Rapid Communications

Electron spin transport driven by surface plasmon polaritons

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We propose a mechanism of angular momentum conversion from optical transverse spin in surface plasmon polaritons (SPPs) to conduction electron spin. Free electrons in the metal follow the transversally spinning electric field of the SPP, and the resulting orbital motions create inhomogeneous static magnetization in the metal. By solving the spin diffusion equation in the SPP, we find that the magnetization field generates an electron spin current. We show that there exists a resonant condition where the spin current is resonantly enhanced, and the polarization of the spin current is flipped. Our theory reveals an alternative functionality of SPPs as a spin current source.

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Introduction. The optical transverse spin is one of the universal properties of evanescent waves [1–3]. It is an exotic circular polarization of an evanescent field whose spinning direction of the field is perpendicular to the propagation direction, unlike ordinary propagating fields. When the decay direction of the evanescent field is not parallel to its propagation direction, the transverse spin exists in the evanescent fields due to the transversality requirement from Gauss law.

A surface plasmon polariton (SPP) is an electromagnetic wave coupled with plasma oscillations localized at a metal-dielectric interface [4]. The SPP possesses transverse spin [5,6] because the decay direction is normal to the interface along which the SPP propagates. The transverse spin in the SPP generates an inhomogeneous magnetization field in the metal. This is because the electron gas in the metal makes orbital motions, following the transversally spinning electric field of the SPP. The electric current given by the curl of this magnetization is divergenceless ($\nabla \cdot \nabla \times = 0$), and it cannot be detected [7]. However, a detectable spin current is generated by the magnetization as shown below.

In metals, there are generally two kinds of electronic transport, not only charge currents but also spin currents. It is known that the spin transport is driven in media with the presence of spin-dependent potentials, such as a strong spin-orbit coupling [8–11], and spin-vorticity coupling [12–14]. In particular, the gradient of effective magnetic fields is utilized in Refs. [11–14]. Effective magnetic fields are created by inhomogeneous spin-orbit coupling [11] or by spin-vorticity coupling [12–14]. That is, a variety of Stern-Gerlach-like effects are exploited for generating spin currents. In this Rapid Communication, we identify the inhomogeneous magnetization field of SPPs as an alternative candidate for driving spin currents, and thus the transverse spin in SPP could be detected via spin current measurements.

In this Rapid Communication, we solve the spin diffusion equation in the presence of inhomogeneous magnetization generated by SPP (Fig. 1), and we find that the spin accumulation and thus the diffusive spin current are created by inhomogeneous magnetization. The spin current can be detected since the divergence of the spin flow does not vanish, unlike the charge current. This means that the transverse spin in SPP drives the electron spin current in the metal. We use Gaussian units in this Rapid Communication, except in the final part where we estimate the order of the magnitude of the spin currents so as to investigate whether or not they are measurable. We bridge two seemingly distant fields: plasmonics and spintronics.

Transverse spin and inhomogeneous magnetization in a surface plasmon polariton. The electric and magnetic fields of a SPP are given by [5,7,15,16]

$$\vec{E} = E_0\left[\left(\vec{u}_x - i\frac{\kappa_1}{k_p}\vec{u}_z\right)e^{-\kappa_1 x}\theta(x) + \epsilon^{-1}\left(\vec{u}_x + i\frac{\kappa_2}{k_p}\vec{u}_z\right)e^{\kappa_2 x}\theta(-x)\right]e^{ik_p z}, \quad (1)$$

$$\vec{H} = E_0\frac{k_0}{k_p}\vec{u}_y[e^{-\kappa_1 x}\theta(x) + e^{\kappa_2 x}\theta(-x)]e^{ik_p z}. \quad (2)$$

Here, we use the Heaviside unit step function $\theta(x)$, and set $k_0 = \omega/c$. The wave number of the SPP is defined by

$$k_p = \frac{\sqrt{-\epsilon}k_0}{\sqrt{-1-\epsilon}}, \quad (3)$$

and the decay coefficients in vacuum and in metal are defined by

$$\kappa_1 = \frac{k_0}{\sqrt{-1-\epsilon}}, \quad (4)$$

$$\kappa_2 = \frac{-\epsilon k_0}{\sqrt{-1-\epsilon}}, \quad (5)$$

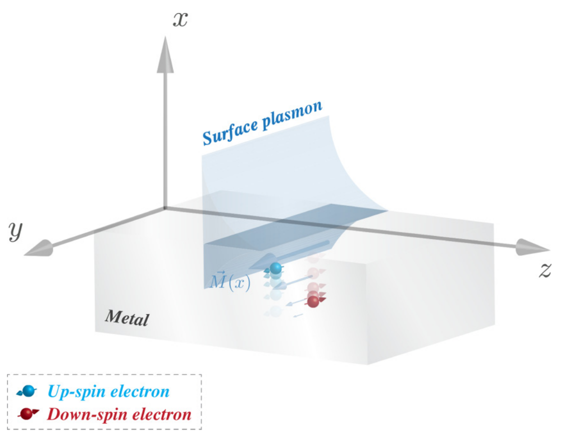

FIG. 1. Schematic of a setup for angular momentum conversion from SPP to electron spin, which we analyze here. We have a dielectric-metal interface where a SPP is excited. The transverse spin of SPP excites the orbital motion of electrons, which create the magnetization field in the metal. Since the transverse spin density decays exponentially, there is a steep gradient of the magnetization field in the metal. This inhomogeneous magnetic field drives the spin current carried by conduction electrons in the metal, whose flow direction is perpendicular to the interface.

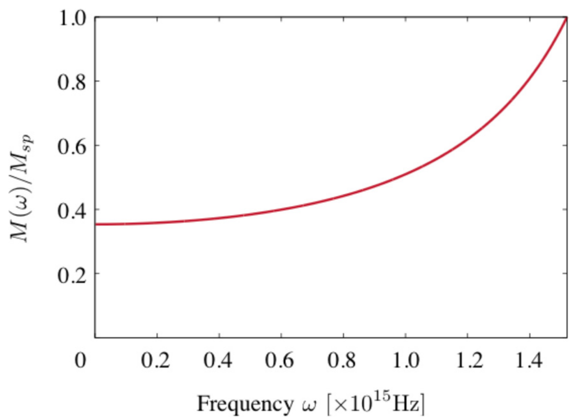

FIG. 2. Frequency dependence of the magnetization density in a SPP. Here, we define $M_{sp} \equiv M(\omega_{sp})$. It is clear that the magnetization is a monotonically increasing function of the SPP frequency. We use the Drude parameter of gold $\omega_p = 2.15 \times 10^{15}$ Hz to draw this graph [22].

respectively. We can obtain these quantities by applying the boundary matching condition at the interface to Maxwell's equations with a Drude free-electron model,

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}. \tag{6}$$

Here, we set the plasma frequency $\omega_p^2 = 4\pi ne^2/m$ and the permeability $\mu = 1$. In Eq. (1), we can see the imaginary unit i at $\vec{u}_z$ while not at $\vec{u}_x$. This implies that there is a phase difference between the longitudinal z component and the transverse x component of the field, and the electric field rotates in the transverse y direction both on the dielectric side and on the metal side. Note that the rotation direction on the dielectric side and that on the metal side are opposite to each other.

We use the Minkowski representation for the spin angular momentum density of an electromagnetic field,

$$\vec{S} := \frac{g}{2}\mathrm{Im}(\tilde{\epsilon}\vec{E}^* \times \vec{E} + \tilde{\mu}\vec{H}^* \times \vec{H}). \tag{7}$$

Here, $g = (8\pi\omega)^{-1}$ is a Gaussian unit factor, the group permittivity $\tilde{\epsilon} = \frac{d(\omega\epsilon)}{d\omega}$, and permeability $\tilde{\mu} = \frac{d(\omega\mu)}{d\omega}$. As Bliokh *et al.* demonstrated in the literature [7], we can decompose the Minkowski representation of the spin angular momentum density of a SPP into two contributions. One is a contribution from the electromagnetic field and the other is from the kinetic motion of electrons in the metal, which corresponds to the dispersion corrected term of the spin angular momentum density. For a SPP, we have

$$\vec{S} = \vec{S}_{\mathrm{em}} + \vec{S}_{\mathrm{mat}} = \frac{g\epsilon}{2}\mathrm{Im}(\vec{E}^* \times \vec{E}) + \frac{g\omega}{2}\frac{d\epsilon}{d\omega}\mathrm{Im}(\vec{E}^* \times \vec{E}). \tag{8}$$

Here, we ignore the magnetic field contribution to the spin angular momentum density, because there is no rotation and $\mathrm{Im}(\vec{H}^* \times \vec{H}) = 0$ in SPPs.

Electrons in a metal follow the motion of the electric fields below the plasma frequency. This implies that the circular motion of the electric field of SPP induces the orbital motion of electrons in the metal, which can be confirmed by simultaneously solving Maxwell's equations and the equation of motion of electron gas in the metal [7]. The orbital motion of electron gas creates an inhomogeneous magnetization field in the metal, which is sometimes referred to as the inverse Faraday effect [15,17–20]. Using the gyromagnetic ratio for an orbiting electron [21], we can write the magnetization density in metal,

$$\vec{M} = -\frac{e}{2mc}\vec{S}_{\mathrm{mat}} = -\frac{ge\omega}{4mc}\frac{d\epsilon}{d\omega}\mathrm{Im}(\vec{E}^* \times \vec{E}) = g|E_0|^2\frac{e}{2mc}\frac{2(1-\epsilon)\sqrt{-\epsilon}}{\epsilon^2}e^{2\kappa_2 x}\vec{u}_y \tag{9}$$

$$\equiv M_0 f(\omega)e^{2\kappa_2 x}\vec{u}_y. \tag{10}$$

Here, we set $M_0 = |E_0|^2\frac{e}{2mc}$ and $f(\omega) = \frac{2g(1-\epsilon)\sqrt{-\epsilon}}{\epsilon^2}$. Figure 2 illustrates the frequency dependence of the magnetization density. Note that the plot is normalized by $M_{sp} = M(\omega_{sp})$. We can find that the magnetization density is a monotonically increasing function of the frequency, which is maximum at the surface plasmon resonance frequency $\omega_{sp} = \omega_p/\sqrt{2}$. From (9), it is clear that the magnetization density exponentially decays toward infinity in the metal. This inhomogeneous magnetization field could drive the electron spin current.

Electron spin current in the inhomogeneous magnetization field. In order to investigate whether the inhomogeneous magnetization of SPPs can generate electron spin currents, we solve the spin diffusion equation [23,24] with a source of the inhomogeneous magnetization field,

$$\left(\partial_t - D_s\nabla^2 + \frac{1}{\tau}\right)\delta\mu = \frac{e}{\sigma_0}D_s\nabla\cdot\vec{j}_s. \tag{11}$$

Here, $\delta\mu$ is the spin accumulation, and $D_s = \lambda_s^2/\tau$ and σ_0 are the diffusion constant and the conductivity of the metal, respectively. The source term on the right-hand side of the diffusion equation (11) contains

$$\vec{j}_s = -\frac{\hbar\sigma_0}{m}\nabla M_y. \tag{12}$$

As can be seen, the source term comes from the inhomogeneous magnetization field created by the SPP. Due to the inversion symmetry breaking at metal surfaces, the Rashba-Edelstein (RE) effect plays a role in the interconversion of spin and charge flows there, and it could modify the spin diffusion length and the spin relaxation time. However, the plasma oscillation of electrons is much faster than the spin dynamics ($\omega_p/2\pi \ll 1/\tau$), and the effective magnetic field by the RE effect $\propto \vec{p} \times \vec{\nabla} V$ rapidly oscillates, where $\vec{p}$ is electron momentum and V is the (static) scalar potential. Therefore, we can safely neglect the RE effect when we analyze the diffusive spin dynamics here.

Our interest is to find the stationary state solution of the diffusion equation (11) and to investigate whether or not a spin current is generated. Explicitly writing the spin diffusion equation (11) in the stationary state, we obtain

$$\nabla^2\delta\mu = \frac{\delta\mu}{\lambda_s^2} + \frac{\hbar e}{m}\nabla^2 M_y. \tag{13}$$

By solving this differential equation (13), we can find that spin accumulation is created in the stationary state,

$$\delta\mu = \frac{\hbar e M_0}{m}\frac{f(\omega)(2\kappa_2\lambda_s)^2}{(2\kappa_2\lambda_s)^2 - 1}e^{2\kappa_2 x}. \tag{14}$$

In Fig. 3, the dependence of the spin accumulation on the SPP frequency and the spin diffusion length is shown. We can clearly see that there is a resonant response whose condition given by

$$(2\kappa_2\lambda_s)^2 - 1 \to 0. \tag{15}$$

The condition is determined by the SPP frequency and the spin diffusion length of the metal. At the condition, the sign of spin accumulation is flipped. The accumulation takes negative values below the condition, whereas positive above it. This Lorentz-type resonance occurs because two different parameters, the spin diffusion length λ_s and the decay length of SPP κ_2, compete with each other. We remind that the form of the stationary spin diffusion equation (13) is the same as that of the differential equation of a driven harmonic oscillator. The inverse of the spin diffusion length $(\lambda_s)^{-1}$ corresponds to the eigenfrequency in the harmonic oscillator equation. These facts imply that the flow direction of the spin current generated by this SPP-induced spin accumulation can be controlled by the frequency or the spin diffusion length.

Indeed, there exists a diffusive spin current driven by this spin accumulation (14),

$$\vec{j}_s^{\,\mathrm{SP}} = \frac{\sigma_0}{e}\nabla\delta\mu \tag{16}$$

$$= \frac{2\sigma_0\hbar M_0}{m}\frac{\kappa_2 f(\omega)(2\kappa_2\lambda_s)^2}{(2\kappa_2\lambda_s)^2 - 1}e^{2\kappa_2 x}\vec{u}_x \tag{17}$$

$$= \frac{2(2\kappa_2\lambda_s)^2}{(2\kappa_2\lambda_s)^2 - 1}\vec{j}_s, \tag{18}$$

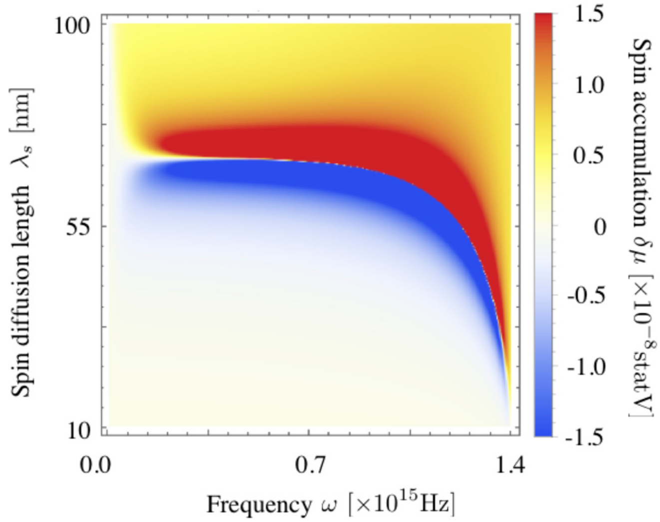

FIG. 3. The dependence of spin accumulation on the frequency of the SPP ω and spin diffusion length λ_s. Note that we limit the plot range of the spin accumulation from -1.5×10^{-8} stat V to 1.5×10^{-8} stat V in order to clarify the sign change at the resonant condition (15), and the accumulation takes much larger values near the condition. The Drude parameter of gold $\omega_p = 2.15 \times 10^{15}$ Hz, $\gamma = 17.14 \times 10^{12}$ Hz is used as in Fig. 2, and we set $E_0 = 1.0$ stat V/cm for simplicity. For the spin diffusion length λ_s, we consider the range from 10 to 100 nm, which is the typical range for gold [24].

whose flow direction is flipped at the resonant condition (15). In Fig. 4, we show the dependence of the diffusive spin current on the SPP frequency and the spin diffusion length. It is

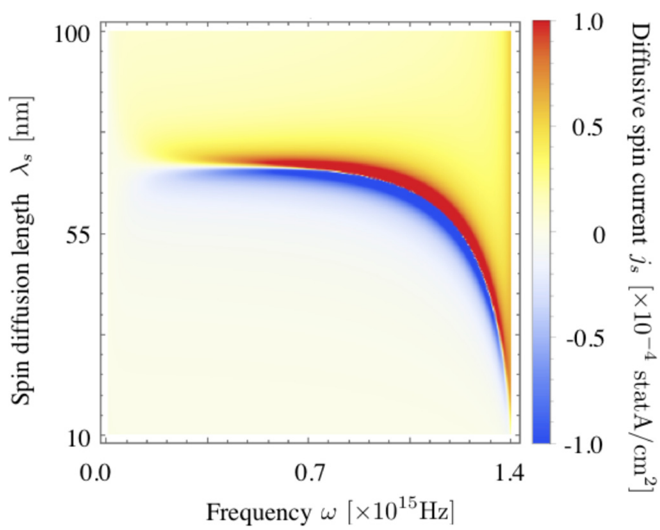

FIG. 4. Diffusive spin current mediated by SPP. This color map shows the amplitude of the spin current as a function of the frequency ω and the spin diffusion length λ_s. We use the Drude parameter of gold as in all previous figures, and we also set $E_0 = 1.0$ stat V/cm for simplicity. It is clear that there exists the resonant response condition (15), and the flow direction of the spin current is flipped at the condition. Note that we set the plot range of the spin current from -1.0×10^{-4} stat A/cm^2 to 1.0×10^{-4} stat A/cm^2, and that the amplitude can be larger near the resonant condition. We also have a relatively large spin current generation near the surface plasmon resonance frequency $\omega_{sp} = \omega_p/\sqrt{2}$.

clear that there exists a resonant response at the condition (15) where the direction of the spin current is flipped. In addition, there is another resonant response at the surface plasmon resonance frequency $\omega_{sp} = \omega_p/\sqrt{2}$ unlike the response of the spin accumulation. This is because the decay length κ_2, which appears in (18), diverges at the frequency.

Finally, we estimate the amplitude of the diffusive spin current at the two resonant conditions, the surface plasmon resonance and the Lorentz-type resonance. We here assume the electric field amplitude of SPP is $E_0 = 6.14 \times 10^2$ V/m, which can be excited by a laser beam with an intensity of 100 mW/cm^2 with the standard Otto configuration [25].

At the surface plasmon resonance, the magnetization reaches its maximum of the order of 10^{-9} G $\approx 10^{-13}$ T, and the decay length is in the order of 10^{-7} m. With these values, we can find that the amplitude of the source (12) is $|\vec{j}_s| \sim 10^3$ A/m^2. In the case of the surface plasmon resonance, the Lorentz-type resonance factor $\frac{(2\kappa_2\lambda_s)^2}{(2\kappa_2\lambda_s)^2-1}$ is asymptotic to 1 (0.99 when $\lambda_s = 40$ nm). The driven spin current is in the order of 10^3 A/m^2.

As for the Lorentz-type resonance, for example, when $\omega = 1.25 \times 10^{15}$ Hz and $\lambda_s = 60$ nm, the Lorentz-type resonance factor is of the order of 10^2, and we can estimate the source $|\vec{j}_s| \sim 10^3$ A/m^2 by the same procedure as before. Therefore, the diffusive current generated at the condition is in the order of 10^5 A/m^2. The spin current with an amplitude of 10^5 A/m^2 can be measured via the inverse spin Hall effect (ISHE) (see, for example, Ref. [26] for the ISHE measurement scheme).

There may be a deviation from the simple Drude model (6) due to electronic excitations other than plasma oscillation. However, at least below the threshold energy ($\approx$0.5 PHz $\approx \omega_{sp}/3$), the Drude model accurately fits experimental results, and this allows our simple analysis by the spin diffusion equation with the source term. We need further analysis with a full quantum mechanical treatment beyond the threshold, where the damping and the shift of the resonance peaks potentially happen, and leave it for future work.

Conclusion. We reviewed the inhomogeneous magnetization field in a surface plasmon polariton (SPP), and proposed a mechanism of electron spin transport driven by the SPP by solving the spin diffusion equation in the presence of the inhomogeneous magnetization of a SPP.

We found that there are two conditions at which the diffusive spin current is resonantly generated. One condition is determined by the frequency of the SPP and the spin diffusion length of electrons in the metal. At this condition, the direction of the spin current is flipped so that we could control the direction of the electron spin flow by utilizing the frequency and the spin diffusion length. The other condition is the surface plasmon resonance (SPR) condition ($\omega = \omega_{sp}$), where the decay length of the surface plasmon κ_2 diverges. Unlike the former condition, the flip of the spin flow direction does not occur at this condition because the SPP cannot exist on the interface beyond the SPR frequency.

When the electric field of the SPP is 6.14×10^2 V/m, which can be created by a laser with a power of 100 mW/cm^2, the source current created by the SPP is in the order of 10^3 A/m^2. The corresponding diffusive current at the stationary state is in the order of 10^5 A/m^2 at one of the Lorentz-type resonance conditions ($\omega = 1.25 \times 10^{15}$ Hz and $\lambda_s = 60$ nm), which is measurable with the inverse spin Hall effect scheme. Conventionally, the magnetoplasmonic effect is too weak to measure (see, for example, Refs. [27,28]); however, the SPP-driven spin current proposed in this Rapid Communication is large enough to detect via the inverse spin Hall measurement. This is partly because of the enhancement of the spin current by the Lorentz-type resonance which results from the competition between the two parameters, the spin diffusion length λ_s and the decay length of the SPP κ_2, in the spin diffusion equation with a source term. That is also because the spin current is driven not by the magnetization itself but by the magnetization gradient, which can be large since the SPP is tightly confined at the interface. This is similar to the fact that spin currents are driven by the steep gradient of the effective magnetic field created by spin-vorticity coupling in a flow of liquid metal, although the effective magnetic field is rather weak [12].

Our proposed system is simple enough to prepare, and this plasmon-mediated spin current generation will be accessible by experiments. This work will be a bridge between two different research fields, plasmonics and spintronics.

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