Tunable optical switches based on spin valley quantum coherence in hybrid WS_2-metallic nanoantenna systems

Seyed M. Sadeghi
Department of Physics and Astronomy, University of Alabama in Huntsville, AL 35899, USA
seyed.sadeghi@uah.edu

Abstract: A tunable optical switching process based on spin valley quantum coherence in a hybrid system consisting of a WS_2 monolayer and a metallic nanoantenna is investigated. This process is induced by plasmonically-mediated intervalley exciton-plasmon coupling which is shown to be quite resilient against ultrafast valley decoherence.

1. Introduction

Optical and material properties of monolayers (MLs) of transition metal dichalcogenides (TMD) hold the promise advanced device applications, ranging from detectors, to light emitters, memory devices, excitonic lasers, etc [1]. Such materials have direct band gaps, high absorption coefficients, and very large spin-orbit coupling [2]. These features have made such materials unique hosts for investigation of coupling of valley excitons with localized surface plasmons resonances (LSPRs) of metallic nanoantennas (mANTs), supporting Rabi splitting, dressed states, and polaritons [3]. TMD-mANT systems can also lead to gain without inversion [4], and coherent transport of energy. [5] In this contribution we study application of such systems for coherent optical switches that can be tuned by varying the intensity of a laser field. Such switches, which are based on intervalley quantum coherence mediated by spin valley exciton-plasmon coupling, offer significant resiliency against valley decoherence.

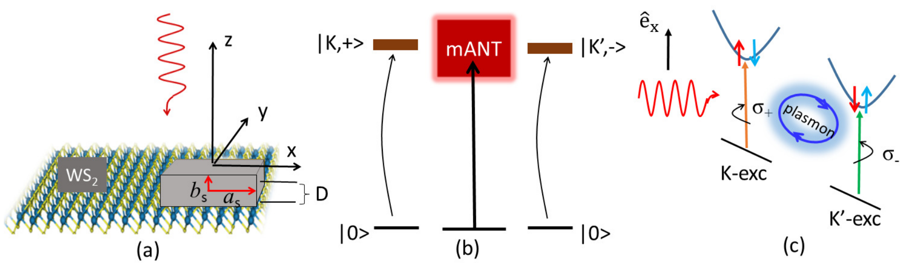

Fig. 1. (a) Schematic of the WS_2-mANT system interacting with a laser field polarized along the x-axis. (b) Electronic structures of spin polarized valley K-exc and K′-exc in the presence of mANT. (c) Schematic of the plasmonically-mediated intervalley coupling.

2. Review of theory

We consider an Ag mANT with semimajor and semiminor axes of a_s and b_s placed on the surface of a WS_2 ML with the center-to-center distance of D (Fig.1a). The materials surrounding these are assumed to have dielectric constant ε_0. The WS_2-mANT system interacts with a laser field linearly polarized along the x-axis $\mathbf{E} = E_0(t)\cos(\omega t)\hat{\mathbf{e}}_\mathbf{x}$. Here ω is the frequency of the laser, $E_0(t)$ is its time-dependent amplitude, and $\hat{\mathbf{e}}_\mathbf{x}$ is the polarization unit vector along the x-axis. Under these conditions the interaction Hamiltonian of the excitons associated with K valley (K-exc) and K′ valley (K′-exc) can have the following form:

$$\hat{H}_{int}^{K,(K')} = -\frac{1}{\sqrt{2}}(\mu_+ E_K a_+^\dagger a_0 + \mu_- E_{K'} b_-^\dagger b_0) + H.C. \quad (1)$$

Here $a_+^\dagger$ ($b_-^\dagger$) and a_0 (b_0) are creator and annihilation operators for K-exc (K′-exc) and ground states. μ_+ and μ_- are dipole moments associated the K-exc and K′-exc transitions (Fig.1b). E_K and $E_{K'}$ refer to the field experienced by K-exc and K′-exc, respectively [5]. The density matrix equations for K and K′ valleys are given by:

$$\frac{d\rho^{K(K')}}{dt} = -\frac{i}{\hbar}[H_0 + H_{int}^{K,(K')}, \rho^{K(K')}(t)] + [\pounds\rho^{K(K')}]_{damp}. \quad (2)$$

Here $[\pounds\rho^{K(K')}]_{damp}$ refers to the damping terms which contain pure dephasing rate, $\gamma_p^{K(K')}$. H_0 is the Hamiltonian of the WS_2 ML in the absence of the laser field and the mANT. Solving these equation under quasi-steady state condition allows one to find the density matrix elements and coherently normalized plasmonic field enhancement factor given by $P_{coh}^{K(K'} = |E_{K,(K')}|^2/|E_0|^2$.

3. Tunable coherent optical switching

For simulation we consider $\mu_-=\mu_+= 1.12\ e\times$nm, the linewidths of K-exc and K′-exc equal to 20 meV, ω_K=2.006 eV, and the radiative lifetime of excitons equal to 1.5 ns [4]. Additionally, for the Ag mANT we assume a_s=9 and b_s=4 nm, and ε_0=3.61 (SiN). We also set D=6 nm and the dielectric constant of the WS_2 ML, ε_{ML} is ~ 13.7. Fig.2a shows the results for P_{coh}^K as a function of detuning of the laser field from the K-exc transition (Δ_{+0}) for different values of the incident laser intensity (legends in W/cm^2). The results suggest sudden changes (arrow) associated with switching between two collective states of the system. Figs.2b-2d show variation of the K-exc population, and real and imaginary parts of valley polarization ($\rho_{+,0}^K$), respectively. Note that as the laser intensity changes the position of transition associated with the switching is shifted, suggesting its tunability.

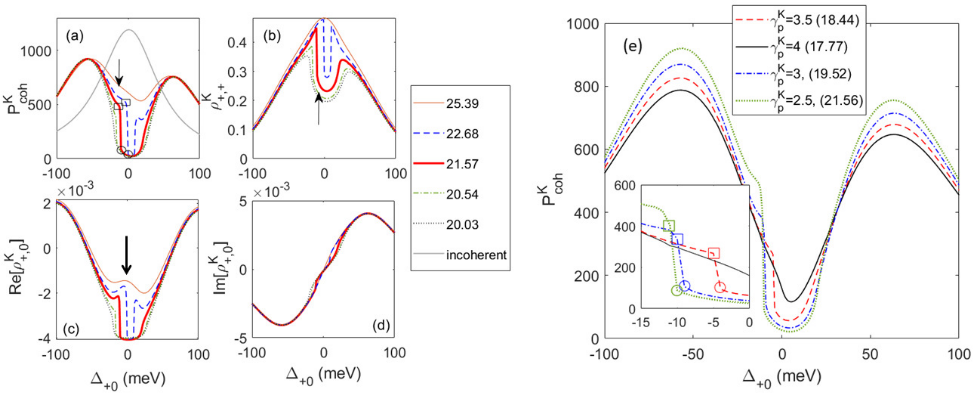

Fig. 2. Variation P_{coh}^K (a), K-exc population (b), Re[$\rho_{+,0}^K$] (c) and Im[$\rho_{+,0}^K$] (d) as a function Δ_{+0} for various laser intensity (legends in W/cm^2). (e) shows P_{coh}^K as a function of Δ_{+0} for γ_p^K=4 (solid line), 3.5 (dashed line), 3 (dashed-dotted line), 2.5 ps^{-1} (dotted line). Numbers in parentheses in the legend of (e) refer the values of laser intensity in W/cm^2.

Fig.2e shows variations of P_{coh}^K for various values of valley pure dephasing rate (γ_p^K). This parameter includes contributions of various processes that can lead to polarization decoherence. The results show that the switching process can occur even when γ_p^K=4 ps^{-1}, indicating a good resiliency against valley decoherence.

4. Conclusions

The potential of TMD-mANT systems for coherent devices based on spin valley quantum coherence was studied. Such systems can sustain coherent exciton-plasmon coupling under ultrafast polarization dephasing (300 fs).

References

1. C. Cong, J. Shang, Y. Wang, T. Yu,"Optical Properties of 2D Semiconductor WS2," Adv Opt. Mat. 6, 1700767 (2018)
2. W. Liu et al, "Strong exciton–plasmon coupling in MoS2 coupled with plasmonic lattice," Nano Lett. 16, 1262–1269 (2016)
3. T. Chervy et al, "Room Temperature Chiral Coupling of Valley Excitons with Spin-Momentum Locked Surface Plasmons," ACS Photonics 5, 1281-1287 (2018)
4. S. M. Sadeghi and J. Z. Wu, "Gain without inversion and enhancement of refractive index via intervalley quantum coherence transfer in hybrid WS 2-metallic nanoantenna systems," Phys Rev A 103, 043713 (2021)
5. S. M. Sadeghi and J. Z. Wu, "Coherent transport of energy and polarization between monolayers of transition metal dichalcogenides," 2D Materials 8, 045023 (2021)