Resonances in Ferromagnetic Gratings Detected by Microwave Photoconductivity

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We investigate the impact of microwave excited spin excitations on the DC charge transport in a ferromagnetic (FM) grating. We observe both resonant and nonresonant microwave photoresistance. Resonant features are identified as the ferromagnetic resonance (FMR) and ferromagnetic antiresonance (FMAR). A macroscopic model based on Maxwell and Landau-Lifschitz equations reveals the macroscopic nature of the FMAR. The experimental approach and results provide new insight in the interplay between photonic, spintronic, and charge effects in FM microstructures.

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The connection between the DC and high frequency response of the metal to external fields looks like a one-way path. On the one hand, it is text book knowledge that due to the ohmic dissipation, the DC conductivity \( \sigma_0 \) of the metal to external fields looks like a one-way path. On the other hand, there is little knowledge about the inverse effect of the high frequency response on the DC transport in metals, which is in contrast to the case of semiconductors, where a whole zoo of photoconductivity phenomena, ranging from the intrinsic, extrinsic, to the bolometric effect, are all based on such an influence.

Recently, a breakthrough has been achieved in ferromagnetic (FM) metals. By combining the giant magnetoresistance effect of a FM multilayer with the microwave absorption, high frequency resonances were detected by measuring the DC resistance \( R \). It was the first photoconductivity experiment on FM multilayers, which bridged static and dynamic properties, and paved the way for recent highlights of generating microwave oscillations by a spin-polarized DC current \( I \). Despite of broad interest in studying the interplay of static and dynamic responses in FM multilayers, the basic question of the impact of the high frequency response on the DC transport in a single layer FM metal remains open.

In this paper, we answer this question by performing microwave photoconductivity measurements directly on a single layer FM microstrip. Our primary aim is to explore the bolometric effect \( B \) in the FM metal, which may bridge the high frequency absorbance \( A(\omega) \) with the DC resistance change \( \Delta R \) via a simple relation

\[
\Delta R = S \cdot A(\omega),
\]

where \( S = \frac{\partial R}{\partial C_e} \) is a sensitivity parameter that depends on the specific heat \( C_e \) of electrons, the incident power \( P_0 \) of the radiation, and the energy relaxation time \( \tau_e \) of photo-excited spin/charges. The relation was previously only known for semiconductors [3]. We demonstrate that based on the interplay of the spin dynamics and the DC charge transport, both the ferromagnetic resonance (FMR) [4] and ferromagnetic antiresonance (FMAR) [8] can be detected by the photoconductivity technique. Using a model based on Maxwell and Landau-Lifschitz equations, we reveal the unique macroscopic nature of the FMAR in the FM grating, which has the potential to integrate spintronic and photonic features in FM microstructures.

Our experiments are performed on an array of Ni_{80}Fe_{20} (Permalloy, Py) microstrip with a width \( W = 50 \) \( \mu \)m and a thickness \( d = 60 \) nm. As illustrated in insets of Fig. 1, the strip has a total length \( L \approx 10 \) cm and runs meandering in a square of about 3\( \times \)3 mm\(^2\), forming 30 periods of FM grating with a period \( a = 70 \) nm. The Py strip is deposited on a semi-insulating GaAs substrate using photolithography and lift-off techniques. The DC conductivity \( \sigma_0 \) of the Py strip is determined to be 3.2 (5.0) \( \times \)10\(^4\) \( \Omega^{-1} \)cm\(^{-1}\) at 300 (4.2) K. A swept-signal generator is connected with a circular oversized waveguide, which brings the microwave radiations with \( f \) between 17.5 - 20 GHz down to the sample set in a cryostat.

Before discussing the photoconductivity of the Py strip, we show in Fig. 1 the static property of our sample without microwave radiations. By applying the external magnetic field \( H = B/\mu_0 \) along the easy axis parallel (\( \theta = 0^\circ \)) to the current flow in the strip, we measure the anisotropic magnetoresistance (AMR) and plot it [7] in Fig. 1(a). The sharp minimum at \( \pm 1.2 \) mT corresponds to the coercive field of the strip [8], which increases with increasing the angle \( \theta \) (not shown). At \( \theta = 90^\circ \) when the applied B field is along the hard axis perpendicular to the strip plane, perpendicular AMR is measured and plotted in Fig. 1(b). The estimated saturation magnetization \( (M_s) \) is about 1.2 T/\( \mu_0 \) and the normalized AMR is about 3.2%, both in agreement with earlier reports [8].

We perform the photoconductivity experiment at \( \theta = 90^\circ \) in the Faraday configuration with the microwave wave vector \( \mathbf{k} \parallel \mathbf{B} \). Fig. 2 shows typical photoresistance traces measured as a function of the B field at 4.2 K for different microwave frequencies. The curves are vertically offset for clarity. A DC current of \( I = 90 \) \( \mu \)A is applied. The radiation-induced voltage change \( \Delta V \) is
measured via lock-in technique by modulating the microwave power with a frequency of 123 Hz. The photoresistance \( \Delta R = \Delta V/I \) measures the microwave-induced DC magnetoresistance change of the Py strip. In addition to a nonresonant background photoresistance at the order of \( 10 \text{ m}\Omega \), which is about a few ppm of the DC magnetoresistance \( R \) of the Py strip, we observe clearly two resonances. One appears as a peak and the other as a dip. The resonant field for both shifts with \( f \). We find that \( \Delta R \) increases with increasing power. The data shown in Fig. 2 are measured by setting the output power of the swept-signal generator at 24 dbm, however, the power that reaches the sample via the long waveguide is significantly reduced. At 17.75 GHz when \( f \) approaches the cut off frequency of the waveguide, \( \Delta R \) is obviously reduced.

To shed light onto the observed photoconductivity effect, we begin by analyzing the magnetodynamic response function of our sample. The dynamic susceptibility tensor \( \tilde{\chi} \), which links the dynamic magnetization \( m \) and the dynamic magnetic field \( h \) via \( m = \tilde{\chi} \cdot h \), can be obtained by solving Landau-Lifschitz equation \( 8 \). For simplicity, we restrict our analysis to the field range of \( H > M_0 \) where resonances are observed. Since in our sample \( d \ll L, W \), we start by treating it as a 2D film, taking into account the demagnetization field but neglecting the anisotropy and the exchange field. We get the dynamic permeability tensor

\[
\tilde{\mu} = \mathbb{1} + \tilde{\chi} = \begin{pmatrix} \mu_L & \mu_T & 0 \\ -\mu_T & \mu_L & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

with the longitudinal (\( \mu_L \)) and transversal (\( \mu_T \)) complex permeability given by

\[
\mu_L = 1 + \frac{i \omega_M \omega}{(\omega_r - i \omega)^2 - \omega^2}
\]

\[
\mu_T = \frac{i \omega_M \omega}{(\omega_r - i \omega)^2 - \omega^2}.
\]  

FIG. 1: (color online). (a) Parallel (\( \theta = 0^\circ \)) and (b) perpendicular (\( \theta = 90^\circ \)) AMR effect measured with the applied magnetic field and current bias as shown in the inset.

FIG. 2: (color online). Microwave photoresistance (vertically offset for clarity) of the Py strip measured as a function of the magnetic field at 4.2 K and at different microwave frequencies. The inset shows the measurement configuration.

Here, \( \alpha \) is the dimensionless Gilbert damping parameter. We define \( \omega_M = \gamma M_0 \) and \( \omega_r = \gamma (H - M_0) \), with \( \gamma = g \mu_B \mu_0 / \hbar \) the gyromagnetic ratio which depends on the \( g \) factor and the Bohr magneton \( \mu_B \).

The dynamic permeability tensor \( \tilde{\mu} \) describes the gyrotropic response of the FM metal. In the Faraday configuration, its eigenvalues can be found by solving the equation \( k(k \cdot h) + (k^2 \epsilon_0 - k^2)h = 0 \) deduced from Maxwell equations \( 10 \). We obtain

\[
\mu \pm = \mu L \mp i \mu T = \frac{\omega_r + \omega_M \mp \omega - i \alpha \omega}{\omega_r \pm \omega - i \alpha \omega}
\]

which define two circular polarized electromagnetic eigenmodes propagating in the FM film, whose wave vectors are given by \( k_+^2 = \epsilon \mu L \pm \epsilon_0 k_0^2 \). Here \( \epsilon = \epsilon_0 / \epsilon_0 \omega \) is the complex permittivity of the FM film, \( \epsilon_0 \), \( c \), and \( k_0 = \omega / c \) are the permittivity, the velocity and the wave vector of light in vacuum. The \( k_+ \) mode results from the strong coupling of the right circular electromagnetic wave with the magnetization, which excites the FMR at the resonant frequency \( \omega_r \). The FMR is inactive for the left circular electromagnetic wave and hence the \( k_- \) mode is only weakly influenced by the magnetization.

In Fig. 3(a), we plot the magnetic-field dispersion of the peak (solid square) and dip (open circle) measured from photoconductivity spectra. By fitting the dispersion of the peak using the relation \( \omega_r = \gamma (H - M_0) \), we obtain \( \gamma = 183 \mu_0 \text{ GHz/T} \) (corresponding to \( g = 2.08 \)) which agrees well with the published values \( 11 \), and \( M_0 = 1.15 \text{ T/} \mu_0 \) which is consistent with the value (1.2 T/\( \mu_0 \))
The significant discrepancy reflects an intriguing macroscopic nature of the FMAR in the microstructured FM layer. As shown in insets of Figs. 1 & 2, our grating has a large $L/W$ ratio with a period $(a = 70 \, \mu m)$ much smaller than the wavelength of the imposed microwave ($\lambda \approx 1.5 \, cm$). Similar metallic gratings with subwavelength period have long been investigated, which display anomalous optical effects [12]. Recently, they have got renewed interest due to exotic photonic effects showing extraordinary optical transmission [13]. We demonstrate here that the FM grating has its own unique macroscopic optical behavior based on the spin dynamics. In the simplest approximation, we treat the grating as a linear polarizer with a permittivity tensor \( \tilde{\epsilon} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \epsilon & 0 \\ 0 & 0 & 1 \end{pmatrix} \), in which we neglect the microscopic geometric details of the patterned FM film, but focus instead on its macroscopic characteristics of the anisotropic conductivity. By using \( \tilde{\epsilon} \) instead of \( \epsilon \) in Maxwell equations, we find that the eigenmode propagating in the FM grating is nearly linear polarized with the wave vector given by \( k_2^\parallel \approx \epsilon L \kappa_2^2 \).

The characteristics of \( \mu_L \) plotted in Fig. 3(c) looks at first glance similar to that of \( \mu_+ \). Indeed, both define the same FMAR since a linear polarized electromagnetic wave can be split equally into a left and a right circular polarized wave, with only the right one active for FMAR. The characteristic difference between \( \mu_L \) and \( \mu_+ \) lies in the FMAR. From \( \text{Re}(\mu_L) = 0 \), we get \( \omega_L = \gamma \sqrt{H - M_0} \) for the FMAR, which we plot in Fig. 3(a) as the dotted curve. It allows us to identify the photoresistance dip as the FMAR in the FM grating. The small discrepancy left might be lifted if one includes the details of the sample geometry [14].

Before addressing the technical and physical implication of our results, we go a step further to calculate the absorbance \( A(\omega) \) of the Py grating on top of an insulating GaAs substrate. The procedure is similar to that we derived recently for a semiconductor multilayer system [15], except now we include \( \mu_L \) given in Eq. (2). The results of \( A(\omega) \) plotted in Fig. 4 recover nicely the main feature [16] of \( \Delta R \) shown in Fig. 2. In particular, the agreement of the calculated line shape for the FMAR with the measured curve is excellent, which allows us to fit accurately the dimensionless Gilbert damping parameter \( \alpha = 0.0075 \) [17]. The result also confirms Eq. (1), which demonstrates that the bolometric effect in the FM metal bridges the spin dynamics and the DC charge transport.

We summarize our work from both technical and physical point of view. The technical difference between the photoconductivity and transmission experiment is obvious. While a transmission experiment measures \( A(\omega) \) in Eq. (1) (or equivalently, the high frequency surface

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{(color online). (a) The measured resonance positions for the photoresistance peak (solid square) are fitted to the FMAR dispersion (solid line). The measured (open circle) FMAR dispersion is compared with that calculated using \( \mu_+ \) (dashed line) and \( \mu_L \) (dotted curve). (b) \( \mu_+ \) and (c) \( \mu_L \) are calculated at \( \omega/2\pi = 35 \, \text{GHz} \), using the parameters \( M_0 = 1.15 \, T/\mu_0 \), \( \alpha = 0.0075 \), and \( \gamma = 183 \mu_0 \, \text{GHz/T} \). Arrows indicate the condition for \( \text{Re}(\mu) = 0 \).}
\end{figure}
than one order of magnitude larger than the thickness $d = 60 \text{ nm}$ of the Py, the FMAR is clearly observed as a reduction of the nonresonant photoresistance. Our technique may also provide a new alternative means to investigate spin excitations such as quantized spin waves, which were used to be measured by Brillouin light scattering spectroscopy \cite{18}. In principle, the photoconductivity technique can probe the spin dissipation via $\alpha$, as well as the energy dissipation via $\tau$, both are currently of great interest for investigating magnetodynamics.

From the physical point of view, we uncover an intrinsic different nature of the FMR and FMAR. While both have the common microscopic origin of the magnetodynamic excitation with Larmor precession of spins, FMAR is sensitive to the macroscopic geometric pattern. We demonstrate a characteristic frequency shift of the FMAR in the periodic FM grating from that known for FM films. Similar gratings made of normal metals are currently of great interest for their enhanced transmission ability based on macroscopic optical effects \cite{13}. Replacing normal metals with the FM metal, one may bring in new optical effects utilizing the strong coupling of the electromagnetic wave with magnetodynamic excitations. The macroscopic nature of the FMAR, together with its intrinsic nature for enhancing transmission through FM films, could pave the way for integrating spintronic and photonic effects using FM microstructures.

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{absorbance.png}
\caption{(color online). The microwave absorbance of the Py grating calculated for different microwave frequencies. The curves are vertically offset for clarity.}
\end{figure}

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