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Ultrafast Magnetisation Dynamics Driven by Terahertz Light Fields via Spin Hall and Rashba–Edelstein Effects

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Ultrafast control of magnetisation states in magnetically ordered systems represents a key technological challenge for developing memory devices operating on picosecond timescales. This challenge has stimulated extensive research into ultrafast magnetisation dynamics, spin transport, and magnetoresistance phenomena across a wide range of conventional and emerging magnetic materials. To achieve coherent manipulation with light fields, terahertz (THz) radiation has been proposed as a driver due to its picosecond field oscillations and thus strong ponderomotive potential. We have demonstrated THz-field-driven generation of spin currents via the spin Hall effect and the ultrafast spin Seebeck effect. These mechanisms enabled THz spin-orbit torque-driven high-energy magnon excitation and spintronic frequency multiplication. However, the coupling between light-field-driven spin currents and magnetoresistance effects at optical frequencies remains largely unexplored.

Unidirectional spin Hall magnetoresistance (USMR) provides a simple two-terminal geometry for electrical detection of magnetisation states in magnetic heterostructures. Conventional USMR has been observed under direct current at low frequencies (kHz range), but its operation at light frequencies has not yet been investigated. Using nonlinear THz spectroscopy, we report an ultrafast version of the USMR effect in magnetic heterostructures, manifested through THz second-harmonic generation detected in a far-field configuration. By analysing the in-plane angular dependence between THz polarisation and sample's magnetisation orientation, we disentangle the USMR contribution from thermally driven spintronic frequency multiplication processes. Moreover, at interfaces exhibiting pronounced inversion symmetry breaking, Rashba–Edelstein effects participate in the magnetoresistance dynamics, offering additional tunability toward 2D magnetic heterostructures.

Our results enable non-destructive studies of light-field-driven spin-dependent scattering dynamics in magnetic heterostructures based on heavy metals or Rashba-split systems, providing new insights into ultrafast magnetism and advancing THz spintronics.

Field of Condensed Matter

Magnetism

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