Ultrafast Antiferromagnetic Switching of Mn2Au with Laser-induced Optical Torques

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Recent *ab initio* work [1] has suggested a novel option for direct Nèel vector control of antiferromagnets (AFMs): the induction of staggered fields using direct optical laser excitation. The frequency dependence of the induced staggered magnetic fields was calculated for optical and THz excitations, and is shown to generate a net non-staggered torque. This torque could potentially switch the AFM order parameter.

We present atomistic spin dynamics simulations of an optical frequency excitation from ultrafast laser pulses on Mn_2Au [2] using the coupling scheme suggested in Freimuth *et al.* [1]. To distinguish between the other laser excitation torques acting through spin transfer techniques [3], we call this generated torque a laser optical torque (LOT). We focus our work here on demonstrating the possibility to switch the Nèel vector in AFM using purely LOTs in optical frequencies. Additionally, we provide a method using the LOT symmetry to preferentially control the switching direction of the Nèel vector, allowing for deterministic, non-toggle all-optical switching (AOS) in AFM.

Optically-induced torques show strong crystal symmetry and frequency dependent coupling to the polarised electric field components of the laser. A full analysis of the symmetry requirements in the Mn_2Au bulk crystal is based on the Keldysh non-equilibrium formalism in [1]. The magnitude and spatial symmetry of the predicted torque depends both on the local orientation of the Nèel vector $\boldsymbol{L}$, as well as the electric field $\boldsymbol{E}$ direction of the applied optical pulse.

The torque tensors depend on the vector components of the electric polarisation and AFM order parameter (Fig. 1). Our chosen laser geometry can be approximated to follow the trigonometric relation $\sin(2\varphi - 2\phi)$, with φ the azimuthal angle of the electric field polarisation of the laser, and ϕ the azimuthal angle of the magnetisation. Taking the physical constants into the variable $\tau(I,\omega)$, the induced field from the laser can be written as

$$\boldsymbol{H}_{LOT} = \frac{1}{\mu_s}\tau(I,\omega)\sin(2\varphi - 2\phi)\hat{z} \times \hat{\boldsymbol{S}} \qquad (1)$$

The staggered fields then lead to a non-staggered effective torque. A linearly polarised pulse with $\boldsymbol{E} \parallel \langle \mathbf{110} \rangle$ and intensity I=10 GW/cm^2, set at a photon energy of $h\nu = 1.55$ eV, will produce a LOT of magnitude $\approx$12 x 10^{-24} J, which corresponds to an effective field of 17.3 mT on each magnetic moment, canting the local Nèel vector out-of-plane.

Unlike traditional Nèel SOT, the LOT has the additional feature of changing sign during the switching: the intrinsic spatial symmetry defined in Eq. (1) ensures the induced LOT changes its sign for any 90-degree rotation of the Nèel vector (Fig. 1). This allows for both clockwise and counter-clockwise switching by means of the same laser polarisation.

The sin2 reliance on the electric field polarisation of the generated torque in Eq. (1) allows a shift of the maximal torque away from the easy axis by rotation of the laser polarisation vector. Contrary to the toggle switching caused by $\boldsymbol{E} \parallel \langle 100 \rangle$ or $\langle 010 \rangle$, shifting the azimuthal angle of the laser polarisation will create an asymmetric torque profile (Fig. 1). Thus, the magnetisation will experience a larger torque when starting from only two of the four easy axis directions, giving a preference between clockwise and counter-clockwise switching. This generation of a quadrant-asymmetric torque introduces an additional level of control to the switching process, allowing for preferential, non-toggle switching.

Since Mn_2Au is a metallic conductor, strong laser intensities will induce transient heating to the system. We include this effect using the common two-temperature model (TTM). Fig. (2) shows the switching probability for different laser polarisations and different starting easy axis directions. Fig. (2a) confirms robust toggle switching for a wide range of pulse durations with no overshooting. Fig. (2b) demonstrates the preferential switching nature between starting easy axes, with Fig. (2c) confirming the ability to toggle switch both starting easy axes with the same laser polarization, changing only the pulse fluence and duration. Thus, a combination of pulses of the same laser polarisation could deterministically switch the Nèel order. That is, could intentionally direct the Nèel order between starting axes without knowing the initial position. This effect is a result of crystal and non-centrosymmetric symmetry breaking, and is not unique to Mn_2Au. Recent *ab initio* results have shown this LOT for the altermagnets RuO_2 and CoF_2 as well [4]. This suggests that laser optical torques could be a new and critical feature for AFM spintronics.

References

[1] F. Freimuth, S. Blügel, and Y. Mokrousov, Physical Review B, vol. 103, no. 17, May (2021)

[2] J. Ross et al., arXiv, 2311.00155. Dec (2023)

[3] Y. Behovits et al., Nature Communications, vol. 14, no. 1, Sep. (2023)

[4] T. Adamantopolous et al., NPJ Spintronics, vol. 2, no. 1. Sep (2024).

Figures

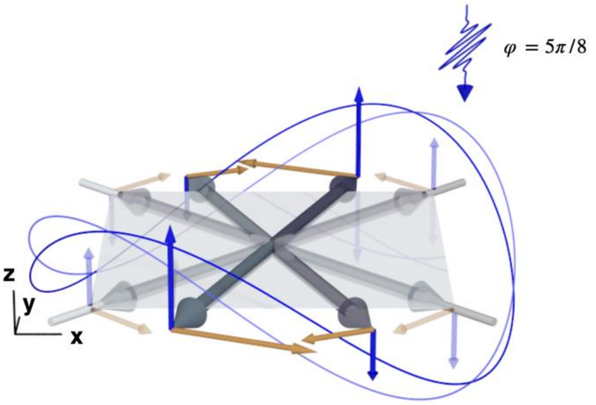

Figure 1. *Diagram of torque symmetry described by Eq. 1 for various laser polarisations.*

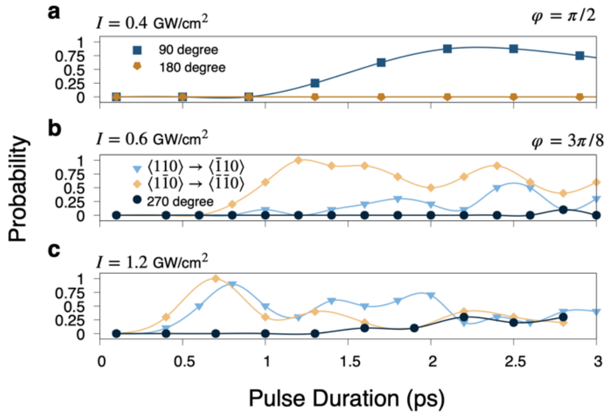

Figure 2. *Switching probabilities including the TTM for different laser polarisations and starting easy axes showing toggle, preferential, and deterministic switching.*