

NANO-OPTICS

Plasmon-boosted magneto-optics

Enhancing magneto-optic effects may help to reduce the size of photonic devices. Recent research by several groups shows that the features of metal optical components can be exploited to enhance typically weak magneto-optic effects.

Ming Liu and Xiang Zhang

In 1842, Michael Faraday observed that the polarization plane of light rotates when light propagates through glass in a magnetic field. The direction of rotation depends only on the direction of the magnetic field; it is independent of the propagation direction of the light. The Faraday effect, as it later became known, is caused by the slightly different propagation speeds of left and right circularly polarized light. This discovery, together with the Kerr effect (found three decades later by John Kerr), gave rise to the branch of physics known as magneto-optics, which is concerned with the peculiarities of interactions between optical radiation and matter in the presence of a magnetic field. These effects have been exploited in numerous applications, including optical isolators for laser stabilization, Kerr microscopy for magnetic imaging and magneto-optical memories for data storage.

Optical isolators — devices that allow unidirectional light transmission, making them the photonic analogue of diodes — have become indispensable components in optical telecommunications and laser applications for stabilizing propagating photons and preventing undesired feedback. However, optical isolators are generally bulky because a long propagation distance of a few millimetres is required to rotate the polarization plane of light by 45°, owing to the weak Faraday effect in available magneto-optical materials. Furthermore, optical isolators also suffer from a narrow wavelength range or bandwidth. Over the past decade, magneto-optical devices have been miniaturized in an attempt to reduce costs and realize on-chip integration, which demands generating a strong Faraday effect on a small scale. Strong optical resonances in photonic crystals¹ and ring resonators² can effectively enhance Faraday rotation and hence reduce device sizes by an order of magnitude, but they further reduce the bandwidth. The surface-plasmon-resonance-enhanced magneto-optical effect has been demonstrated on gold-coated ferromagnetic nanoparticles with a broad bandwidth; however, losses

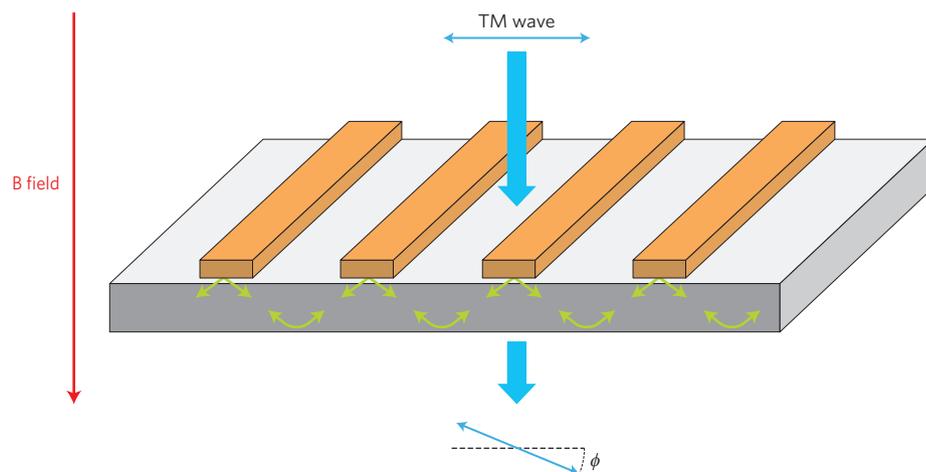


Figure 1 | Schematic of the Faraday effect in a plasmonic-magneto-optical hybrid waveguide system. TM-polarized incident light stimulates plasmonic resonance on periodic gold nanowires, which is coupled to a magneto-optical waveguide. Nonzero-order diffracted light undergoes total internal reflection in the waveguide, resulting in the Faraday rotation, ϕ , being accumulated.

make the enhancement factor too low for applications³.

Now, writing in *Nature Communications*, Chin and co-workers⁴ at the Universities of Stuttgart and Augsburg in Germany and Lomonosov Moscow State University in Russia adopt a new approach to overcome this challenge: they demonstrate a plasmonic-magneto-optical hybrid waveguide that exhibits a large enhancement of Faraday rotation.

To realize a more efficient yet miniaturized device, the researchers patterned a one-dimensional periodic array of 60-nm-thick and 120-nm-wide gold nanowires on a 150-nm-thick bismuth–iron–garnet film. When they applied a magnetic field of 0.14 T normal to the film, the polarization rotated by 0.8° to provide a total transmittance of about 40%. At a wavelength of 963 nm, the researchers measured a half-value bandwidth of 22 nm, which is comparable to that of commercial magneto-optic devices, and a Faraday rotation enhancement of almost nine relative to that without gold nanowires.

Chin *et al.* attributed this enhanced Faraday rotation to mode coupling. For

the plasmonic structure shown in Fig. 1, a transverse magnetic (TM) mode (magnetic field parallel to the wires) and a transverse electric (TE) mode (electric field parallel to the wires) can be excited simultaneously. When an incident TM wave is diffracted into the magneto-optical film by the periodic nanowires, nonzero diffraction orders undergo total internal reflection at the boundaries of the bismuth–iron–garnet film, thus causing them to bounce back and forth inside the film. They acquire a small Faraday rotation with each pass through the film. The rotated light excites the TE mode, which couples to free space as a TE wave, leading to a large Faraday rotation for the system.

The enhancement provided by plasmonic structures to magneto-optical thin films is simple to understand. By concentrating the electromagnetic energy in small volumes near the metal–dielectric interface, plasmonics provides abundant routes to enhance and manipulate light–matter interactions (for example, surface-enhanced Raman spectroscopy) and has found broad applications in other nonlinear optical processes. A similar

magneto-plasmonic heterostructure (a hybridized nanostructured gold layer on a planar ferromagnetic bismuth–iron–garnet film), designed by Belotelov, Akimov and co-workers⁵, has shown a giant resonant enhancement of the transverse magneto-optical Kerr effect of 10^3 . Wurtz *et al.* used a subwavelength hole array in a metal film deposited on a magneto-optical layer to boost the cross-polarized light transmission by two orders of magnitude in a weak magnetic field, owing to the enhanced Faraday rotation in plasmonic resonances⁶.

In addition to the strong enhancement of the electromagnetic field, another important advantage of interfacing plasmonics with magneto-optical materials is the degree of engineering control that is possible through changing the design of the metal structures. By varying the periodicity of the nanowires, Chin *et al.* were able to tune the operation wavelength of the plasmonic-magneto-optical hybrid structure over a range of about 150 nm. Over the past decade, such control of light–matter interactions has been demonstrated in metamaterials, even to the extent that they

can exhibit physical properties not found in nature, such as negative refraction⁷. Furthermore, judiciously tailored plasmonic structures can potentially break rotational symmetry in polarization space, resulting in an artificial magnetic field that imparts circular birefringence to transmitted light. The artificial magnetic field allows spin-dependent surface plasmons to be excited⁸ and is responsible for the recent observation of the photonic spin–Hall effect in metamaterials with rapidly changing phase discontinuities⁹. The ability to use the spin–orbital interaction of light without employing magneto-optic materials or external magnetic fields may further extend the application of plasmonics and is promising for realizing spin-optic devices on the nanoscale.

The plasmonic-enhanced magneto-optical effect reported provides a new way for realizing active control in plasmonic devices through the application of a magnetic field. Incorporating this concept with more efficient magneto-optical materials can further enhance the thin-film Faraday effect, thus making it suitable

for applications such as light modulation, polarization control and Kerr microscopy. Beyond plasmonics, emerging low-dimensional materials with potentially giant Faraday effects, such as graphene¹⁰, may also find applications. □

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References

1. Kahl, S. & Grishin, A. M. *Appl. Phys. Lett.* **84**, 1438–1440 (2004).
2. Bi, L. *et al. Nature Photon.* **5**, 758–762 (2011).
3. Jain, P. K., Xiao, Y. H., Walsworth, R. & Cohen, A. E. *Nano Lett.* **9**, 1644–1650 (2009).
4. Chin, J. Y. *et al. Nat. Commun.* **4**, 1599 (2013).
5. Belotelov, V. I. *et al. Nature Nanotech.* **6**, 370–376 (2011).
6. Wurtz, G. A. *et al. New J. Phys.* **10**, 105012 (2008).
7. Valentine, J. *et al. Nature* **455**, 376–379 (2008).
8. Gorodetski, Y., Niv, A., Kleiner, V. & Hasman, E. *Phys. Rev. Lett.* **101**, 043903 (2008).
9. Yin, X., Ye, Z., Rho, J., Wang, Y. & Zhang, X. *Science* **339**, 1405–1407 (2013).
10. Crassee, I. *et al. Nature Phys.* **7**, 48–51 (2011).

OPTICAL RESONATORS

Chaos aids energy storage

Deformed optical resonators that support chaotically propagating modes have been shown to store more light energy than conventional cavities.

Marc Sciamanna

Chaotic processes are observed in dynamical systems in which the final state shows an exponential sensitivity to slight changes to the initial conditions — a phenomenon termed ‘the butterfly effect’ by Edward Lorenz¹ in 1972 and subsequently popularized in various books and movies. Chaotic dynamics has been reported in almost every field of science. In optics, chaos is found in, for example, the output of a laser diode², the power fluctuations of light propagating in a passive cavity filled with a nonlinear medium³ and the complex spatiotemporal patterns generated by lasers with high Fresnel numbers⁴.

A system that behaves chaotically is unpredictable, which is usually undesirable. However, several specific features of chaos have turned out to be useful for improving the performance of optical systems. For instance, the high dimensionality of optical chaos combined with the chaos-filtering property of synchronized

coupled oscillators has enabled the secure transmission of messages at gigabit-per-second bit rates over kilometre-long optical-fibre networks⁵. In addition, random number generation at bit rates several orders of magnitude higher than those of electronic schemes has been achieved using chaotic lasers by exploiting their random-like output and applying suitable post-processing⁶. Finally, the high entropy of chaotic light scattering in asymmetric optical resonators has helped to improve the output power and beam directionality of microcavity lasers⁷.

Now, writing in *Nature Photonics*, Liu *et al.* report yet another benefit of optical chaos: an enhancement in the amount of energy that can be stored in a resonator pumped by a broadband light source⁸. This work is highly relevant to two areas of great interest to the optical community. The first is the development of broadband optical resonators with high *Q* factors (generally defined as the ratio of the energy stored

to the energy dissipated in a resonator). Microresonators with small volumes, high *Q* factors and large free spectral ranges are critical for the development of low-threshold microlasers, ultrasmall filters and switches, and experiments on cavity quantum electrodynamics⁹. The second area, which is of more fundamental interest, is the experimental realization of a ‘chaotic’ resonator — a resonator whose optical modes are not limited to the regular periodic orbits of circulating light beams, such as the whispering gallery modes of circular optical resonators; instead, it supports a rich and complex set of ray trajectories. The resulting wave chaos of such a resonator exhibits many similar features to the paths of chaotic dynamic billiard balls and is an excellent system for studying more fundamental concepts of quantum chaos such as chaos tunnelling¹⁰.

To introduce optical chaos and achieve enhanced energy storage, Liu *et al.* fabricated a variety of deformed dielectric