Excitation of Continuous Magnetostatic Surface Spin Wave in Ferromagnetic Thin Films

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Spin waves are promising phenomenon for the future spintronic devices. The stable excitation of continuous spin wave is crucial technology for the realization of the signal processing devices. To obtain the basic characteristics of continuously excited spin wave, we fabricated asymmetric transmission antennas on a Ni$_{81}$Fe$_{19}$ thin film in order to excite and detect the signal of continuous spin waves. By controlling an external magnetic field and an rf magnetic field, we observed a waveform of propagating spin wave in time domain. We examined the stability of magnetostatic spin wave waveforms by analyzing the time domain signals, and proved that the signals keep clear sinusoidal waveform up to 20 $\mu$m propagation distance. The monochromaticity of excited wave was investigated by calculating Fourier spectrum, showing a narrower full width half maximum (FWHM) than the previously used pulse excitation method.

Key words: spin wave, magnon, spintronics, ferromagnetic thin film, high frequency device

1 Introduction

Intensive research about the spin wave propagation has been performed in recent decades. Paying an attention to the ultrafast propagation and the low power consumption, spintronic integrated circuits (ICs) are suggested theoretically$^{1-4)}$. The logic circuits using spin wave interference have been proposed$^{2,3)}$. Although a prototype of a spin wave logic circuit was demonstrated by using yttrium iron garnet (YIG) samples, the true signal processing within ferromagnetic material is not yet achieved; the binary 0/1 states was created by a superposition of induced voltages in a microwave antenna, not by the spin wave interference within ferromagnetic materials. It will be difficult to further develop the suggested prototype, since it needs much larger device architecture than a simple interference circuit with the dimension of spin wave wavelength. Further, the YIG sample is difficult to miniaturize. We have to directly control a phase and a non-reciprocal excitation of spin waves within a ferromagnetic metallic thin film.

So far, the spin wave experiment in metallic thin films was performed with a pulse excitation method. However, the basic property of continuous spin wave excitation is not so clear, which is considered to be suitable for the signal processing because of its spatiotemporal stability$^{5-14)}$.

In this paper, we reported the details of a continuous spin wave excitation method, and investigated the spatiotemporal stability of continuous spin wave by using a time-domain measurement. An amplitude dependence of the propagation distance is slightly different from the pulse excitation method. We show that the continuous microwave excitation improves the line width of spin wave resonance.

Fig. 1 (a), (b) Optical-micrograph images of the sample. The widths of the ground lines and the signal lines are 9 $\mu$m and 3 $\mu$m, respectively. The gap $g$ between the signal and ground lines is designed to be 2 $\mu$m to match the characteristic impedance (50 $\Omega$). The propagation distance is defined as the distance between two opposite signal lines. (c) Schematic illustration of measurement setup.
Fig. 2 Induced signals $V_{\text{total}}$ and $V'_{\text{total}}$ in response to the external magnetic fields applied to $x$ and $y$ direction. The frequency and the power of the CW are 5.5 GHz and 20 dBm, respectively. The distance between the excitation and detection antennas is 20 μm. The background $V_{\text{induce}}$ is canceled out by taking difference between $V_{\text{total}}$ and $V'_{\text{total}}$.

2 Experimental

2.1 Set-up of Measurement

A micro-fabricated sample is shown in Fig. 1(a). Rectangle permalloy (Ni$_{81}$Fe$_{19}$) thin film (35 nm) was fabricated on a Si substrate. The geometry of rectangle 120×200 μm$^2$ is patterned by using an electron beam lithography and lift-off method. Next, an insulating spacer SiO$_2$ was sputtered (40 nm). A set of asymmetric coplanar strip lines (ACPSs) (Ti 5 nm / Au 125 nm) were fabricated on them. A center position of the sample is enlarged in Fig. 1(b). The upper ACPS in Fig. 1(b) is used as an antenna to excite the magnetostatic surface spin wave (MSSW) and the bottom ACPS in Fig. 1(b) acts as an antenna to detect the signal of propagated MSSW. The widths of the ground lines and the signal lines are set to be 9 and 3 μm, respectively, and the gap between the ground line and the signal line in ACPS is 2 μm. We can define a propagating distance $d$ as the length between the excitation and detection antennas.

Schematic illustration of experimental setup is shown in Fig. 1(c). By a continuous wave (CW) signal generator, an rf current was applied into the upper (excitation) antenna, generating an rf magnetic field. Spin waves are then excited by the rf field and propagate in the direction of the arrow in Fig. 1(b). A real-time oscilloscope (16 GHz bandwidth, Lecroy WaveMaster 816Zi) was connected to the bottom (detection) antenna to detect a signal of propagating spin wave. An external magnetic field $H$ was applied to $x$ and $y$ directions.

2.2 Procedure of Data Analysis

To obtain a signal of spin wave, we have to consider a strong background signal: the induced electromotive voltage at certain

$$ V_{\text{total}}(f) = V_{\text{induce}}(f) + V_{\text{MSWW}}(H_x; f), $$

where $V_{\text{MSWW}}(H_x; f)$ is a signal of MSSW, and $V_{\text{induce}}(f)$ is the induced voltage. In Fig. 2, an example of the $V_{\text{total}}(H_x = 300 \text{ Oe, } f = 5.5 \text{ GHz})$ is exhibited. In the case if we apply the external magnetic field $H_x$ to $x$ direction (see Fig. 1(c)), the sum of a MSSW and an induced voltage is observed in the oscilloscope. A total voltage $V_{\text{total}}(H_x; f)$ is expressed as follows:

$$ V_{\text{total}}(H_x; f) = V_{\text{induce}}(f) + V_{\text{MSWW}}(H_x; f). $$

The $V'_{\text{total}}(H_x; f)$ is shown in Fig. 2. Due to the strong attenuation against MSBVW, we can neglect the signal of MSBVW. From the frequency domain measurement using a vector network analyzer, we confirmed that a induced signal in the MSBVW configuration is three orders of magnitude smaller than that in the MSSW configuration. In this experiment, the spin wave signal of the MSBVW is ignored, i.e. $V_{MSBVW} = 0$. Since the induced electromotive force $V_{\text{induce}}(f)$ has no dependence on the direction of the magnetic field, we can subtract the unfavorable background noise by

$$ V_{\text{total}}(H_x; f) - V'_{\text{total}}(H_x; f) = V_{\text{MSWW}}(H_x; f). $$

Finally, we obtain the signal of MSSW $V_{\text{MSWW}}(H_x; f)$ as shown by the bottom waveform in Fig. 2.
3 Results and Discussion

3.1 \( f-H \) Dispersion Relation of Excited Waves

To check the physical origin of the excited waves, the intensity of spin wave amplitude \( I_{SW} \) was examined as functions of frequency and external magnetic field. We have swept the external magnetic field from 0 Oe to 495 Oe, and the CW frequency from 3.0 GHz to 9.9 GHz. The value of \( I_{SW} \) was evaluated from the fast Fourier transform of the temporal variation of \( V_{MSSW} \). Figure 3 shows a color plot of \( V_{MSSW} \). The data are accumulated over 1000 curves. The brighter region represents the stronger power of \( V_{MSSW} \). As clearly seen, a strong oscillation of \( V_{MSSW} \) is excited at certain \( f-H \) condition. Here, we fitted to the brighter region (the broken line in Fig. 3) by the MSSW dispersion relation:

\[
f = \frac{\gamma}{2\pi} \sqrt{\left( H + \frac{4\pi M_s}{2} \right)^2 - \left( \frac{4\pi M_s}{2} \right)^2 \exp (-2kt)},
\]

with the gyromagnetic ratio \( \gamma = 17.6 \) MHz/Oe, the saturation magnetization \( 4\pi M_s = 9900 \) G, the thickness of the ferromagnetic thin film \( t = 35 \) nm, and the wave vector of MSSW \( k = 0.4 \) \( \mu \)m\(^{-1}\). The magnitude of \( 4\pi M_s \) and \( k \) were deduced as fitting parameters. According to the spatial distribution of current-induced Oersted field around the ACPS, the wave vector should be in the range \( 0.1 \leq k \leq 0.7 \) \( \mu \)m\(^{-1}\). The MSSW dispersion explains the experimental results fairly well, meaning that the observed signals in Fig. 2 originate from the MSSW. This is not the FMR resonance, since the resonant frequency (the Kittel’s mode, \( k = 0 \)) always becomes larger at a fixed \( H \) (see the solid line in Fig. 3).

3.2 Characteristics of Continuous MSSW

To clarify the characteristics of continuous MSSWs, we excited MSSWs with an external magnetic field 300 Oe and a CW frequency 5.5 GHz. We changed the distance \( d \) between excitation and detection antennas from 5 to 20 \( \mu \)m. The time-domain waveforms are shown in the inset of Fig. 4, exhibiting clear oscillations in each \( d \). However, compare to the waveform for \( d = 10 \) \( \mu \)m and 20 \( \mu \)m, the waveform at \( d = 5 \) \( \mu \)m is revealed to be distorted. This point is discussed later.

We calculated the Fourier spectrum from the MSSW waveforms. As shown in Fig. 4, there is a single peak centered at 5.5 GHz. The full width half maximum (FWHM) is deduced to be \( \Delta f = 470 \) MHz. The peak frequency \( (f = 5.5 \) GHz\) is unchanged even if we changed the distances \( d = 5 \) \( \mu \)m and \( d = 20 \) \( \mu \)m. Interestingly, the FWHM are also unchanged. Comparing to the MSSW excited in a pulse experiment \( (\Delta f = 880 \) MHz\), the FWHM is reduced by half. It is noted that the mean resonant frequency of the MSSW in the pulse experiment is 5.3 GHz at the field of 300 Oe.

3.3 Attenuation of Continuous MSSW

In Fig. 4, the amplitude of MSSW \( (A_{MSSW}) \) at 10 \( \mu \)m is observed to be 4.6 mV, while it is 0.99 mV at 5 \( \mu \)m and 1.3 mV at 20 \( \mu \)m. This figure shows that MSSWs propagate a long distance with keeping the ideal sinusoidal waveform. Figure 5 shows a distance dependence of the MSSW amplitude. The amplitude values are the average values over several different samples. The number of points are small, however, it appears to have a maximum amplitude at around the distance \( d = 10 \) \( \mu \)m, and it seems to rapidly decay. We fitted the points with the formula

\[
A_{MSSW} = A_0 \exp \left( -\frac{d}{\Lambda} \right)
\]

where \( A_0 \), \( \Lambda \), and \( d \) are a fitting parameter, an attenuation length, and a propagation length of spin wave, respectively. The attenuation length is deduced to be \( \Lambda = 8 \) \( \mu \)m as shown in Fig. 5. Compare to the previously reported value of \( \Lambda = 15 \) \( \mu \)m\(^1\), it appears to be small. Also, we can see that the MSSW amplitude at 5 \( \mu \)m becomes smaller than the other propagating distance.
At present, the detail origin of this suppression of spin wave amplitude is not clarified, however, there is a possibility that the continuously excited waves is caused by a more complicated superposition of waves underneath the excitation ACPS. Since the excitation and detection ACPSs are located closely, the propagating MSSW is directly affected by the current-induced Oersted field from the excitation ACPS. This may cause the distortion and suppression of $V_{MSSW}(d = 5 \mu m)$. This point will be experimented and discussed in a future work.

4 Conclusion

We investigated a basic nature of magnetostatic surface spin wave excited by a continuous rf current. The time-domain waveform was detected to be an ideal sinusoidal waveform even in 20 $\mu m$ propagation distance. The $f-H$ relation was perfectly explained by the dispersion relation of magnetostatic surface spin wave. By analyzing the Fourier spectra of observed waveforms, the line width of excited wave is evaluated to be $\Delta f = 470$ MHz. Compared to the previously used pulse excitation method ($\Delta f = 880$ MHz), a monochromatic magnetostatic surface spin wave in a ferromagnetic thin film was successfully obtained. By measuring the gap dependence of spin wave amplitude, its spatiotemporal stability is exhibited.

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References


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