Electron spin transport driven by surface plasmon polariton

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(Dated: January 28, 2020)

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 SPP, and the resulting orbital motions create inhomogeneous static magnetisation in the metal. By solving the spin diffusion equation in the SPP, we find that the magnetisation field generates an electron spin current. We show that there exists a resonant condition where the spin current is resonantly enhanced, and the polarisation of the spin current is flipped. Our theory reveals a novel functionality of SPP as a spin current source.

Introduction.— The optical transverse spin is one of the universal properties of evanescent waves [1–3]. It is an exotic circular polarisation of 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.

As surface plasmon polariton (SPP) is an electromagnetic wave coupled with plasma oscillations localised 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 inhomogeneous magnetisation 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 magnetisation is divergenceless ($\nabla \cdot \nabla \times \mathbf{E} = 0$), and it cannot be detected [7]. However, a detectable spin current is generated by the magnetisation 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 utilised in [11–14]. The effective magnetic fields are created by the inhomogeneous spin-orbit coupling [11] or by spin-vorticity coupling [12–14]. That is, a variety of the Stern-Gerlach-like effects are exploited for generating spin currents. In this work, we identify the inhomogeneous magnetisation field of SPPs as a new candidate for driving spin currents, and thus the transverse spin in SPP could be detected via spin current measurements. However, to the best of our knowledge, there have not been any experiments or theories related to the spin transport mediated by SPP.

In this paper, we solve the spin diffusion equation in the presence of inhomogeneous magnetisation generated by SPP (FIG. 1). and we find that the spin accumulation and thus the diffusive spin current are created by the inhomogeneous magnetisation. 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 paper except in the final part where we estimate the order of the magnitude of the spin currents so as to investigate whether they are measurable or not. We bridge two seemingly distant fields: plasmonics and spintronics.

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

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

$$\mathbf{H} = E_0 \frac{k_0}{k_p} \mathbf{u}_y \left[ e^{-\kappa_1 z} \theta(x) + e^{i \kappa_2 z} \theta(-x) \right] e^{i k_p z}.$$

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

$$k_p = \sqrt{\frac{-\epsilon k_0}{1 - \epsilon}},$$

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

$$\kappa_1 = \frac{k_0}{\sqrt{1 - \epsilon}},$$

$$\kappa_2 = \frac{-\epsilon k_0}{\sqrt{1 - \epsilon}},$$

respectively. We can obtain these quantities by applying the boundary matching condition at the interface to...
Maxwell’s equations with Drude free electron model
\[
\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}.
\]

(6)

Here, we set the plasma frequency \(\omega_p^2 = 4\pi ne^2/m\) and the permeability \(\mu = 1\). In the equation (1), we can see the imaginary unit \(i\) at \(\vec{u}_z\) while not at \(\vec{u}_x\). This implies that there is 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 in the dielectric side and that in the metal side are opposite to each other.

We use the Minkowski representation for the spin angular momentum density of an electromagnetic field,
\[
\vec{S} := \frac{g}{2} \text{Im}\left(\hat{\epsilon}\vec{E}^* \times \vec{E} + \hat{\mu}\vec{H}^* \times \vec{H}\right).
\]

(7)

Here \(g = (8\pi\omega)^{-1}\) is a Gaussian unit factor, the group permittivity \(\hat{\epsilon} = \frac{d(\omega\epsilon)}{d\omega}\), and permeability \(\hat{\mu} = \frac{d(\omega\mu)}{d\omega}\). As Blokh 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
\[
\vec{S} = \vec{S}_{\text{em}} + \vec{S}_{\text{mat}},
\]

\[
= \frac{g\epsilon}{2} \text{Im}\left(\vec{E}^* \times \vec{E}\right) + \frac{g\omega}{2} \frac{d\epsilon}{d\omega} \text{Im}\left(\vec{E}^* \times \vec{E}\right).
\]

(8)

Here we ignore the magnetic field contribution to the spin angular momentum density, because there is no rotation and \(3\text{Im}\left(\vec{H}^* \times \vec{H}\right) = 0\) 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 orbital motion of electrons in the metal, which can be confirmed by simultaneously solving Maxwell equations and the equation of motion of electron gas in the metal [7].

The orbital motion of electron gas creates an inhomogeneous magnetisation 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 magnetisation density in metal
\[
\vec{M} = -\frac{e}{2mc} \vec{S}_{\text{mat}} = \frac{g\epsilon\omega}{4mc\omega} \frac{d\epsilon}{d\omega} \text{Im}\left(\vec{E}^* \times \vec{E}\right),
\]

\[
= g|E_0|^2 \frac{e^2(1-\epsilon^2)\sqrt{-\epsilon}}{2mc}\epsilon^2 e^{2\kappa_2 z} \vec{u}_y
\]

(9)

\[
= M_0 f(\omega)e^{2\kappa_2 z} \vec{u}_y
\]

(10)

Here we set \(M_0 = |E_0|^2 \frac{e^2}{2mc}\) and \(f(\omega) = \frac{2\sqrt{\epsilon(1-\epsilon)}}{\sqrt{\gamma}}\).

FIG. 1. Schematic of a setup for angular momentum conversion from SPP to electron spin, which we analyse in this paper. 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 magnetisation field in the metal. The 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 magnetisation density in a SPP. Here we define \(M_{sp} \equiv M(\omega_{sp})\). It is clear that the magnetisation is a monotonically increasing function of the SPP frequency. We use Drude parameter of gold \(\omega_p = 2.15 \times 10^{15}\) Hz to draw this graph [22].

\[
M_{sp} = M(\omega_{sp}).
\]

We can find that the magnetisation 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 magnetisation density exponentially decays toward infinity in the metal. This inhomogeneous magnetisation field could drive electron spin current.

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

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

Here, \(\delta \mu\) is the spin accumulation, and \(D_s = \lambda_s^2 / \tau\) and \(\sigma_0\) 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

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

As can be seen, the source term comes from the inhomogeneous magnetisation field created by the SPP. Our interest is to find the stationary state solution of the diffusion equation (11) and to investigate whether the spin current is generated or not. Explicitly writing the spin diffusion equation (11) in the stationary state, we obtain

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

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

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

In FIG. 3, the dependance 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

\[(2\kappa_2 \lambda_s)^2 - 1 \rightarrow 0. \tag{15}\]

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 \(\lambda_s\) and the decay length of SPP \(\kappa_2\), compete with each other. 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 eigen-frequency 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 controled by the frequency or the spin diffusion length.

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

\[
\vec{j}_s^{\text{diff}} = \sigma_0 \nabla \delta \mu, \tag{16}
\]

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

\[
= \frac{2(2\kappa_2 \lambda_s)^2}{(2\kappa_2 \lambda_s)^2 - 1} \hat{\vec{j}}_s \tag{18}
\]

whose flow direction is flipped at the resonant condition (15). In FIG. 4, the dependence of the diffusive spin current on the SPP frequency and the spin diffusion length. It is clear that there exists the 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 \(\kappa_2\), which appear 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/cm² with the standard Otto configuration [25].

At the surface plasmon resonance, the magnetisation
The shift of the resonance peaks potentially happen, and treatment beyond the threshold, where the damping and We need further analysis with full quantum mechanical aysis by the spin diffusion equation with the source term. experimental results [27], and this allows our simple anal-

There may be a deviation from the simple Drude model (6) due to other electronic excitations than plasma os-

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

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

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FIG. 4. Diffusive spin current mediated by SPP. This col-

 concessionally, the magneto-plasmonic effect is too weak to measure (see; for example, [28, 29]); however, the SPP-

Our proposed system is simple enough to prepare, and this plasmon-mediated spin current generation will be ac-

MM is partially Supported by the Priority Program of Chinese Academy of Sciences, Grant No. XDB28000000.

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