Generation of spin currents by surface plasmon resonance

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Surface plasmons, free-electron collective oscillations in metallic nanostructures, provide abundant routes to manipulate light-electron interactions that can localize light energy and alter electromagnetic field distributions at subwavelength scales. The research field of plasmonics thus integrates nano-photonics with electronics. In contrast, electronics is also entering a new era of spintronics, where spin currents play a central role in driving devices. However, plasmonics and spin-current physics have so far been developed independently. Here we report the generation of spin currents by surface plasmon resonance. Using Au nanoparticles embedded in Pt/BiY2Fe5O12 bilayer films, we show that, when the Au nanoparticles fulfill the surface-plasmon-resonance conditions, spin currents are generated across the Pt/BiY2Fe5O12 interface. This spin-current generation cannot be explained by conventional heating effects, requiring us to introduce nonequilibrium magnons excited by surface-plasmon-induced evanescent electromagnetic fields in BiY2Fe5O12. This plasmonic spin pumping integrates surface plasmons with spin-current physics, opening the door to plasmonic spintronics.
Surface plasmons enable subdiffraction-limit localization of light and strong enhancement of electromagnetic fields. Owing to this feature, plasmonics has vast potential in solar cells, light generation, microscopy, data storage and biosensors. One of the other emerging developments in this field is magneto-plasmonics, which offers unique possibilities to manipulate light by the use of external magnetic fields or magnetic materials. Important topics in magneto-plasmonics include the enhancement of magneto-optical effects in plasmonic nanostructures, influence of magnetic fields on surface plasmon resonance (SPR) and observation of SPR in ferromagnetic metals. However, the integration of plasmonics into spintronics is yet to be realized, and the interaction between surface plasmons and spin currents contains unexplored physics.

In the field of spintronics, for spin-current generation, we often rely on a spin pumping effect, which refers to the transfer of spin-angular momentum from magnetization dynamics in a ferromagnet to conduction-electron spins in an attached paramagnet; when a motion of magnetic moments in the ferromagnet is excited, a spin current is pumped out of the ferromagnet into the paramagnet.

Recent studies in spintronics have revealed that there are two types of spin pumping effects. One is coherent spin pumping, which is due to coherent phase precession of the magnetization, that is, ferromagnetic or spin-wave resonances in ferromagnets typically excited by microwave irradiation. The other is incoherent spin pumping, which is due to a nonequilibrium state of spins at a ferromagnet/paramagnet interface excited by incoherent external perturbations; when magnons in the ferromagnet and/or electrons in the paramagnet deviate from thermal equilibrium, a net spin current is generated across the interface. A typical example of the incoherent spin pumping is the spin Seebeck effect, where the magnon/electron distribution functions are modulated by external temperature gradients.

In this work, we report the observation of plasmonic spin pumping; we show that the incoherent spin pumping can be driven by surface plasmons under visible light illumination. This plasmonic spin pumping will invigorate research in both the fields of spintronics and plasmonics, paving the way to create new devices, such as solar spin-current generators and spin-based plasmonic sensors.

### Results

#### Device structure

Figure 1a shows a schematic illustration of the sample system used in the present study. The sample consists of a paramagnetic Pt/ferrimagnetic BiY$_2$Fe$_5$O$_{12}$ bilayer film with Au nanoparticles (NPs) embedded in the BiY$_2$Fe$_5$O$_{12}$ layer. The Au NPs have an in-plane diameter of 30–90 nm and a height of 20–50 nm. A 110-nm-thick BiY$_2$Fe$_5$O$_{12}$ film was then coated on them by means of a metal-organic decomposition (MOD) method (see Methods). Finally, a 5-nm-thick Pt film was sputtered onto the BiY$_2$Fe$_5$O$_{12}$ film. To excite surface plasmons, the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample was illuminated with unpolarized monochromatic light with wavelength $\lambda$ (400–770 nm) and power $P$ from the Pt-film side at normal incidence (Fig. 1a). As the Pt and BiY$_2$Fe$_5$O$_{12}$ layers are very thin, the light passes through the layers and interacts with the Au NPs. We checked that the electric resistance between the ends of the BiY$_2$Fe$_5$O$_{12}$ layer with Au NPs under the light illumination is much greater than the measurement limit of our electrometer ($>2 \times 10^{11}$ Ω) at all the $\lambda$ values; the possibility of optical charge-carrier generation in BiY$_2$Fe$_5$O$_{12}$ is excluded.

In Fig. 1c, we show the light-transmittance spectrum of the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample (see the blue circle data points). We found that the sample exhibits a clear dip structure in the transmittance spectrum around $\lambda = 690$ nm in comparison with the spectra of a Gd$_3$Ga$_5$O$_{12}$ substrate, a plain Pt film and...
interaction in Pt. When magnons in the BiY$_2$Fe$_5$O$_{12}$ film and the excited magnons drive fields concomitant with surface plasmons in Au NPs excite localized SPR\(^1\),\(^2\) in the Au NPs embedded in the BiY$_2$Fe$_5$O$_{12}$ substrate due to the SPR, while that of the Au film does not exhibit strong J due to the SPR, (Fig. 1b). This plasmon-induced spin current is converted into a measurement mechanism of plasmonic spin pumping position and size of Au NPs (Supplementary Figs 1 and 2).

Electromagnetic field distributions. To visualize the SPR in the BiY$_2$Fe$_5$O$_{12}$/Au-NP sample by means of a finite-difference time-domain (FDTD) method\(^25\). Figure 3a shows a schematic illustration of a BiY$_2$Fe$_5$O$_{12}$/Au-NP model used for the FDTD simulations (see Methods for details). As shown in Fig. 3b, under the SPR condition (\(\lambda = 690 \text{ nm}\)), strong evanescent electromagnetic fields, that is, near fields\(^1\),\(^2\), are generated in the BiY$_2$Fe$_5$O$_{12}$ film in the vicinity of the BiY$_2$Fe$_5$O$_{12}$/Au-NP interface, while the enhancement and localization of electromagnetic fields do not appear at \(\lambda = 500 \text{ nm}\) (Fig. 3c), consistent with the light-transmittance spectrum of the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample in Fig. 1c. The FDTD simulations also show that the evanescent electromagnetic fields in the BiY$_2$Fe$_5$O$_{12}$ layer due to the SPR are not affected by the presence of the Pt layer irrespective of the position and size of Au NPs (Supplementary Figs 1 and 2).

Observation of plasmonic spin pumping. To observe the plasmonic spin pumping, we measured an electric voltage \(V\) between the ends of the Pt layer under open circuit condition (with the magnitude \(H\)) to the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample along the \(x\)-\(y\) plane (Fig. 1a). All of the \(V\) measurements were carried out at room temperature and atmospheric pressure.

Measurement mechanism of plasmonic spin pumping. In the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample, if the evanescent electromagnetic fields concomitant with surface plasmons in Au NPs excite magnons in the BiY$_2$Fe$_5$O$_{12}$ film and the excited magnons drive the incoherent spin pumping, a spin current is generated in the Pt layer with the spatial direction \(J_s\) and the spin-polarization vector \(\sigma\) parallel to the magnetization \(M\) of the BiY$_2$Fe$_5$O$_{12}$ film (Fig. 1b). This plasmon-induced spin current is converted into a d.c. charge current \(J_c\) due to the inverse spin Hall effect (ISHE)\(^{14,26,27}\) in the Pt layer owing to the strong spin-orbit interaction in Pt. When \(M\) of the BiY$_2$Fe$_5$O$_{12}$ film is along the \(x\) direction, \(J_c\) is generated along the \(y\) direction because of the following ISHE symmetry:

\[
J_c \propto I_x \times \sigma
\]  

(1)

where the \(x\), \(y\) and \(z\) directions are defined in Fig. 1b. We note that extrinsic artefacts induced by a static magnetic proximity effect\(^28\) at the Pt/BiY$_2$Fe$_5$O$_{12}$ interface are negligibly small in the present structure\(^23,24\). To detect the ISHE induced by the plasmonic spin pumping, we measured an electric voltage \(V\) between the ends of the Pt layer under open circuit condition while illuminating with monochromatic light and applying an external magnetic field \(H\) (with the magnitude \(H\)) to the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample along the \(x\)-\(y\) plane (Fig. 1a). All of the \(V\) measurements were carried out at room temperature and atmospheric pressure.
Now we are in a position to investigate the plasmonic generation of spin currents. The blue circle data points in Fig. 4b are the V/P spectrum in the Pt/BiY2Fe5O12 film that contains Au NPs. Also in this Pt/BiY2Fe5O12/Au-NP sample, when H || x, the V/P signal appears with the same sign (Fig. 4b) and the magnitude of V is proportional to the light power P (Fig. 4c). The sign of the signal at each λ was observed to be reversed by reversing H with a hysteresis loop, indicating that the signal is affected by the M direction of the BiY2Fe5O12 layer (Fig. 4d). As also shown in Fig. 4b, we confirmed that the V/P signal disappears when H is applied along the y direction, consistent with equation (1). These results indicate that the observed V/P signal in the Pt/BiY2Fe5O12/Au-NP sample is due to the ISHE induced by spin currents in the Pt layer. Significantly, Fig. 4b shows that the V/P signal in the Pt/BiY2Fe5O12/Au-NP sample exhibits peak structure and is markedly enhanced around λ = 690 nm. This peak position in the V/P spectrum coincides with the SPR wavelength of this Pt/BiY2Fe5O12/Au-NP sample (Fig. 4a,b). As both the Pt/BiY2Fe5O12/Au-NP and Pt/BiY2Fe5O12 samples are illuminated from the Pt-film side, the temperature rise of the Pt layer is almost the same for both, confirming that the heating of the Pt layer is irrelevant to the ISHE enhancement under the SPR condition in the Pt/BiY2Fe5O12/Au-NP sample (see Supplementary Fig. 4 and Supplementary Note 1), where we note again that the background heating signal does not exhibit strong λ dependence. This peak V/P structure in the Pt/BiY2Fe5O12/Au-NP sample also cannot be explained by the heating of Au NPs or the BiY2Fe5O12 layer under the SPR condition because of the different sign; if the BiY2Fe5O12 layer was heated by electromagnetic loss in Au NPs, the ISHE voltage should decrease under the SPR condition as the temperature gradient generated by the Au-NP heating across the Pt/BiY2Fe5O12 interface is of an opposite sign to the case when the Pt layer is heated (see Supplementary Fig. 4 and Supplementary Note 1). A possible slight heating of Au NPs in the off-resonance region might reduce the magnitude of the background signal slightly, but is also irrelevant to the V/P signal with the positive peak structure. Our numerical calculations of electromagnetic field distributions based on the FDTD method show that the electromagnetic coupling between the Pt film and Au NPs under the SPR condition is too weak to explain the enhancement of the ISHE signal in the Pt/BiY2Fe5O12/Au-NP sample; as no SPR mode due to the coupling appears in the configuration used in this study, the temperature rise of the Pt layer is not changed by the SPR in Au NPs (Supplementary Figs 1 and 2).

We also performed control experiments by using different materials. We found that similar V/P signals appear in a
Along the x direction. The scale bars represent V/P = 20 × 10⁻⁶ V W⁻¹. All the control experiments were performed by using the samples of a 10 mm × 5 mm rectangular shape.

Au-film/BiY₂Fe₅O₁₂/Au-NP sample, where the Pt film is replaced with a 5-nm-thick Au film (Fig. 5a,b); as Au is a typical metal far from ferromagnetism, proximity ferromagnetism in Pt cannot be the origin of the observed peak voltage structure. In contrast, this voltage signal was found to disappear in a Cu/BiY₂Fe₅O₁₂/Au-NP sample, where the Pt layer is replaced with a 5-nm-thick Cu film in which the spin-orbit interaction is far from ferromagnetism, proximity ferromagnetism in Pt or the ISHE, in the voltage generation (Fig. 6a,c). The voltage dependence of the light transmittance of the Cu/BiY₂Fe₅O₁₂/Au-NP (a) and Pt/Gd₃Ga₅O₁₂/Au-NP (b) samples. (c,d) H dependence of V/P in the Cu/BiY₂Fe₅O₁₂/Au-NP (c) and Pt/Gd₃Ga₅O₁₂/Au-NP (d) samples for various values of λ (λ = 760, 740,…, 400 nm), measured when H was along the x direction. The scale bars represent V/P = 20 × 10⁻⁶ V W⁻¹. All the control experiments were performed by using the samples of a 10 mm × 5 mm rectangular shape.

Figure 6 | Control experiments using different materials. (a,b) λ dependence of the light transmittance of the Cu/BiY₂Fe₅O₁₂/Au-NP (a) and Pt/Gd₃Ga₅O₁₂/Au-NP (b) samples. (c,d) H dependence of V/P in the Cu/BiY₂Fe₅O₁₂/Au-NP (c) and Pt/Gd₃Ga₅O₁₂/Au-NP (d) samples for various values of λ (λ = 760, 740,…, 400 nm), measured when H was along the x direction. The scale bars represent V/P = 20 × 10⁻⁶ V W⁻¹. All the control experiments were performed by using the samples of a 10 mm × 5 mm rectangular shape.

Au-film/BiY₂Fe₅O₁₂/Au-NP sample, where the Pt film is replaced with a 5-nm-thick Au film (Fig. 5a,b); as Au is a typical metal far from ferromagnetism, proximity ferromagnetism in Pt cannot be the origin of the observed peak voltage structure. In contrast, this voltage signal was found to disappear in a Cu/BiY₂Fe₅O₁₂/Au-NP sample, where the Pt layer is replaced with a 5-nm-thick Cu film in which the spin-orbit interaction is far from ferromagnetism, proximity ferromagnetism in Pt or the ISHE, in the voltage generation (Fig. 6a,c). The voltage signal also disappears in a Pt/Gd₃Ga₅O₁₂/Au-NP sample, where the Pt film is replaced with a 5-nm-thick Au film (Fig. 5a,b); as Au is a typical metal far from ferromagnetism, proximity ferromagnetism in Pt or the ISHE, in the voltage generation (Fig. 6a,c). The voltage dependence of the light transmittance of the Cu/BiY₂Fe₅O₁₂/Au-NP (a) and Pt/Gd₃Ga₅O₁₂/Au-NP (b) samples. (c,d) H dependence of V/P in the Cu/BiY₂Fe₅O₁₂/Au-NP (c) and Pt/Gd₃Ga₅O₁₂/Au-NP (d) samples for various values of λ (λ = 760, 740,…, 400 nm), measured when H was along the x direction. The scale bars represent V/P = 20 × 10⁻⁶ V W⁻¹. All the control experiments were performed by using the samples of a 10 mm × 5 mm rectangular shape.

Separation of plasmonic spin pumping from heating effects. To further verify the effect of surface plasmons on the spin-current generation, we measured the V/P spectra in the Pt/BiY₂Fe₅O₁₂/Au-NP samples on changing the contact condition between BiY₂Fe₅O₁₂ and Au NPs. Here, we prepared the Pt/BiY₂Fe₅O₁₂/Au-NP samples by means of two different annealing conditions for the BiY₂Fe₅O₁₂ layer (see Methods for details). In the Pt/BiY₂Fe₅O₁₂/Au-NP sample used for the experiments in Fig. 4, Au NPs are densely embedded in the BiY₂Fe₅O₁₂ film (Fig. 7a–c), where the peak V/P structure appears under the SPR condition (Fig. 8a–d). In contrast, we also fabricate the Pt/BiY₂Fe₅O₁₂/Au-NP sample in which the Au NPs are separated from the BiY₂Fe₅O₁₂ film by small voids (Fig. 7d–f), which interrupt the interaction between magnons in BiY₂Fe₅O₁₂ and surface plasmons in Au NPs as the evanescent electromagnetic fields generated by the SPR are localized in the vicinity of Au NPs (Supplementary Fig. 5). The difference in the SPR wavelength between the ‘contacted’ and ‘voided’ Pt/BiY₂Fe₅O₁₂/Au-NP samples is attributed to the difference in the dielectric constant of the medium around Au NPs; As Au NPs in the voided Pt/BiY₂Fe₅O₁₂/Au-NP sample are surrounded by voids, its SPR
wavelength is closer to that of plain Au NPs without BiY₂Fe₅O₁₂ (compare Figs 2a and 8c,h). In the voided Pt/BiY₂Fe₅O₁₂/Au-NP sample, dip structure was found to appear in the $V/I$ spectrum under the SPR condition (Fig. 8f–i). This behaviour was observed not only in one sample but also in our different samples as exemplified in Fig. 8e,j. The dip $V/I$ signal in the voided Pt/BiY₂Fe₅O₁₂/Au-NP sample is attributed to the heating of Au NPs by the SPR, which generates the temperature gradient across the Pt/BiY₂Fe₅O₁₂ interface and the longitudinal spin Seebeck voltage along the direction opposite to the case when the Pt layer is heated (see Supplementary Figs 4, 5 and Supplementary Note 1). These results indicate that the enhancement of the ISHE under the SPR condition, observed in the contacted Pt/BiY₂Fe₅O₁₂/Au-NP sample, requires direct contact between the BiY₂Fe₅O₁₂ and the Au NPs and cannot be explained by conventional heating effects, providing evidence for the operation of the plasmonic spin pumping due to nonequilibrium magnons excited by surface plasmons.

**Discussion**

The above experiments clearly show that the spin current generated by the light illumination in the contacted Pt/BiY₂Fe₅O₁₂/Au-NP sample is strongly enhanced under the SPR condition, and this enhancement is not connected to extrinsic heating effects. So then, what is the origin of the spin current under the SPR condition? Following previous studies on the incoherent spin pumping [31,32], to generate the positive ISHE voltage in the present configuration, magnons in the BiY₂Fe₅O₁₂ layer should be excited (see Supplementary Notes 1 and 2). A potential candidate for the magnon-excitation mechanism in the present sample structure is the strong evanescent electromagnetic fields (near-field photons) concomitant with surface plasmons. If the near-field photons excite magnons via the magnon–photon interaction [33–38] near the BiY₂Fe₅O₁₂/Au-NP interface, the excited magnons in the BiY₂Fe₅O₁₂ layer produce a spin current owing to the incoherent spin-pumping mechanism and the positive ISHE voltage in the Pt layer: this is the plasmonic spin pumping. Using a standard many-body technique, we formulate theoretically the plasmonic spin pumping based on magnon–photon Raman scattering process (Supplementary Fig. 6). The spin current pumped by light illumination is described as

$$J_S = \Gamma^+ \Gamma^- G_S \frac{\hbar v a t}{c z} |E|^2$$

within the linear response region (see Supplementary Note 2 for details). Here, $\Gamma^+ (\Gamma^-)$ is the dimensionless magnon–photon coupling constant, $G_S$ the strength of the magnetic coupling at the
Pt/BiY$_2$Fe$_5$O$_{12}$ interface, $\hbar$ the Planck constant divided by $2\pi$, $\nu$ the photon frequency, $c$ the velocity of light, $\alpha$ the effective block spin volume, $z$ the Gilbert damping constant and $E$ the electric field amplitude induced by surface plasmons. Equation (2) indicates that the plasmon-induced spin current in the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample is proportional to the electromagnetic energy in the BiY$_2$Fe$_5$O$_{12}$ layer ($\propto |\mathbf{E}|^2$), a situation consistent with the experimental results in Fig. 4c as $|\mathbf{E}|^2$ generated by surface plasmons is proportional to the incident light power $P$. The observed peak ISHE voltage in the contacted Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample is attributed to the strong evanescent electromagnetic fields enhanced by surface plasmons, while the spin current described by Equation (2) is undetectably small in the plain Pt/BiY$_2$Fe$_5$O$_{12}$ film due to the small energy transfer from external photons to magnons (see Supplementary Note 2). Note that the ratio of the voltage enhancement in Fig. 4b does not correspond to that of the $|\mathbf{E}|^2$ enhancement due to the presence of the background heating signal.

The plasmonic spin pumping observed here can be applied to the construction of light/spin-current converters for driving spintronic devices. The plasmonic spin pumping also adds a light/voltage conversion function to spin Seebeck thermoelectric devices$^{2,3}$, enabling hybrid voltage generation from both light and heat in a single device. The plasmonic spin pumping follows the same scaling law as the spin Seebeck effect: the output power is increased simply by extending the device area. This light/voltage conversion is conceptually different from that based on a PN junction, and is free from the output-voltage limitation caused by built-in potential. Although the spin and electric voltages generated by the plasmonic spin pumping are still small, there is plenty of scope for performance improvement; they can be enhanced by using magnetic insulators with large magnon–photon coupling, improving magnetic-insulator/NP interfaces for efficient magnon-plasmon energy transfer, and introducing plasmonic crystals that exhibit sharp and strong SPR. Plasmonic spintronics based on the interaction between surface plasmons and spin currents is still in its infancy; more detailed experimental and theoretical investigations are necessary to obtain full understanding of the mechanism of the plasmonic spin pumping and to quantitatively evaluate plasmon-magnon-electron conversion efficiency, which might be realized by removing the size, position and shape variations of Au NPs.

Methods

Preparation process of Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP samples. The Au NPs were formed by the following two-step procedures: fabrication of a 5-nm-thick Au thin film on a Gd$_3$Ga$_5$O$_{12}$ (111) substrate by using a d.c. sputtering system and heating the Au film at 1,000 °C for 30 min (ref. 6). To increase the density of Au NPs, these procedures were repeated three times. The BiY$_2$Fe$_5$O$_{12}$ thin film was then formed by the MOD method$^{22}$. The MOD solution for the contacted (voided) Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample includes Bi, Y and Fe carbonylates, dissolved in organic solvents with the concentration of 3%. Its chemical composition is Gd$_3$Ga$_5$O$_{12}$. The spin-coating and annealing processes for the Gd$_3$Ga$_5$O$_{12}$ film in the contacted Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample. Finally, a 5-nm-thick Pt film was deposited over the whole surface of the Gd$_3$Ga$_5$O$_{12}$ film. The mean distance between the Pt film and Au NPs in the Pt/Gd$_3$Ga$_5$O$_{12}$/Au-NP sample is ~100 nm, which is comparable to that in the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample.

Numerical calculation. To investigate the electromagnetic field distributions induced by surface plasmons, we performed the numerical calculation based on the FDTD method$^{23}$ using KeyFDTD (Science Technology Research Institute, Japan). The simulation results shown in Fig. 3 were obtained from a model comprising a BiY$_2$Fe$_5$O$_{12}$ rectangular parallelepiped with the size of 150 nm × 150 nm × 140 nm and a Au sphere with the in-plane diameter $d_{\text{Au}}$ of 70 nm and the height $h_{\text{Au}}$ of 40 nm embedded at the center of the BiY$_2$Fe$_5$O$_{12}$, where the distance $L$ between the tops of the BiY$_2$Fe$_5$O$_{12}$ and the Au is 50 nm. The unit cell of the model is $2\times 2 \times 1$ nm. A flat light source is placed on the top of the BiY$_2$Fe$_5$O$_{12}$ rectangular parallelepiped in the $x$-$y$ plane, which generates plane electromagnetic waves with the polarization along the $x$ direction and the wave vector $k$ along the $z$ direction (note that the incident light used in the experiments is unpolarized). Here, the $x$, $y$, and $z$ directions are defined in Fig. 3a. At the outer boundaries of the BiY$_2$Fe$_5$O$_{12}$, we set a periodic boundary condition. Under this condition, we calculated the distribution of the electric field intensity $|\mathbf{E}|$ while fixing the wavelength of the incident electromagnetic waves. In Fig. 3b,c, we plot the $|\mathbf{E}|$ distribution in the BiY$_2$Fe$_5$O$_{12}$/Au-NP model in the $x$-$y$ plane cross the centre of the Au sphere. By using the FDTD method and similar models, we have also investigated the electromagnetic coupling between the Pt film and Au NPs in the Pt/BiY$_2$Fe$_5$O$_{12}$/Au-NP sample, which might affect the voltage signal under the SPR condition, by comparing the simulated distributions of $|\mathbf{E}|$ induced by the SPR between the BiY$_2$Fe$_5$O$_{12}$/Au-NP models with and without the Pt layer for various values of $L$, $d_{\text{Au}}$, and $h_{\text{Au}}$ (Supplementary Figs 1 and 2). In Supplementary Fig. 5, we compared the $|\mathbf{E}|$ distributions between the BiY$_2$Fe$_5$O$_{12}$/Au-NP models with and without a void. The refraction index and absorption-constant spectra of BiY$_2$Fe$_5$O$_{12}$, Au and Pt in the calculations were obtained from refs 37–39, respectively.

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Author contributions
K.U. and E.S. planned and supervised the study. K.U. designed the experiments, prepared the samples, collected and analysed all of the data and performed the numerical calculation. H.A. and S.M. developed the explanation of the experiments. D.K. performed the scanning electron microscopy. S.I. performed the transmission electron microscopy. Z.Q. supported the sample preparation. K.U. and H.A. wrote the manuscript with input from E.S. and S.M. All authors discussed the results.

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