Broadband excitation of spin wave using microstrip line antennas for integrated magnonic devices

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Abstract

Strong- and broadband-spin wave (SW) excitation/detection structures are useful for magnonic devices. In particular, such structures are essential for observing magnonic bandgaps of magnonic crystals (MCs). Therefore, this study proposes a manufacturable broadband-SW excitation/detection antenna structure suitable for evaluating MCs. The antenna structure comprises a microstrip line fabricated on a yttrium iron garnet on a metal-covered silicon substrate. Calculations were performed using a three-dimensional finite integration technique and dispersion curves of SWs. The proposed structure exhibited high performance because of the significantly short distance between the signal line and ground plane. The generated bandwidth was ∼1.69 GHz for the 8.9 µm-wavelength SW at a frequency of 4 GHz. This work proposed an appropriate antenna structure for observing magnonic bandgaps, showing high potential for the development of MCs in integrated SW devices.

Keywords: forward volume spin wave, magnetostatic wave, yttrium iron garnet, magnonic crystal, YOM substrate

(Some figures may appear in colour only in the online journal)

1. Introduction

Spin wave (SW) [1, 2] devices have attracted the interest of researchers as next-generation computing elements because of their low loss and wave functionalities, unlike complementary metal-oxide-semiconductor field-effect transistors. To control SW propagation, one-dimensional (1D) magnonic crystals (MCs) using the interference of SWs have been widely studied [3–11] and reviewed [12, 13]. The 1D MCs can demonstrate the filtering [14, 15], confinement [16, 17], and phase shifting (slowing) [18] of SWs and can also be used in SW integrated circuits including logic gates [19–27]. In these applications, forward volume SWs (FV SWs) propagating is suitable because of their in-plane isotropy. In addition, the waveguide (WG) comprising yttrium iron garnet (YIG) is useful because of long propagation length of SWs [19, 28, 29]. However, only a few reports have experimentally demonstrated
1D MCs [7, 30] and 2D MCs [31, 32] using FV SWs with YIG. These works used microstrip line antennas generating broad SW bands (1.7–2.0 GHz [7, 33], 5.7–7.0 GHz [30], 8.3–8.6 GHz [31]) to observe magnonic bandgaps. In addition, they used YIG films with a thickness of $>10$ µm (10.2 µm [7], 100 µm [30, 31]), hindering the integration of MCs into SW circuits. On the other hand, coplanar antennas [19, 34] have been widely used for the excitation of SWs in nanometer-thick films; but their excitation bandwidth is quite narrow and unsuitable for MCs. To reduce the YIG thickness and integrate MCs on a chip while providing a broadband SW for observation of magnonic bandgaps, an improved SW-excitation/detection structure is essential. Hence, this study proposes a manufacturable antenna structure exciting/detecting broadband SWs, suitable for evaluating MCs. The bandwidth, intensity of SWs, and figure of merit (FOM) are calculated and compared with other conventional antenna structures with various structural parameters.

2. Calculation model

Figure 1 shows the calculation model of the SW-excitation structure composed of a signal line (SL)/ WG/ground plane (GP)/substrate. In general, thin and narrow SLs generate broadband SWs, but the intensity of these SWs decreases because of the large distance between the SL and GP, reducing the high-frequency electric field and magnetic field in the WG. Hence, the distance between the SL and GP should be reduced while narrowing the SL width to generate strong and broadband SWs. However, such a structure has not been demonstrated so far because of the difficulty associated with its fabrication; in particular, handling the sample is difficult. When the WG is composed of a few micrometers of YIG without substrates, the WG breaks because of the brittle property of the YIG. Hence, we propose placing the single crystalline YIG film on a metal-covered Si substrate. This structure is fabricable because of the recent research of bonding techniques, like the bonding between two garnets [35], garnet and Si [36, 37], garnet and GaAs [38], and two metals [39]. In addition, deposition techniques of YIG onto non-garnet substrates are also developing [39–41], promising for obtaining the proposed SW excitation/detection structure.

In the calculation model, the SL and GP were composed of Cu, the WG was YIG, and the substrate was Si. The material parameters used in the simulation were as follows: conductivity of Cu $\sigma = 5.96 \times 10^7$ S m$^{-1}$ [42], the relative permittivity of YIG $\varepsilon_{\text{YIG}} = 15.3$ [19], Gilbert damping constant $\alpha = 2.4 \times 10^{-4}$ [29], gyromagnetic ratio $\gamma = 2.8$ MHz Oe$^{-1}$, saturation magnetization $4\pi M_s = 1800$ G, the relative permittivity of Si $\varepsilon_{\text{Si}} = 12$ and conductivity of Si $50$ S m$^{-1}$. The sizes of the WG, GP, and substrate were all $100 \times 100$ µm. The length of the SL was 100 µm, and it was placed above the center of the WG without any gaps. The thicknesses of the SL, GP, and substrate were fixed to fabricable general values of 0.1 µm, 0.1 µm, and 380 µm, respectively. The WG thickness and SL width were varied. The internal bias magnetic field between 790 and 1400 Oe was applied perpendicular to the film plane to generate the FV SWs.

3. Calculation procedure

3.1. Outline

SW intensity spectra were calculated as follows. First, the magnetic field distribution excited by the antenna structures was calculated using a three-dimensional (3D) model. Second, the magnetic field distribution was fast Fourier transformed to the SW intensity spectra versus wavenumber $k$. Third, the dispersion curves of the SWs were calculated. Fourth, the SW intensity spectra versus $k$ were substituted for the dispersion curves, and the SW intensity spectra versus frequency $f$ were obtained.

3.2. Magnetic field distribution

Calculation of excited magnetic field was performed using a 3D simulator based on the finite integration technique (Dassault Systemes Simulia CST Studio Suite 2018) [43, 44] because of the excellent agreement between the calculated and experimental results in previous studies [7, 19]. The 3D model was discretized into tetragonal mesh cells. The electric and magnetic fields of the cells were determined using the integral form of Maxwell’s equation combined with the continuity boundary conditions [43]. In this software, we set the ‘waveguide port’ plane at the edge of the SL and directly above the GP. The width and height of the ‘port area’ were $40 \times$ WG thickness + SL width and $21 \times$ WG thickness + SL height, respectively. The input power to the port was 0.5 W. Reflection at this port was almost zero. The observed frequency was 4 GHz. Hence, the distribution of the $x$-directional magnetic field $h_x$ was obtained directly above the WG and along the WG-width direction. The $y$-directional position was set at the center. The values of $h_x(y)$ between meshes were complemented and obtained in $\Delta x$ of 1 nm increments.
3.3. SW intensity spectrum versus wavenumber

The range of the obtained $h_\lambda$ is from $x = -50 \, \mu m$ to $+50 \, \mu m$. This range is not sufficient to obtain a high-resolution SW intensity spectrum versus $k$. A value of 0 was added (zero paddings) to $h_\lambda$ to increase this resolution. This data set can be defined as $h_{\lambda,0}$ and described as

$$h_{\lambda,0}(x) = \begin{cases} 0 & (-500 \, \mu m < x < -50 \, \mu m) \\ h_\lambda(x) & (-50 \, \mu m \leq x \leq +50 \, \mu m) \\ 0 & (+50 \, \mu m < x < +500 \, \mu m) \end{cases}.$$  

(1)

$h_{\lambda,0}(x)$ was Fourier transformed into the SW intensity spectrum versus $k$, $H(k)$, using MATLAB (MathWorks, version 2020) via the following equations:

$$H(k) = \frac{2}{N} \sum_{i}^{N-1} h_{\lambda,0}(i) \exp \left(-j \frac{N' \Delta k i}{N} \right),$$  

(2)

$$k = \frac{2 \pi n}{N' \Delta x},$$  

(3)

where $i$ and $n$ are positive integers (0, 1, 2, …), $N$ is the data length of $h_{\lambda,0}(x) (= 100 \, 002)$, $N'$ is the data length of $h_{\lambda,0}(x) (= 1000 \, 002)$, and $j$ is an imaginary unit.

3.4. Dispersion curve

The wavenumber $k_{\rm air/WG/GP}$ of the SW propagating in the WG sandwiched between a dielectric layer (= air) and a metal layer (= GP) was calculated using the equations shown in [33]:

$$k_{\rm air/WG/GP} = \frac{1}{t_{\rm WG} \sqrt{\mu}} \ln \sqrt{\frac{\mu - 1}{\mu + 1}}.$$  

(4)

$$\mu = 1 + \frac{(\gamma H_{\rm in} + i \alpha f) (\gamma \cdot 4 \pi M_{x})}{(\gamma H_{\rm in} + i \alpha f)^2 - f^2}.$$  

(5)

where $t_{\rm WG}$ is the thickness of the WG layer, $\mu$ is the permeability, and $H_{\rm in}$ is the internal magnetic field.

In a conventional microstrip line antenna, the following equation was used to calculate the dispersion curve [7] instead of equation (4)

$$k_{\rm air/WG/substrate} = \frac{1}{t_{\rm WG} \sqrt{\mu}} \ln \sqrt{\frac{\mu - 1}{\mu + 1}}.$$  

(6)

In this study, the internal magnetic field was tuned so that the SW with a wavelength $\lambda$ of 8.9 $\mu m$ ($k = 0.706 \, \mu m^{-1}$) [19] was excited at $f = 4 \, GHz$.

3.5. SW intensity spectrum versus frequency

The SW intensity spectrum was obtained by substituting the dispersion curve (described in section 3.4) for the SW intensity spectrum versus $k$ (described in section 3.3).

3.6. SW intensity, bandwidth, and FOM

To draw a comparison with other antenna structures, the working frequency $f$ was set at 4 GHz, and the SW intensity at $f = 4 \, GHz$ was defined as $H_{\text{GHz}}$. Bandwidth was defined as a continuous frequency band with an SW intensity $>0.5 H_{\text{GHz}}$. The FOM was defined as $H_{\text{GHz}} \times \text{bandwidth}$.

4. Results and discussion

4.1. Influence of signal line width

Figure 2 shows the calculated results for the $h_\lambda$ distribution, SW intensity versus $k$, dispersion curve, and SW intensity versus $f$ for various SL widths $w_{\text{SL}}$. Figure 3 shows $H_{\text{GHz}}$, bandwidth, and FOM with various $w_{\text{SL}}$; it also includes the calculated results that are not shown in figure 2. In this calculation, the following parameters were used: the GP thickness $t_{\text{GP}} = 0.1 \, \mu m$, the SL thickness $t_{\text{SL}} = 0.1 \, \mu m$, WG thickness $t_{\text{WG}} = 1 \, \mu m$, and the conductivity of SL and GP $\sigma = 5.96 \times 10^7 \, S \, m^{-1}$. The SW intensity at $k = 0$ increased as $w_{\text{SL}}$ increased (figure 2(b)) because of the broadening of $h_\lambda$ (figure 2(a)), similar to a previous report [45].

The same five dispersion curves are shown in figure 2(c) because of unrelation between the dispersion curve and $w_{\text{SL}}$. The calculated results of the SW intensity are shown in figure 2(d). When the $w_{\text{SL}}$ became larger, the second and third bands occurred. The working frequency (4 GHz) shifted from the first band to the second band. This behavior showed the mountain-shaped spectrum of $H_{\text{GHz}}$ versus $w_{\text{SL}}$ in figure 3(a).

The largest value of $H_{\text{GHz}}$ was observed at $w_{\text{SL}} = 2 \, \mu m$ (figure 3(a)). The bandwidth shown in figure 3(b) gradually decreased as $w_{\text{SL}}$ increased. The steep change in bandwidth between $w_{\text{SL}} = 7$ and $8 \, \mu m$ was caused by the shift of the working band (from the first to the second band), as shown in figure 2(d). The obtained FOM spectra (figure 3(c)) showed the largest value at $w_{\text{SL}} = 1 \, \mu m$. This value of $w_{\text{SL}}$ was used in the subsequent calculations.

4.2. Influence of waveguide thickness

Figure 4 shows the $h_\lambda$ distribution, SW intensity versus $k$, dispersion curve, and SW intensity versus $f$ for various $t_{\text{WG}}$. Figure 5 shows $H_{\text{GHz}}$, bandwidth, and FOM with various $t_{\text{WG}}$; it also includes calculated results that are not shown in figure 4. In this calculation, the following parameters were used: $t_{\text{GP}} = 0.1 \, \mu m$, $t_{\text{SL}} = 0.1 \, \mu m$, $w_{\text{SL}} = 1 \, \mu m$, and $\sigma = 5.96 \times 10^7 \, S \, m^{-1}$. The value of $h_\lambda$ increased as $t_{\text{WG}}$ became thinner (figure 4(a)) because of the expansion of the radius of curvature of the rotating magnetic field generated around the SL. As the radius of curvature of the rotating magnetic field increased, the $y$ component of the magnetic field passing through the WG reduced, while its $x$ component increased, thus $h_\lambda$ increased. Figures 4(b) and 5(a) show an increase in the SW intensity caused by the thinning of the WG. The increase in $h_\lambda$ also increased the SW intensity. These SW intensity spectra were substituted into the dispersion curves (figure 4(c)), and the SW intensity spectra...
Figure 2. (a) The $x$-directional magnetic field $h_x$ distributions, (b) SW intensity spectra versus wavenumber $k$, (c) dispersion curves, and (d) SW intensity spectra versus frequency $f$ with various SL widths $w_{SL}$ (0.4, 0.6, 1, 3, and 10 $\mu$m).

Figure 3. (a) SW intensity at the frequency $f$ of 4 GHz ($H_{4GHz}$), (b) bandwidth of the SW intensity spectra versus frequency $f$, and (c) FOM with various SL width $w_{SL}$.

(figure 4(d)) were obtained. The dispersion curve in the bottom of figure 4(c) was cut off at around 4.0 GHz because of no solution of the equation (4). As $t_{WG}$ reduced, the SW intensity increased, while the bandwidth reduced (figures 5(a) and (b)). The narrowing of the bandwidth observed when $t_{WG} < 2 \mu$m in figure 5(b) was a result of the steep slope of dispersion curves shown in figure 4(c). Eventually, the largest value of FOM was 28.2 GHz$\cdot$Oe at $t_{WG} = 1 \mu$m. The values of $H_{4GHz}$ and bandwidth were 16.6 Oe and 1.7 GHz, respectively. Therefore, the antenna structure was determined as described above.

4.3. Comparison with other antenna structures

The SW intensity spectrum versus $f$ obtained using the determined structure (figure 6(a)) was compared with those of other antenna structures. The spectrum with the largest FOM is shown in figure 6(d). The well-known and conventional microstrip line structure used in previous works [7, 20, 32, 46, 47] (figure 6(b)) was composed of a 500 $\mu$m-thick gadolinium gallium garnet (GGG) substrate/1 $\mu$m-thick WG (YIG)/0.1 $\mu$m-thick SL (Cu)/500 $\mu$m-thick substrate (FR4)/18 $\mu$m-thick GP (Cu). Most structural parameters were set to the same as those used in the structure proposed in this work. The values of $w_{SL}$, $\alpha$, and $\sigma$ were the same as those above. The top structure comprising a YIG grown on a GGG substrate was bonded to the bottom structure using a flip-chip bonding technique. The dispersion curve was calculated using equation (6). Figure 6(e) shows the SW intensity spectrum versus $f$ of this conventional microstrip line structure. In addition, $H_{4GHz}$ was 6.7 Oe, the bandwidth was 1.5 GHz, and the FOM was 10.1 GHz$\cdot$Oe (table 1).

Similarly, the SW intensity spectrum generated by a coplanar antenna (figure 6(c)) was also calculated with the same $t_{SL}$, $t_{WG}$, $\alpha$, and $\sigma$. The thickness of the GGG substrate was 500 $\mu$m, and the dispersion curve was also calculated using equation (6). Figure 6(f) shows the calculated spectra. Thus, $H_{4GHz}$ was 17.9 Oe, the bandwidth was 0.5 GHz, and the FOM was 9.0 GHz$\cdot$Oe (table 1).

In table 1, The antenna structure of this work showed the FOM of 28.2 GHz$\cdot$Oe, $\sim$2.8 times larger than that of the conventional microstrip line, mostly because of the large $H_{4GHz}$ generated by the short distance between the SL and GP. On the other hand, the $H_{4GHz}$ generated by the coplanar antenna was close to that obtained in this work. However, the bandwidth was as small as one-third of that in this work. This work’s FOM was approximately three times larger than that of the coplanar antenna.
Figure 4. (a) The $x$-directional magnetic field $h_x$ distributions, (b) SW intensity spectra versus wavenumber $k$, (c) dispersion curves, and (d) SW intensity spectra versus frequency $f$ with various WG thicknesses $t_{WG}$ (0.1, 0.3, 1, 3, and 20 $\mu$m).

Figure 5. (a) SW intensity at the frequency $f$ of 4 GHz ($H_{4GHz}$), (b) bandwidth of the SW intensity spectra versus frequency $f$, and (c) FOM with various WG thicknesses $t_{WG}$.

The obtained bandwidth of this work’s antenna structure was 1.7 GHz, larger than values obtained in other works (0.3 GHz [7], 1.3 GHz [30], and 0.3 GHz [31]). Therefore, the proposed antenna structure using a YIG film placed on a metal (YOM) substrate showed better performance for magnonic devices with a broad and strong excitation band.

4.4. Importance of conductivity

The SW intensity spectra versus $f$ with various $\sigma$ were calculated to determine the importance of the conductivity $\sigma$ of the SL and GP. Figures 7 and 8 show the calculated spectra. The bandwidth did not change significantly, but the $x$-directional magnetic field $h_x$ was reduced as the conductivity reduced because of the reduction of the magnetic flux density between the SL and GP. As a result, the FOM increased as $\sigma$ increased. Therefore, a higher conductivity is better for increasing the SW intensity. The conductivity of Cu was sufficient to obtain these results. In contrast, the smoothness of the excitation band was degraded to $\sigma < 1 \times 10^5$ S m$^{-1}$. Thus, a conductivity of Cu or higher is required for obtaining an appropriate SW intensity spectrum.
Figure 6. (a) Microstrip line structure proposed in this paper, (b) conventional microstrip line structure, and (c) coplanar antenna structure. (d), (e) and (f) SW intensity spectra versus frequency $f$ generated by each of the corresponding structures.

Table 1. Comparison of antenna structures.

| Antenna type                  | Figure | $H_{4GHz}$ (Oe) | Bandwidth (GHz) | FOM (GHz∙Oe) |
|-------------------------------|--------|-----------------|-----------------|-------------|
| Microstrip line (this work)   | 6(a)   | 16.6            | 1.7             | 28.2        |
| Conventional microstrip line  | 6(b)   | 6.7             | 1.5             | 10.1        |
| Coplanar antenna              | 6(c)   | 17.9            | 0.5             | 9.0         |

Figure 7. (a) The $x$-directional magnetic field $h_x$ distributions, (b) SW intensity spectra versus wavenumber $k$, (c) dispersion curves, and (d) SW intensity spectra versus frequency $f$ with various GP and SL conductivities $\sigma$ ($1 \times 10^4$, $1 \times 10^5$, $5.96 \times 10^7$, $1 \times 10^8$, and $1 \times 10^9$ S m$^{-1}$).
5. Conclusion

The optimal structural parameters of the microstrip line antenna using a YOM substrate were determined by calculations at a frequency f of 4 GHz. The wavelength λ and wavenumber k of the excited/detected SWs were 8.9 μm and 0.706 μm⁻¹, respectively. The largest FOM in this study was obtained with the structure shown in figure 1 with an SL thickness tSL = 0.1 μm, an SL width wSL = 1 μm, a WG thickness tWG = 1 μm, a GP thickness tGP = 0.1 μm, and the conductivity of GP and SL σ = 5.96 × 10³ S m⁻¹. The largest FOM was 28.2 GHz-Oe, and the bandwidth was 1.7 GHz (3.0 GHz–4.7 GHz), useful for observing the magnonic bandgap of MCs. In addition, this calculation showed the importance and evidence of a YOM substrate. This work will further the development of SW devices and substrates.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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