Tunable Magneto-Optical Kerr Effects of Nanoporous Thin Films

Weiwei Zhang¹, Jianjun Li¹, Xiaokun Ding², Philippe Pernod², Nicolas Tiercelin² & Yujun Song¹

Magnetoplasmonics, combining magnetic and plasmonic functions, has attracted increasing attention owing to its unique magnetic and optical properties in various nano-architectures. In this work, Ag, CoFeB and ITO layers are fabricated on anodic aluminum oxide (AAO) porous films to form hybrid multi-layered nanoporous thin films by magnetron sputtering deposition process. The designed nanostructure supports localized surface plasmon resonance (LSPR) and tunable magneto-optical (MO) activity, namely, the sign inversion, which can be controlled by AAO porous film geometry (pore diameter and inter-pore spacing) flexibly. The physical mechanism of this special MO phenomena is further analyzed and discussed by the correlation of Kerr rotation and electronic oscillations controlled by the surface plasmon resonance that is related to the nanoporous structure.

Plasmonics¹,² preserves varieties of applications in high dimensional data storage³–⁸, high sensitive chemical detection⁹–¹³ and biosensing¹⁴–¹⁹ and so forth²⁰. This is mainly attributed to the ability of surface plasmons to conduct the subdiffraction-limit of light, to enhance the local surface electromagnetic fields²¹ or to allow localization of light at nanoscale dimensions²². It has been reported that plasmonic properties of metal nanoparticles intrinsically rely on their size, shape, surface topography, crystal structure, inter-particle spacing and dielectric environment²³,²⁴. One development in plasmonics is magnetoplasmonics. Magnetoplasmonics promotes great interests on the momentum in photonics and magnetism sectors that are concerned with the resonant enhancement of light-magnetic-matter interaction²⁵ with the rapid development of nanofabrication techniques²⁶ (e.g., nanoimprint²⁷,²⁸, lithography²⁹–³⁵, physical vapor deposition³⁶,³⁷ and microfluidic synthesis process³⁸–⁴⁰). One topic in magnetoplasmonics is the enhancement of the magneto-optical effects in plasmonic nanostructures⁴¹. Magnetoplasmonics in nanostructures has potential to provide the flexibility in the reception and emission of photon and the light control at nanoscale, which are crucial in lots of emergent nano-optical applications⁴². For instance, when an incident light beam is well coupled to surface plasmon polaritons inside the noble metal film (e.g., Ag⁴³–⁴⁵ and Au⁴⁶–⁴⁸) that has been deposited on magnetic components (e.g., Co, CoFeB, CoPt and NiO) and then reflected back to the optical field, its properties (e.g., intensity and the polarization status) become much sensitive to the medium permittivity and magnetization⁴⁹.

The polarization status of light, used as information carriers, not only has great potential in biochemosensing⁵⁰, optical communications and ultra-sensitive imaging⁵¹, but also plays important roles in the photonic transfer of quantum information⁵²–⁵⁳. A coupled model of incoming electromagnetic excitation and the collective oscillation of free-electrons near the surface of metallic nanostructures has attracted more and more attention owing to their enhanced plamonic and magneto-optical properties⁵⁴, such as enhanced Raman scattering⁵⁵,⁵⁶, tunable nonlinear optical effects, surface plasmon polariton (SPP) and magneto-optical (MO) effects (i.e., Zeeman, Faraday or Kerr effects⁵⁷). Anomalous magneto-optical Kerr effects (MOKE) phenomena have been observed in various nanostructures⁵⁸–⁶⁰,⁶³,⁶⁴. Localized surface plasmon resonance (LSPR) can be exploited in controlled manipulation of the MO response of nanostructured ferromagnetic nickel nanodisks, in which the inverted Kerr rotation is observed⁶⁵. Calculations of bi-layered perforated nanostructure films formed by a gold layer and a smooth iron garnet layer show much higher transverse MOKE than the bare garnet film⁶⁷. Hexagonally arrayed ferromagnetic nanowire films exhibit an enhanced Kerr rotation, which shows a strong dependence on nanowire diameters⁶⁸. Optical and MO properties of hexagonally arrayed ferromagnetic nanoporous films show a complex MO spectrum with a much higher polarization rotation than that of the pure Co film⁶⁹,⁷⁰. And some other systems accompanied by the enhanced MO response like Au/Co/Au nanosandwiches⁶⁸,⁶⁹, gold-coated maghemite nanoparticles⁷¹, ferromagnetic garnet films incorporating Au nanoparticles⁷², Co@Ag core-shell nanoparticles⁷³ and

¹Department of Applied Physics, Center for Modern Physics Technology, Beijing Key Laboratory for Magneto-Photoelectrical Composite and Interface Science, University of Science and Technology Beijing, Beijing, 100083, China. ²Univ. Lille, CNRS, Centrale Lille, ISEN, Univ. Valenciennes, UMR 8520-IEMN-LIA LICS, F-59000, Lille, France. Correspondence and requests for materials should be addressed to Y.S. (email: songyj@ustb.edu.cn)
Anodic aluminum oxide (AAO) porous film, long-range ordered self-organized hexagonal columnar cells with central, cylindrical, uniform-size holes, can be fabricated by the traditional 2-step anodizing process economically. This special nanoporous structure is assigned to the mechanical stress at the aluminum/alumina interface. This is proposed to cause repulsive forces between the neighboring pores. The porous film is a useful template in the fabrication of devices (e.g., photoelectronic device and nanoparticle assemblies) whose interfacial interaction can be regulated by the AAO structure, such as pore size, membrane thickness and surface morphologies and various functional nanostructures (e.g., solar cells, nanotubes, nanofibers, catalysts and metal nanowires). To date, the AAO porous film also has a wide applications in ultrafiltration, biosensors, photonic, masking and information storage. Many types of nanocomposites have been fabricated on the AAO porous film by magnetron sputtering deposition process and the deposited thin films can form a densely packed, regular and almost petal like structure around the pores. This special structure permits an opportunity to realize LSPR, to enhance Fabry-Pérot interferences and to tailor magneto-optical Kerr effects.

In this work, a porous nanostructure with intertwined plasmonic and magnetic properties is developed via depositing Ag, CoFeB and ITO layers on morphology controlled AAO porous film to form hybrid multi-layered nanoporous films by a magnetron sputtering deposition process. From the analysis of the experimental data, the nanoporous structure supports localized surface plasmon resonance and tunable inversion of MOKE hysteresis loops.

**Results**

**Morphology and Composition.** To study the effect of the AAO porous film geometry on the surface plasmon activity and MOKE inversion, the inter-pore spacing of two AAO substrates was first set to two different values (i.e., 110 nm and 450 nm). Then, the pore diameter of three samples with the same inter-pore spacing 110 nm was set to 40 nm, 60 nm and 100 nm. Similarly, the pore diameter of three samples with the same inter-pore spacing 450 nm was set to 130 nm, 160 nm and 200 nm. Finally, hybrid multi-layered films Ag (5 nm)/CoFeB (10 nm)/ITO (10 nm)/Ag (5 nm) were fabricated on the prepared AAO templates. Thus, six hybrid multi-layered samples with different nanoporous geometries were fabricated and characterized.

Fig. 1 gives the typical top view SEM images of the already fabricated hybrid multi-layered nanoporous films. After deposition, the surface morphologies of the samples become more distinct and comparable with the changes of the AAO pore diameter (D) and inter-spacing (S). From the local-magnified angle-tilted SEM image (schemed in the Fig. 2a) of sample (b) (S = 110 nm, D = 60 nm), it is clearly noticed that most holes approximately present a nanofunnel morphology (the red circle is larger than the green one). A simplified nanostructure is sketched in Fig. 2b. EDS (Fig. 2c) confirms the existence of Ag, Co, Fe, In, Sn and O elements in the films and they originate from the deposited Ag layer, CoFeB layer and ITO layer respectively.

**Magneto-Optical Kerr Rotation and Magnetic Domain.** Fig. 3a shows the polar magneto-optical Kerr effect (P-MOKE) hysteresis loops of the prepared six nanoporous samples. At the first glance, it is evidently verified that an anomalous inverted Kerr hysteresis is observed by modifying the AAO porous film geometries (pore diameter and inter-spacing). Similarly, the sign inversion (Fig. 3b) is also detected in the longitudinal magneto-optical Kerr effect (L-MOKE) configuration simultaneously. It has been clarified that the sign of the MOKE is defined by both incoming and reflecting polarization of light, and a clockwise or an anticlockwise axis determines the sign change. However, when the same incoming polarization and the same axis of the polarizing ellipse viewed along the reflected direction are used, the inversion information in both P-MOKE and L-MOKE can be definitely observed.

The dramatic changes of the sign inversion can also be reflected by the direction rotation of typical magnetic domains (represented by the color mapping rotation, Fig. S1 in Supplementary Information) with the external applied magnetic field along the longitudinal direction of the samples. The first two samples ((I) S = 110 nm, D = 40 nm and (II) S = 110 nm, D = 60 nm) display an apparent color change rotation with the magnetic field changing from 1200 Oe to 600 Oe, 0 Oe, −600 Oe, −1200 Oe and back to −600 Oe. However, as both the AAO pore diameters and inter-pore spacing are further increased (S = 450 nm, D = 130 nm and S = 450 nm, D = 160 nm), directions of the magnetic domain distribution (as relatively indexed by the field intensity, or color change) distinctly show opposite behavior. Another result worth noting is that the magnetic domain distribution is not so distinctly exhibited when the AAO pore diameters are 100 nm (Fig. S1(III)) and 200 nm (Fig. S1(VII)), possibly due to the much reduced wall thickness among pores.

Therefore, under certain conditions, the sign of the MOKE loops in our proposal system is related to the pore diameter and inter-spacing. Thus, changing the AAO pore geometry allows us to tailor the MOKE sign. In order to unambiguously illustrate the physical mechanism of nanoporous structure related MO phenomena, the surface plasmon resonance property was investigated.

**Optical response.** Fig. S2 in the Supplementary Information gives the absorbance of the pure AAO porous film (S = 110 nm, D = 60 nm) and the various films deposited on the same template. In this figure, the origin of oscillations observed in each spectrum is related to the optical modes of the Fabry-Pérot cavity. Furthermore, it is observed that when the Ag layer is coated on the surface of the AAO porous film, the absorbance intensity and amplitude of Fabry-Pérot interference resonances are greatly enhanced. It is well known that the noble metal Ag with a very high electrical conductivity can provide abundant free electrons, which can well couple with the electromagnetic (EM) field of light to generate the surface plasmon resonance. For the special designed hybrid multi-layered nanoporous structure (Ag (5 nm)/ITO (10 nm)/CoFeB (10 nm)/ITO (10 nm)/Ag...
Figure 1. Top-viewed SEM images of multi-layered nanoporous arrayed films deposited on six AAO templates with different geometries (a) $S = 110$ nm, $D = 40$ nm, (b) $S = 110$ nm, $D = 60$ nm, (c) $S = 110$ nm, $D = 100$ nm, (d) $S = 450$ nm, $D = 130$ nm, (e) $S = 450$ nm, $D = 160$ nm and (f) $S = 450$ nm, $D = 200$ nm.

(5 nm)) with a highly specific surface area, the resonance can be excited not only on the surface of the nanopore film but also localized around the pore side and the inner part of the pore.

Fig. 4a shows the optical absorbance of the prepared samples, whose resonances present an apparent Fabry-Pérot interference usually existing in the nanohole films. Clearly, for the same inter-pore spacing 110 nm, the peaks exhibit a blue shift with the nanopore diameter increase from 40 nm, to 60 nm and to 100 nm at one optical oscillation period located between 640 nm and 900 nm (Fig. 4b). The wavelength of the laser light (660 nm) in our experiments is just in this wavelength range. Analysis of the Kerr hysteresis loops and the peak positions of the far-field absorbance intensity (Fig. 4b) indicates that there are the same signs when the peaks are at the same side of the given excitation line, while the signs are definitely inversed for those on the opposite sides (i.e., those with inter-spacing of 450 nm and diameter of 130 nm, 160 nm and 200 nm). From previous studies of
magnetoplasmonics, oscillation shapes of the absorbance efficiency are directly related to the surface plasmon resonance. Thus, it is concluded that the special MO phenomena are well related to the surface plasmon resonance which can be controlled by the designed nanoporous system.

**Discussion**

The physical mechanism of the anomalous MOKE phenomena in the multi-layered nanoporous films can be unambiguously clarified. It is well known that the coupling of the transverse magnetic model (TM or p-polarization) and the transverse electric model (TE or s-polarization) can account for the sign inversion of the MOKE rotation. Taking P-MOKE as an example, when the TE electron oscillation mode in the noble metal Ag surface is excited owing to the introduced s-polarization light, due to the applied magnetic field, TM electron oscillation mode can be induced as a consequence of the spin-orbit (SO) coupling. The new hybrid oscillation mode has a strong effect on the Kerr information (i.e., Kerr rotation and ellipticity) and the phases between the two modes account for the sign of the Kerr rotation. It is well known that the tunable electron oscillations can be realized by the surface plasmon resonances, which are related to the designed nanostructure. Therefore, in this work, proper choosing the AAO porous film can control the surface plasmon resonance which has an effect on the electron oscillation modes. Furthermore, tunable sign inversion can be realized.

Besides the simplified physical mechanism of our result, we provide a clear expression of AAO geometry controlled effects on the MO response.

It is well known that when the magnetic field is applied to the surface of the sample, the permittivity tensor that contains nine complex components can be written in the following form:

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & i\varepsilon_{x1} & i\varepsilon_{x2} \\ -i\varepsilon_{1x} & \varepsilon_{yy} & i\varepsilon_{y2} \\ -i\varepsilon_{2x} & -i\varepsilon_{2y} & \varepsilon_{zz} \end{bmatrix}$$

(1)

where the diagonal component $\varepsilon_{ii}$ ($i = x, y, z$) is the dielectric function of the non-magnetized material. This component does not depend on magnetization $M$ when the first order magnetization is considered, and it has an effect only on the pure optical property. On the basis of the modified Drude model for the noble metal silver in our experiment, it can be expressed as

$$\varepsilon_{ii} \approx \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}(i = x, y, z)$$

(2)
Here, \( \omega_p \) is the Drude plasma frequency and \( \gamma = \frac{1}{\tau} \) is the inverse electron relaxation time. The off-diagonal component \( \varepsilon_i (i = 1, 2, 3) \) is linearly dependent of magnetization\(^{51}\). For the different MOKE configurations, the control of the magneto-optical Kerr effect rotation originates from only one of the excited off-diagonal components \( \varepsilon_1, \varepsilon_2 \) and \( \varepsilon_3 \) when the external magnetic field is applied along the x, y or z direction, which are related to the P-MOKE, transversal Kerr effect (T-MOKE) or L-MOKE, respectively.

Figure 3. (a) P-MOKE and (b) L-MOKE loops of hybrid multi-layered nanoporous arrayed films deposited on six AAO templates with different geometries. (I) \( S = 110 \text{ nm}, D = 40 \text{ nm} \); (II) \( S = 110 \text{ nm}, D = 60 \text{ nm} \); (III) \( S = 110 \text{ nm}, D = 100 \text{ nm} \); (IV) \( S = 450 \text{ nm}, D = 130 \text{ nm} \); (V) \( S = 450 \text{ nm}, D = 160 \text{ nm} \) and (VI) \( S = 450 \text{ nm}, D = 200 \text{ nm} \).
For the P-MOKE in s-configurations (Fig. 5a), the off-diagonal term $\varepsilon_1$ is activated by the magnetization samples along the $z$ axis, and the new permittivity tensor can be described by the equation 3 in which all the other terms are equal to zero.

**Figure 4.** Absorbance intensity of hybrid multi-layered nanoporous arrayed films deposited on six AAO templates with different geometries. (I) $S = 110$ nm, $D = 40$ nm; (II) $S = 110$ nm, $D = 60$ nm; (III) $S = 110$ nm, $D = 100$ nm; (IV) $S = 450$ nm, $D = 130$ nm; (V) $S = 450$ nm, $D = 160$ nm and (VI) $S = 450$ nm, $D = 200$ nm. (a) Full range spectra. (b) Magnified local spectra with the vertical black line marks excitation at 660 nm.
When the TE electron oscillation mode with the amplitude $E_{yy}$ is induced as a consequence of the incident light in the wavelength of 660 nm, the light induced complex dipole along the y axis can be written as a function of the polarization $\alpha_{yy}$, namely, $P_y = \alpha_{yy} E_{yy}$ (see refs 50, 51, 106, 108.). The complex dipole can be generated by the SO coupling that transfers the oscillations to the orthogonal direction.

$$P_x = \alpha_{xx} E_{xx} = \alpha_{xy} E_{yy} = \frac{-i \varepsilon \varepsilon_{yy} \alpha_{yy}}{(\varepsilon - \varepsilon_m)^2} = \alpha_{xx} \alpha_{yy} E_{yy}$$

(4)

In this expression, the constant $\varepsilon_m$ is the dielectric function of the surrounding medium. The tuning of the phase and amplitude of the polarization can be achieved by the two orthogonal dipoles in the plane of the samples referring to our detecting system. The similar expression of the Kerr rotation in refs 1, 35 and 37 for nanoparticle arrays is used.

$$\theta_k = \text{Re} \left( \frac{P_x}{P_y} \right) + \text{Im} \left( \frac{P_x}{P_y} i \right)$$

(5)

In our investigation, we only focus on the Kerr rotation angle, named as $\phi_k$.

$$\phi_k^P = \text{Re} \left( \frac{P_x}{P_y} \right) = \text{Re} \left( \frac{\alpha_{xx} \alpha_{yy} E_{yy}}{\alpha_{yy} E_{yy}} \right)$$

$$= \text{Re} (\alpha_{xx} e^{i \phi_k})$$

$$= \text{Re} (\alpha_{xx} \alpha_{yy} e^{i (\phi_k + \phi_{xx})})$$

$$= \text{Re} (\alpha_{xx} \alpha_{yy} \cos \phi - i \alpha_{xx} \alpha_{yy} \sin \phi)$$

$$= \alpha_{xx} \alpha_{yy} \cos \phi$$

(6)

The equation shows how the Kerr rotation $\phi_k^P$ is related to the two phases of the intrinsic properties $\alpha_{xx}$ and $\alpha_{yy}$ owing to the excitation along x axis in the s-configurations. Clearly, the exponential notation expressions $e^{i \phi_k}$ can definitely describe the combined phase $\phi$ between the two polarizations ($\alpha_{xx}$ and $\alpha_{yy}$). Clearly, by selecting proper diameters and distances between two nanopores, the combined phase can be changed enough to produce a reversal sign.

However, for the L-MOKE in s-configuration (Fig. 5b), the off-diagonal term $\varepsilon_{ij}$ is activated by the magnetization along the x axis, and the new permittivity tensor can be described by the equation 7 in which all the other terms are equal to zero.
\[
\varepsilon_L = \begin{pmatrix}
\varepsilon_{xx} & 0 & 0 \\
0 & \varepsilon_{yy} & i\varepsilon_{yz} \\
0 & -i\varepsilon_{yz} & \varepsilon_{zz}
\end{pmatrix}
\]

Through the SO coupling, the light induced dipole \( P_L \) generates \( P_z \).

\[
P_z = \alpha_{yy}E_y = \alpha_{yy}E_y = \frac{-i\varepsilon_{yy}\alpha_{yy}E_y}{(\varepsilon - \varepsilon_m)} = \alpha_{zz}\alpha_{yy}E_y
\]

And the Kerr rotation \( \phi_k^L \) in the L-MOKE configuration can be expressed as:

\[
\phi_k^L = \text{Re} \left( \frac{P_z}{P_L} \right) = \text{Re} \left( \frac{\alpha_{yy}\alpha_{yy}E_y}{\alpha_{yy}E_y} \right) = \text{Re} \left( \alpha_{yy}\alpha_{zz} \right) = \text{Re} \left( \alpha_{yy}\alpha_{zz} e^{i\phi} \right) = \text{Re} \left( \alpha_{yy}\alpha_{zz} \cos \phi - i\alpha_{yy}\alpha_{zz} \sin \phi \right) = \alpha_{yy}\alpha_{zz} \cos \phi
\]

Different from the P-MOKE configuration, \( \phi_k^L \) is related to the two phases of the intrinsic properties \( \alpha_{yy} \) and \( \alpha_{zz} \) due to the excitation along \( z \) axis in the s-configurations.

**Conclusion**

In this work, we have presented an exhaustive analysis about correlation of the hybrid multi-layered nanoporous system and the inversion sign of the Kerr hysteresis. The analysis confirms that the phases of the TM and TE electron oscillation modes account for the sign inversion of the MOKE rotation. The electron oscillation modes can be tuned at will by the surface plasmon resonance which is controlled by choosing an AAO porous film with proper pore diameter and inter-pore spacing.

The study broadens the understanding of MOKE in the nanoporous magnetoplasmonic systems. It is an opportunity to allow a more precise design of nanostructured optical and magneto-optical devices for future biotechnological applications and magneto-optical sensors.

**Methods**

**Fabrication of Hybrid Multi-layered Nanoporous Films with Controlled AAO Substrates.** Hybrid multi-layered films Ag (5 nm)/ITo (10 nm)/CoFeB (10 nm)/ITo (10 nm)/Ag (5 nm) were fabricated on the prepared six different AAO substrates, respectively, by a multi-step magnetron sputtering deposition process at room temperature. Noticing that the noble metallic Ag and conductive indium tin oxides (ITO) targets were sputtered in a 15 mTorr Ar gas atmosphere using the direct current (dc) sputtering apparatus (MSP-300C, WeNi Chuangshi Inc.) with the power of 50 W. The ferromagnetic CoFeB layer was sputtered in a 0.75 mTorr Ar gas atmosphere using the radio frequency (rf) sputtering apparatus with the power of 100 W.

**Characterization of the Structure and Composition.** Scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) was used to characterize the top morphologies, angle tilted magnified surface information and compositions of the multi-layered nanoporous films.

**Characterization of Magneto-optical Kerr Rotation and Magnetic Domain.** The magneto-optical activity and the information of the magnetic domains of the prepared samples were investigated by the NanoMOKE-3 instrument (Durham Magneto Optics Ltd), a high-performance magneto-optical magnetometer and video Kerr microscopy.

With 660 nm monochromatic s-polarization light (incident angle 2°) and proper choice of a continuously changed external applied magnetic field \( H \) whose direction is perpendicular to the sample's surface, the polar magneto-optical Kerr effect (P-MOKE) with the magnetic field ranged from -1250 Oe to +1250 Oe with a ramp of 2.061 Oe/step was characterized. This experiment configuration was sketched in Fig. 5a.

As shown in Fig. 5b, when the direction of the magnetic field was parallel to the surface and the s-polarization light's incident angle was changed to 45°, the longitudinal magneto-optical Kerr effect (L-MOKE) information can be collected. In this experiment, similarly to the P-MOKE configuration, the excitation light wavelength was also 660 nm.

**Characterization of optical response.** In order to construct a reasonable model to interpret the special MO phenomena in hybridization of nanostructures and find the optical resonance position defined by the amplitude and the phase of the dipolar surface plasmon resonance (SPR) directly, far-field absorbance was evaluated and analyzed by the conventional UV-Vis-NIR spectrophotometer (UV 3600, 190 nm-3500 nm) from 300 nm to 1000 nm at room temperature.
References

1. Barnes, W. L., Dereux, A. & Ebbesen, T. W. Surface plasmon subwavelength optics. Nature 424, 842–830, doi:10.1038/nature02074 (2003).

2. Di Pietro, P. Observation of Dirac plasmons in a topological insulator. Nat Nano 8, 556–560, doi:10.1038/nnano.2013.134 (2013).

3. Won, K. View from… SMO-NP 2009: The promise of plasmonics. Nat Photon 3, 500–501 (2009).

4. Cui, Y., Phang, J. Y., Hegner, R. S., Lee, Y. H. & Ling, X. Y. Plasmonic Silver Halide Nanoparticle Structures for Two-Dimensional Multiple-Digit Molecular Data Storage Application. ACS Photonics 1, 631–637, doi:10.1021/acsphotonics.1000114 (2014).

5. O’Connor, D., McCurry, M., LaFerty, B. & Zayats, A. V. Plasmonic waveguide as an efficient transducer for high-density data storage. Applied Physics Letters 95, doi:10.1063/1.3527701 (2009).

6. Lee, I.-M., Kim, S., Oh, D. & Lee, B. In Information Optics and Optical Data Storage Vol. 7851 Proceedings of SPIE-The International Society for Optical Engineering (eds F. Song et al.) (2010).

7. O’Connor, D. & Zayats, A. V. DATA STORAGE The third plasmonic revolution. Nature Nanotechnology 5, 482–483 (2010).

8. Park, S. & Hahn, J. W. Plasmonic data storage medium with metallic nano-aperture array embedded in dielectric material. Optics Express 17, 20203–20210, doi:10.1364/oe.17.020203 (2009).

9. Rodriguez-Fortuno, F. J. et al. Highly-sensitive chemical detection in the infrared regime using plasmonic gold nanocrosses. Applied Physics Letters 98, doi:10.1063/1.3558916 (2011).

10. Matsuura, R., Tawa, K., Kitayama, Y. & Takeuchi, T. A plasmonic chip-based bio/chemical hybrid sensing system for the highly sensitive detection of C-reactive protein. Chemical Communications 52, 3883–3886, doi:10.1039/c5cc07868g (2016).

11. Kong, X. et al. In Frontiers in Biological Detection: From Nanosensors to Systems VII Vol. 9725 Proceedings of SPIE (eds B. L. Miller et al.) (2016).

12. Liang, X. et al. Tuning plasmonic and chemical enhancement for SERS detection on graphene-based Au hybrids. Nanoscale 7, 20188–20196, doi:10.1039/c5nr06010a (2015).

13. Barbellion, G., Bijeon, J. L., Lerondel, G., Plain, J. & Royer, P. Detection of chemical molecules with integrated plasmonic glass nanotips. Surface Science 602, L119–L122, doi:10.1016/j.susc.2008.06.032 (2008).

14. Pellegrotti, J. V. et al. Plasmonic Photothermal Fluorescence Modulation for Homogeneous Biosensing. ACS Sens. 1, 1351–1357, doi:10.1021/acssens.6b00512 (2016).

15. Tort, N., Salvador, J. P. & Marc, M. P. Multimodal plasmonic biosensing nanostructures prepared by DNA-directed immobilization of multifunctional DNA-gold nanoparticles. Biosens. Bioelectron. 90, 13–22, doi:10.1016/j.bios.2016.11.022 (2017).

16. Nishiguchi, K., Sueyoshi, K., Hisamoto, H. & Endo, T. Fabrication of gold-deposited plasmonic crystal based on nanoimprint lithography for label-free biosensing application. Japanese Journal of Applied Physics 55, doi:10.7567/jap.55.08re02 (2016).

17. Himnan, S. S. & Cheng, Q. Bioinspired assemblies and plasmonic interfaces for electrochemical biosensing. Journal of Electroanalytical Chemistry 781, 136–146, doi:10.1016/j.jelechem.2016.05.014 (2016).

18. Castro Arias, J., Cattoni, A., Decanini, D., Collin, S. & Haghiiri-Gosnet, A. M. Biosensing on a Chip: Study of Plasmonic Nanostructures Integrated in Microfluidic Devices. (2017).

19. Aristov, A. I. et al. 3D plasmonic crystal metamaterials for ultra-sensitive biosensing. Scientific Reports 6, doi:10.1038/srep25380 (2016).

20. Vinogradov, A. P. et al. In Magnetophotonics: From Theory to Applications (eds Mitsuturu Inoue, Miguel Levy, & Alexander V. Baryshev) 1–17 (Springer Berlin Heidelberg, 2013).

21. Uchida, K. et al. Generation of spin currents by surface plasmon resonance in Au nanoparticles embedded in Bi:YIG film. Journal of Magnetism and Magnetic Materials 321, 843–845, doi:10.1016/j.jmmm.2008.11.064 (2009).

22. Maksymov, I. S. Magneto-plasmonic nanoantennas: basics and applications (Review) arXiv. arXiv, 15 pp.-15 pp. (2016).

23. Liang, H. et al. Giant enhancement of Kerr rotation in two-dimensional Bismuth iron garnet/Ag photonic crystals. Chinese Physics B 24, doi:10.1088/1674-1056/24/6/067807 (2015).
44. Yaman, H., Takeda, K. & Kobayashi, M. Fabrication and magnetooptical properties of perpendicularly magnetic CoPt nanostructures formed by surface agglomeration of Ag. Japanese Journal of Applied Physics 54, doi:10.7567/jap.54.06509 (2015).
45. Yaman, H., Takeda, K. & Kobayashi, M. Magnetooptical Enhancement and Chemical Sensing Applications of Perpendicularly Magnetic CoPt/Ag Stacked Structures with a ZnO Intermediate Layer. Materials Transactions 57, 892–897, doi:10.2320/matertrans.M2015395 (2016).
46. Hamidi, S. M. & Ghaedi, O. Enhanced magneto-plasmonic effect in Au/Co/Au multilayers caused by exciton-plasmon strong coupling. Journal of Magnetism and Magnetic Materials 414, 122–125, doi:10.1016/j.jmmm.2016.04.060 (2016).
47. Kravets, A. F., Borodnova, T. I. & Kravets, V. G. Strong plasmon enhancement of magneto-optical Kerr rotation in Co-AIO nanogrannular films coated with gold nanoparticles. Journal of the Optical Society of America B-Optical Physics 33, 302–307, doi:10.1364/josab.33.000302 (2016).
48. Li, J., Tang, T., Zhang, Y. & Luo, L. Enhancement of the transverse magneto-optical Kerr effect via resonant tunneling in Au/CeTiOx/Au trilayers and its application. Laser Physics 27, doi:10.1088/1555-6611/aaf4f7 (2017).
49. Bossini, D., Belotelov, V. I., Zvezdin, A. K., Kalish, A. N. & Kimel, A. V. Magnetoplasmonics and Femtosecond Optomagnetism at the Nanoscale. Acs Photonics 3, 1385–1400, doi:10.1021/acsphtics.6b00107 (2016).
50. Bonanni, V. et al. Designer Magnetoplasmonics with Nickel Nanoferrromagnets. Nano Letters 11, 5333–5338, doi:10.1021/nl2028443 (2011).
51. Lodewijks, K. et al. Magnetoplasmonic Design Rules for Active Magneto-Optics. Nano Letters 14, 7207–7214, doi:10.1021/nl504166n (2014).
52. Northup, T. E. & Blatt, R. Quantum information transfer using photons. Nature Photonics 8, 356–363, doi:10.1038/nphoton.2014.53 (2014).
53. Peyronel, T. et al. Quantum nonlinear optics with single photons enabled by strongly interacting atoms. Nature 488, 57–60, doi:10.1038/nature11361 (2012).
54. Chen, J. Y. et al. Time-Resolved Magneto-Optical Kerr Effect of Magnetic Thin Films for Ultrafast Thermal Characterization. The journal of physical chemistry letters 7, 2328–2332, doi:10.1021/acs.jpclett.6b00945 (2016).
55. Song, Y. et al. Microfluidic synthesis of cobalt nanoparticles. Chem. Mater. 18, 2817–2827 (2006).
56. Kreibig, U. & Vollmer, M. Optical Properties of Metal Clusters. (Springer, 1995).
57. Belotelov, V. I., Belotelov, V. I., Zvezdin, A. K., Kalish, A. N. & Kimel, A. V. Magnetoplasmonics and Femtosecond Optomagnetism at the Nanoscale. Acs Photonics 3, 1385–1400, doi:10.1021/acsphtics.6b00107 (2016).
58. Walter, D. Metal clusters (Chichester, New York: Wiley) (1999).
59. Kazuma, M., Takehito, K. & Tsuguo, S. Anal. Chem. 70, 5037–5041 (1998).
60. Nie, S. & Emory, S. R. Probing Single Molecules and Single Nanoparticles by Surface-Enhanced Raman Scattering. Science 275, 1102–1106 (1997).
61. Kim, H. B. et al. Anal. Chem. 68, 409 (1996).
62. Xu, H.-N. & Patel, R. Imaging and Assembly of Nanoparticles in Biological Systems. In Handbook of Nanostructured Bitumaterials and their Applications in Nanobiotechnology (Ed. Nalwa H S), p. 1–22. Vol. 1 (2005).
63. Armeles, G., Cebollada, A., Garcia-Martín, A. & González, M. U. Magnetoplasmonic: Combining Magnetic and Plasmonic Functionalities. Advanced Optical Materials 1, 10–35, doi:10.1002/adom.201200111 (2013).
64. Raschke, G. et al. Nano Letters 3, 935–938 (2003).
65. González-Díaz, J. B. et al. Enhanced Magneto-Optics and Size Effects in Ferromagnetic Nanowire Arrays. Advanced Materials 19, 2643–2647, doi:10.1002/adma.200602938 (2007).
66. Song, Y. et al. Investigations into sulfolobetine-stabilized Cu nanoparticle formation: toward development of a microfluidic synthesis. J. Phys. Chem. B 109, 9330–9338 (2005).
67. Wurtz, G. A. et al. Controlling optical transmission through magneto-plasmonic crystals with an external magnetic field. New Journal of Physics 10, 105012, doi:10.1088/1367-2630/10/10/105012 (2008).
68. González-Díaz, J. B. et al. Plasmonic Au/Co/Au Nanowires with Enhanced Magneto-optical Activity. Small 4, 202–205, doi:10.1002/smll.200700594 (2008).
69. Thompson, G. E., Furneaux, R. C., Wood, G. C., Richardson, J. A. & Goode, J. S. Nucleation and growth of porous anodic films on aluminium. Nature 272, 433–435, doi:10.1038/272433a0 (1978).
70. Jessensky, O., Müller, F. & Gosele, U. Self-organized formation of hexagonal pore arrays in anodic alumina. Applied Physics Letters 72, 1173–1175, doi:10.1063/1.121004 (1998).
71. Masuda, H., Hasegawa, F. & Ono, S. Self-ordering of cell arrangement of anodic porous alumina formed in sulfuric acid solution. Journal of the Electrochemical Society 144, L127–130, doi:10.1149/1.1837634 (1997).
72. Huber, C. A. et al. Nanowire array composites. Science (New York, N.Y.) 263, 800–802, doi:10.1126/science.263.5148.800 (1994).
73. Song, Y., Wang, Y., Li, B. B., Fernandes, C. & Ruda, H. E. Interface interaction induced ultra-dense nanoparticles assemblies. Nanoscale 5, 6779–6789, doi:10.1039/c3nr1366a (2013).
74. Awad, A. M., Shehata, O. S. & Heikal, F. E. T. Effect of various de-anodizing techniques on the surface stability of non-colored and colored nanoporous AAO films in acidic solution. Applied Surface Science 359, 939–947, doi:10.1016/j.apsusc.2015.10.221 (2015).
75. Kituchi, T., Nishinaga, O., Natsui, S. & Suzuki, R. O. Self-Ordering of Anodic Porous Alumina via Selenic Acid Anodizing. Electrochimica Acta 137, 728–735, doi:10.1016/j.electacta.2014.06.078 (2014).
76. Cepak, V. M. et al. Chemical Strategies for Template Syntheses of Composite Micro- and Nanostructures. Chemistry of Materials 9, 1065–1067, doi:10.1021/cm970014c (1997).
77. Lee, W. R., Gosele, U. & Nielsch, K. Fast fabrication of long-range ordered porous alumina membranes by hard anodization. Nature Materials 5, 741–747, doi:10.1038/nmat1717 (2006).
78. Karmhag, R., Tesfamichael, T., Wackelgard, E., Niklasson, A. & Nygren, M. Oxidation kinetics of nickel particles: Comparison between free particles and particles in an oxide matrix. Solar Energy 68, 329–333, doi:10.1016/s0038-092x(00)00025-6 (2000).
79. Che, G., Lakshmi, B. B., Fisher, E. R. & Martin, C. R. Carbon nanotubule membranes for electrochemical energy storage and production. Nature 393, 346–349 (1998).
80. Che, G., Lakshmi, B. B., Martin, C. R. & Fisher, E. R. Metal-nanocluster-filled carbon nanotubes: Catalytic properties and possible applications in electrochemical energy storage and production. Langmuir 15, 750–758, doi:10.1021/la980663i (1999).
81. Che, G., Lakshmi, B. B., Martin, C. R., Fisher, E. R. & Ruoff, R. S. Chemical Vapor Deposition Based Synthesis of Carbon Nanotubes and Nanofibers Using a Template Method. Chemistry of Materials 10, 260–267, doi:10.1021/cm970412f (1998).
Byun, J. L. Method for manufacturing metal oxide nanostructure of porous network structure, involves injecting photo catalyst substance precursor into anode oxidation aluminum (AAO) template. KR2015021095-A (2015).

Wang, Q., Shimizu, T. & Shingubara, S. Control of crystalline orientation and diameter of Si nanowires based on VLS method and electrodeposition of catalyst using AAO template. (2011).

Ibanes, J. J. et al. In Physics of Semiconductor: 30th International Conference on the Physics of Semiconductors Vol. 1399 AIP Conference Proceedings (eds J. Ihm & H. Cheong) (2011).

Nielch, K. et al. Hexagonally ordered 100 nm period nickel nanowire arrays. Applied Physics Letters 79, 1360–1362, doi:10.1063/1.1399006 (2001).

Furneaux, R. C., Rigby, W. R. & Davidson, A. P. The formation of controlled-porosity membranes from anodically oxidized aluminum. Nature 337, 147–149, doi:10.1038/337147a0 (1989).

Chaturvedi, P., Rodriguez, S. D., Vlassiouk, I., Hansen, I. A. & Smirnov, S. N. Simple and Versatile Detection of Viruses Using Anodized Alumina Membranes. ACS Sens. 1, 488–492, doi:10.1021/acssens.6b00033 (2016).

Alighoul, S., Hallat, M., Zivanovic, S., Que, L. & Shah, G. V. Measurement of serum prostate cancer markers using a nanopore thin film based optothermal chip. Biosens. Bioelectron 77, 491–498, doi:10.1016/j.bios.2015.10.006 (2016).

Silina, Y. E., Kychmenko, T. A. & Koch, M. Nanoporous anodic aluminum oxide films for UV/vis detection of noble and non-noble metals. Anal. Methods 8, 45–51, doi:10.1039/c5ay02498f (2016).

Lee, S. B. et al. Antibody-based bio-nanotube membranes for enantiomeric drug separations. Science 296, 2198–2200, doi:10.1126/ science.1071396 (2002).

Taberna, L., Mitra, S., Poizot, P., Simon, P. & Tarascon, J. M. High rate capabilities Fe3O4-based Cu nano-architected electrodes for lithium-ion battery applications. Nature Materials 5, 567–573, doi:10.1038/nmat1672 (2006).

Lombardi, L., Magagnin, L., Cavalliott, P. L., Carraro, C. & Maboudian, R. Electrochemical fabrication of supported Ni nanostructures through transferred porous anodic alumina mask. Electrochemical and Solid State Letters 9, D13–D16, doi:10.1149/1.2181287 (2006).

Li, F., Zhang, L. & Metzger, R. M. On the growth of highly ordered pores in anodized aluminum oxide. Chem. Mater. 10, 2470–2480 (1998).

Norek, M. et al. Multi-band emission in a wide wavelength range from tin oxide/Au nanocomposites grown on porous anodic alumina substrate (AAO). Applied Surface Science 287, 143–149, doi:10.1016/j.apsusc.2013.09.101 (2013).

Högemann, D., Josephson, L., Weissleder, R. & Basilion, J. P. Bioconjug. Chem. 11, 941–946 (2000).

Santos, A. et al. Tunable Fabry-Perot interferometer based on nanoporous anodic alumina for optical biosensing purposes. Nanoscale Res. Lett. 7, 4, doi:10.1186/1556-276x-7-370 (2012).

Gardelis, S., Nasiopoulos, A. G., Gianneta, V. & Theodoropoulou, M. Photoluminescence-induced oscillations in porous anodic aluminium oxide films grown on Si: Effect of the interface and porosity. Journal of Applied Physics 107, 943205, doi:10.1063/1.3432694 (2010).

Berciaud, S. et al. Ultrasensitive and Single-Molecule Detection Technologies. Proceedings of SPIE-The International Society for Optical Engineering 6092 60920A/6092A/6092A/60928 (2006).

Musken O. L., D. F. N., Vallee P., Broyer M. AIP. Phys. Lett. 88, 063109 (2006).

Chan, S., Okuyama, K., M. D. L. & Juan, F. Aerosol Science and Technology 37, 791–803 (2003).

Maccarreri, N. et al. Tuning the Magneto-Optical Response of Nanosize Ferromagnetic Ni Disks Using the Phase of Localized Plasmons. Physical Review Letters 111, 5, doi:10.1103/PhysRevLett.111.167401 (2013).

Chin, Y. J. et al. Nonreciprocal plasmonics enables giant enhancement of thin-film Faraday rotation. Nature Communications 4, 1599, doi:10.1038/ncomms2609 (2013).

Maccarreri, N. et al. Ultrasensitive and label-free molecular-level detection enabled by light phase control in magnetoplasmonic nanoantennas. Nature Communications 6, 6150, doi:10.1038/ncomms7150 (2015).

Graham, D. L., Ferreira, H. A. & Freitas, P. P. Trends in Biotechnology 22, 455–462 (2004).

Maccarreri, N. et al. Effects of a non-absorbing substrate on the magneto-optical Kerr response of plasmonic ferromagnetic nanodisks. physica status solidi (a) 211, 1067–1075, doi:10.1002/pssa.201300701 (2014).

Acknowledgements
This work was supported by NSFC (Grant No. 51371018) and the Fundamental Research Funds for the Central Universities (FR-BR-15-027A & FR-BR-14-001B). The authors appreciate Professor Kaiyou Wang and Mr. Yu Sheng from Institute of Semiconductors of Chinese Academy of Sciences for the help in the use of the NanoMOKE-3 system.

Author Contributions
W.W.Zhang, J.J.Li and X.K.Ding planned the experiments. Y.J.Song, W.W.Zhang and J.J.Li performed the experiment. Y.J.Song, W.W.Zhang, P.Pernod and N.Tiercelin analyzed the data. Y.J. Song and W.W. Zhang wrote the main manuscript text. All authors have approved the final version of the manuscript.

Additional Information
Supplementary information accompanies this paper at doi:10.1038/s41598-017-03241-7

Competing Interests: The authors declare that they have no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.