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ABSTRACT

Magnons, the quanta of collective spin excitations in magnetically ordered materials, have distinct properties that make them uniquely appealing for quantum information applications. They can have ultra-small wavelengths down to the nanometer scale even at microwave frequencies. They can provide coupling to a diverse set of other quantum excitations, and their inherently gyrotropic dynamics forms the basis for pronounced nonreciprocities. In this article, we discuss what the current research challenges are for integrating magnetic materials into quantum information systems and provide a perspective on how to address them.

I. INTRODUCTION

The coherent manipulation and control of individual quantum states is at the heart of many new approaches to ultimate-precision sensors, securely encrypted communication, and beyond classical computation.[1] In order to pursue this goal, a wide variety of fundamental excitations are being considered, each with their own distinct advantages and drawbacks. For example, microwave photons are often used in superconducting quantum systems for their ease of being incorporated into well-defined circuitry for complex interactions, but require very low temperatures to operate in the single quantum limit.[2] On the other hand, optical photons are robust against decoherence even at room temperature and therefore are well suited for long-distance transportation of quantum information.[3] These two examples highlight the fundamental dilemma that is inherent to many quantum systems, namely the desire to maintain long spatial and temporal coherence, while at the same time having the ability to coherently manipulate on demand quantum states with high fidelity. These two requirements for functional quantum systems are often antagonistic due to their underlying physics. Thus, it is expected that for the realization of large-scale quantum information systems many different quantum excitations will be integrated to incorporate their specific advantages.

For practical implementations of quantum measurements or computation approaches, one often desires to have a well-defined system with only two distinct and isolated states. This is naturally achieved by spin-$\frac{1}{2}$ systems, where the individual spin up and down states can be controlled by intrinsic and extrinsic magnetic fields. Given the relatively long coherence times of both nuclear and electronic spins, it is not surprising that some of the early implementations of quantum computation were performed by using nuclear spins[4,5] and that electron spins at atomically sized defects provide some of the most promising new sensing technologies.[6] However, the long coherence is due to the relatively weak coupling of individual spins, which also makes it challenging to integrate them with more complex hybrid quantum systems. This challenge can be overcome by using larger spin ensembles, or ultimately strongly interacting spin systems, such as magnetically ordered materials, which provide some of the highest spin-densities found in nature.

In these magnetically ordered systems, the fundamental excitations are given by magnons. The high spin-density associated with magnetically ordered materials enables strong coupling to magnons. This of course gives rise to challenges with respect to their coherence time, but nevertheless coherent interactions with magnons at the single quantum level have already been demonstrated.[7–9] As discussed in detail in this Perspective, magnons provide several unique properties that can enhance and broaden the current technology for quantum information processing and engineering.[10–12]

Among the distinct advantages of magnons is that they can couple to a wide variety of other excitations, including microwave and optical photons, phonons, other magnons, and individual spin systems. Thus, magnons are well-suited to act as a transducer between different quantum excitations, e.g., between microwave and optical photons.[15] As shown in Fig. 1, magnetic elements can be readily integrated into planar, high-quality, superconducting microwave circuitry.[13,14] Compared to other microwave excitations (photons or phonons), the wavelengths of magnons can be significantly shorter, which makes magnetic elements more suitable for miniaturization and their performance less restricted by their dimensions. At the same time, the use of magnetic materials in spintronic applications[16,17] has established advanced approaches for integrating them even with complex nanoscale devices. However, one of the more distinct advantages of magnetic systems is that the breaking of time-reversal symmetry by the magnetic order and the corresponding gyrotropic magnetization dynamics has an intrinsic chirality, which results in pronounced nonreciprocities. Therefore, magnetic materials are key to many directional microwave devices, such as isolators or circulators. Such unidirectional microwave propagation is highly desirable for quantum devices, since it provides noise isolation, but also can be utilized for novel chiral quantum systems.[18]

The goal of this Perspective is to provide an overview of the current challenges and opportunities for integrating magnetic materials into more sophisticated quantum information systems. We first will discuss in Sec. II magnetic damping, which is the key material parameter determining the coherence of magnons. Thus, reducing magnetic damping is paramount for utilizing magnetic materials, and we will discuss several strategies for doing so in hybrid quantum devices. We note that reducing damping also has become a key challenge for current spintronics devices.[17] Next, we will discuss in Sec. III pathways for engineering nonreciprocities into miniaturized microwave devices that can potentially be integrated directly onto a chip. This ability has implications well beyond just quantum devices, since the nonreciprocity is also required for many classical microwave applications. Finally, in Sec. IV, we will discuss two aspects of hybrid magnon devices directly relevant for quantum state transfers (QST). First, we will discuss how different magnon systems can be remotely coupled via microwave photons, and, subsequently, we discuss the new opportunities that arise from coupling different quantum systems via nonreciprocal propagating magnons.

II. MATERIAL OPTIMIZATION FOR LOW MAGNETIC DAMPING

Maintaining the coherence of quantum states is essential for quantum information processing. To achieve this in a hybrid quantum system, strong coupling between constitute subsystems as well as low decoherence in each subsystem is desirable such that a high cooperativity can be obtained.[10] In the scope of this paper, we focus on damping of magnons in magnetic materials, which are essential components of hybrid magnonics. Magnons are quanta of spin waves that are collective excitations of spin precession in a magnetically ordered material. Damping is the relaxation of this precession motion toward the equilibrium spin direction due to energy loss. This leads to the observed field (or frequency) linewidth ΔH of the magnon mode in, e.g., ferromagnetic resonance (FMR) measurements. A widely used empirical formula for ΔH is[19]

$$\Delta H = \Delta H_0 + \frac{2\pi f \alpha}{\gamma}, \tag{1}$$

where the first term ΔH_0 is called the inhomogeneous broadening, and the second term includes the Gilbert damping derived from the Landau–Lifshitz–Gilbert equation,[20]

$$\frac{d\mathbf{M}}{dt} = -\gamma\mu_0 \mathbf{M} \times \mathbf{H} + \frac{\alpha \mathbf{M}}{M} \times \frac{d\mathbf{M}}{dt}. \tag{2}$$

Here, f is the resonance frequency, γ is the gyromagnetic ratio, α is called the Gilbert damping parameter, μ_0 is the Bohr magneton, $\mathbf{M}$ is the magnetization, and $\mathbf{H}$ is an effective magnetic field comprised of both externally applied fields, as well as internal magnetic fields, which can originate from exchange coupling, crystalline anisotropies, and other possible contributions.

This empirical expression (1) can fit many experimental measurements well, but not all, especially in situations when non-Gilbert damping becomes important.[21,22] A microscopic description of magnon damping is generally complicated due to a wide variety of possible contributions. Moreover, damping also depends on the shape and quality of the sample, and the temperature in a non-trivial way.[21–23] There is no universal rule for optimizing magnon damping in all magnetic materials. In this Perspective, we will discuss this for magnetic insulators, specifically yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG), and

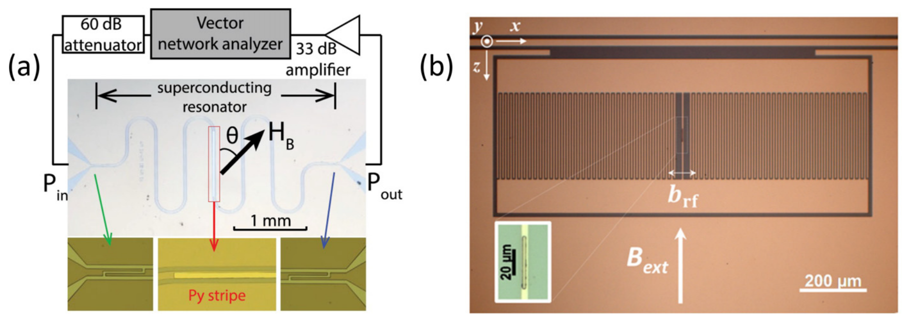

FIG. 1. Examples of magnetic elements integrated with superconducting resonators based on (a) striplines or (b) lumped element structures. Both structures demonstrated strong coupling between magnons and microwave photons. Research in (a) studies how magnon–photon coupling behaves in the nonlinear excitation regime, and research in (b) studies how magnon–photon coupling changes in different resonator geometry and corresponding impedance. The schematic in (a) is reproduced with permission from Li *et al.*, Phys. Rev. Lett. **123**, 107701 (2019). Copyright 2019 American Physical Society.[13] The schematic in (b) is reproduced with permission from Hou *et al.*, Phys. Rev. Lett. **123**, 107702 (2019). Copyright 2019 American Physical Society.[14]

magnetic conductors separately, as they are dominated by different damping mechanisms. Consequently, strategies for optimization are also suggested to be different for these two categories of materials, particularly for thin-film samples at cryogenic temperatures due to their potential applications in quantum information science.

A. Yttrium iron garnet, a ferrimagnetic insulator

The ferrimagnetic insulator yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) is one of the best low-damping magnetic materials, which has $\alpha \sim 10^{-5}$ for bulk samples.[24] The low damping is due to two important factors. First, magnon scattering to conduction electrons is absent in the insulator. Second, the magnetic ion Fe^{3+} has nearly zero orbital angular momentum. Therefore, the spin–orbit coupling (SOC) is weak, and thus the spin-lattice relaxation time is long. The main contribution to damping in YIG is magnon–magnon scattering. Three-magnon processes induced by dipolar interactions dominate the damping of magnons with smaller wave-number k, while four-magnon processes induced by both dipolar interactions and exchange interactions become more significant for large-k modes.[19] For the uniform precession mode (the Kittel mode), i.e., $k = 0$, these two contributions are also small, leading to extremely low magnetic damping observed in FMR measurements.[24]

The intrinsic damping in ideal YIG is very small. However, in some situations, experimentally observed damping can be larger. This is particularly significant in YIG thin films whose damping parameter is typically an order of magnitude larger compared to bulk samples.[25] One important damping source in YIG thin films comes from surface imperfections.[26–29] Defects on sample surfaces or its interfaces with other materials cause two-magnon scattering, which can increase the FMR linewidth. A theoretical description of this mechanism was proposed by Arias and Mills in 1999,[30] where the Kittel mode can be scattered to several degenerate modes of similar energy and small wavenumbers by surface defect potentials. This damping effect is enhanced for thinner YIG films as the surface to volume ratio is increased. Many experimental works have confirmed this by an observed trend of increasing damping with decreasing film thickness.[26,27,31] Meanwhile, smaller damping has been observed in films with smoother surfaces.[26–29]

Magnon damping in YIG films at low temperatures has very intriguing behaviors. Jermain *et al.* studied magnon damping in 15-nm YIG film from room temperature (297 K) to $\sim$10 K and had several interesting observations.[21] As the temperature decreases, the slope of the FMR linewidth ΔH vs frequency f increases, indicating a higher damping parameter α for lower temperatures [see Fig. 2(a)]. Meanwhile, as the temperature goes below $\sim$50 K, the linewidth ΔH strongly deviates from the linear dependence on the frequency f. This implies that non-Gilbert damping starts to become important. Moreover, for a fixed frequency of 9.4 GHz, the linewidth ΔH shows a non-monotonic variation with decreasing temperature T. A peak was observed near 25 K, where the value of ΔH was 28 times larger than at room temperature [see Fig. 2(b)]. Such a "temperature-peak" character was also reported in Ref. 22 for a YIG sphere. In both studies, the authors explained the increased low-temperature damping by slow-relaxing impurities[32–35] that are perhaps rare earth or Fe^{2+} impurities introduced during film growth.

Another important damping source for YIG thin films at low temperatures comes from the substrate. High-quality YIG films are usually grown via epitaxy on gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG) for its close lattice matching with YIG. At low temperatures $\lesssim$70 K, GGG exhibits paramagnetic behavior and couples magnetically to YIG, acting as a damping source for magnons in YIG.[36–38] In the work of Kosen *et al.*,[39] magnon damping in YIG films at millikelvin (mK) temperatures with and without GGG substrate has been investigated. Significantly increased magnon linewidth was observed for YIG/GGG, while substrate-free YIG can possibly achieve lower damping than the room-temperature value. Moreover, they observed that damping above 1 K shows a similar temperature-peak behavior due to slow-relaxing impurities, while below 1 K, the damping saturates, which is attributed to two-level fluctuators. Similar effects of impurity damping and substrate damping were also reported in Ref. 38. In both works, the thickness of films is on the micrometer level, so the two-magnon scattering effect is likely to be smaller than for films with sub-micrometer thickness.

Improving sample perfection and minimizing substrate effects with more advanced experimental techniques is, therefore, a main direction for future efforts to reduce damping further. Over the last decade, many efforts have been made to fabricate YIG thin films with better crystal quality and, especially, smoother surfaces, via different growing methods and pre- or post-processing strategies. A detailed

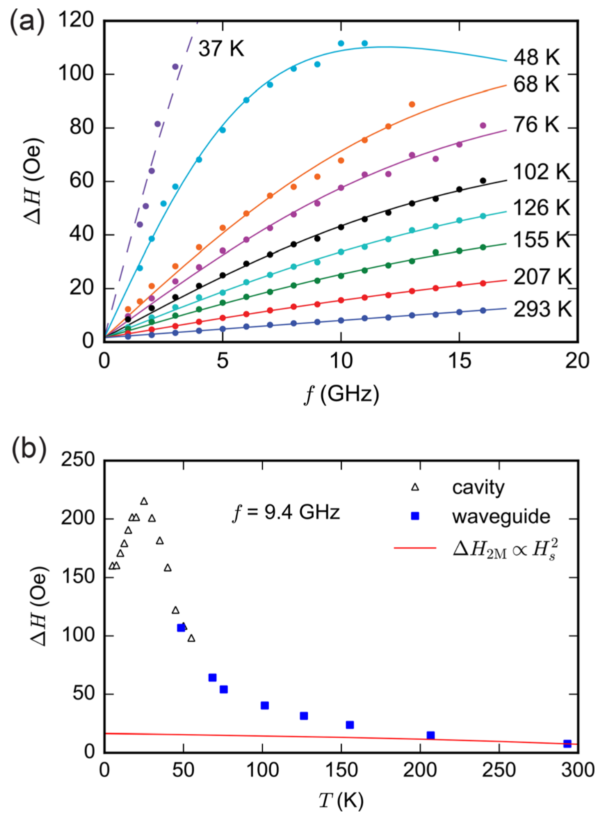

FIG. 2. (a) Field linewidth ΔH vs frequency f for a YIG thin film on a gadolinium gallium garnet substrate at different temperatures. (b) Temperature dependence of the field linewidth ΔH at fixed frequency $f = 9.4$ GHz. Reproduced with permission from Jermain *et al.*, Phys. Rev. B **95**, 174411 (2017). Copyright 2017 American Physical Society.[21]

review on YIG thin film synthesis can be found in Ref. 25. Particular attention has also been paid on the atomic structure of the sample surface or its interface with the substrate. Several studies have observed the presence of a Fe-loss and Ga-rich transition layer between YIG and GGG.[40–42] This transition layer, also known as the magnetically dead layer has a thickness of several nanometers, depending on the growth process. Near the top of YIG films, Song *et al.* have reported oxygen deficiency within a thin surface layer of a few nanometers and the presence of a disordered layer.[43] How these surface structural effects influence the damping and the magnetization of YIG films remains an interesting research topic. On the other hand, at cryogenic temperatures, relaxation due to impurities, such as rare-earth elements and Fe^{2+} ions, and relaxation due to substrate effects from GGG start to dominate.[21,22,38,39] Growing YIG films with high chemical purity should be pursued. At a few Kelvin or even lower temperatures, coupling to the substrate GGG is a main source of damping. Alternative substrates or free-standing YIG are potential solutions to be considered. Silicon has been tried as another substrate for YIG, which, at room temperature, gives apparently larger damping than YIG/GGG.[44,45] At cryogenic temperatures, it is not clear whether YIG/Si could possibly outperform YIG/GGG since Si does not magnetically couple to YIG. Trempler *et al.*[46] presented a process that can transfer single-crystal yttrium–iron–garnet microstructures from GGG to other kinds of substrates and reported low damping on the order of 10^{-4} at 5 K. Recently, Guo *et al.*[47] have tried embedding a thin diamagnetic $Y_3Sc_{2.5}Al_{2.5}O_{12}$ (YSAG) bilayer between YIG and GGG to eliminate the exchange coupling between both. As a result, they obtained much reduced damping at 2–5 K in this YIG/YSAG/GGG structure compared to YIG/GGG. In a subsequent work from the same group, they grew YIG films on a new diamagnetic $Y_3Sc_2Ga_3O_{12}$ (YSGG) single-crystal substrate and observed smaller damping than for YIG/GGG.[48]

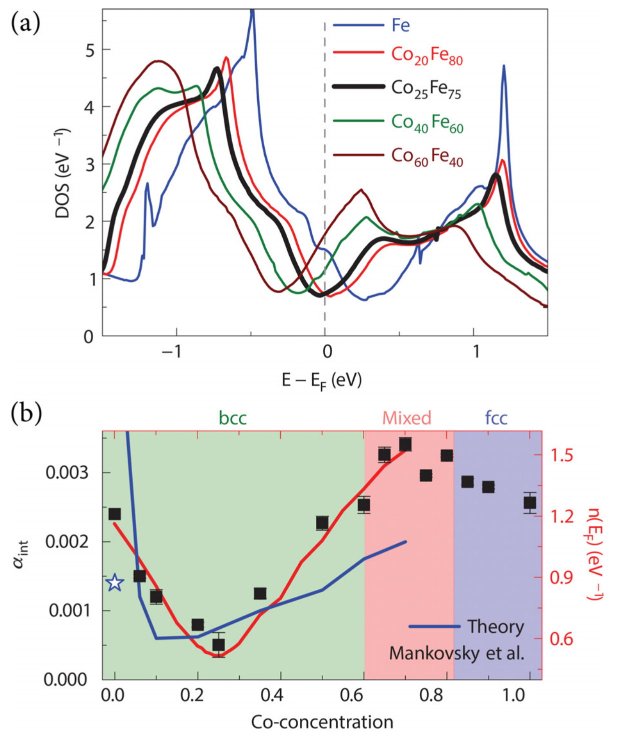

FIG. 3. (a) Electronic density of states (EDOS) of cobalt–iron (Co–Fe) alloy with different Co concentrations. (b) Experimentally measured intrinsic damping of Co–Fe alloys with different Co concentrations, compared to theoretical calculations from Mankovsky *et al.*[49] The change of the electronic density of states (EDOS) is also shown in the plot. Reproduced with permission from Schoen *et al.*, Nat. Phys. **12**, 839–842 (2016). Copyright 2016 Nature Publishing Group.[50]

B. Metallic ferromagnets

Ferromagnetic (FM) metals and alloys are another category of promising magnetic materials for hybrid magnonics applications, especially since their integration into heterostructures and devices is significantly easier than for insulating materials such as YIG. However, these metallic materials, such as permalloy ($Ni_{80}Fe_{20}$, Py), have generally larger magnetic damping than insulators due to the presence of conduction electrons that contribute as a dominant damping pathway. Experimentally measured damping for Py films is typically one order of magnitude larger than YIG films,[51] i.e., 10^{-3}. Nevertheless, an ultralow damping on the order of 10^{-4} was observed in 10-nm thick polycrystalline cobalt–iron (CoFe) alloy films with 25% Co concentration.[50] In these experiments, intrinsic damping due to electron–magnon scattering was on the same order of magnitude as other extrinsic damping mechanisms including spin pumping and radiative damping. The lowest total damping was achieved by minimizing the intrinsic damping, which corresponds to a minimized magnon–electron scattering indicated by a sharp minimum of the electronic density of states (EDOS) at the Fermi level, as illustrated in Figs. 3(a) and 3(b). Comparably low damping was also reported in a single-crystal $Co_{25}Fe_{75}$ sample by Lee *et al.*[52] These observations suggest the possibility for metallic ferromagnets to have damping properties almost comparable to YIG, while also having the advantage that the magnetization is about one order of magnitude larger, enabling stronger coupling. In order to optimize these materials for low damping, the key factor is the electronic structure of the material.

Theories of magnon–electron damping in metallic ferromagnetic materials have been investigated for quite some time. Two early models developed by Kamberský are the breathing Fermi surface (BFS) model[53] and the torque correlation (TC) model.[54] In the BFS model, magnetization precession induces electron–hole (e–h) pairs near the Fermi level E_f by pushing some occupied (unoccupied) states above (below) the Fermi level E_f through spin–orbit interaction. These e–h pairs are damping sources for magnons. In this case, longer lifetime of the e–h pairs is associated with larger magnon damping. This leads to a naively counter-intuitive result that this damping mechanism is enhanced at lower temperatures and in cleaner samples because it is proportional to the electron scattering time τ. Similar results to the BFS model were also derived by Korenman and Prange for explaining the observed increased low-temperature magnetic damping (at that time it was called "anomalous damping") in nickel and cobalt.[55] The BFS damping mechanism was later recognized as the conductivity-like damping in contrast to the resistivity like damping, which is detailed in the TC model.[54,56,57] In the TC model, the spin–orbit torque $\Gamma^-_{mn} = \langle m, \mathbf{k}|[\sigma^-, \hat{H}_{SO}]|n, \mathbf{k}\rangle$ induces damping. Here, $\hat{H}_{SO}$ is the Hamiltonian of spin–orbit interactions, which should not be confused with the magnetic field. $|n, \mathbf{k}\rangle$ is the eigenstate with band index n and wavevector $\mathbf{k}$. This spin–orbit torque can be decomposed into the intra-band ($m = n$) part and the inter-band ($m \neq n$) part.[56,57] While the intra-band part essentially reproduces the same phenomena as in the BFS model, the inter-band part becomes important only when the spectral overlap between different bands becomes large. This can arise from broadening of energy bands by increased temperature or disorder. The inter-band part is therefore considered as resistivity-like damping as it is inverse proportional to the electron scattering time τ and is enhanced when the temperature is high or when the system is more disordered. These two mechanisms, i.e., intra-band and inter-band scattering, imply an interesting result that magnon damping in metallic materials is *not monotonically* dependent on the temperature or disorder, which both are correlated with the electron scattering time τ. This trend explicitly shows up in first-principles calculations[58] and is indeed observed in several 3*d* transition metals.[59] The BFS model and TC model have also been generalized to non-local and anisotropic versions by replacing the scalar damping parameter with a damping tensor $\tilde{\boldsymbol{\alpha}}$.[60–65]

Magnetic damping at low temperatures is of particular interest here since we are aiming for quantum information science applications. In this low scattering limit, damping is largely dominated by the intra-band scattering mechanism. Theories have demonstrated the explicit dependence of damping on the electronic density of states and spin–orbit interaction.[57] One simplified but useful formula states $\alpha \sim N(E_F)|\Gamma^-|^2\tau$, highlighting that the density of states at the Fermi level $N(E_F)$, the spin–orbit coupling (SOC) parameter $\Gamma^- = \langle[\sigma^-, \hat{H}_{SO}]\rangle_{E=E_F}$ at the Fermi energy, and the electron scattering time τ are key factors determining the intra-band damping. Many experiments, combined with first-principles studies, have confirmed that damping can be reduced by minimizing $N(E_F)$.[50,66–68] Recently, Khodadadi *et al.*[23] observed that at 10 K an epitaxial thin film of pure iron with imperfect crystallinity exhibits lower Gilbert damping than the cleaner counterpart. This is again explained by the intra-band conductivity-like damping being proportional to τ and therefore inversely proportional to lattice disorder. In addition, experimentally measured damping shows giant anisotropy in some materials such as Fe and Co–Fe–(B) thin films on substrates.[69–72] This can be explained by the anisotropy in SOC or the anisotropy in $N(E_F)$ induced by interfacial effects.

Minimizing electron–magnon scattering is the main pathway for reducing magnetic damping in metallic materials. The available phase space for optimal materials is very broad and includes different magnetic metals and alloys. This situation is very different from the case of YIG being the “dominant” low-damping material among magnetic insulators. In addition, any factor affecting electronic properties in a material can possibly be considered as a tuning factor for magnon–electron damping. Alloy compositions, temperature, crystal quality, and chemical doping are several factors that can affect magnetic damping in metallic magnets.[23,50,67,68,73–76] Recently, Wang *et al.*[77] found that structural transformations from the crystalline to the amorphous state provide a pathway for reducing magnetic damping in Co–Fe–C alloy films. Therefore, we expect that combined theoretical, computational, and experimental efforts will be pursued for a more efficient exploration of optimal low-damping metallic magnetic materials. Recently emerged studies in two-dimensional (2D) van der Waals magnets and topological magnetic semi-metals may bring new theoretical insight into electronic structure and magnetic dynamics in such novel materials.[78–82] In the computational community, first-principles calculations of intrinsic magnon damping in magnetic metals and alloys have already been done for many years, providing qualitatively good agreement with experiments.[49,58,63,83–88] With the developing computational power for more precise material simulations and new developing techniques such as machine learning, we may expect even more efforts and contributions from this community toward an efficient way of material discovery and optimization. Nevertheless, experiments are naturally required for verifying all theories and computational methods developed and test the true performance of the optimized materials in real material systems and devices.

III. SPIN-WAVE NONRECIPROCITY

Wave nonreciprocity is the phenomenon that waves propagating along one direction have a different dispersion relation or amplitude than those propagating along the opposite direction. Some necessary conditions for systems to have wave nonreciprocity are broken time-reversal symmetry,[89–95] or structures having asymmetric features.[95,96] One example is a system having an array of triangular reflectors where one wave is pointing at a vertex of the triangular reflector and the other wave is pointing at an edge so that two oppositely propagating waves experience different potentials for scattering.[95] Another example is a system having an ordered nonlinear region (left)/filter (right) where a wave passes through the nonlinear region first and is converted to another mode by a nonlinear process, and the converted mode passes through the filter, but another wave which hits the filter first does not pass the filter.[96]

Here, we will focus on spin wave nonreciprocity with a linear excitation level in systems with broken time-reversal symmetry corresponding to every ferromagnetic material, which inherently have broken time-reversal symmetry due to their net magnetization. Nonreciprocal characters of magnon propagation have been implemented to ferromagnetic systems in several ways as an intrinsic property or an extrinsic property of the system. Implementable intrinsic properties that can support nonreciprocal magnon propagation are interfacial Dzyaloshinskii–Moriya (DM) interaction[97–102] from layered structures of ferromagnet (FM)/heavy metal (HM), bulk DM interaction with materials whose lattice structures do not have inversion symmetry,[103,104] interlayer dipolar interaction between two FM layers,[91,94,105–110] altered Maxwell boundary condition in the presence of nearby metallic layer,[111–114] and altered exchange boundary condition (EBC) by using surface anisotropy.[115] These nonreciprocal magnetic systems are expected to provide noise isolation in quantum information systems on the chip level because isolators, used in conventional quantum information systems with microwave photons in order to prevent backflow of thermal radiation at the output line, may be replaced by these nonreciprocal magnetic systems, which can be integrated closer to superconducting devices.

Interfacial DM interactions have a term proportional to $\mathbf{S}_i \times \mathbf{S}_j$, which have different signs at opposite spin wave chirality or equivalently opposite spin wave propagating direction, so that DM interactions generate nondegenerate magnon dispersions between opposite propagation directions. More precisely, there is an additional linear dependence on the wavevector, k, in the dispersion, $\omega(k)$,[97] so two magnons propagating in opposite directions have different bandwidths and group velocities, thereby they have also different attenuations. Note that since interfacial DM interaction is an interlayer exchange interaction acting on an atomic length-scale, it is effective only for ultra-thin films of typically a few nanometers. Bulk DM interactions can also generate nondegenerate magnon dispersions[116,117] in similar ways with those originating from interfacial DM interactions mentioned above so they can also generate nonreciprocity of magnon propagation. However, bulk DM interactions typically require single crystal materials without structural chiral twins. This requirement limits the appeal of such materials for devices based on thin films.

Interlayer dipolar interactions between two FM layers generate terms that are nonsymmetric under wavevector inversion, such that they have a maximum nonreciprocity when the equilibrium magnetization is perpendicular to the magnon wavevector, $\mathbf{M}_0 \perp \mathbf{k}$.[107] There are two possible configurations in the $\mathbf{M}_0 \perp \mathbf{k}$ geometry, which are parallel (ferromagnetic coupling between FM layers; $\mathbf{M}_1 \cdot \mathbf{M}_2 > 0$) and anti-parallel [antiferromagnetic (AFM) coupling between FM layers; $\mathbf{M}_1 \cdot \mathbf{M}_2 < 0$]. In the parallel configuration, nonreciprocity due to interlayer dynamic dipolar interaction exists except in a case of $M_1 = M_2$, which effectively corresponds to a single layer with double thickness. Nonreciprocity becomes more pronounced with larger $|M_1 - M_2|$ values. In the anti-parallel configuration, nonreciprocity always exists and is generally bigger than that in the parallel configuration.[107] Figure 4 shows two interlayer dipolar fields with two oppositely propagating spin wave modes in the anti-parallel configuration. Since the y-component of the dynamic dipolar field and the time-varying component of magnetization are antiparallel in Fig. 4(b), the spin wave described in Fig. 4(b) has a higher frequency than the spin wave described in Fig. 4(a).

There are a number of ways to engineer either FM or AFM coupling between two FM layers. These are, for example, direct interlayer exchange interaction,[118,119] indirect interlayer exchange interaction with a non-magnetic spacer[120] [such as Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction],[107,108,121,122] and shape anisotropy (such as using a magnonic crystal or grating layer).[94,106] Noticeable nonreciprocity with FM couplings between layers has been observed for multi-layer heterostructures where different saturation magnetizations, M_s, are assigned at different layers.[109] One strong point of using FM coupled systems is that they show nonreciprocity over a wide range of applied magnetic fields, i.e., a strong magnetic field does not break FM coupled states when field and magnetization are pointing the same direction, which will simplify applications to magnonic devices. On the other hand, an AFM coupled system can typically maintain its AFM coupled state within a relatively limited range of applied magnetic fields. For instance, AFM coupled systems can have operating ranges of applied magnetic fields as has been demonstrated for Co nanowires, which maintained their AFM arrangement over 800 Oe.[94,106]

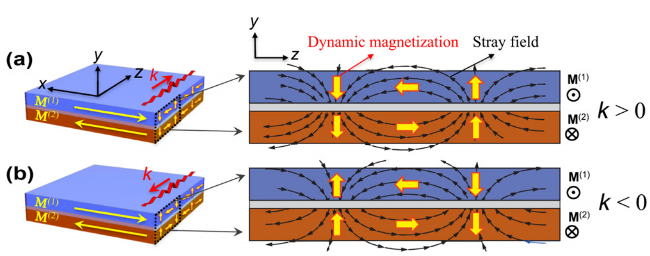

FIG. 4. Dynamic dipolar field due to time-varying component of magnetization in the presence of an excited spin wave mode propagating along z-axis. The static magnetizations are aligned along x-axis, and the dynamic dipolar field has only y- and z-components. The dynamic dipolar field with $k_z > 0$ is given at (a), and with $k_z < 0$ is given at (b). Reproduced with permission from Gallardo *et al.*, Phys. Rev. Appl. **12**, 034012 (2019). Copyright 2019 American Physical Society.[107]

An alternative pathway for engineering nonreciprocities is given by controlling the boundary conditions for chiral surface spin waves, known as Damon–Eshbach (DE) modes. In the presence of a metallic layer, the Maxwell boundary condition is altered so that the normal component of the magnetic field, $\mathbf{h}_\perp(\mathbf{r}, t)$, needs to be zero at the FM/metal interface.[114] This asymmetric Maxwell boundary condition between two surfaces results in a nondegenerate dispersion of Damon–Eshbach (DE) surface spin waves,[111] but, in this case, the wavevector direction is indirectly related to the altered Maxwell boundary condition. Since DE surface waves propagating in opposite direction excite on opposite surfaces ($\mathbf{k} \propto \mathbf{n} \times \mathbf{M}_0$ where $\mathbf{n}$ is a film normal), each DE surface wave is subject to a different Maxwell boundary condition so that they have different dispersion relations.

Similarly, when a magnetic film has an out-of-plane uniaxial surface anisotropy at one surface or different anisotropies at opposite surfaces, each surface has a different exchange boundary condition (EBC) or a different spin pinning as one can find in the Rado–Weertman relation.[123,124] As a result, the dispersion relation of DE surface waves becomes nondegenerate, and in this case also has an implicit relation between wavevector direction and the perturbed EBC. From the same argument used for the Maxwell boundary condition, each of the DE surface waves is subject to different EBCs so that they have different dispersion relation.

In addition to mechanisms for the nonreciprocity described above, it is possible that interlayer direct exchange interactions from exchange biased FM/antiferromagnet (AFM) bilayer system would also be able to create nonreciprocity. The interlayer exchange interaction results in asymmetric spin pinning at opposite surfaces; therefore, surface spin waves propagating on each surface should have different dispersion relation or different amplitude profiles along thickness direction. The interlayer exchange interactions have been broadly studied in the context of various phenomena, for example, exchange bias,[125–127] exchange spring,[128–130] giant magnetoresistance (GMR),[131] and spin Hall effect.[132] However, so far AFM/FM interlayer exchange coupling has not been sufficiently studied in terms of magnetization dynamics, especially in the context of spin wave propagation. To study how the interlayer exchange interaction affects spin wave propagation, FM/AFM bilayer structures are adequate systems because they do not have interlayer dipolar interactions that FM1/FM2 bilayer systems have in addition to interlayer exchange interactions.

Aside from tailored spin wave dispersions, a practical approach for implementing nonreciprocal magnon propagation is given by specific geometries of antenna that can selectively excite a desired chirality of spin waves so that the antenna preferentially excites a spin wave propagating in one way compared to the opposite direction.[106,133,134] For example, an Oersted field generated from a current through a thin wire placed on top of a film has a definite chirality, i.e., the Oersted field rotates clockwise or counterclockwise as one moves perpendicular to the wire in the film, and this chirality will be reversed if one moves the wire from above the film to below the film. Therefore, the Oersted field excites only one set of spin waves with the same chirality, or the same propagation direction, much more efficiently compared to the other.[133] The same mechanism also applies to the coplanar waveguide (CPW) geometry.[135] Figure 5(a) shows a case of CPW where the

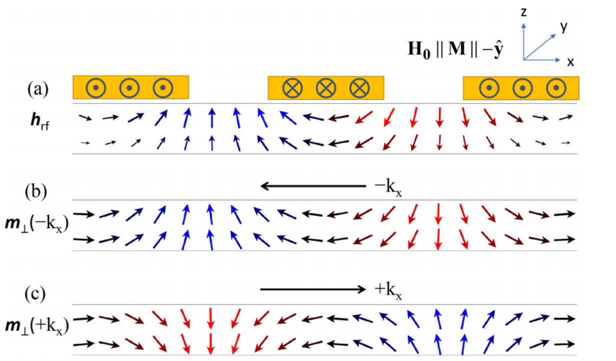

FIG. 5. (a) Oersted field from microwave signal applied to a coplanar waveguide (CPW), dynamic magnetization map of a spin wave propagating at (b) the $-x$ direction, and (c) the $+x$ direction. All of the figures show only time-varying component of a magnetic field or magnetizations.

time-varying Oersted field has the same chirality as that of the time-varying component of the magnetization of a spin wave propagating at the $-x$ direction as one can see in Fig. 5(b), i.e., both vectors rotate counterclockwise as one sweeps the coordinate to the $+x$ direction. A spin wave propagating in a $+x$ direction has opposite chirality as one can see in Fig. 5(c). Therefore, the CPW excites more efficiently a spin wave propagating to the $-x$ direction than a spin wave propagating in the $+x$ direction.

There are other systems supporting wave nonreciprocity, which are not pure spin wave nonreciprocal devices. One example are systems using magnon–phonon interaction.[91,93,99,136–146] A widely used mechanism is based on Rayleigh surface acoustic waves (RSAWs), which are a kind of circularly polarized wave with opposite chirality in opposite propagating direction. These RSAWs can excite FMR only when the RSAWs have the same chirality as that of the precessing magnetic moments in FM. This chirality selectivity is known as magneto-rotation coupling.[136,142] By using the magneto-rotation coupling, a system can have wave nonreciprocity even if its magnetic part does not have nonreciprocity by itself.

There are other systems using magnon–phonon interaction, where the magnetic part already has nonreciprocity due to interlayer dipolar interaction or interfacial DM interaction as described above.[91,93,99,139,144] One notable feature is that some studies reported very high amplitude nonreciprocities, for example, one paper reported 100% isolation[136] in which the magnetic part does not have inherent spin wave nonreciprocity, and another paper reported 48.4 dB isolation[139] where the magnetic part has a definite spin wave nonreciprocity due to interlayer dipolar interaction from an antiferromagnetically coupled bilayer structure.

Another feature to note is that there are well-established methods to achieve low insertion loss ($\sim$1 dB) transduction from microwave to surface acoustic wave (SAW).[147] To achieve an insertion loss better than 3 dB, one needs transducer geometries that allow unidirectional propagation of SAW because bidirectional loss already has 3 dB due to its bidirectionality. These unidirectional transducing schemes have been achieved in multiple ways, such as single-phase unidirectional interdigital transducers (SPUIDT).[148,149] A low insertion loss transduction is expected to be an essential feature to establish a nonreciprocal quantum state transfer channel, which can be used in noise-resilient quantum information devices.[150,151] One study used a unidirectional interdigitated transducer (UDT) to establish a phonon-mediated quantum state transfer and remote qubit entanglement[152] without using magnetic materials. One can expect that a much higher isolation can be achieved and thereby better noise protection if one uses both a combination of UDT and a nonreciprocal magnetic system. Since these systems have no bulky element in contrast to typical microwave systems, one can fabricate such integrated quantum information devices on a single chip. This possibility of miniaturization may be able to contribute to realization of high-density, multi-qubit quantum computing processors.

One interesting thing to note is that two different mechanisms of nonreciprocity can interfere "constructively" or "destructively." This depends on how a system is configured. For example, a recent theoretical study expects that a multi-layer system with both interlayer dipolar interactions and interfacial DM interactions is able to have an enhanced nonreciprocity compared to that of interfacial DM interaction alone.[153] We speculate that there are many other ways to integrate multiple mechanisms of nonreciprocity so that the mechanisms interfere constructively, resulting in systems with enhanced nonreciprocity.

IV. MAGNONS IN HYBRID QUANTUM DEVICES

After optimizing the coherence and nonreciprocity of magnons in ideal candidate materials, the ultimate goal is to coherently couple them to other quantum modules and even qubits to form a hybrid quantum system for faithful quantum information processing. In the past decade, many research groups have established coupling between magnons and microwave photons in a cavity[8,154–159] or a coplanar circuit structure.[13,160–162] In the work by Tabuchi *et al.*,[8] coherent coupling between a magnon and a superconducting qubit mediated by a microwave cavity has been demonstrated. This breakthrough opens the possibility for magnons to transfer quantum states in quantum information systems. Additional protocols for establishing coupling between magnons and spin qubits have also been proposed theoretically.[163–165] In this Perspective, we will discuss two particular examples: remote magnon–magnon coupling via microwave photons and using nonreciprocal magnons for quantum state transduction.

A. Remote magnon–magnon coupling

In addition to coupling magnons to microwave photons and qubits, ongoing efforts of hybrid magnonics also include coupling of multiple remote magnonic resonators aiming to explore remote magnon–magnon entanglements[168,169] and implement non-Hermitian magnon–magnon interactions. In particular, remote magnon–magnon interaction can be achieved by dispersive coupling [Fig. 6(a)], where the two magnonic resonators are coupled via exchanging virtual photons through a mutually coupled photon cavity, which is far detuned from the magnon mode, or $|\omega_r - \omega_m| \gg g_{m-r}$, where ω_r is the resonator frequency, ω_m is the magnon frequency, and g_{m-r} is the magnon–photon coupling strength. This technique has been commonly used in qubit operation in order to minimize the additional loss from the photon cavity.

The first demonstration of remote magnon–magnon coupling was done by Lambert *et al.*,[166] where two single-crystal YIG spheres with a diameter of 1 mm were placed within a coaxial transmission line cavity [Fig. 6(b)]. By exciting the second harmonic of the standing wave mode in the cavity, the two YIG spheres are simultaneously

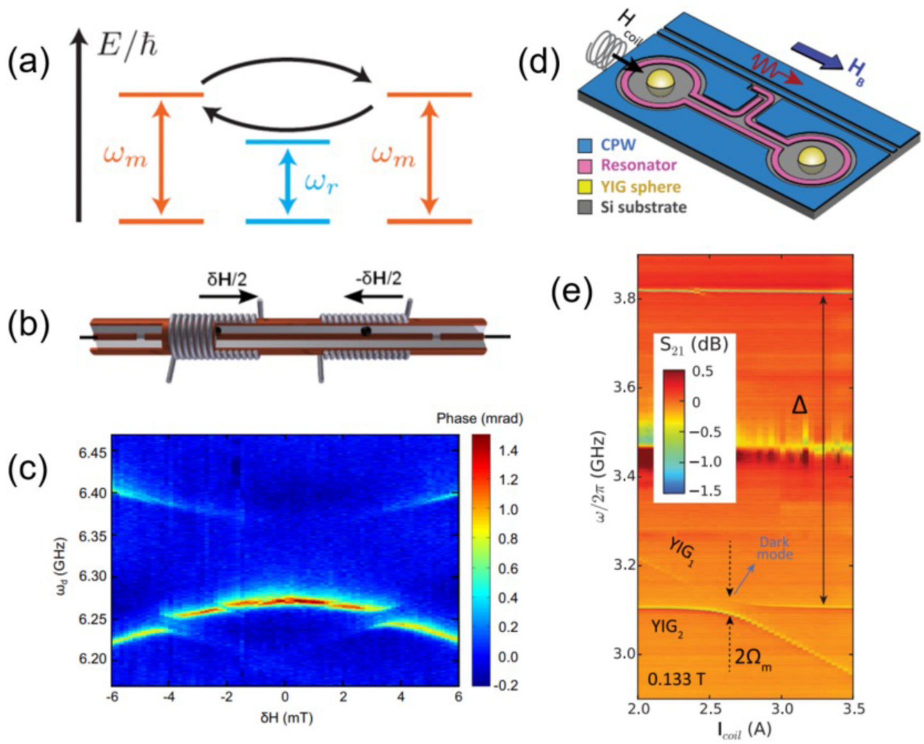

FIG. 6. (a) Schematics of magnon–magnon coupling (ω_m) mediated by a photon cavity (ω_r) in the dispersive regime. (b) Cavity design and YIG sphere placement of a coaxial transmission line cavity. (c) Strong coupling of the two YIG spheres mediated by the coaxial transmission line cavity in the dispersive regime. (d) Cavity design and YIG mounting of a NbN superconducting coplanar resonator. (e) Strong coupling between the two chip-embedded YIG spheres with the magnon modes detuned from the superconducting resonator by $\Delta/2\pi = 0.7$ GHz. Schematics in (b) and (c) are reproduced with permission from Lambert *et al.*, Phys. Rev. A **93**, 021803(R) (2016). Copyright 2016 American Physical Society.[166] Schematics in (d) and (e) are reproduced with permission from Li *et al.*, Phys. Rev. Lett. **128**, 047701 (2022). Copyright 2022 American Physical Society.[167]

coupled to the microwave photon mode with maximal strength. In addition, two coils were wrapped around the transmission line in order to provide detuning magnetic field δH and control magnon–magnon interaction. Shown in Fig. 6(c), clear mode splitting is measured between the two YIG spheres when $\delta H = 0$, meaning when the two YIG magnon modes are degenerate in frequency. Here, the cavity resonance frequency is $\omega_r/2\pi = 7$ GHz, which is well detuned from the two degenerate magnon mode of $\omega_m/2\pi = 6.3$ GHz.

Recently, Li *et al.* have demonstrated similar results with a much smaller system.[167] By using a superconducting coplanar resonator, the microwave cavity can be made with micrometer-wide signal lines, which allows for convenient circuit design and device integration on a chip. In addition, a miniaturized microwave cavity enables smaller effective volumes and leads to larger microwave coupling efficiency to magnetization, meaning that the system can be used to couple to smaller magnetic systems along with higher coupling strength. In the work from Li *et al.*, two smaller YIG spheres with a diameter of 0.25 mm were embedded in two etched sockets on the Si substrate supporting the NbN superconducting resonator. The superconducting resonator was designed with two circular antenna to provide a nearly uniform microwave field onto the YIG spheres at the center [Fig. 6(d)]. Furthermore, a local NbTi superconducting coil has been placed next to one sphere for controlling the magnon–magnon frequency difference. Strong magnon–magnon coupling can be clearly observed in Fig. 6(e), with the superconducting cavity frequency ($\omega_r/2\pi = 3.8$ GHz) being detuned from the degenerate magnon frequency ($\omega_m/2\pi = 3.1$ GHz).

The remote coupling of magnonic resonators offers a new path to implement hybrid magnonic networks with tunable magnonic interactions, such as band structures.[10] Compared with magnonic crystals that are based on propagating magnons, the band structure of a hybrid magnonic network can be controlled by modifying one or a few magnonic resonator nodes, offering more flexibility of control. The main challenges are the scalability and readout. As more magnonic nodes are involved, there is also the need to incorporate more controlling coils for the current schematic, which will complicate the circuit design. Also it is desired to access the magnon status of each individual magnonic node. The two examples above rely on the readout from the cavity, which will be decoupled from the hybrid magnonic mode with certain phase relationships (dark mode). It is thus desirable to have one designated readout antenna for each magnonic node, similar to the readout of multiple entangled qubits. To replace the use of a local coil, we also envision the use of magnetic thin-film devices, where their frequencies can be modified with spin torques, electric fields, or circuit embedded current lines providing an Oersted field.

B. Magnons for nonreciprocal quantum state transfer

1. Role of nonreciprocity in quantum state transfer

Quantum state transfer (QST) mediated by propagating wavepackets is a promising way to distribute quantum information between distant qubits in so-called cascaded quantum systems, where the output of one qubit forms the input of another.[170,171] In this scenario, one can use temporal modulation of stimulated emission and absorption to realize deterministic QST with near-unit efficiency.[172] This method can readily be used to realize remote entanglement, and we can thus envision the realization of complex, distributed quantum networks.

QST through propagating wavepackets has the following benefits: (1) no static hybridization between qubits and (2) no requirements on length of transmission line channels. This is in contrast to quantum bus-type mediation of interactions, which are mediated through standing waves—a common approach for mediating interactions in closed systems.[173,174]

Realization of QST in this way relies on directional elements. First, they aid in avoiding standing waves in finite-length transmission lines, thus ensuring the "propagating wavepacket" scenario. Second, they "route" wavepackets between emitters (senders) and absorbers (receivers), which makes it also highly appealing to have *in situ* tunable directionality.

Chiral networks have been predicted to have interesting features that may be useful for studying open quantum systems, and for suppressing noise and loss. For one, driving cascaded systems has been predicted to enable the realization of dissipatively stabilized remote-entangled states.[175] In addition, chiral coupling of unidirectionally traveling wavepackets to qubits could allow remarkably noise-resilient distribution of quantum states and entanglement.[150,151]

2. State of the art and current approaches

QST through traveling signals is particularly interesting in superconducting microwave quantum circuits. These systems can combine low intrinsic photon loss with excellent temporal control over qubit-photon coupling (for a review, see Ref. 2). At the same time, the need for distributing quantum information across multiple devices has been recognized as an important need for building large-scale quantum devices from the bottom up,[176–183] making QST a very timely topic.

Several experiments have, in recent years, demonstrated deterministic QST and entanglement with decent fidelities using the above-mentioned approach.[184–187] In these experiments, the directionality was provided by commercial microwave circulators. The use of these elements and associated connectors has, however, resulted in levels of photon loss that make scaling beyond two nodes difficult to impossible. In addition, these circulators have fixed directionality, preventing the construction of networks with high connectivity.

One way to overcome these challenges is to realize nonreciprocal elements using Josephson circuits. The introduction of magnetic flux through loops containing junctions allows breaking Lorentz symmetry and the realization of devices in which microwave excitations are emitted or scattered nonreciprocally.[188,189] Importantly, such Josephson circuits can be expected to be lossless, and magnetic flux tuning, which is a well-established tool in quantum circuits, allows *in situ* control over the directionality. Recent theoretical[190–194] and experimental[195–198] works have explored Josephson-based directional devices and how to construct multinode quantum networks from them. These results show great promise for realizing high-fidelity state transfer.

3. Potential for magnon-mediated QST

While the above approach for realizing synthetic nonreciprocity is highly appealing, there are downsides. In particular, the fact that many of the proposed devices are fairly narrow-band and that they require multiple control channels (rf or dc connections) to tune and/or operate raises the question whether simpler passive devices are possible to be integrated into quantum circuits in a similar way. The recent advances in hybrid-magnon devices could potentially show the way toward such elements as we described in Sec. III. The operating band of hybrid magnonic devices is easily adjustable with varying magnetic field strengths and these hybrid magnonic systems do not need multiple control channels but rather just a rf channel. Figure 7 shows a schematics of a unidirectional quantum state transfer in a system, which could realize the above-mentioned noise-resilient quantum information device. Strong coupling between magnonic systems and superconducting resonators have been demonstrated recently, for example, in both Figs. 1(a) and 1(b), and strong coupling between superconducting resonators and transmon qubits is a well-known fact.[199] Also, transmon qubits need to be placed at a location where voltage or electric field of a superconducting resonator is maximum, and the magnonic systems need to be placed at a location where current or magnetic field of a superconducting resonator is maximum. Therefore, integrating both magnonic system and transmon qubit into a superconducting resonator is relatively straightforward. However, the design in Fig. 7 omits the specific details needed for realizing such a system.

In parallel, there are studies of magnon-assisted nonreciprocal microwave photon propagation in the context of chiral cavity quantum electrodynamics.[200–203] For example, for a ferrimagnetic-cylinder-loaded Y-shaped cavity, it was demonstrated that this device acts as a microwave circulator.[200] The main mechanism was due to the fact that two almost-degenerate chiral magnon–polariton modes with opposite propagation direction were canceled at one port and not canceled at the other port. A study of a more complicated system consisting of a 5×5 array of cavities, where four of them include ferrimagnetic sphere inside, has been reported.[204] It turned out that the system has bulk modes and chiral unidirectional surface modes with topological properties. Also, a ferrimagnetic sphere-loaded X-shaped cavity showed nonreciprocal microwave propagation.[205] This system has both coherent and dissipative coupling between magnon and cavity photons and the dissipative coupling parameter has a phase difference between two oppositely propagating microwave photons so the system has nonreciprocal propagation character.

Devices based on currently known hybrid-magnon circuits might need external magnetic fields, which is not readily compatible with many quantum device platforms, in particular superconducting qubits. However, there have been significant advances in field-compatible qubits, such as spin-qubits or variations of superconducting devices,[206] that suggest this may not be an insurmountable roadblock.

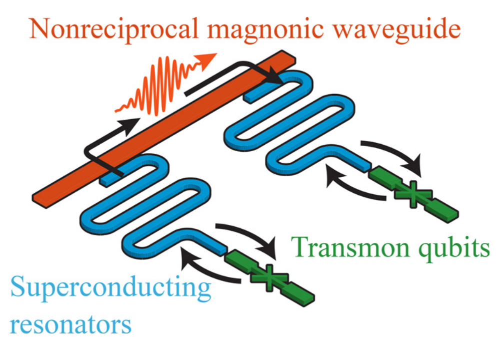

FIG. 7. Schematic of unidirectional quantum state transfer with nonreciprocal magnetic waveguide. The system consists of two transmon qubits (green), a nonreciprocal magnonic waveguide (orange), and two intermediary superconducting resonator (blue).

V. CONCLUSIONS

Hybrid quantum systems are gaining increasing interest for their potential in coherent information processing because one can expect to exploit combined advantages from each hybridizing component. In this context, magnon-based hybrid systems, known as hybrid magnonics, possess unique advantages from magnons, quanta of spin waves in a magnetic material. Magnons can hybridize to a variety of other excitations, especially microwave photons, in the strong coupling regime. The intrinsic nonreciprocity opens the potential of magnons for unidirectional quantum state transfer. The characteristic dispersion relation of magnons allows for miniaturized microwave magnonic devices. All these suggest that magnon-based hybrid quantum systems are very promising candidate platforms for quantum information science.

To achieve robust hybrid-magnon quantum devices, it is essential to have optimized material candidates with low magnetic damping such that the coherence of the hybrid systems can stay as long as possible. Both the ferrimagnetic insulator YIG and metallic ferromagnets show promising potential toward this end. Considering the on-chip integrability and the relevance for quantum information applications, we are especially interested in the damping behavior of these materials in a thin film structure and at low environmental temperatures. For YIG, due its exceptionally low intrinsic damping, research using advanced experimental techniques should be focused on reducing external damping sources that can come from surface imperfections, chemical impurities, and substrate (GGG) effects. For metallic ferromagnets, magnon–electron scattering dominates the damping in most situations and complicates its temperature dependence. First-principles calculations of the electronic structure can provide guidance for searching possible promising materials. Engineering electron energy bands by tuning alloy compositions, chemical doping, and structure amorphization provide several pathways for optimization. Recently increased interest in 2D van der Waals magnets and topological magnetic semi-metals may provide other new opportunities toward this goal.

Another advantage of magnon-based hybrid quantum systems is that ferro/ferrimagnetic systems naturally have time reversal symmetry breaking due to the presence of non-zero net magnetization. This feature allows one to generate and engineer wave nonreciprocity in ferro/ferrimagnetic systems. We have reviewed various mechanisms, which result in spin wave nonreciprocity. A nonreciprocal hybrid magnetic system has unique properties including tunable operating frequency by changing applied field, and it is miniaturizable compared to currently used microwave devices (e.g., isolators or circulators). As described in Sec. III, these nonreciprocal magnetic systems may be able to provide noise isolation on the chip level. Also, as described in Sec. IV B, there are protocols of quantum state transfer in the presence of background noise,[150,151] which need a nonreciprocal channel between qubits. We think nonreciprocal magnetic systems may be able to provide suitable functionality to establish such noise-resilient quantum information devices with the field-compatible qubits.[206]

With optimized low damping and nonreciprocity in ideal material candidates, coupling them to hybrid quantum systems for coherent information processing is the ultimate goal. The past decade has witnessed wide-spread effort and significant progress toward this goal. Two particular relevant aspects have been discussed in this Perspective: remote magnon–magnon coupling mediated by microwave photons in a superconducting coplanar resonator and the possibility for magnons assisting with nonreciprocal quantum state transfer. Furthermore, there are many additional fundamental opportunities worth exploring, such as to manifest hybrid magnonic quantum information devices on a single chip, including low magnetic damping, low-insertion-loss transduction between microwave photon and magnon, large enough magnon amplitude nonreciprocity, and magnetic field resilient qubit development. The field is attracting continuous interest from the scientific community. With ongoing and more future efforts, we believe that magnon-based hybrid systems will be one of the promising platforms for faithful coherent quantum information processing.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhihao Jiang and Jinho Lim contributed equally to this work. The whole manuscript was prepared and reviewed by all authors.

Zhihao Jiang: Conceptualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Jinho Lim:** Conceptualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Yi Li:** Conceptualization (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Wolfgang Pfaff:** Conceptualization (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Tzu-Hsiang Lo:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jiangchao Qian:** Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **André Schleife:** Conceptualization (equal); Supervision (equal); Writing – review & editing (equal). **Jian-Min Zuo:** Conceptualization (equal); Supervision (equal); Writing – review & editing (equal). **Valentine Novosad:** Conceptualization (equal); Supervision (equal); Writing – review & editing (equal). **Axel Hoffmann:** Conceptualization (equal); Funding acquisition (lead); Project administration (lead); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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