

# Z-shaped waveguides using complete band gaps in magnonic crystals of yttrium iron garnet and a copper hole array

Kanta Mori<sup>1,2</sup>, Takumi Koguchi<sup>1</sup>, Toshiaki Watanabe<sup>3</sup>, Hibiki Miyashita<sup>1,2</sup>, Dan Shabaev<sup>1,2</sup>, Dirk Grundler<sup>4</sup>, Mitsuteru Inoue<sup>1</sup>, Kazushi Ishiyama<sup>1</sup>, and Taichi Goto<sup>1,\*</sup>

<sup>1</sup>Research Institute of Electrical Communication, *Tohoku University*, 2-1-1 Katahira, Aoba, Sendai, Miyagi, 980-8577, Japan

<sup>2</sup>Graduate School of Engineering, *Tohoku University*, 6-6 Aramaki, Aoba, Sendai, Miyagi, 980-8579, Japan

<sup>3</sup>*Shin-Etsu Chemical Co., Ltd.*, 2-13-1 Isobe, Annaka, Gunma 379-0195, Japan

<sup>4</sup>Institute of Materials (IMX) and Institute of Electrical and Micro Engineering (IEM), School of Engineering, *Ecole Polytechnique Federale de Lausanne (EPFL)*, Lausanne 1015, Switzerland



(Received 3 April 2025; revised 1 November 2025; accepted 15 April 2026; published 27 May 2026)

Guiding spin wave (SW) signals around turns in integrated magnonic circuits remains a challenge. Here, we calculated efficient SW transmission through Z-shaped turns of 120° using low-loss magnonic crystal (MC) waveguides comprising yttrium iron garnet (YIG) and a Cu hole array. The MCs were optimized using a finite integration technique, showing a complete magnonic band gap with a width of 15.1 MHz at a center frequency of 1.811 GHz. The MC waveguide showed  $5.7 \times 10^3$  times stronger SW propagation than ridge-type waveguides by avoiding SW depression caused by inhomogeneous internal magnetic field distributions in the YIG film. The effect of the bending radius on the SW propagation was evaluated through simulations. The proposed MC waveguide plays a vital role in SW waveguide integration by maintaining homogeneous magnetic field distributions throughout the unprocessed YIG film.

DOI: [10.1103/m64z-lh2m](https://doi.org/10.1103/m64z-lh2m)

## I. INTRODUCTION

Recent advances in information-processing technologies have led to growing concerns regarding device heating issues, driving significant interest in spin wave (SW)-based integrated circuits (ICs) that generate minimal Joule heating. SWs [1,2], as propagating wave phenomena, offer promising opportunities for creating task-specific multi-input and/or multioutput devices [3–5] and neuromorphic computing elements [6–8] through phase interference effects. For these emerging SW applications, SW waveguides with low loss and high flexibility are crucial.

In general, ridge-type waveguides consisting of etched magnetic media are used in both experiments [9–18] and calculations [19–21]. In particular, yttrium iron garnet (YIG) [22–27] is widely used as a waveguide material because of its long propagation length. To realize complex

functionality using SWs, for example, multi-input/output logic [4,5,28,29], the waveguides need to be bent.

However, unlike electronic and photonic circuits, spin wave circuits using ridge-type waveguides suffer from the degradation of SW intensity owing to the nonuniformity of the internal magnetic fields in the waveguide. The increasing shape anisotropy from progressive circuit integration causes greater inhomogeneity in the internal magnetic fields, significantly deteriorating the performance of SW waveguides. To address these challenges, two-dimensional (2D) magnonic crystal (MC) [30,31] waveguides have attracted considerable attention. MCs are periodic structures artificially created on SW waveguides. One-dimensional MCs have been the subject of intense study, both theoretically [32–35] and experimentally [36–39], leading to the development of SW filters [40], phase shifters [41], SW confinement [42], and magnon transistors [22]. Meanwhile, 2D MCs [30,43,44] have been explored for their ability to generate a complete magnonic band gap (CMBG), offering enhanced control over SWs within a 2D plane [45]. CMBGs can confine SWs and prevent unwanted propagation, which is expected to reduce the losses. MC-based straight waveguides have been demonstrated in experiments [46,47]. Schwarze and Grundler used CoFeB antidot lattices to

\*Contact author: taichi.goto.a6@tohoku.ac.jp

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

create MC waveguides, showing faster SW propagation than conventional ridge waveguides, which was attributed to the wider effective width of the MC waveguides [46]. Similarly, Madami *et al.* successfully demonstrated straight MC waveguides using permalloy antidot lattices [47]. To realize SW ICs, the next crucial step is to demonstrate bent MC waveguides beyond straight configurations. However, CMBGs for forward volume spin waves (FVSWs), an essential component of bent MC waveguides, have not been demonstrated thus far [48–50], despite being theoretically predicted using the plane-wave method (PWM) [30,48,51] and micromagnetic simulations [52]. FVSWs are the most suitable mode for SW ICs [3,4] due to their in-plane isotropy. Unlike the other two modes (backward volume and surface modes), FVSWs maintain a constant relationship between the SW propagation direction and the bias magnetic field direction, even when the waveguide is bent. This ensures that the SW wavelength remains unchanged, thus enabling reliable phase interference and low-loss propagation, which are advantageous for integration.

In our previous study, we demonstrated 2D MCs using a hexagonal Cu disk array on a YIG film without inducing an internal magnetic field inhomogeneity, potentially addressing the fundamental issue with ridge waveguides [50]. However, CMBGs were not achieved because of the MC design [50]. Therefore, in this study, we computationally improved the MC design by changing the Cu disk array to a hole array on a YIG film to achieve CMBGs. The CMBGs allowed us to create and simulate bent MC waveguides comprising Z-shaped line defects with 120° turns.

## II. CALCULATION OF THE MC SHOWING A CMBG

### A. Calculation model

The 2D MCs and waveguides were designed and explored using a simulator (CST STUDIO SUITE 2022 SP5) based on the three-dimensional (3D) finite integration technique (FIT) [53,54] owing to the good agreement with the experimental results [3,24,50]. The 3D models used in the calculations are shown in Figs. 1(a)–1(c). An overview of the sample is presented in Fig. S1 in Supplemental Material [55]. A 15 mm × 15 mm × 10 μm YIG film was positioned on two 18-μm-thick microstrip lines (MSLs). These MSLs were formed on a 30 × 30 × 0.4 mm<sup>3</sup> dielectric substrate, with the ends of the MSLs electrically connected to a ground plane on the back side of the dielectric substrate via a hole with a diameter of 0.85 mm. The width of the MSLs that excited the SWs was 60 μm. As depicted in Fig. 1(b), an 8.85 mm × 6.31 mm × 2 μm Cu film with a hexagonal hole array was placed on the YIG surface. The lattice constant  $a$  was 450 μm, and the hole radius  $r$  was varied. To reduce the signals propagating between the MSLs through the Cu, slits with a width of  $g$  were introduced following the hexagonal structure. In the following, we vary the slit width  $g$  to optimize the CMBG. Note that the periodic structure between the MSLs represents an MC with a two-element basis consisting of a hole and a slit. SW absorbers composed of 30-nm-thick Au films were placed around the hole array to suppress reflected and transmitted waves [24–26,50]. The target SW wavelength was selected to be several hundred micrometers because of the high intensity required to achieve noticeable

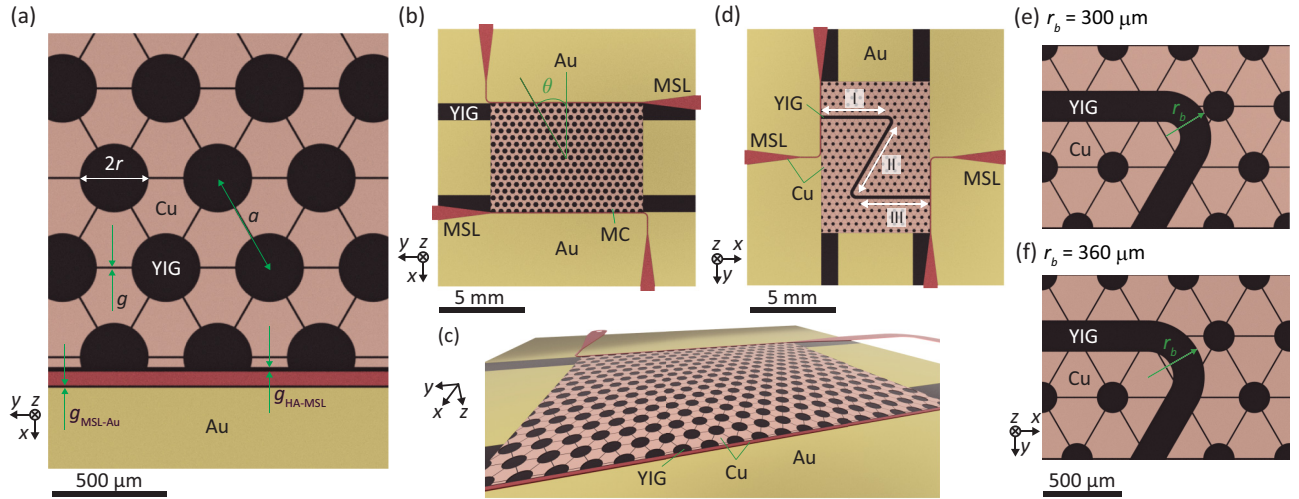


FIG. 1. The magnonic crystal (MC) calculation models. (a) Enlarged view of the hole array (HA). (b) Bottom view of the yttrium iron garnet (YIG) with the MC and microstrip lines (MSLs) fabricated on the dielectric substrate. (c) Bird's eye view of (b). (d) Bottom view of the Z-shaped MC waveguide incorporating 120° turns. Labels I, II, and III denote the three sections of the waveguide before, between, and after the two 120° bends, respectively. The corners with bending radii  $r_b$  of (e) 300 μm and (f) 360 μm.

MBGs [50]. The explored wavelength was consistent with that of a recent universal inverse-design magnonic device [7]. The air gap between the hole array (HA) and MSL  $g_{\text{HA-MSL}}$  and the air gap between the MSL and the Au absorber  $g_{\text{MSL-Au}}$  were set to 20 and 10  $\mu\text{m}$ , respectively. These air gaps were designed to be sufficiently smaller than the SW wavelength to prevent resonance [26]. The  $8.42 \times 16.85 \text{ mm}^2$  input/output ports, with a characteristic impedance of 50  $\Omega$ , were situated at the end faces of the MSLs. The model incorporated a 12-mm air space in the  $+z$  direction and 1-mm air spaces in all other directions from the edges of all objects, including the ports. The overall calculation area was  $17 \times 17 \times 21.44 \text{ mm}^3$ . Perfectly matched layers were applied to all the boundaries of the calculation area. The input radio frequency (rf) power was 0.5 W. The physical parameters of YIG were as follows: saturation magnetization  $4\pi M_s = 1735 \text{ G}$  [50], relative permittivity  $\epsilon_{r,\text{YIG}} = 15.3$  [50], gyromagnetic ratio  $\gamma/2\pi = 2.8 \text{ MHz/Oe}$ , damping  $\alpha = 1 \times 10^{-5}$ . The damping factor was set smaller than the experimental values to clearly observe the MBG in this initial calculation; however, most features of the MBG were not influenced by this difference. A uniform internal magnetic field  $H_{\text{in}} = 600 \text{ Oe}$  in the  $+z$  direction was set in the YIG. This uniform internal field was used for structural optimization, as described in Sec. II, to reduce the computational requirements while maintaining good agreement with the experimental results, as demonstrated in our previous MC studies [24,50]. For the waveguide comparisons in Sec. III C, we applied an external field of  $H_0 = 2335 \text{ Oe}$  to include the demagnetization effects. The relative permittivity of the dielectric substrate (Panasonic, MEGTRON6)  $\epsilon_{r,\text{NM}}$  was 3.7, the conductivity of Cu  $\sigma_{\text{Cu}}$  was  $5.96 \times 10^7 \text{ S/m}$  [56], and the conductivity of Au  $\sigma_{\text{Au}}$  was  $4.56 \times 10^7 \text{ S/m}$  [56]. The skin depth of Cu at the ferromagnetic resonance (FMR) frequency ( $f_{\text{FMR}} = \gamma H_{\text{in}}/2\pi = 1.680 \text{ GHz}$ ) was 1.59  $\mu\text{m}$ . To

minimize eddy currents induced by propagating SWs, the thickness of the hole array was set to 2  $\mu\text{m}$ , which was greater than the skin depth [57].

### B. Influence of slit width

The transmission  $S_{21}$  spectra were calculated while the slit width  $g$  was varied from 0 to 20  $\mu\text{m}$ . The SW incident angle to the hole array,  $\theta$ , was  $0^\circ$ , and the hole radius  $r$  was 150  $\mu\text{m}$ . The calculated transmission spectra are shown in Figs. 2(a) and 2(b). At  $g = 0 \mu\text{m}$ , the transmission  $S_{21}$  remained high across all frequencies. We attribute this observation to the coupling between the input and output MSLs through eddy currents in Cu. The observed transmission characteristics arise from fundamentally different electromagnetic propagation mechanisms in the presence and absence of slits. At  $g = 0$ , the hole array formed a continuous Cu film between the MSLs, enabling direct electromagnetic wave transmission that dominated the SW signals. For  $g \neq 0$ , the slits decouple the electromagnetic transmission between MSLs, allowing observation of SW propagation. Therefore, even small slit widths produce transmission spectra that are distinctly different from those in the case of  $g = 0$ . The multiple dips observed in the  $g = 0$  spectrum arose from the electromagnetic standing waves between the Cu film edges rather than from the SW interference effects. The SW propagation band starting between frequencies  $f = 1.68$  and 2.00 GHz was observed when  $g$  ranged from 0.5 to 20  $\mu\text{m}$  because of the decoupling between two MSLs. Furthermore, the first and second MBGs are identified by sharp drops in transmission at  $f = 1.80$  and 1.88 GHz.

### C. Definition of MBG and CMBG

The MBGs were quantitatively evaluated using the following steps: a line was drawn starting from the maximum

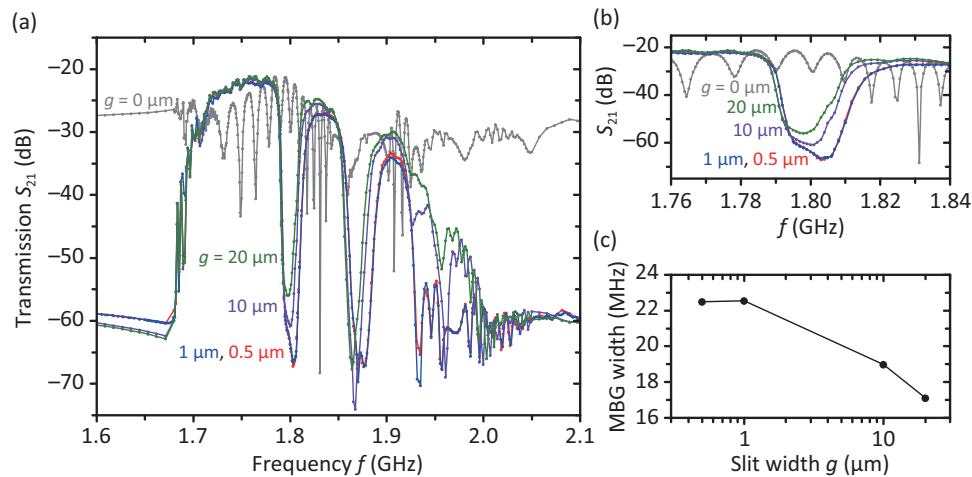


FIG. 2. (a) Transmission  $S_{21}$  spectra with varying slit width  $g$ . (b) Enlarged view of (a) in the vicinity of the first magnonic band gap (MBG). (c) Slit width  $g$  dependence of the MBG width.

point of  $S_{21}$  in the frequency range higher than that of the MBG, extending tangentially towards the lower frequency side of the local minimum [Fig. S2(a) in the Supplemental Material [55]]. This line was subtracted from the overall spectrum [black line in Fig. S2(b) in the Supplemental Material [55]]. The MBG in the subtracted spectrum was fitted with a Gaussian function as defined by the following equation [red line in Fig. S2(b) in the Supplemental Material [55]]:

$$S_{21}^{\text{sub}} = \frac{D}{w} \sqrt{\frac{4\ln 2}{\pi}} \exp\left(-\frac{4(\ln 2)(f - f_{\text{MBG}})^2}{w^2}\right), \quad (1)$$

where  $D$  is the area of the Gaussian function,  $w$  is the width of the Gaussian peak, and  $f_{\text{MBG}}$  is the center frequency of the MBG. The MBG width  $w_{\text{MBG}}$  is defined as follows:

$$w_{\text{MBG}} = f_{\text{high}} - f_{\text{low}}, \quad (2)$$

where  $f_{\text{high}}$  and  $f_{\text{low}}$  are the frequencies when  $S_{21}^{\text{sub}}$  is equal to a certain threshold value  $S_{21}^{\text{th}}$ .

The CMBG was defined as the overlap region of MBGs at  $\theta = 0^\circ$  and  $30^\circ$  due to structural symmetry. A hexagonal structure has sixfold rotational symmetry, and combined with mirror symmetry, the  $0^\circ$ – $30^\circ$  range represents a necessary and sufficient investigation region. The CMBG width and the CMBG center frequency are denoted as  $w_{\text{CMBG}}$  and  $f_{\text{CMBG}}$ , respectively. The slit width dependence of  $w_{\text{MBG}}$  with a threshold  $S_{21}^{\text{th}}$  of  $-20$  dB is shown in Fig. 2(c). The MBG width  $w_{\text{MBG}}$  increased as the slit width  $g$  decreased, saturating at  $g \leq 1$   $\mu\text{m}$ . Therefore, considering the ease of fabrication, the slit width of 1  $\mu\text{m}$  was identified as the optimal value.

#### D. Influence of hole radius

Transmission  $S_{21}$  spectra were calculated at  $\theta = 0^\circ$  and  $30^\circ$  while the hole radius  $r$  was varied from 50 to 175  $\mu\text{m}$ . The slit width  $g$  was set to 1  $\mu\text{m}$ . Figures 3(a) and 3(b) show the intensity of  $S_{21}$  and real parts of  $S_{21}$ , respectively. As shown in Fig. 3(a), within the SW propagation band, MBGs were observed. The phase shift in the real part of  $S_{21}$  shown in Fig. 3(b) indicates the presence of MBGs. The MBGs at  $\theta = 0^\circ$  and  $30^\circ$  overlapped for hole radii  $r$  from 50 to 125  $\mu\text{m}$ , indicating the presence of CMBGs. As the hole radius  $r$  increased, the MBG overlapping region decreased. No distinct overlap was observed at  $r = 150$  or 175  $\mu\text{m}$ . In addition,  $S_{21}$  decreased as the hole radius  $r$  decreased. This suggests that a smaller hole radius leads to a larger Cu area, resulting in greater SW attenuation owing to eddy currents.

Figures 4(a) and 4(b) show the MBG frequency region with various hole radii when  $S_{21}^{\text{th}} = -20$  dB and the CMBG width  $w_{\text{CMBG}}$  versus the hole radius  $r$  at  $S_{21}^{\text{th}} = -10$ ,  $-20$ , and  $-30$  dB. An overlapping region exists between the two

MBGs at  $\theta = 0^\circ$  and  $30^\circ$ , as shown in Fig. 4(a). In Fig. 4(b), at  $S_{21}^{\text{th}} = -10$  dB, CMBGs were present in the  $r$  range from 50 to 150  $\mu\text{m}$ . At more rigid thresholds of  $S_{21}^{\text{th}} = -20$  and  $-30$  dB, CMBGs were present in the  $r$  ranges from 75 to 125  $\mu\text{m}$  and from 100 to 125  $\mu\text{m}$ , respectively, with  $w_{\text{CMBG}}$  peaking at  $r = 100$   $\mu\text{m}$  in both cases. Therefore, in this work, the threshold  $S_{21}^{\text{th}}$  of  $-20$  dB was adopted, and the optimal hole radius was determined to be 100  $\mu\text{m}$ . Note that the value of  $-20$  dB represents an intensity reduction to approximately 1/10, which is more stringent than the full width at half maximum commonly used to define peak width. We considered this threshold appropriate for discussing the practical application potential. However, more rigorous scientific criteria may exist for this definition.

#### E. Influence of the SW incident angle

The transmission spectra were calculated at  $r = 100$   $\mu\text{m}$  and  $g = 1$   $\mu\text{m}$  while the SW incident angle  $\theta$  was varied from  $0^\circ$  to  $30^\circ$ . Figures 5(a) and 5(b) show the incident angle dependence of the intensity and real part of  $S_{21}$ , respectively. The light blue region in Fig. 5(a) and the striped region in Fig. 5(b), starting at  $f_{\text{FMR}} = 1.68$  GHz, indicate the SW propagation band. At  $f = 1.811$  GHz, the MBGs are observed as black regions for all incident angles, as shown in Fig. 5(a). These MBGs are designated as the first MBGs, and an enlarged view is shown in Fig. 5(c). Figure 6 shows the first MBG frequency region for each SW incident angle. The first MBGs shifted slightly towards higher frequencies as the incident angle decreased but remained nearly constant, resulting in the opening of the CMBG. Furthermore, as shown in Figs. 6(a) and 6(b), the second MBGs appeared at higher frequencies than the first MBGs, from 1.83 to 1.90 GHz, and significantly shifted towards higher frequency as the incident angle increased. These MBG tendencies are in good agreement with a previous report [50]. The edge modes at hole boundaries or metal/YIG interfaces can potentially influence the band structure. Although such modes have been reported in antidot structures, their presence and contribution to our CMBG system remain to be investigated.

#### F. Comparison

The designed 2D MC possesses a CMBG with a bandwidth of 15.1 MHz and a center frequency of 1.811 GHz. In our previous work, the 2D MCs comprising a hexagonal Cu disk array on a 13- $\mu\text{m}$ -thick YIG film exhibited MBGs only within SW incident angles of  $10^\circ$  to  $30^\circ$  [50]. Chi *et al.* reported an MBG at only one incident angle in a square lattice 2D MC, where periodic grooves were formed on a 100- $\mu\text{m}$ -thick YIG film [48]. In contrast, this study found that the 2D MC opened the MBGs at all incident angles, creating a CMBG.

Krawczyk and Grundler predicted a CMBG for FVSWs with a bandwidth of 0.5 GHz in a square-lattice 2D MC

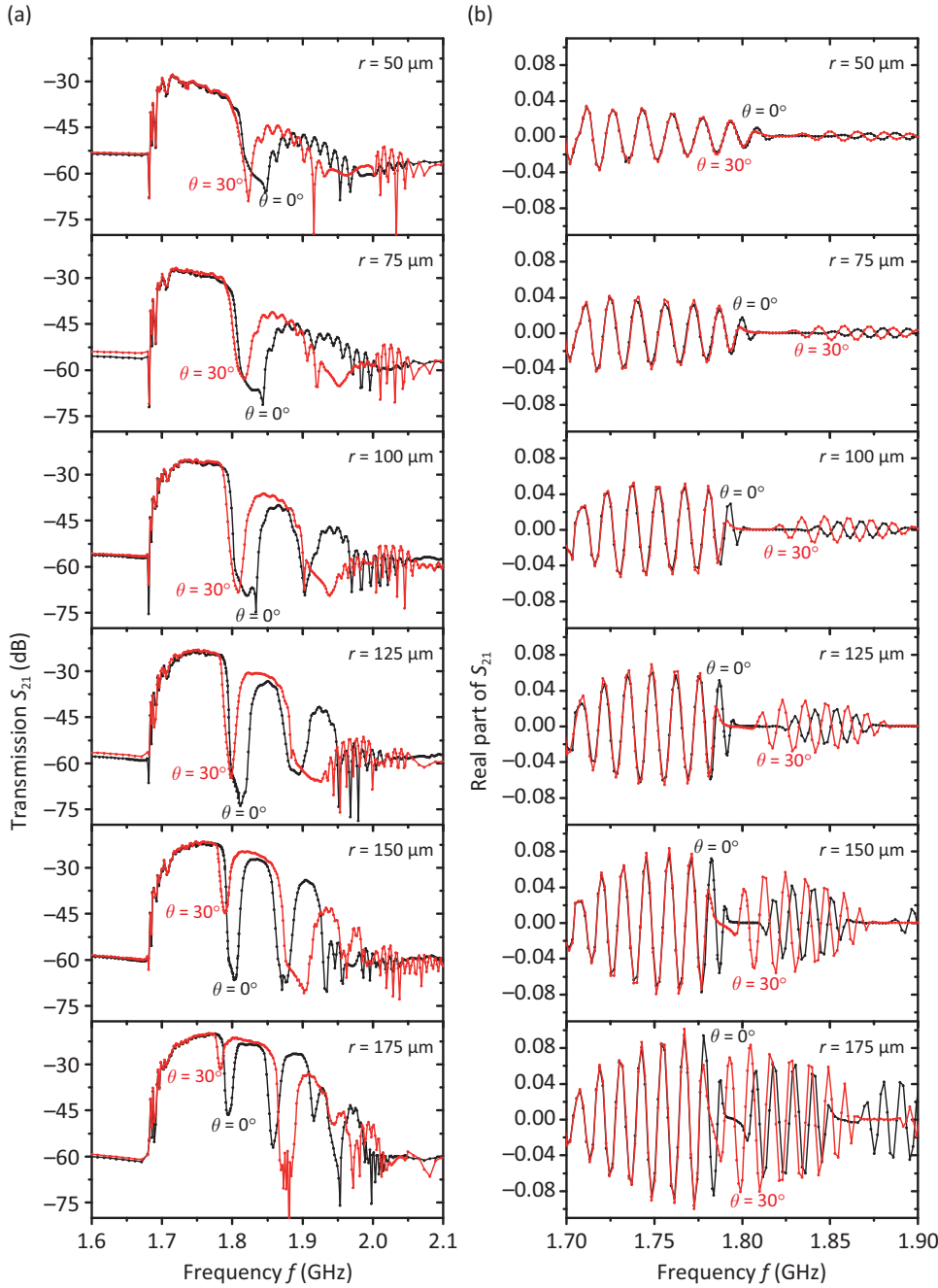


FIG. 3. (a) The transmission  $S_{21}$  spectra and (b) the real part of  $S_{21}$  spectra with varying hole radius  $r$  of the hole array. The slit width was 1  $\mu\text{m}$ . Black and red lines show the spectra at incident angles of  $\theta = 0^\circ$  and  $30^\circ$ .

made of 41-nm-thick CoFeB and 240-nm-diameter antidots using the PWM [30]. Using micromagnetic simulations, Schwarze *et al.* predicted a CMBG with a bandwidth of 1.4 GHz for a square-lattice 2D MC made of 22-nm-thick permalloy and 240-nm-diameter antidots [52]. These bandwidths were significantly larger than those in this study because of the difference in the dispersion relations between the exchange and dipolar SWs. Therefore, a large bandwidth in the exchange SW region can be achieved by using a 2D MC composed of a nanopatterned metal film on YIG.

### III. CALCULATION OF Z-SHAPED MC WAVEGUIDE

#### A. Calculation model of Z-shaped MC waveguide

A Z-shaped line defect with two  $120^\circ$  corners was introduced into the optimized MC ( $g = 1 \mu\text{m}$ ,  $r = 100 \mu\text{m}$ ), as shown in Figs. 1(d)–1(f), and SW propagation was calculated. The defect width was set to 200  $\mu\text{m}$  ( $= 2r$ ), and the bending radius was designated as  $r_b$ . To suppress the SW signals that propagated between the MSLs without passing through the defect, the length of the MSLs was shortened

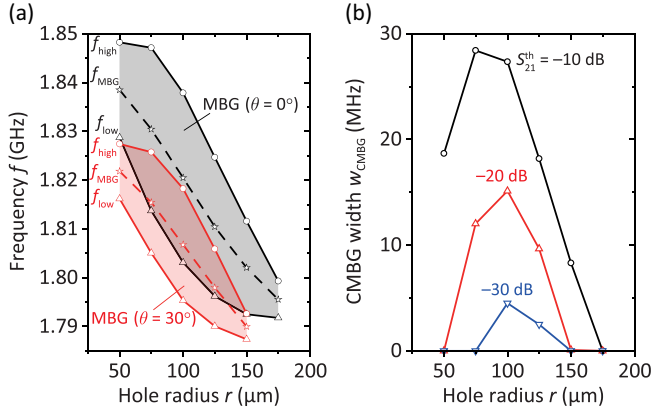


FIG. 4. (a) Magnonic band gap (MBG) frequency region with various hole radii  $r$  at  $S_{21}^{\text{th}} = -20$  dB. Circles mark the high-frequency edge, triangles mark the low-frequency edge, and stars indicate the center frequency of the MBG. Black and red plots correspond to spin wave (SW) incident angles  $\theta = 0^\circ$  and  $30^\circ$ , respectively. (b) Complete MBG (CMBG) width  $w_{\text{CMBG}}$  vs hole radius  $r$  with various threshold values  $S_{21}^{\text{th}}$ .

to half of that in the previous model, as shown in Fig. 1. In addition to these modifications, the calculation conditions were the same as those described in the previous section.

### B. SW propagation along Z-shaped MC waveguide

Figure 7(a) shows the transmission  $S_{21}$  spectra of the Z-shaped MC waveguide at  $r_b = 300$  and  $360$   $\mu\text{m}$ , as shown in Figs. 1(e) and 1(f), as well as in the absence of

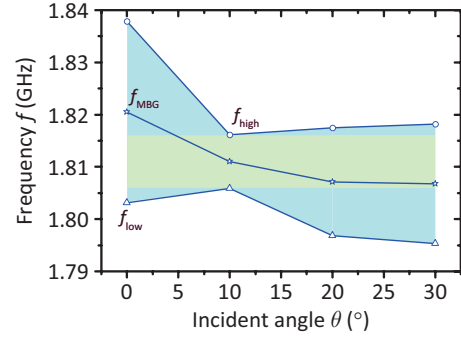


FIG. 6. Spin wave incident angle dependence of the first magnonic band gap (MBG). Triangles and circles indicate the low-frequency edge  $f_{\text{low}}$  and high-frequency edge  $f_{\text{high}}$  of the MBG, respectively. Stars indicate the center frequency  $f_{\text{MBG}}$ . The yellow rectangle indicates the frequencies that reside in an incident-angle-independent complete MBG.

a line defect. Figure S3 in the Supplemental Material [55] shows the overall transmission spectra. At  $f = 1.811$  GHz, corresponding to  $f_{\text{CMBG}}$ , transmission  $S_{21}$  significantly increased with the introduction of line defects. The multiple peaks observed within the CMBG frequency range arose from the transverse width modes in the defect because the defect width exceeded the SW wavelength at these frequencies. Figure 7(b) shows the distribution of the in-plane component of the rf magnetic field [ $h_{\text{ip}} = (h_x^2 + h_y^2)^{1/2}$ ] at the midplane of the YIG film at  $r_b = 360$   $\mu\text{m}$  and  $f = 1.811$  GHz, corresponding to FVSW intensity. As shown in Fig. 7(b), transmission  $S_{21}$  increased

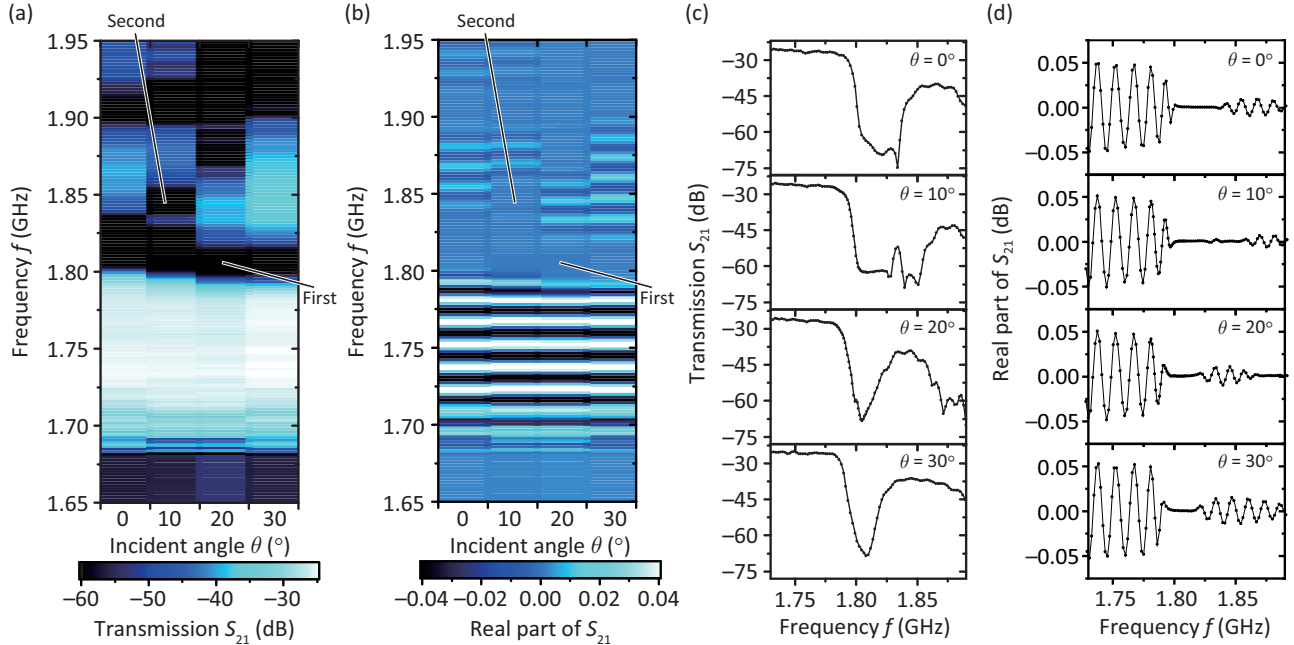


FIG. 5. (a) Transmission  $S_{21}$  and (b) the real part of  $S_{21}$  vs spin wave incident angle. (c),(d) Enlarged views of the transmission  $S_{21}$  and the real part of  $S_{21}$  spectra are shown near the first magnonic band gaps in (a) and (b), respectively.

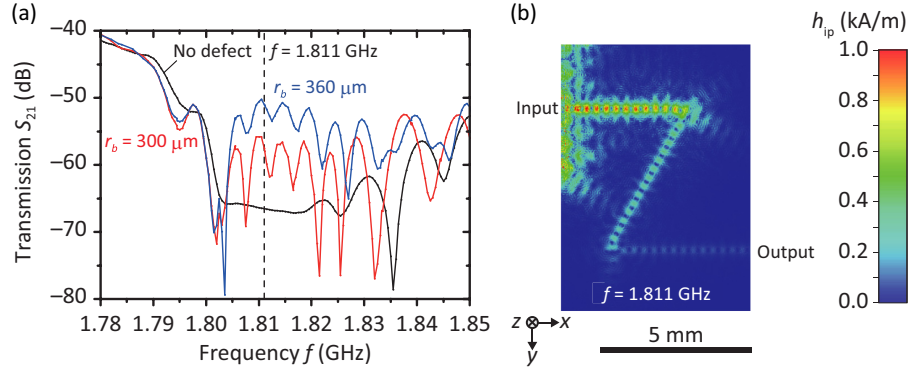


FIG. 7. (a) The transmission spectra near the complete magnonic band gap for the Z-shaped waveguide based on the magnonic crystal. (b) The distribution of the forward volume spin wave in-plane component of the rf magnetic field  $h_{ip}$  at the midplane of the yttrium iron garnet film at  $f = 1.811$  GHz and  $r_b = 360$   $\mu\text{m}$ .

because of the propagation of the SW confined within the defect by the CMBG. Moreover, at  $f = 1.811$  GHz, the transmission  $S_{21}$  values were  $-61.5$  and  $-50.3$  dB at the bending radii  $r_b = 300$  and  $360$   $\mu\text{m}$ , respectively. This suggests that the bending losses decreased as the SW waveguide bent more gradually. Figure 8 shows the SW energy  $E_{\text{SW}}$  profile along the defect, calculated by integrating the Poynting vector across a  $200 \times 400$   $\mu\text{m}^2$  area, including the line defect. The Z-shaped defect was divided into three sections before and after bending, and the SW energy profile in each section was approximated using the following equation:

$$E_{\text{SW}} = Ae^{-Bx}, \quad (3)$$

where  $A$  and  $B$  are constants.  $A$  is the initial energy at the starting point of the profile.  $B$  corresponds to the SW propagation loss, and is the inverse of the decay length. The same value of  $B$  was used for all sections because the SW propagation loss can be considered equal for all

straight sections. The value of  $B$  was obtained from the approximation function, shown as black plots in Fig. 8, representing the SW energy propagating in the straight-line defect waveguide as shown in Fig. S4 in the Supplemental Material [55]. For the Z-shaped waveguide, step-like losses of the SW energy were observed before and after each bend, corresponding to the bending loss  $L_b$ . The obtained values of  $A$  and  $B$  are listed in Table I. The loss per bend is calculated using the following equation:

$$L_b (\%) = \frac{(1 - A_{\text{II}}/A_{\text{I}}) + (1 - A_{\text{III}}/A_{\text{II}})}{2} \times 100. \quad (4)$$

The subscripts of  $A$  represent the waveguide section numbers. The bending losses were 74.8% and 49.8% at  $r_b = 300$  and  $360$   $\mu\text{m}$ , respectively. As the bending radius  $r_b$  increased and the bend became more gradual, the bending loss decreased significantly, similar to the improvement in  $S_{21}$  shown in Fig. 7. The calculated bending loss of the 2D-MC-based Z-shaped waveguide was high; however, the loss was reduced by optimizing the corner structure. These detailed optimization results will be discussed in a subsequent publication.

### C. Comparison of Z-shape waveguides

In actual situations, an internal magnetic field distribution occurs in the waveguide owing to the demagnetizing

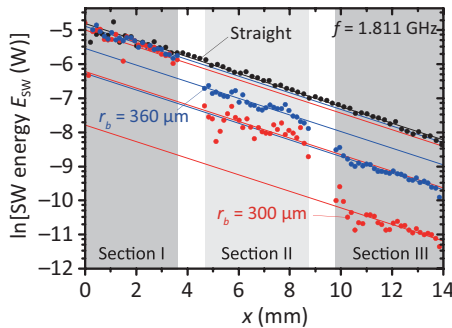


FIG. 8. The distribution of the spin wave (SW) energy along the Z-shaped magnonic crystal waveguide at  $f = 1.811$  GHz. Black, blue, and red plots show the SW energy propagating in the straight waveguide, the bending waveguide with  $r_b = 360$   $\mu\text{m}$ , and that with  $r_b = 300$   $\mu\text{m}$ . The lines correspond to Eq. (5) with the parameters shown in Table I.

TABLE I. The parameters of the approximation curves.

| Section | $r_b$             | $A$ (W)               | $B$ (1/mm)             |
|---------|-------------------|-----------------------|------------------------|
| —       | Straight          | $8.21 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |
| I       | 300 $\mu\text{m}$ | $6.76 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |
| II      | 300 $\mu\text{m}$ | $1.99 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |
| III     | 300 $\mu\text{m}$ | $4.18 \times 10^{-4}$ | $2.438 \times 10^{-1}$ |
| I       | 360 $\mu\text{m}$ | $7.55 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |
| II      | 360 $\mu\text{m}$ | $3.93 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |
| III     | 360 $\mu\text{m}$ | $1.90 \times 10^{-3}$ | $2.438 \times 10^{-1}$ |

field distribution. This phenomenon significantly influences the characteristics of the SW waveguides. Hence, the propagation properties of the Z-shaped MC waveguide [Fig. 9(a)] were compared with those of a ridge waveguide [Fig. 9(b)], considering the inhomogeneous internal magnetic field distribution. The width of the ridge waveguide was 200  $\mu\text{m}$ , the same as the width of the line defect in the MC waveguide. Unlike the models shown in Fig. 1, these models account for the inhomogeneous demagnetizing field inside the YIG film by applying an external magnetic field of  $H_0 = 2335$  Oe along the  $+z$  direction, rather than using a homogeneous internal magnetic field  $H_{\text{in}} = 600$  Oe. The value of  $H_0$  was determined by summing the internal magnetic field (600 Oe) and the YIG magnetization (1735 G).

Figures 9(c) and 9(d) show the calculated distribution of the FVSW  $h_{\text{ip}}$  in the MC waveguide at  $f = 1.814$  GHz and in the ridge waveguide at  $f = 2.105$  GHz. These frequencies are different from the  $f_{\text{CMBG}}$  of 1.811 GHz because of the consideration of the demagnetizing field (see details in Figs. S5 and S6 in the Supplemental Material [55]). The ridge waveguide cannot propagate SWs because of the effective width narrowing caused by the inhomogeneous internal magnetic field, whereas the MC waveguide enables SW propagation because of its homogeneous internal magnetic field. The transmission  $S_{21}$  was  $-49.87$  dB

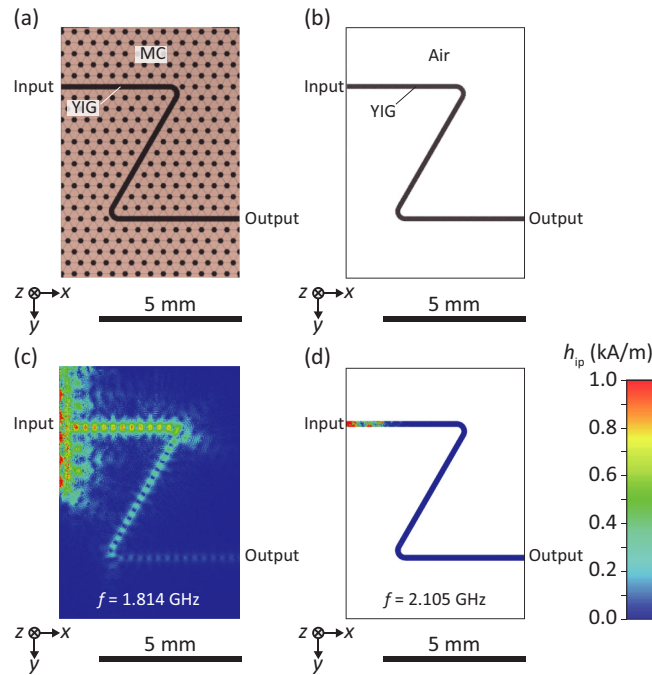


FIG. 9. The calculation models of (a) the Z-shaped magnonic crystal (MC) waveguide and (b) the Z-shaped ridge waveguide. The distribution of forward volume spin wave in-plane component of the rf magnetic field  $h_{\text{ip}}$  at the midplane of the yttrium iron garnet (YIG) film (c) in the MC waveguide at  $f = 1.814$  GHz and (d) in the ridge waveguide at  $f = 2.105$  GHz.

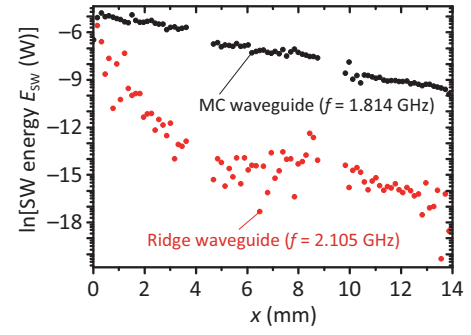


FIG. 10. Spin wave (SW) energy profiles along the Z-shaped waveguides, accounting for the inhomogeneous internal magnetic field. Black and red plots indicate the SW energy profiles in the magnonic crystal (MC) waveguide at  $f = 1.814$  GHz and the ridge waveguide at  $f = 2.105$  GHz, respectively.

for the MC waveguide at  $f = 1.814$  GHz and  $-61.33$  dB for the ridge waveguide at  $f = 2.105$  GHz, resulting in the transmission  $S_{21}$  of the MC waveguide being 3.74 times higher than that of the ridge waveguide. For the MC waveguide, the transmission calculation considers the SWs excited outside the defect region. Thus, improving the antenna design to eliminate this contribution would further increase the SW transmission. Figure 10 shows the SW energy profiles inside the defect of the MC waveguide at  $f = 1.814$  GHz and inside the ridge waveguide at  $f = 2.105$  GHz, accounting for the inhomogeneous internal magnetic fields. The SW energy in the MC waveguide was significantly higher than that in the ridge waveguide, being  $5.7 \times 10^3$  times greater around the output corresponding to  $x = 14$  mm. In addition, the Cu disk array could not function as a waveguide owing to the lack of a CMBG (see details in Fig. S7 in the Supplemental Material [55]). Therefore, the hole-array MC waveguide with the CMBG propagated SWs more efficiently than the ridge and disk-array MC waveguides.

#### D. Fabrication considerations

The proposed Z-shaped MC waveguide is more complex than the conventional ridge waveguides. However, the fabrication process remains practical. The hexagonal hole array and the slits between holes can be patterned simultaneously in a single lithography step using standard equipment with 1- $\mu\text{m}$  resolution. This fabrication approach required the same number of processing steps as our previously reported MC structure comprising a hexagonal Cu disk array [50]. The same fabrication equipment, such as mask aligners or laser lithography systems, can be employed without modification. The critical dimensions (hole diameter of around 200  $\mu\text{m}$ , lattice constant 450  $\mu\text{m}$ , slit width 1  $\mu\text{m}$ ) are within the resolution limits of these standard techniques and comparable to those successfully fabricated in our previous studies [24,50],

ensuring high reproducibility. We have already fabricated test devices and successfully observed the CMBG, confirming the feasibility of the proposed design. Detailed experimental results will be reported in future studies.

#### IV. CONCLUSION

A 2D MC consisting of a 10- $\mu\text{m}$ -thick YIG film and a 2- $\mu\text{m}$ -thick hexagonal Cu hole array was designed and studied using a 3D FIT simulation to exhibit a CMBG. The obtained CMBG had a width of 15.1 MHz and center frequency of 1.811 GHz. A Z-shaped line defect with two  $120^\circ$  turns was introduced into the MC, and the FVSW propagation was calculated. At the CMBG frequency, propagation of the FVSW through the line defect was observed. The proposed waveguide demonstrated a SW transmission efficiency  $5.7 \times 10^3$  times higher than that of a conventional ridge waveguide. To better understand the fundamental physical mechanisms underlying the CMBG formation, rigorous band structure calculations using the PWM would provide deeper insights. Further structural improvements of the bent waveguide would enhance SW propagation intensity and enable various applications. Therefore, this study demonstrated the directional control of FVSW propagation using the CMBG of the MC, showcasing its utility. Our approach avoids SW depression caused by inhomogeneous internal field distributions and uses an unetched YIG film. We consider this waveguide technique essential for advanced 2D FVSW control and an important milestone in the development of SW ICs.

#### ACKNOWLEDGMENTS

This work was partly supported by the Japan Society for the Promotion of Science (JSPS) Grants No. 20H02593, No. 23H01439, No. 23K17758, and No. JPJSBP120249401; the New Energy and Industrial Technology Development Organization (NEDO) Grant No. JPNP20004; the Inamori Foundation, and the Amada Foundation. T.G. acknowledges support from the TI-FRIS Fellowship. D.G. thanks SNSF for support via Grant No. 197360. We also acknowledge the shared facilities of TU-FTC, TU-LNS, TU-CINTS, and TU-GIMRT.

#### DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

- 
- [1] D. D. Stancil and A. Prabhakar, *Spin Waves* (Springer, New York, 2009).
  - [2] S. O. Demokritov and A. N. Slavin, *Magnonics* (Springer, New York, 2012).

- [3] T. Goto, T. Yoshimoto, B. Iwamoto, K. Shimada, C. A. Ross, K. Sekiguchi, A. B. Granovsky, Y. Nakamura, H. Uchida, and M. Inoue, Three port logic gate using forward volume spin wave interference in a thin yttrium iron garnet film, *Sci. Rep.* **9**, 16472 (2019).
- [4] N. Kanazawa, T. Goto, K. Sekiguchi, A. B. Granovsky, C. A. Ross, H. Takagi, Y. Nakamura, H. Uchida, and M. Inoue, The role of Snell's law for a magnonic majority gate, *Sci. Rep.* **7**, 7898 (2017).
- [5] T. Fischer, M. Kewenig, D. A. Bozhko, A. A. Serga, I. I. Syvorotka, F. Ciubotaru, C. Adelman, B. Hillebrands, and A. V. Chumak, Experimental prototype of a spin-wave majority gate, *Appl. Phys. Lett.* **110**, 152401 (2017).
- [6] K. An, M. Xu, A. Mucchietto, C. Kim, K. W. Moon, C. Hwang, and D. Grundler, Emergent coherent modes in nonlinear magnonic waveguides detected at ultra-high frequency resolution, *Nat. Commun.* **15**, 7302 (2024).
- [7] N. Zenbaa, C. Abert, F. Majcen, M. Kerber, R. O. Serha, S. Knauer, Q. Wang, T. Schrefl, D. Suess, and A. V. Chumak, A universal inverse-design magnonic device, *Nat. Electron.* **6**, 106 (2025).
- [8] C. H. Marrows, J. Barker, T. A. Moore, and T. Moorsom, Neuromorphic computing with spintronics, *npj Spintron.* **2**, 12 (2024).
- [9] K. Yamanoi, S. Yakata, T. Kimura, and T. Manago, Spin wave excitation and propagation properties in a permalloy film, *Jpn. J. Appl. Phys.* **52**, 083001 (2013).
- [10] V. Vlaminc and M. Bailleul, Spin-wave transduction at the submicrometer scale: Experiment and modeling, *Phys. Rev. B* **81**, 014425 (2010).
- [11] M. P. Kostylev, A. A. Serga, T. Schneider, B. Leven, and B. Hillebrands, Spin-wave logical gates, *Appl. Phys. Lett.* **87**, 153501 (2005).
- [12] N. Sato, K. Sekiguchi, and Y. Nozaki, Electrical demonstration of spin-wave logic operation, *Appl. Phys. Express* **6**, 063001 (2013).
- [13] T. Schneider, A. A. Serga, B. Leven, B. Hillebrands, R. L. Stamps, and M. P. Kostylev, Realization of spin-wave logic gates, *Appl. Phys. Lett.* **92**, 022505 (2008).
- [14] A. V. Chumak, P. Pirro, A. A. Serga, M. P. Kostylev, R. L. Stamps, H. Schultheiss, K. Vogt, S. J. Hermsdoerfer, B. Laegel, P. A. Beck, and B. Hillebrands, Spin-wave propagation in a microstructured magnonic crystal, *Appl. Phys. Lett.* **95**, 262508 (2009).
- [15] K. Vogt, H. Schultheiss, S. J. Hermsdoerfer, P. Pirro, A. A. Serga, and B. Hillebrands, All-optical detection of phase fronts of propagating spin waves in a  $\text{Ni}_{81}\text{Fe}_{19}$  microstripe, *Appl. Phys. Lett.* **95**, 182508 (2009).
- [16] H. Qin, R. B. Holländer, L. Flajšman, and S. van Dijken, Low-loss nanoscopic spin-wave guiding in continuous yttrium iron garnet films, *Nano Lett.* **22**, 5294 (2022).
- [17] T. Brächer, M. Fabre, T. Meyer, T. Fischer, S. Auffret, O. Boulle, U. Ebels, P. Pirro, and G. Gaudin, Detection of short-waved spin waves in individual microscopic spin-wave waveguides using the inverse spin Hall effect, *Nano Lett.* **17**, 7234 (2017).
- [18] K. Vogt, H. Schultheiss, S. Jain, J. E. Pearson, A. Hoffmann, S. D. Bader, and B. Hillebrands, Spin waves turning a corner, *Appl. Phys. Lett.* **101**, 042410 (2012).

- [19] A. I. Nikitchenko and N. A. Pertsev, Spin-orbit torque control of spin waves in a ferromagnetic waveguide, *Phys. Rev. B* **104**, 134422 (2021).
- [20] S. Bance, T. Schrefl, G. Hrkac, A. Goncharov, D. A. Allwood, and J. Dean, Micromagnetic calculation of spin wave propagation for magnetologic devices, *J. Appl. Phys.* **103**, 07E (2008).
- [21] P. Clausen, K. Vogt, H. Schultheiss, S. Schäfer, B. Obry, G. Wolf, P. Pirro, B. Leven, and B. Hillebrands, Mode conversion by symmetry breaking of propagating spin waves, *Appl. Phys. Lett.* **99**, 162505 (2011).
- [22] A. V. Chumak, A. A. Serga, and B. Hillebrands, Magnon transistor for all-magnon data processing, *Nat. Commun.* **5**, 4700 (2014).
- [23] P. Frey, A. A. Nikitin, D. A. Bozhko, S. A. Bunyaev, G. N. Kakazei, A. B. Ustinov, B. A. Kalinikos, F. Ciubotaru, A. V. Chumak, Q. Wang, V. S. Tiberkevich, B. Hillebrands, and A. A. Serga, Reflection-less width-modulated magnonic crystal, *Commun. Phys.* **3**, 17 (2020).
- [24] T. Goto, K. Shimada, Y. Nakamura, H. Uchida, and M. Inoue, One-dimensional magnonic crystal with Cu stripes for forward volume spin waves, *Phys. Rev. Appl.* **11**, 014033 (2019).
- [25] N. Kanazawa, T. Goto, K. Sekiguchi, A. B. Granovsky, C. A. Ross, H. Takagi, Y. Nakamura, and M. Inoue, Demonstration of a robust magnonic spin wave interferometer, *Sci. Rep.* **6**, 30268 (2016).
- [26] K. Shimada, T. Goto, N. Kanazawa, H. Takagi, Y. Nakamura, H. Uchida, and M. Inoue, Extremely flat transmission band of forward volume spin wave using gold and yttrium iron garnet, *J. Phys. D: Appl. Phys.* **50**, 275001 (2017).
- [27] A. V. Sadovnikov, V. A. Gubanov, S. E. Sheshukova, Y. P. Sharaevskii, and S. A. Nikitov, Spin-wave drop filter based on asymmetric side-coupled magnonic crystals, *Phys. Rev. Appl.* **9**, 051002 (2018).
- [28] S. Klingler, P. Pirro, T. Brächer, B. Leven, B. Hillebrands, and A. V. Chumak, Design of a spin-wave majority gate employing mode selection, *Appl. Phys. Lett.* **105**, 152410 (2014).
- [29] K. Vogt, F. Y. Fradin, J. E. Pearson, T. Sebastian, S. D. Bader, B. Hillebrands, A. Hoffmann, and H. Schultheiss, Realization of a spin-wave multiplexer, *Nat. Commun.* **5**, 3727 (2014).
- [30] M. Krawczyk and D. Grundler, Review and prospects of magnonic crystals and devices with reprogrammable band structure, *J. Phys.: Condens. Matter* **26**, 123202 (2014).
- [31] A. V. Chumak, A. A. Serga, and B. Hillebrands, Magnonic crystals for data processing, *J. Phys. D: Appl. Phys.* **50**, 244001 (2017).
- [32] V. V. Kruglyak, M. L. Sokolovskii, V. S. Tkachenko, and A. N. Kuchko, Spin-wave spectrum of a magnonic crystal with an isolated defect, *J. Appl. Phys.* **99**, 08C906 (2006).
- [33] A. N. Kuchko, M. L. Sokolovskii, and V. V. Kruglyak, Spin wave spectrum of a magnonic crystal with an internally structured defect, *Phys. B* **370**, 73 (2005).
- [34] F. S. Ma, H. S. Lim, V. L. Zhang, S. C. Ng, and M. H. Kuok, Magnonic band structure investigation of one-dimensional bi-component magnonic crystal waveguides, *Nanoscale Res. Lett.* **7**, 498 (2012).
- [35] S. A. Nikitov, P. Tailhades, and C. S. Tsai, Spin waves in periodic magnetic structures—magnonic crystals, *J. Magn. Magn. Mater.* **236**, 320 (2001).
- [36] C. Banerjee, S. Choudhury, J. Sinha, and A. Barman, Pseudo-one-dimensional magnonic crystals for high-frequency nanoscale devices, *Phys. Rev. Appl.* **8**, 014036 (2017).
- [37] M. A. Morozova, S. V. Grishin, A. V. Sadovnikov, D. V. Romanenko, Y. P. Sharaevskii, and S. A. Nikitov, Band gap control in a line-defect magnonic crystal waveguide, *Appl. Phys. Lett.* **107**, 242402 (2015).
- [38] H. Qin, G.-J. Both, S. J. Hämäläinen, L. Yao, and S. van Dijken, Low-loss YIG-based magnonic crystals with large tunable bandgaps, *Nat. Commun.* **9**, 5445 (2018).
- [39] Z. K. Wang, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, S. Jain, and A. O. Adeyeye, Observation of frequency band gaps in a one-dimensional nanostructured magnonic crystal, *Appl. Phys. Lett.* **94**, 083112 (2009).
- [40] S.-K. Kim, K.-S. Lee, and D.-S. Han, A gigahertz-range spin-wave filter composed of width-modulated nanostrip magnonic-crystal waveguides, *Appl. Phys. Lett.* **95**, 082507 (2009).
- [41] Y. Zhu, K. H. Chi, and C. S. Tsai, Magnonic crystals-based tunable microwave phase shifters, *Appl. Phys. Lett.* **105**, 022411 (2014).
- [42] N. Kanazawa, T. Goto, and M. Inoue, Spin wave localization in one-dimensional magnonic microcavity comprising yttrium iron garnet, *J. Appl. Phys.* **116**, 083903 (2014).
- [43] S. Tacchi, G. Gubbiotti, M. Madami, and G. Carlotti, Brillouin light scattering studies of 2D magnonic crystals, *J. Phys.: Condens. Matter* **29**, 073001 (2017).
- [44] B. Lenk, H. Ulrichs, F. Garbs, and M. Münzenberg, The building blocks of magnonics, *Phys. Rep.* **507**, 107 (2011).
- [45] S. Mamica, M. Krawczyk, and D. Grundler, Nonuniform spin-wave softening in two-dimensional magnonic crystals as a tool for opening omnidirectional magnonic band gaps, *Phys. Rev. Appl.* **11**, 054011 (2019).
- [46] T. Schwarze and D. Grundler, Magnonic crystal wave guide with large spin-wave propagation velocity in CoFeB, *Appl. Phys. Lett.* **102**, 222412 (2013).
- [47] M. Madami, G. Gubbiotti, S. Tacchi, G. Carlotti, and S. Jain, Study of the spin excitations in antidot lattices with line defects, *Phys. B* **435**, 152 (2014).
- [48] K. H. Chi, Y. Zhu, and C. S. Tsai, Two-dimensional magnonic crystal with periodic thickness variation in YIG layer for magnetostatic volume wave propagation, *IEEE Trans. Magn.* **49**, 1000 (2013).
- [49] K. H. Chi, Y. Zhu, and C. S. Tsai, Confinement of magnetostatic forward volume waves in two-dimensional magnonic crystals with line defects, *J. Appl. Phys.* **115**, 17D125 (2014).
- [50] K. Mori, T. Koguchi, T. Watanabe, Y. Yoshihara, H. Miyashita, D. Grundler, M. Inoue, K. Ishiyama, and T. Goto, Orientation-dependent two-dimensional magnonic crystal modes in an ultralow-damping ferrimagnetic waveguide containing repositioned hexagonal lattices of Cu disks, *Phys. Rev. Appl.* **21**, 014061 (2024).
- [51] J. O. Vasseur, L. Dobrzynski, B. Djafari-Rouhani, and H. Puzskarski, Magnon band structure of periodic composites, *Phys. Rev. B* **54**, 1043 (1996).
- [52] T. Schwarze, R. Huber, G. Duerr, and D. Grundler, Complete band gaps for magnetostatic forward volume waves in a two-dimensional magnonic crystal, *Phys. Rev. B* **85**, 134448 (2012).

- [53] T. Weiland, Time domain electromagnetic field computation with finite difference methods, *Int. J. Numer. Modell.: Electron. Netw. Devices Fields* **9**, 295 (1996).
- [54] T. Weiland, M. Timm, and I. Munteanu, A practical guide to 3-D simulation, *IEEE Microw. Mag.* **9**, 62 (2008).
- [55] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/m64z-lh2m> for additional figures.
- [56] R. A. Matula, Electrical resistivity of copper, gold, palladium, and silver, *J. Phys. Chem. Ref. Data* **8**, 1147 (1979).
- [57] S. Chakrabarti and D. Bhattacharya, Magnetostatic volume waves in lossy YIG film backed by a metal of finite conductivity, *IEEE Trans. Microw. Theory Tech.* **47**, 1132 (1999).