Magneto-dependent plasmon drag in permalloy structures

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Abstract. Plasmon-enhanced photovoltages in 1D profile-modulated permalloy films strongly depend on magnetic field, with a characteristic hysteresis. The effect is discussed in terms of the anomalous Nernst effect.

Keywords: Plasmonics; Nanostructures; Magneto-optic systems

Coupling of plasmonic and magnetic effects can bring many new possibilities and advantages, such as compact magneto-optical devices, fast magnetization switching and nonreciprocal plasmonics [1]. The experiments in this direction are mostly focused on core-shell nanoparticles, which have a magnetic core (Co, Fe-Co, iron oxide) and a plasmonic shell (Au) or heterostructures of plasmonic and magnetic materials [2]. Significant enhancement of magneto-optical activity and an increase in photomagnetization under illumination with circularly polarized light are observed at the plasmon resonance conditions, which clearly indicates the participation of surface plasmons in the spin angular momentum (SAM) exchange between light and matter. The effects are explained with strongly enhanced electric fields at resonance conditions, and also discussed in terms of an enhanced inverse Faraday effect [3].

In our experimental work, we explore the possible magnetic dependence of plasmon drag voltages in structures that combine both plasmonic and magnetic properties. Plasmon drag is a giant enhancement of photocurrents observed earlier in gold and silver structures [4,5] under surface plasmon polariton (SPP) resonance. As shown in [6] SPPs propagating at the boundary between a dielectric and a metal have SAM associated with the rotation of the optical electric field polarization in the skin layer. Transfer of SAM to a material can result in spin polarization [7] and significant gradients of spin polarization across the skin-layer. In this case, one can expect spin currents and consequently, charge currents due to spin-orbital interaction via the Inverse Spin Hall Effect (ISHE) [8].

Our experimental structures are permalloy (Ni-Fe alloy) thin films with one-dimensional (1D) profile modulation, see Fig. 1 (a) for the schematics and Atomic Force Microscopy (AFM) image. The fabrication starts with obtaining polycarbonate grating substrates from disassembling commercial DVD-R discs by carefully taking out the polymer, plastic, silver and protective coating layers. Then, permalloy (Py) with 40 nm thickness is deposited on the prepared and precut DVD and glass substrates using e-beam evaporation. The AFM confirms that the Py/DVD systems have the periodicity, p, of 740 nm with the modulation height, h, of 60-80 nm. Optical reflectivity spectra at p-polarization show well-pronounced dips (Fig. 1(b)), which are ascribed to the 1st order SPP mode. The $\omega(k)$ dispersion curve, Fig. 1 (c), is typical for SPP and the Q-factor of the resonance is estimated in the range of 3-10 depending on the wavelength. The magnetic properties of our structures are characterized with the ferromagnetic resonance (FMR) method, which confirms in-plane uniaxial magnetic anisotropy with an anisotropy field H_a of ~ 60-90 Oe depending on the particular sample.

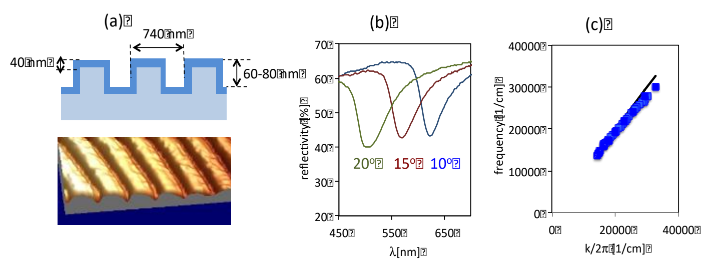

Fig. 1. (a) Schematics (top) and AFM image (bottom) of Py/DVD structure; (b) Reflectivity spectra at different incidence angles as indicated; (c) SPP dispersion curve (points) and a photon line (solid trace).

The experimental setup for photocurrent measurements is shown in Fig. 2 (a). The permalloy/DVD structure is illuminated with the second harmonic of a Nd:YAG laser at 532 nm in p-polarization, with ~10 ns pulse duration and energy of ~0.15 mJ per pulse. The voltage (Figs. 2 (b, c)) generated across the sample is measured with a Tektronix Digital Oscilloscope with 50 Ω internal resistance. The applied magnetic field is parallel to the direction of the grooves. In the experiment shown in Figs. 2 (b, c), we set the illumination angle in the range of the SPP resonance ~ ± 20° in order to achieve the maximal electric signal, and compare the signals at the magnetic field H_0 = 85 Oe directed down (-z direction) and up (+z). In Fig 2 (b), the SPP is excited in x direction, and the photoinduced electric signals have negative polarity, which corresponds to the drag of electrons in x direction. As one can see, the peak magnitudes of the photoinduced voltage are different for the opposite directions of H field. The difference between the signals $\Delta U = U(-H_0) - U(H_0)$ is shown in green color. In Fig. 2 (c), the SPP is excited in the opposite direction, electrons drift in -x direction, but ΔU has the same polarity and almost the same amplitude as in the previous case. At the SPP resonance conditions, ΔU is higher (up to ~3 times) in magnitude than that off resonance, see Fig. 2 (d). The polarity of ΔU always stays the same.

In Fig. 2(e), the photoinduced voltage is recorded with respect to the applied external magnetic field H, which is slowly varied in the range between ±85 Oe. In Fig 2 (e), the field H first increases from negative to positive values (step 1-2). The voltage of ~ 3.7 mV does not show any significant change in the magnitude until the applied magnetic field reaches to 45 Oe. A steep drop in U from 3.7 mV to 2.4 mV is observed at 49 Oe. The voltage saturates at about 2.3 mV with a further increase in the magnetic field. Reversing the magnetic field sweep (step 2-3) does not affect the voltage until the field reaches negative values of ~ - 45 Oe. The voltage changes back to the original value 3.7 mV at ~ - 60 Oe with the further increase in H in the –z direction, forming a full hysteresis loop. In Fig. 2 (f), we test the effect of the field sweep when the SPP is excited in the opposite direction. Note that the magnitudes of the switching fields are comparable with the anisotropy fields H_a estimated from FMR characterization in our samples, indicating that the origin of the magnetic photocurrents is directly related to the magnetization of the sample.

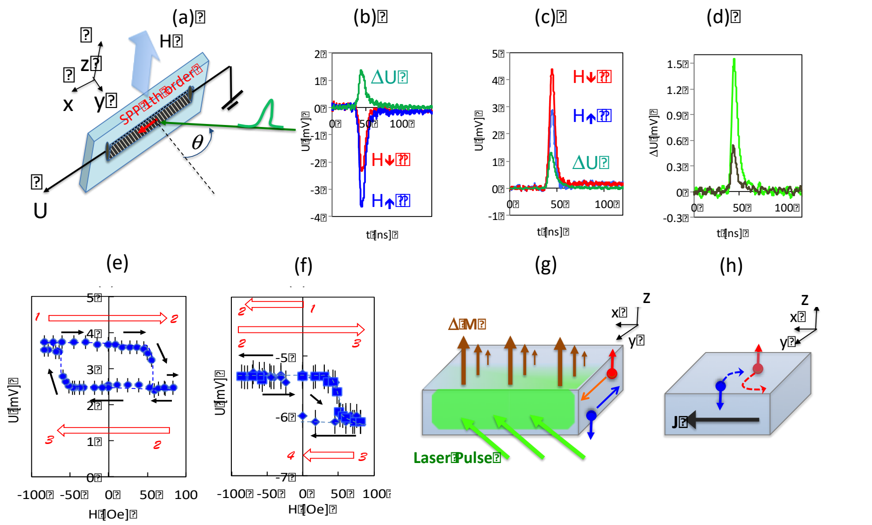

Fig. 2. (a) Experimental setup; (b) Typical photoinduced electric signals at the magnetic field H =85 Oe directed down (red) and up (blue). Difference between them is shown in green; (c) Same at different direction of illumination; (d) ΔU at the SPP resonance conditions, $\theta = 21^o$ (light green), and off resonance (black). (e) Hysteresis in photoinduced voltages with variation of the magnetic field. The field sweep direction is shown with the red arrows. Black arrows indicate the direction of the signal change. Dashed lines are guide for eye. Figs (e) and (f) correspond to different directions of illumination for the same sample. Fig.(g) illustrates a response in the total magnetization to the pulsed illumination and distribution of ΔM across the sample thickness and directions of electron spin diffusion (red and blue arrows); (h) Charge current J in x direction due to spin currents across the thickness of the film.

Summarizing our experimental observations, the magnetic part of the photoinduced voltage in profile-modulated permalloy films is related to the magnetization, and switches sign at the opposite directions of magnetization. It is significantly enhanced by SPP, however shows the same polarity at opposite directions of SPP propagation. Let us assume that the pulsed illumination results in a significant temperature gradient, which leads to a gradient in spin polarization (Fig. 2 (g)), and the role of plasmonic resonance is only to achieve a higher temperature gradient due to more efficient absorption. The anomalous Nernst effect (ANE) [9, 10] describes generation of voltage in ferromagnetic materials in the presence of a thermal gradient ∇T and magnetization M, as $E_{ANE} = -N\mu_0 M \times \nabla T$, where μ_0 is the permeability of a free space and the N is the Nernst coefficient. Note, that the magneto-dependent voltages observed in our experiments exceed 1 mV, and are significantly higher the typical values of ANE (< 1 μV) in permalloy reported in refs. [9, 10]; this may be related to strong transient thermal gradients in our systems. The theoretical analysis is in progress.

In conclusion, significant magnetic dependence of plasmon-enhanced photocurrents is observed in 1D profile modulated permalloy films, manifesting a coupling of plasmonic, electric and magnetic effects, which can open new opportunities in plasmonics and nanomagnetics.

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Introduction

- We explore **coupling of plasmonic, electric and magnetic effects** in profile modulated **permalloy structures**, which have **both plasmonic** properties and **uniaxial magnetic anisotropy** with an in-plane easy axis.
- **Strong photocurrents** observed under plasmon resonance conditions show the clear dependence on the magnetic field with characteristic hysteresis. The effects are discussed in the frame of the **anomalous Nernst effect**.

Background

- **Coupling of plasmonic and magnetic effects** can **bring many new possibilities** and advantages, such as:
  - compact magneto-optical devices, fast magnetization switching, nonreciprocal plasmonics.[1]
- **Significant enhancement of magneto-optical activity:**
  - **increase in photomagnetization** at the illumination with circularly polarized light at the plasmon resonance conditions, indicates the **participation of surface plasmons in the spin angular momentum (SAM) exchange between light and matter**. [2,3]
  - The effects are explained with strongly **enhanced electric fields** at resonance conditions, and also discussed in terms of an **enhanced inverse Faraday effect.**
- **SPPs propagating** at the metal dielectric interface have **SAM** associated with the **rotation of the optical electric field** polarization in the skin layer.
  - **Transfer of SAM to a material via spin orbital interaction** can result in substantial **spin polarization**.
  - Strong **enhancement of photocurrents** in gold and silver structures observed at SPP resonance [4], [5] is commonly discussed in terms of **linear momentum exchange between light and matter** [6], [7].
  - However, surface charges or highly nonlinear electron motion can play a significant role [6]. If **SAM transfer creates spin polarization**, the overall picture of the **photoinduced electric effects** may be very **different** from that in a purely **non-magnetic case**, bringing a new dimension to this research area.

Objective

- We look for the signature of this process in **photocurrent behavior and explore** the possible **magneto-dependent response to plasmon excitation** in systems which combine plasmonic and magnetic properties.

Experimental

Fabrication & Characterization

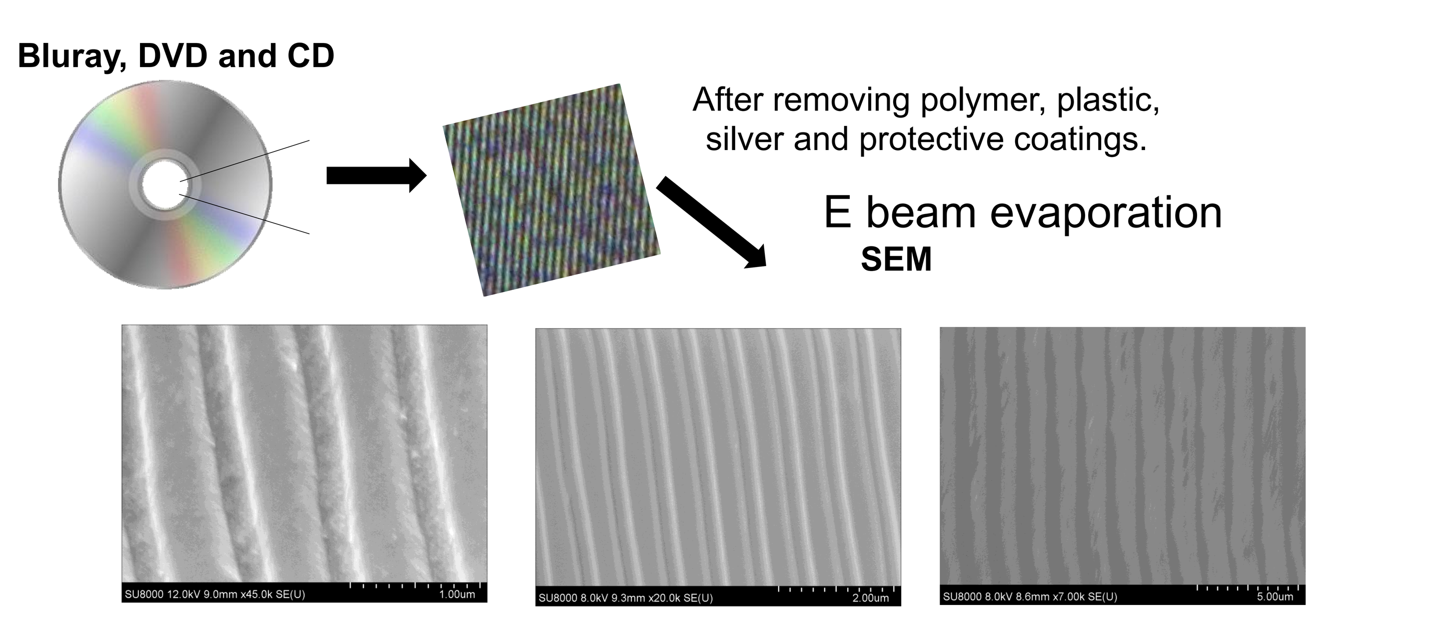


Figure 1: Fabrication of Periodic plasmonic structure with e-beam evaporation and SEM studies

AFM and optical studies

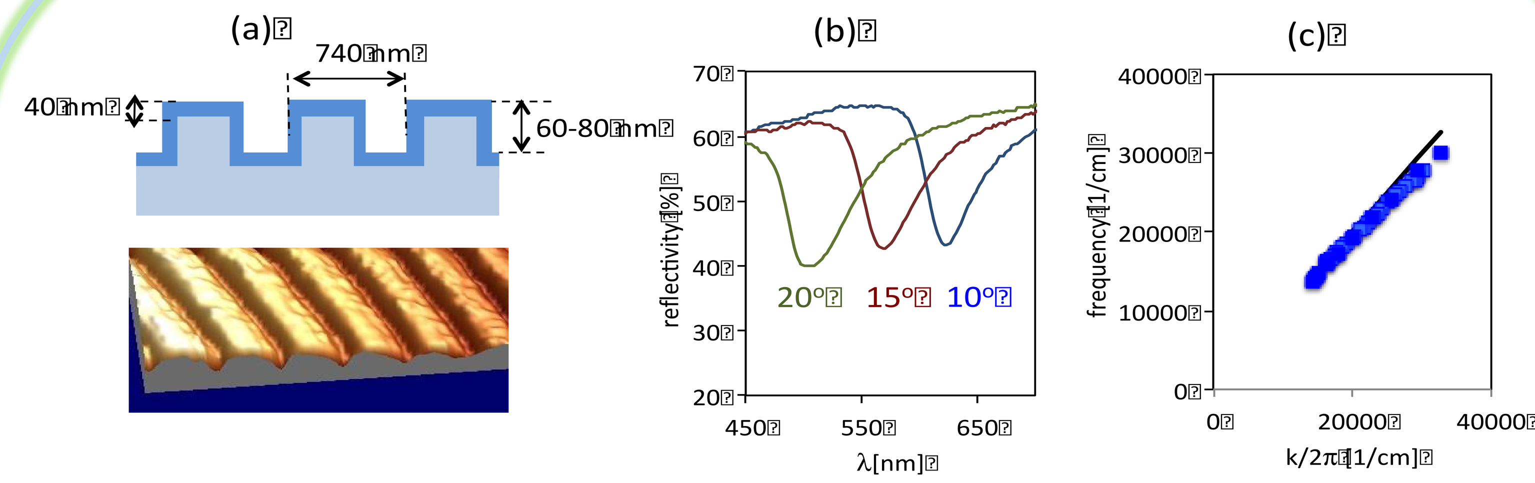


Fig. 2. (a) Schematics (top) and AFM image (bottom) of Py/DVD structure; (b) Reflectivity spectra at different incidence angles as indicated; (c) SPP dispersion curve (points) and a photon line (solid trace).

- Reflectivity spectra show well-pronounced dips, which are ascribed to the SPP mode (1-th order SPP), following the equation,

$$k_{spp} = 2\pi/p + k_0 \sin\theta, \qquad (1)$$

where k_{spp}, k_0 are correspondingly the SPP and photon k vectors, and q is the angle of incidence.

- The $\omega(k)$ dispersion curve, Fig. 2 (c), derived from the spectral positions of the dips at various angles is typical for SPP. The Q-factor of the resonance estimated in the range of 3-10 depending on the wavelength.

Magnetic Studies

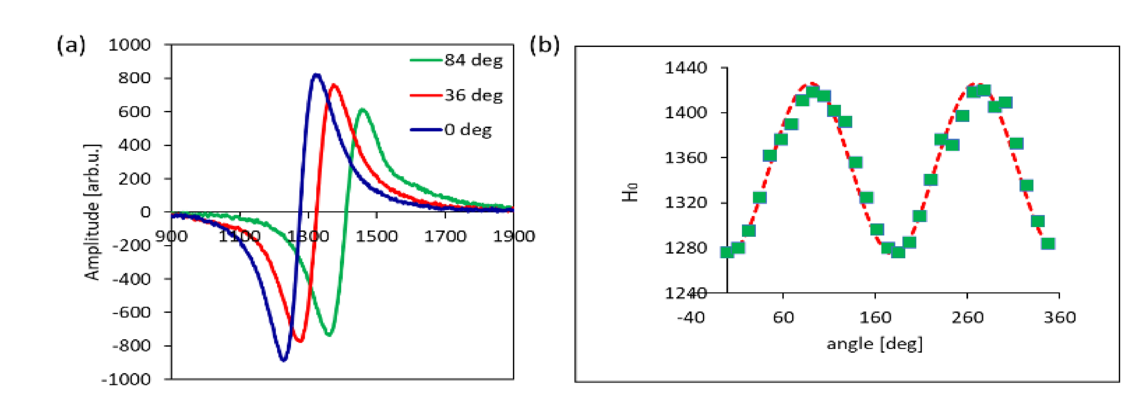


Fig. 3 (a) The angular dependence of the FMR spectra for py/DVD (b) The angular dependence of the resonant field for py/DVD

- Permalloy is a soft ferromagnetic with a very high magnetic susceptibility (up to 90000).
- The magnetic properties of our structures are characterized with the ferromagnetic resonance (FMR) method,
- which confirms in-plane uniaxial magnetic anisotropy
- with the anisotropy field H_a of ~ 60-90 Oe depending on a particular sample

Experimental set up and Results

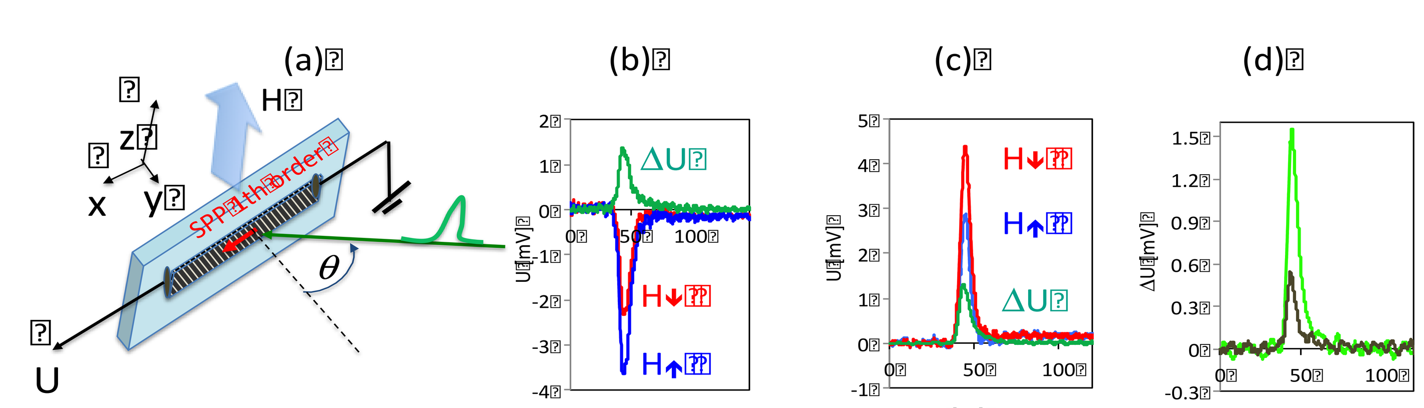


Fig. 4. (a) Experimental setup; (b) Typical photoinduced electric signals at the magnetic field H =85 Oe directed down (red) and up (blue). Difference between them is shown in green; (c) Same at different direction of illumination; (d) ΔU at the SPP resonance conditions, θ = 21° (light green), and off resonance (black).

- The sample is illuminated with:
  - the second harmonic of a Nd:YAG laser at 532 nm
  - in p-polarization, with ~10 ns pulse duration
  - and energy of ~0.15 mJ per pulse.
  - The direction of the magnetic field is parallel to the direction of the grooves.
- peak magnitudes of the photoinduced voltage varies with the direction of applied H. The difference between the signals $\Delta U = U(-H_0) - U(H_0)$:
  - is shown in green color.
  - Polarity and magnitude of ΔU is independent of direction of SPP
  - At the SPP resonance, ΔU is higher than off SPP Fig. 4 (d).

Results and Discussion

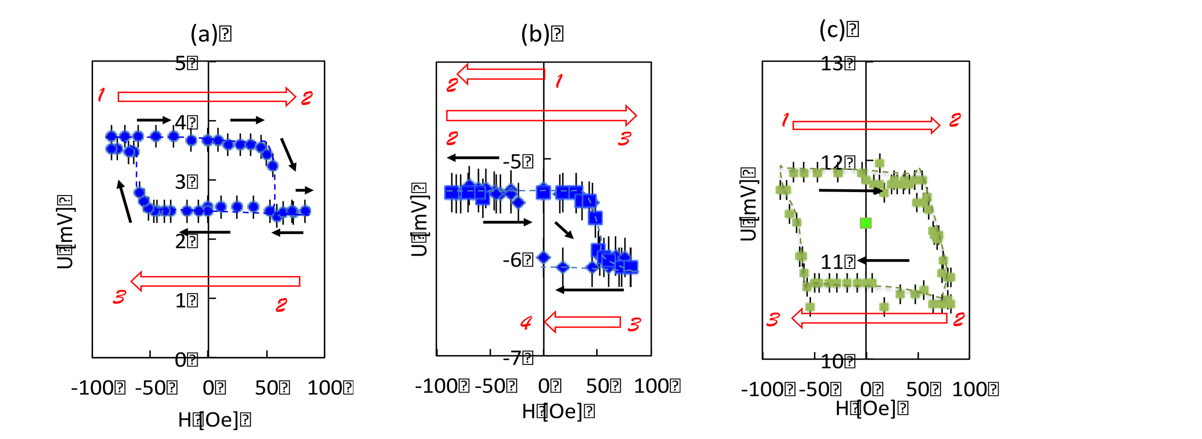


Fig 5. Hysteresis in photoinduced voltages at the variation of magnetic field. The field sweep direction is shown with the red arrows. Black arrows indicate the direction of the signal change. Dashed lines are guide for eye. Figs (a) and (b) correspond to different directions of illumination for the same sample. Data in (c) is obtained in a different sample. The data point shown in light green is obtained before introducing the field.

- In Fig. 5, the photoinduced voltage is recorded with respect to applied external magnetic field H, which is slowly varied in the range between ±85 Oe.
  - A hysteresis behavior of photovoltage is observed in Fig. 5.
  - Magnitudes of the switching fields are comparable with the anisotropy fields H_a estimated from FMR characterization
  - Indicating that the origin of the magnetic photocurrents is directly related to the magnetization of the sample.
- Tests of magnetoresistance and reflectivity in a magnetic field:
  - Indicates that effects are not related to strong dependence of the electrical conductivity or optical permittivity on magnetic field.

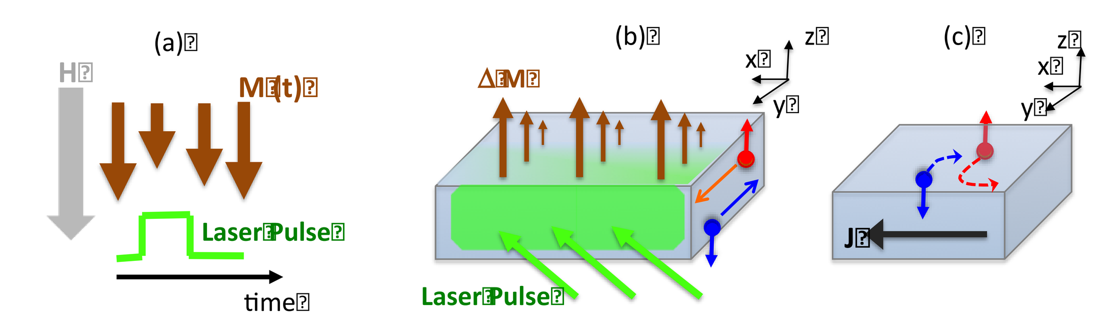
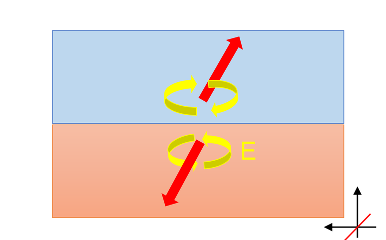


Fig. 6. (a) Response in the total magnetization to the pulsed illumination; (b) Distribution of ∇M across the sample thickness and directions of electron spin diffusion (red and blue arrows); (c) Charge current J.

- Summarizing our experimental observations:
  - The magnetic part of the change of photoinduced voltage is related to spin polarization, and switches sign at the opposite directions of magnetization



- It is significantly enhanced by SPP, however shows the same polarity at the opposite direction of SPP propagation.
- We believe that the effect is related to heating rather than the direct SAM transfer, and can be discussed in the frame of the anomalous Nernst effect (ANE),
- The pulsed illumination results in a significant temperature gradient, which leads to a gradient in spin polarization (Fig. 6 (b)).
- ANE describing generation of voltage in ferromagnetic materials in the presence of thermal gradient ∇T and magnetization M, as

$$E_{ANE} = -N\mu_0 M \times \nabla T,$$

where μ_0 is the permeability of a free space and the N is the Nernst coefficient.
- In this case, the role of plasmonic resonance is only to achieve a higher temperature gradient due to more efficient absorption.
- Theoretical work is underway.

Conclusion

- In conclusion, significant magnetic dependence of plasmon-enhanced photocurrents is observed in 1D profile modulated permalloy films, manifesting the coupling of plasmonic, electric and magnetic effects, which can open new opportunities in plasmonics and nanomagnetics.

Acknowledgements

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