; (230,5440); Polarization selective devices

In the non-paraxial regime of light, spin and angular momentum cannot be separated but are coupled, the so-called spin-orbit interaction of light [*1*]. This realization has sparked a tremendous activity in the optics community in the last couple of years. One novel consequence of this spin-orbit interaction of light is spin-controlled directional coupling of light. Evanescent fields or highly confined optical modes in photonic structures, e.g., semiconductor and metal nanowires or photonic crystal waveguides, have a non-negligible longitudinal component of electric field. As a result, they are able to exhibit extraordinary transverse spin angular momentum. This unique property provides potential for unique applications, e.g. a chiral-spin entangled quantum network or a single photon optical diode [*2*].

Meanwhile, 2-dimensional atomically thin transition metal dichalcogenides (TMDs) have been attracting enormous attention in the wide fields of research. In particular, TMDs materials are promising optoelectronic materials due to their outstanding optical properties. They have direct bandgaps consisting of two (energy-degenerate) valleys at the corners of the Brillouin zone (K, K'), which provide an opportunity to manipulate the additional degree of freedom, i.e., the valley degree of freedom. Due to the optical selection rule, i.e., angular momentum conservation, we can control the valley polarization (as well as spin) of TMDs materials using optical pumping with a circular polarized light [*3*]. These unique properties make TMDs materials an intriguing platform for valley and spin physics studies, such as valley-Hall effect, valley-selective circular dichroism, valley magnetic moment [*4*].

Here, we demonstrate a new way to control the valley information through local manipulation of light fields at the nanoscale. We utilized a silver nanowire to provide strong transverse optical spin momentum to TMDs materials. In plasmonic modes of the silver nanowire, there is an one-to-one relation between the sign of the local optical spin and the propagation direction of the mode. Thus, if the handedness of the local optical spin and the one associated with the transition dipole of a valley are the same, the light is emitted in one direction, if they're opposite, the emission is in the other direction. As a result, a direct coupling was achieved between valley pseudospins and optical pathways [5] as illustrated in Fig. 1a.

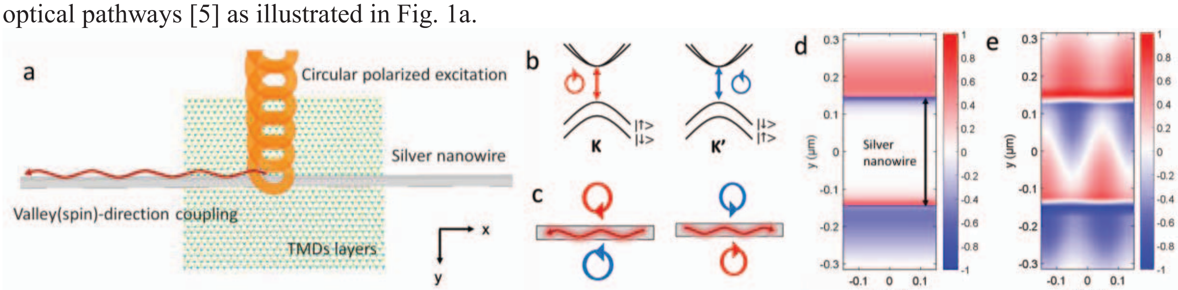

Fig. 1. (a) An illustration of a valley-path locking system. (b) Valley-dependent optical selection rule of TMDs. (c) The handedness of the transverse optical spin depending on the propagation direction. (d) The density of the transverse optical spin near an infinite silver nanowire. (e) The calculated directionality of circular dipole near an finite silver nanowire.

In order to understand the optical transverse spin momentum near a silver nanowire, we conducted numerical modeling using a finite difference eigenmode (FDE) solver. The silver nanowire have a plasmonic guided mode which consist of strong evanescence fields near the interface between the silver nanowire and the glass substrate on which the TMDs layers are placed. The strong transverse confinement of the plasmonic modes leads to the transverse optical spin angular momentum. The longitudinal component of the electric field have a comparable amplitude and ~±90 degrees of phase difference compare to the transverse component. The sign of this phase difference depends on the propagation direction of light, that leads optical spin-propagation locking system. We calculated the local density of the transverse optical spin of the plasmonic mode, using the Stokes parameter $S_3 = -2\,\mathrm{Im}(E_x E_y^*) / (E_x^2 + E_y^2)$, as shown in Fig 1d. The spin angular momentum has an opposite handedness either with the opposite side of the y position or with different propagation directions (Fig. 1c).

The emission from one valley in TMDs can be described by a circular dipole radiation due to their valley-dependent optical selection rules. The circular dipole radiation near a plasmonic nanowire is directly simulated using three-dimensional finite-difference time-domain (FDTD) method. Figure 1e indicates the directionality of emission of a left-handed circular dipole as a function of its position on the *x-y* plane. The sign of the directionality is changed as across the wire along the y direction that agrees well with stokes parameter in Fig. 1d. In addition, the color of this contour plot is opposite for a right-handed circular dipole. The existence of the interference patterns along the wire originates from the finite length of the silver nanowire : the constructive and destructive interferences with reflected fields from the end of the silver nanowire.

For an experimental demonstration, we used a far-field microscope to examine directional emission of TMDs. The valley-polarized excitons are locally excited with circularly polarized laser and their directional emissions are characterized by measuring the wavelength-dependent intensities of the light at the end of the silver nanowire. The directionality of emission depends both on the valley polarization, the handedness of the excitation laser, and on the position of an excited exciton in TMDs (Fig. 2a and 2b). In addition, under linear polarization excitation generating non-polarized valley pseudospin, the exciton emission shows non-directional emission (Fig. 2c). The fitting results suggest that experimental data is mostly limited by the finite valley polarization of TMDs and finite size of excitation focal spot and shows a good agreement with the calculated directionality of a circular dipole.

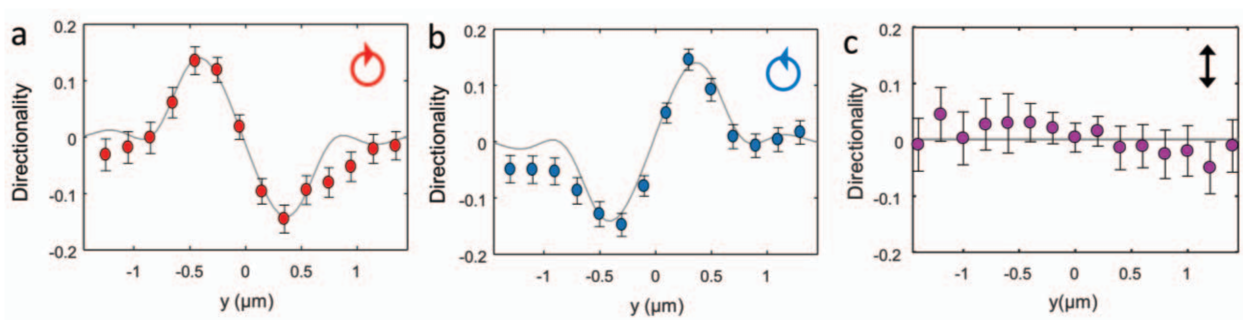

Fig. 2. Measured directionality as a function of excitation position with left (a) and right (b) handed and linearly (c) polarization.

To conclude, valley(spin)-dependent directional coupling to the plasmonic guided mode was investigated theoretically and experimentally. Due to the high degree of valley polarization of TMDs together with the high density of transverse optical spin of plasmonic modes, high valley-to-path efficiency was demonstrated at room temperature. This results paves the way towards a new platform for manipulate a valley pseudospin in integrated valleytronics devices using nanophotonics structures.

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