Robust and disorder-immune magnetically tunable one-way waveguides in a gyromagnetic photonic crystal

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We experimentally realize one-way waveguides that work within the magnetic resonance–induced band gap in a gyromagnetic photonic crystal made from ferrite rods. Our microwave measurements show that the one-way transport band is magnetically tunable and robust against back scattering induced by external disturbance. More importantly, the unidirectional transport is immune to lattice disorders by a much greater extent than the conventional one-way waveguide that works within the Bragg scattering–induced band gap. The experimental observation has been confirmed by numerical simulations, which show that the robust one-way transport property originates from the localized magnetic surface plasmon resonance.

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I. INTRODUCTION

Photonic crystals (PCs) have been attracting great attention for decades as powerful tools to model the flow of light. Introduction of magneto-optical materials brings new, fabulous characters of chiral edge states[1,2] when a direct current (DC) magnetic field is exerted on such magneto-optical photonic crystals (MOPCs) to induce time-reversal symmetry (TRS) breaking and band degeneracy splitting to form a new band gap. The chiral edge state is related to the nontrivial topological properties of the band structure and implies a unique unidirectional flow of light on the basis of which a one-way waveguide can form. Such one-way waveguides have been realized in a gyromagnetic photonic crystal (GPC),[3,4] the counterpart of an MOPC in a microwave regime, where the unidirectional transport of an electromagnetic wave is quite robust against back scattering induced by the external perturbation and the interface configuration.[4,5]

Up to now, most studies have focused on the conventional one-way waveguide that works within the Bragg scattering–induced band gaps.[3–10] Recent theoretical studies by Liu *et al.* show that one-way waveguide can also form at a certain frequency near the magnetic surface plasmon (MSP) resonance frequency of ferrite materials.[11,12] In this work, we present an experimental study of the one-way transport properties in this magnetic-resonance regime. We show that the new one-way waveguide of our design is robust not only against external perturbation but also against lattice site disorders in a certain width of frequency.

II. RESULTS AND DISCUSSION

In our experiment, we chose ferrite rods made from yttrium–iron–garnet (YIG) (with the rod axes in the z direction) to comprise the GPC. Considering transverse magnetic (TM) mode (with the electric field polarized in the z direction), the permeability becomes a second-rank tensor when applying a DC magnetic field in the z direction:[13]

$$\boldsymbol{\mu} = \begin{pmatrix} \mu_r & -i\mu_i & 0 \\ i\mu_i & \mu_r & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

The tensor elements are $\mu_r = 1 + \frac{\omega_m(\omega_0 + i\alpha\omega)}{(\omega_0+i\alpha\omega)^2-\omega^2}$ and $\mu_i = \frac{\omega_m\omega}{(\omega_0+i\alpha\omega)^2-\omega^2}$. Here, $\omega_0 = \gamma H_0$ is the precession frequency, where γ is the gyromagnetic ratio and H_0 is the applied magnetic field; $\omega_m = 4\pi\gamma m_s$ is the characteristic frequency, with $4\pi m_s$ as the saturation magnetization; and $\alpha = \frac{\mu_0\gamma\Delta H}{2\omega}$ is the damping factor of YIG, where ΔH is the linewidth.[14,15] Also, μ_i is divergent at ω_0, and ω_0 often lies within the first band of the GPC when the magnetic resonance is neglected.[14] Due to the magnetic resonance, YIG shows complex metallic behaviors around ω_0, and some new gaps form in this frequency regime of the GPC.[12] These new gaps, which are different from the conventional bang gap resulting from Bragg scattering, are related to the MSP resonance and the spin-wave resonance. As a result, these band gaps have unique properties of magnetic tunability and immunity to lattice disorders. Our following experimental studies confirm that the one-way waveguide working within these regimes is indeed magnetically controllable and lattice disorder immune.

In our design of the one-way waveguide, as depicted in Fig. 1, the lower part of the waveguide is a two-dimensional (2D) square-lattice GPC consisting of YIG ferrite rods. The lattice constant is $a = 1.45$ cm and radius of rod is $r = 0.016$ cm. The parameters of YIG are $4\pi m_s = 1800$ Gauss (G) and $\varepsilon = 14.5\varepsilon_0$. For practical consideration, the loss factor of the YIG material has also been taken into account,[15] where the linewidth is set to be $\Delta H = 30$ Oe. To achieve the confinement of edge states at the interface and the formation of guided modes, a perfect electric conductor (PEC) wall is placed at the upper part of the bulk GPC to form a waveguide that supports unidirectional transport of an electromagnetic wave under an applied DC magnetic field. The experimental configuration, as depicted in Fig. 1, is similar to that adopted in Ref. 4. The width of the waveguide is defined as the distance between the metal wall and the center of the first row of the rods. If the width of the waveguide is too small, it no longer supports the MSP mode, because there is a cutoff frequency for the waveguide. Thus, the width is set to 1.75 cm for better experimental observation.

Our experiment is carried out in a wide scattering chamber with a detect feed and a probe feed connected to an Agilent N5230A microwave vector network analyzer (Fig. 1). The detect feed and probe feed are both monopole antennas, and

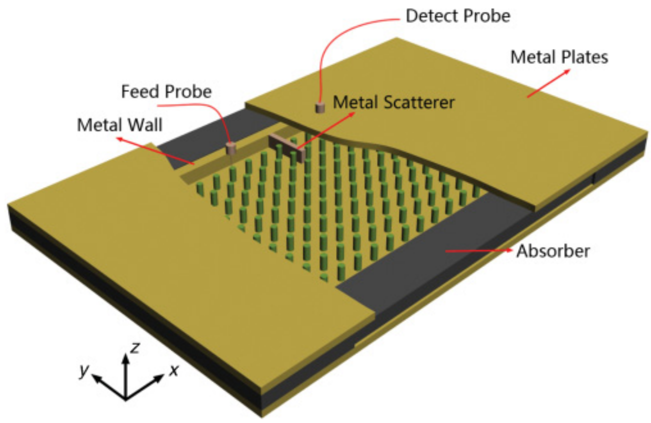

FIG. 1. (Color online) Schematic configuration of experiments of the one-way transport for a microwave in GPC waveguides made from a square lattice of YIG rods in the lower part and a metal wall in the upper part. The GPC structures are placed within a scattering chamber made from two parallel metal plates with 7 mm of separation and surrounded by microwave absorbing materials. The DC magnetic field is in the z direction.

the distance between them is $7a$. The major components of the scattering chamber are two parallel metal plates with 7 mm of separation. This guarantees that the physics of the system can be thought of as infinite 2D PC structures for the TM polarized wave.[14,15] The whole chamber is placed in the space between two specially designed NbFeB permanent magnets, which can finely tune the magnetic field magnitude by adjusting the distance between the two magnets.[14]

We first calculate the transmission spectra of the bulk GPC and our waveguide by using the multiple scattering method.[16] The plane wave source and point source are used when calculating the transmission spectra of the bulk GPC and the waveguide, respectively. In the simulations, the upper PEC wall in Fig. 1 is modeled as a rectangular box, with its edge made from a series of close-packed PEC rods. As the radius of the PEC rods is far smaller than the wavelength of the microwave and is much smaller than that of the YIG rods, this rectangular box can well simulate the PEC wall with smooth edges that is used in the experiments. The calculation results for a DC magnetic field of 2980 G are displayed in Fig. 2. It is seen from Fig. 2(a) that the bulk GPC exhibits two obvious low transmission regions, one ranging from 9.40 to 9.70 GHz and the other from 13.66 to 14.50 GHz. They correspond to two new band gaps of the GPC that the GPC with TRS does not have. The first band gap (9.40–9.70 GHz), which appears in the spectrum as a narrow and deep valley, is related to the MSP resonance, because it is located near the MSP resonance frequency of 10.86 GHz and it is a new band gap in the first band gap of MOPC with TRS. The second band gap (13.66–14.50 GHz), which appears in the spectrum as a wide valley, has been discussed systematically in recent literature.[3–10,14,15,17] It originates from the splitting of the degeneracy point between the second and the third bands in the GPC when the magnetic field is exerted on. Both regions show unidirectional characters, as shown in the spectrum of the waveguide [Fig. 2(b)] but have different chiralities. The narrow shaded (yellow) region is left handed, and the wide

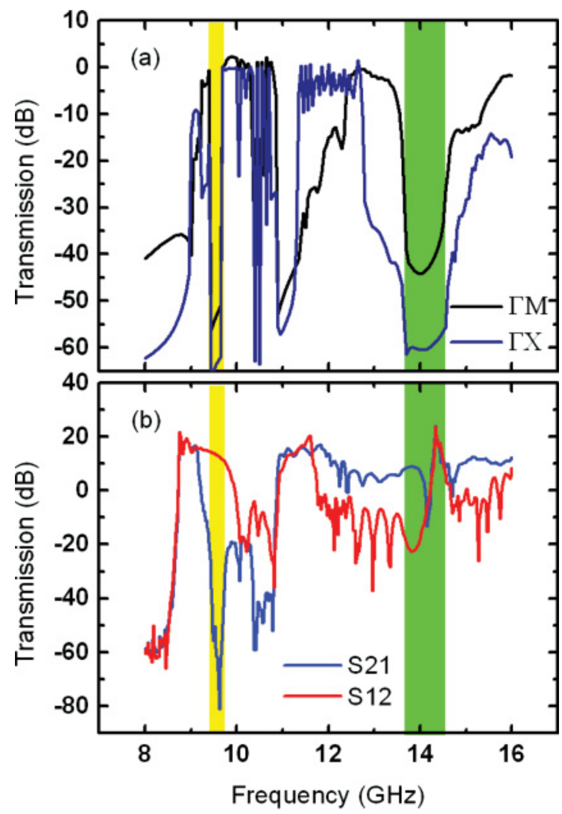

FIG. 2. (Color online) Calculated transmission spectra of the (a) bulk GPC and (b) waveguide in our design. The narrow shaded (yellow) and wide shaded (green) regions of the extremely low transmission correspond, respectively, to the lower and higher photonic band gaps of the bulk GPC. S21 and S12 correspond to the transmission when microwave propagates from left to right (forward direction) and from right to left (backward direction) in the waveguide, respectively. In the lower band gap, the forward mode is the unidirectional mode, whereas in the higher band gap, the backward mode is the unidirectional mode.

shaded (green) region is right handed. The one-way waveguide operating at the wide shaded region, as first investigated by Wang *et al.*[3,4] has been under extensive theoretical and experimental studies, while the one-way waveguide operating at the narrow shaded region, which is near the MSP resonance frequency, has not been observed experimentally so far. For simplicity, we call these two regions the MSP resonance region and the degeneracy-splitting region, respectively.

In our experiment, we first measure the spectrum of the waveguide under a DC magnetic field of 2980 G. There are two regions with big contrast between S21 and S12 in the spectrum [Fig. 3(a)]. The narrow shaded (yellow) region, which is left handed, ranges from 9.42 to 9.72 GHz. The wide shaded (green) region, which is right handed, is between 13.68 and 14.18 GHz. Although the unidirectional characters of these two regions are based on different mechanisms, both should be robust against a metal scatterer in the waveguide. To prove this, we insert a metal scatterer in the waveguide [Fig. 3(b)]. The measured spectrum [Fig. 3(b)] still shows big contrast for the forward and the backward wave within the two frequency regions, and the trace S12 in the narrow shaded region and trace S21 in the wide shaded region still

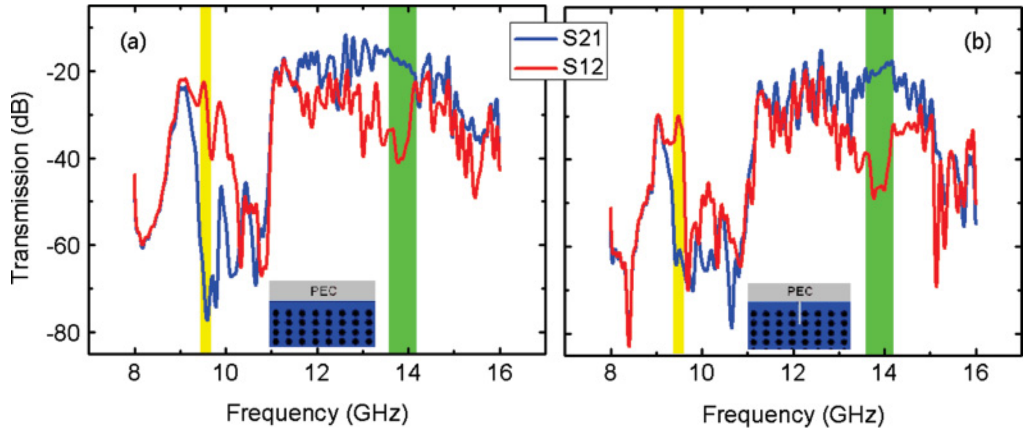

FIG. 3. (Color online) Measured transmission spectra of the one-way waveguide (a) without and (b) with a scatterer, whose geometric configurations are schematically illustrated in the insets.

have high transmission. S12 becomes somewhat attenuated by the metal obstacle in the narrow shaded region. To understand this, we made numerical simulations. The results (not shown here) indicate that the attenuation is mainly induced by the metal protrusion–enhanced absorption of YIG in the MSP region. Strong interaction occurs between the metal protrusion and the metal-like YIG rods. When YIG material absorption is neglected intentionally, S12 is not influenced by the metal obstacle and the wave transport attenuation is absent.

The one-way property in the second band gap (wide shaded region) resulting from Bragg scattering has been studied widely in previous literature, and we now look closely at the first band gap (narrow shaded region) near the MSP resonance. Our calculation and experiment results are displayed in Fig. 4. The first remarkable thing is that the narrow shaded region is tunable under a DC magnetic field. Comparing to the narrow shaded region, the wide shaded region seems to have negligible change under a varying magnetic field. When tuning the magnetic field from 2980 to 2516 G, the narrow shaded region moves to the lower frequency. The lower-edge frequency of the narrow shaded band moves from 9.40 to 8.40 GHz in calculation and from 9.42 to 8.30 GHz in experiment. Good agreement between theory and experiment has been achieved. The shift is $\sim$1 GHz. In comparison, the shift of the lower-edge frequency for the wide shaded region is only 0.14 GHz in calculation and 0.15 GHz in experiment, much smaller than in the narrow shaded band. The one-way waveguide working in the MSP resonance region has a more sensitive response to the external magnetic field than that working in the degeneracy-splitting region. Contrast between the forward and the backward transmission of the microwave can also be seen in the dip near the narrow shaded region from the high-frequency side in Fig. 4. However, according to our calculation results of field distributions, waveguide modes based on MSP cannot be formed in this region. Thus, we do not pay attention to this region.

We go on to compare the one-way waveguide working in the two frequency regions by introducing a lattice disorder into the original GPC with a regular lattice array. Because the two unidirectional frequency regions have different physical origins, it is expected that one-way waveguides in these two regions might have very different responses to the lattice disorder. To begin with, we define the degree of the lattice disorder as η, and the corresponding lattice displacement is defined as $d = r_d(a - 2r)\eta$ (r_d is a random number uniformly distributed between -0.5 and 0.5). The one-way transport property is calculated and measured for different magnitudes of the lattice disorder. The results when η is 0, 0.3, and 0.75 under $H_0 = 2980$ Oe are displayed in Fig. 5. Both theoretical and experimental data clearly show the remarkable difference between the two unidirectional regions in response to lattice disorders. In detail, in the degeneracy-splitting band gap that originates from Bragg scattering, the signal contrast between the forward and the backward waves becomes degraded gradually with the increase of the lattice-disorder degree. Up to a very large lattice disorder with $\eta = 0.75$, the one-way effect is shadowed by the rapidly oscillating spectrum that looks like noise. This means that the one-way property for this band is fragile against the lattice disorder. In contrast, within the MSP resonance region, there is still a big contrast in S12 and S21 even at a large lattice disorder with $\eta = 0.75$, indicating more robust one-way property for this band against the lattice disorder.

To understand more clearly how the one-way waveguide is influenced by the lattice disorder, we calculate the field distribution patterns at 9.5 and 14 GHz at $\eta = 0.75$. The results, displayed in Fig. 6, enable us to better understand the underlying physics compared with spectrum analysis. In the strongly disordered structure, the electromagnetic wave at 14 GHz (within the degeneracy-splitting band) is no longer confined at the metal–YIG interface but rather is widely dispersed into the bulk of the disordered YIG lattice structure. The transport channel of the electromagnetic wave has simply been destroyed by the strong lattice disorder for the degeneracy-splitting band. The electromagnetic wave at 9.5 GHz (located within the MSP region) shows a different behavior. It is still strongly confined at the metal–YIG interface even at this strong disorder situation, and little energy is dispersed into the bulk YIG structure. In other words, the transport channel of the electromagnetic wave is immune to strong lattice disorders; thus, the TRS breaking induced by the external magnetic field can

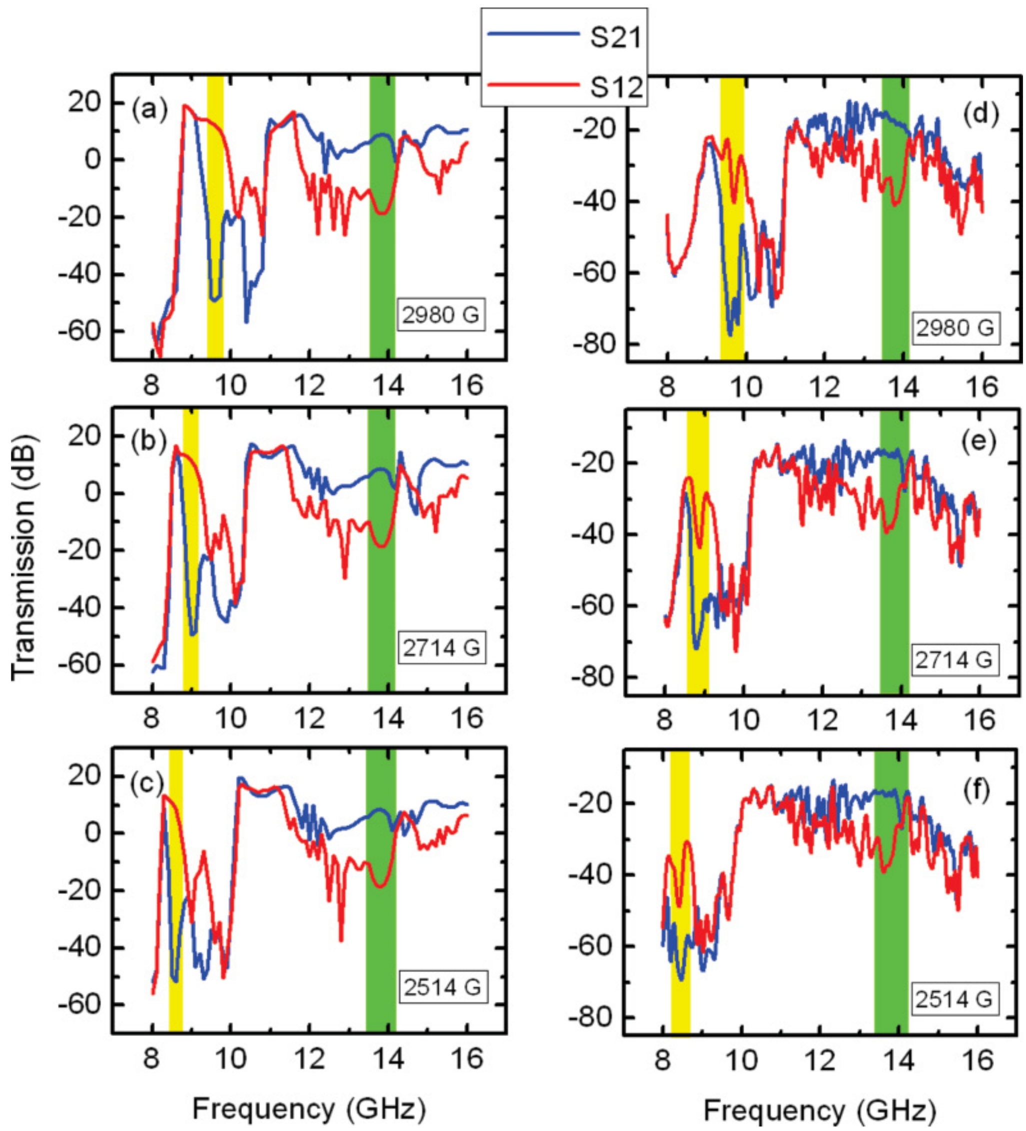

FIG. 4. (Color online) (a)–(c) Calculated and (d)–(f) measured one-way transmission spectra under different magnitudes of the DC magnetic field. The calculation and experiment both show that the narrow shaded (yellow) region (MSP resonance region) is tunable under a varying DC magnetic field. However, the wide shaded (green) region (degeneracy-splitting region) seems to have negligible change under a varying magnetic field.

still create a significant unidirectional transport property in this channel.

The distinct difference of one-way transport in the two frequency bands against a lattice disorder can further be understood by relating it with the band gap picture. From the field pattern, it can be conjectured that the degeneracy-splitting band gap (∼14 GHz) is closed by the lattice disorder at a sufficiently high degree of disorder, as a result of which the electromagnetic wave can freely go into the bulk of the YIG structure. Previous studies showed that the formation of usual photonic band gaps either originates from the long-range order or from the short-range order.[18] Lattice site disorder breaks both the long- and the short-range orders and affects the photonic band gap seriously.[19,20] As the disordered YIG structure now becomes a freely propagating media for the electromagnetic wave in both directions, the interface between the metal cladding and the GPC cannot be thought of as a waveguide anymore. Although the breaking of TRS may lead to some asymmetry, which can also been seen from Figs. 5(b) and 6(a), the one-way property eventually disappears because of the absence of "way" with the increase of the lattice disorder. In comparison, in the MSP resonance region, the band gap (∼9 GHz) is mainly caused by the metallic behavior of the YIG material; thus, it may be not influenced so much by the lattice disorder. Because its band structure is lattice disorder immune, the metal–YIG interface can still be thought as a waveguide. The TRS breaking induces an apparent unidirectional guided wave property.

The disorder-immune one-way transport property in the MSP resonance region also originates from the nature of MSP resonance. Similar to the usual localized surface plasmon transport in an array of metal nanorods or nanospheres,[21] in the current ferrite structure, the electromagnetic wave transports via hopping between localized MSP modes in

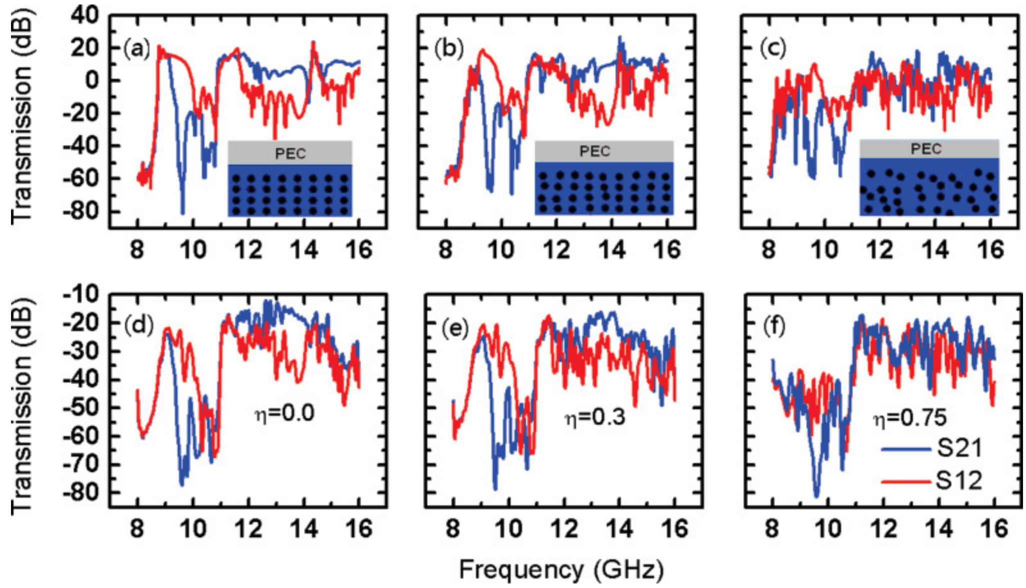

FIG. 5. (Color online) (a)–(c) Theoretical and (d)–(f) experimental results of unidirectional transport in response to increasing the lattice disorder in YIG rods as (a) and (d) $\eta = 0.0$, (b) and (e) $\eta = 0.3$, and (c) and (f) $\eta = 0.75$, respectively. The insets in (a)–(c) illustrate the schematic configuration of the disordered GPC structures.

neighboring YIG rods, so it is not sensitive to the orientation direction of each rod. In other words, in this MSP frequency region, the one-way waveguide mode is supported by a short-range interaction of MSP. In the near-resonance region, the electromagnetic wave cannot penetrate deeper into the ferrite rods but rather couples to the MSP as a kind of surface

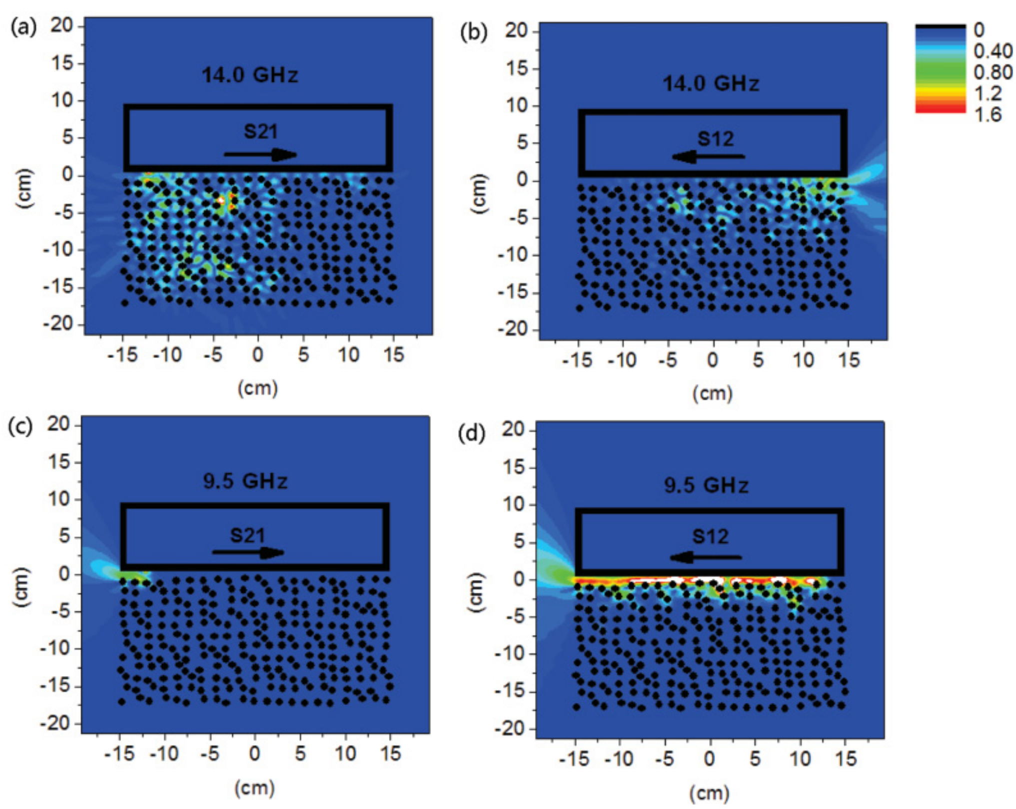

FIG. 6. (Color online) Calculated field distribution pattern for forward and backward transport of an electromagnetic wave in a lattice-disorder waveguide with $\eta = 0.75$ at (a) and (b) 14 GHz (located within the degeneracy-splitting region) and at (c) and (d) 9.5 GHz (located within the MSP resonance region). The upper rectangular box in the four panels consists of a series of close-packed tiny PEC rods placed at its edge, and it is used to model the PEC wall in Fig. 1.

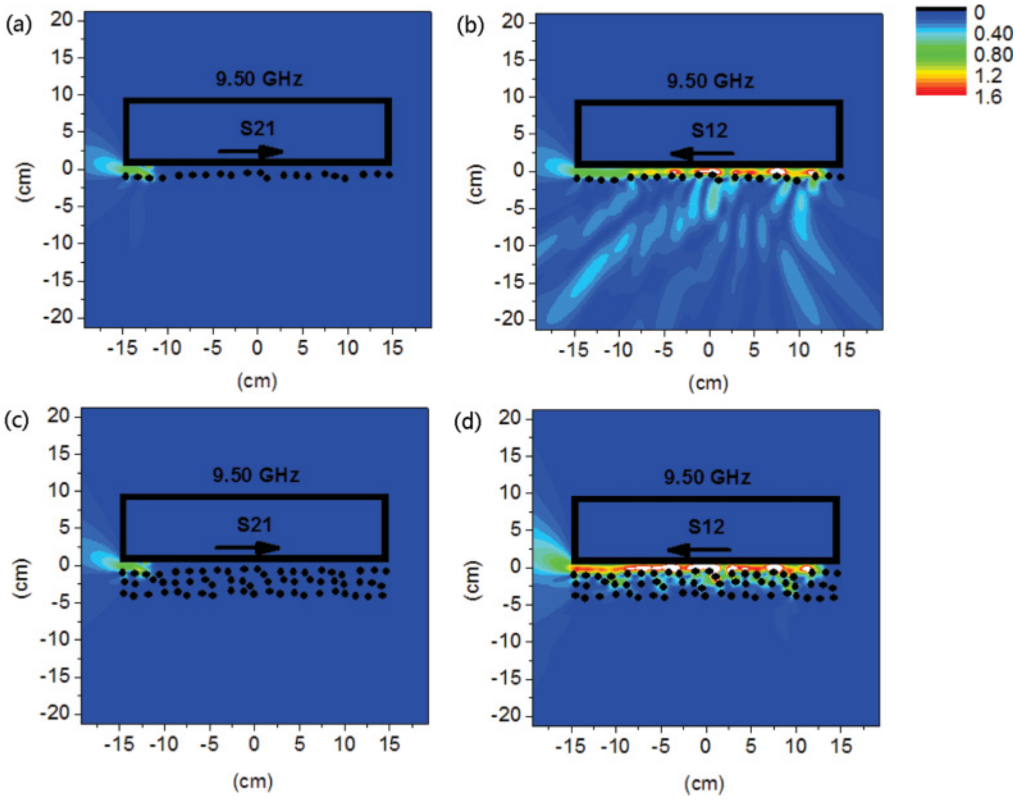

FIG. 7. (Color online) Calculated field distribution pattern for forward and backward transport of an electromagnetic wave in a lattice-disorder waveguide with $\eta = 0.75$ at 9.5 GHz (located within the MSP resonance region) when the number of the YIG row is (a) and (b) 1 and (c) and (d) 3.

wave located at the interface between the rods and the air background. There is a specific chirality for the MSP under a static magnetic field, so the coupling of neighboring MSP modes can only be carried out in one direction inside the metal–GPC waveguide. When we change the position of each rod around its original site, the mean distance between them is not enlarged. This explains why the one-way property does not degrade much even though the lattice order has been seriously destroyed.

To see whether the preceding conjecture holds true or not, we consider electromagnetic wave transport along the interface between a metal cladding and one or three rows of YIG rods instead of a large YIG crystal. The calculated field patterns, displayed in Fig. 7, clearly support the preceding physical picture over MSP transport. The distinct one-way transport property appears even for only one row of YIG rods. More importantly, the strong confinement of the electromagnetic wave within the metal–YIG structure has become apparent even for only three rows of YIG rods under strong lattice disorders, and the obvious unidirectional transport of this guided mode is robust against such a strong lattice disorder. The MSP resonance nature of this low-frequency band makes the unidirectional transport immune against lattice disorders.

III. CONCLUSIONS

We have experimentally investigated one-way waveguides that work in the MSP frequency band of ferrite materials comprising a GPC. The one-way waveguide is widely tunable versus the external magnetic field, robust against intruding scatterers, and immune to lattice disorders. The superior property is attributed to electromagnetic wave transport via localized MSP modes between neighboring ferrite rods. In comparison, the conventional one-way waveguide that works in the degeneracy-splitting frequency band is more fragile against lattice disorders because Bragg scattering is more easily influenced by long- and short-range disorders. The new scheme of the one-way waveguide will open up an avenue to explore physics in various TRS breaking systems and engineer unidirectional photonic devices that are robust against fabrication inaccuracy.

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