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Observation of Anti- $\mathcal{PT}$ -Symmetry Phase Transition in the Magnon-Cavity-Magnon Coupled System

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As the counterpart of $\mathcal{PT}$ symmetry, for anti- $\mathcal{PT}$ -symmetry abundant phenomena and potential applications have been predicted or demonstrated theoretically. However, experimental realization of the coupling required in anti- $\mathcal{PT}$ symmetry is difficult. By our coupling two yttrium iron garnet spheres commonly to a microwave cavity, the large cavity dissipation rate makes the magnon-magnon coupling dissipative and purely imaginary. Thereby, the hybrid magnon-cavity system obeys a two-dimensional anti- $\mathcal{PT}$ Hamiltonian. In terms of the magnon-readout method, the method adopted here, we demonstrate the validity of our method in constructing an anti- $\mathcal{PT}$ system and present the counterintuitive level-attraction process. Our work provides a platform to explore the anti- $\mathcal{PT}$ -symmetry properties and paves the way to study dynamical evolution and topological properties around exceptional points in multimagnon-cavity systems.

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I. INTRODUCTION

In the real world, quantum systems interact with the surrounding environment and evolve from being closed originally into open ones [1,2]. Hamiltonians describing open systems are generally non-Hermitian. Because of the nonconserving nature, the eigenenergies are complex numbers and the corresponding dynamics are complicated [3]. One special type of non-Hermitian system, which respects parity-time ($\mathcal{PT}$) symmetry, has triggered unprecedented interest and has been widely explored theoretically and experimentally [4–7]. Another special type of non-Hermitian system is the anti- $\mathcal{PT}$ symmetric system, which is the counterpart of the $\mathcal{PT}$ -symmetric system and always preserves properties conjugated to those observed in $\mathcal{PT}$ -symmetric ones [8,9]. On the basis of the conjugated properties, abundant phenomena and potential applications of anti- $\mathcal{PT}$ systems have been predicted or demonstrated theoretically, especially around the exceptional points (EPs). Examples include unidirectional light propagation [10], flat full transmission bands [11], enhanced sensor sensitivity [12], construction of a

topological superconductor [13], and potential effects on evasion of quantum measurement back-action [14]. Motivated by the intriguing phenomena and various potential applications, experimental realizations of anti- $\mathcal{PT}$ symmetric systems are highly desirable. However, because of the requirement of purely imaginary coupling constants between two bare states, there have been few experimental studies on anti- $\mathcal{PT}$ symmetry [8,9,15,16].

Recently, collective excitations of spin ensembles in ferromagnetic systems (also called “magnons”) have drawn considerable attention due to their very high spin density, low damping rate, and high cooperativity with microwave photons [17,18]. Especially the ferromagnetic mode in an yttrium iron garnet (YIG) sphere can strongly [19–22] and even ultra-strongly [23,24] couple to the microwave cavity photons, leading to cavity-magnon polaritons. On the basis of cavity-magnon polaritons, quantum memories have been realized [25] and remote coherent coupling between two magnons has been proposed [26] and observed [27]. At the same time, coupled cavity-magnon polaritons are attractive systems for exploring non-Hermitian physics because of the operability of the parameter space around EPs [15,28,29], as well as their easy reconfiguration, their flexible tunability, and especially the strong compatibility

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with microwaves [30,31], optics [32–35], and mechanical resonators [36,37].

Here we propose a coupled magnon-cavity-magnon polariton system to experimentally demonstrate anti- $\mathcal{PT}$ symmetry [11]. The purely imaginary coupling between two spatially separated and frequency-detuned magnon modes is realized by our engineering the dissipative reservoir of the cavity field. Differently from previous cavity-magnon-polariton experiments, in which the signals are extracted from the cavity [19–24], we obtain the signals directly from the magnons by use of the coupling-loop technique. The experimental data fit well not only with the original-experiment-Hamiltonian-calculated transmission spectrum but also with the one predicted by the standard anti- $\mathcal{PT}$ Hamiltonian. By continuously tuning the non-Hermitian control parameter (e.g., the cavity decay rate), we present the spontaneous symmetry-breaking transition at the EPs, which is accompanied by energy-level attraction. The results are compared with the data normally obtained from the cavity. This comparison demonstrates that the magnon-readout technique enables us to measure the magnon state separately in a multimagnon-cavity coupled system and allows the exploration of many significant phenomena. Our work provides a technology to extract signals from hybrid multimagnon-cavity systems. By using this technique, we also construct a platform to explore the anti- $\mathcal{PT}$ -symmetry properties, and this may pave the way to study dynamical evolution processes around the EPs, such as the topological phase transition and the nonreciprocal energy transfer.

II. EXPERIMENTAL METHODS

Our experimental setup is schematically shown in Fig. 1(a). Two YIG spheres are placed inside a three-dimensional oxygen-free-copper cavity with inner dimensions of $40 \times 20 \times 8 \text{ mm}^3$. The YIG spheres of 0.3-mm diameter are glued on one end of two glass capillaries, which are anchored at two mechanical stages. The YIG spheres are placed near the magnetic field antinode of the cavity mode TE_{101} through two holes in the cavity wall. Two grounded loop readout antennae, antenna 1 and antenna 2, are coupled with YIG sphere 1 and YIG sphere 2, respectively. In this setup, we can change the positions of the YIG spheres relative to the loop antennae by tuning the mechanical stages. In our experiment, we focus on the Kittle mode, which is a spatially uniform ferromagnetic mode. To avoid involving other magnetostatic modes, the antennae are carefully designed and assembled. Antenna 3, with a length-tunable pin, is used to control the dissipation rate of the cavity. When we probe the system from the cavity, antenna 1 and antenna 2 are removed. The whole system is placed in a static magnetic bias field, which is created by a high-precision room-temperature electromagnet. The bias magnetic field and the magnetic field of the

FIG. 1. (a) Our experimental system. Two YIG spheres are placed inside a three-dimensional oxygen-free-copper cavity. Antenna 1 and antenna 2 are coupled to the YIG spheres, and antenna 3 is coupled to the cavity. These three antennae can be connected to a vector network analyzer to measure the transmission spectra S_{11} , S_{22} , and S_{33} . In the experiment, antenna 3 can be used to control the dissipation rate of the cavity. The colored-slice figure shows the simulated magnetic field distribution of the cavity TE_{101} mode. (b) The coupling mechanism between two YIG spheres. When the cavity dissipation rate κ is much larger than the dissipation rates of the two magnons (i.e., $\kappa \gg \gamma_1, \gamma_2$), the two magnons are dissipatively coupled with each other and the cavity behaves as a dissipative-coupling medium.

cavity TE_{101} mode are nearly perpendicular at the sites of the two YIG spheres.

In our system, the two YIG spheres work in the low-excitation regime, and thus the collective spin excitation of the YIG spheres can be regarded simply as harmonic resonators. In the dissipative regime, our system can be approximately described by the standard anti- $\mathcal{PT}$ Hamiltonian [11] (see Sec. C in Supplemental Material [38] for details):

$$H_{\text{eff}} = \begin{pmatrix} \Omega - i(\gamma + \Gamma) & -i\Gamma \\ -i\Gamma & -\Omega - i(\gamma + \Gamma) \end{pmatrix}, \quad (1)$$

where $i\Gamma$ is the dissipative-coupling rate and $\Omega = (\omega_1 - \omega_2)/2$ is the effective detuning in the rotating reference frame with frequency $(\omega_1 + \omega_2)/2$, where ω_1 (ω_2) is the resonant frequency of magnon 1 (magnon 2). For the Kittle mode, the frequency of a magnon linearly depends on the bias field $\vec{B}_i$; that is, $\omega_i = \gamma_0 |\vec{B}_i| + \omega_{m,0}$ ($i = 1, 2$), where $\gamma_0 = 28 \text{ GHz/T}$ is the gyromagnetic ratio and $\omega_{m,0}$ is determined by the anisotropy field. To obtain the effective Hamiltonian in Eq. (1), we further require that the dissipation rates of the two magnons are nearly equal (i.e., $\gamma_1 \approx \gamma_2 = \gamma$) and the magnon-1 cavity coupling rate g_{13} approximately equals the magnon-2 cavity coupling rate g_{23} (i.e., $g_{13} \approx g_{23} = g$). In the regime of $\kappa \gg \gamma$ and $\kappa \gg |\omega_3 - \omega_{1(2)}|$, with cavity dissipation rate κ , the effective coupling rate $\Gamma = g^2/\kappa$. We can conveniently obtain the eigenvalues of the Hamiltonian in Eq. (1), $\lambda_{\pm} =$

$-i(\gamma + \Gamma) \pm \sqrt{\Omega^2 - \Gamma^2}$. When $|\Omega| > |\Gamma|$, the eigenvalues are normally complex, and the system works in the anti- $\mathcal{PT}$ -symmetry-broken phase regime. If $|\Omega| < |\Gamma|$, the eigenvalues are purely imaginary and the system works in the anti- $\mathcal{PT}$ -symmetry phase regime. The condition $|\Omega| = |\Gamma|$ defines the EP.

We can probe the magnon-cavity-polariton system from either the magnon or the cavity. When we probe the system from the magnon, we carefully tune the mechanical stage and change the positions of the YIG spheres relative to the positions of the readout antennae to change the external dissipation rate γ_{11} (γ_{21}) of magnon 1 (magnon 2) so that the readout antennae are critically coupled to the magnons; that is, $\gamma_{i0} \approx \gamma_{i1}$ ($i = 1, 2$), where γ_{i0} is the intrinsic dissipation rate of the magnon. In this situation, the total dissipation rate of magnon 1 (magnon 2) should be $\gamma_i = \gamma_{i0} + \gamma_{i1} \approx 2\gamma_{i0}$ ($i = 1, 2$). In this setup, the dissipation rate of the cavity is controlled by our changing solely the pin length of antenna 3. When we probe the system from the cavity, the signal is injected into the cavity from antenna 3, and the reflected signal is measured from the same port. In this case, the overall dissipation rate of magnon 1 (magnon 2) equals the intrinsic dissipation rate; that is, $\gamma_i = \gamma_{i0}$ ($i = 1, 2$). In this measurement setup, we require that antenna 3 is critically coupled to the cavity. To achieve this requirement, we paste carbon tape at the electric field antinode of the cavity mode to change the cavity intrinsic dissipation rate κ_{int} and change the pin length of antenna 3 to change the dissipation rate κ_3 , such that the condition $\kappa_{\text{int}} \approx \kappa_3$ can be satisfied. All system parameters used in both readout methods are presented in Table I, which shows that the difference between g_{13} and g_{23} and the difference between γ_1 and γ_2 are both less than 5% of their average values. Therefore, we can safely ignore the difference between dissipation rates γ_1 and γ_2 and the difference between coupling rates g_{13} and g_{23} (see Sec. A in Supplemental Material [38] for details) [11].

Using the magnon-readout method, we read the reflection parameters S_{11} and S_{22} from antenna 1 and antenna 2, respectively. In this case, the magnon-readout antennae are coupled to the YIG spheres and to the cavity simultaneously. In other words, the applied probe microwave signal through antenna 1 (antenna 2) drives not only magnon 1 (magnon 2) but also the cavity with

relative phase φ_{13} (φ_{23}) simultaneously. The reflected signals from magnon 1 (magnon 2) and the cavity also preserve the same relative phase φ_{13} (φ_{23}). On the basis of the mechanism, we can solve the input-field–output-field relation as $s_{\text{out}} = -s_{\text{in}} + \sqrt{\kappa_k} e^{i\varphi_{k3}} c + \sqrt{\gamma_{k1}} a$ ($k = 1, 2$). Compared with the magnon-readout method, the cavity-readout method is much simpler. The injected signal from antenna 3 drives only the cavity, and the input-field–output-field relation has the normal form, $s_{\text{out}} = -s_{\text{in}} + \sqrt{\kappa_3} c$. Using the magnon-cavity-magnon coupled original Hamiltonian and the input-field–output-field relation, we can solve the whole spectrum with the standard input-output theory in both readout methods (see Sec. B in Supplemental Material [38] for details) [39–41].

III. RESULTS

On the basis of the magnon-readout method, we can demonstrate that the approximation used in our system is valid and construct the anti- $\mathcal{PT}$ symmetry. We apply bias magnetic fields B_1 and B_2 to bias magnon 1 and magnon 2 at frequency ω_1 and ω_2 , respectively. In our experiment, the resonant frequencies ω_1 and ω_2 are set to satisfy the relationship $\omega_1 - \omega_2 = 2\pi \times 5.4$ MHz, and thus the effective detuning in this configuration $|\Omega| = 2\pi \times 2.7$ MHz, which is constant in all experiments. Then we measure the reflection parameters S_{11} and S_{22} from antenna 1 and antenna 2, respectively. As shown in Fig. 2(a), the measured S_{11} and S_{22} data are fitted well with the calculated spectra with use of the original-experiment Hamiltonian (see Sec. B in Supplemental Material [38] for details). This result proves that the physical model used in solving the measurement spectra is sufficient. On the other hand, the anti- $\mathcal{PT}$ Hamiltonian in Eq. (1) describes a system with dissipatively coupled detuned resonators. We can solve the corresponding reflection spectra with the standard anti- $\mathcal{PT}$ Hamiltonian in Eq. (1), as shown in Fig. 2(b), in which the resonant dips are marked with triangles. To compare the experimental results with the spectra predicted by the standard anti- $\mathcal{PT}$ Hamiltonian, we draw the triangles at the same position in Fig. 2(a). We conclude from this comparison that the resonance occurs at the right frequency and amplitude, which are predicted by the standard anti- $\mathcal{PT}$ Hamiltonian. The measurement

TABLE I. Parameters used in the cavity-readout and magnon-readout methods. γ_1 and γ_2 are the dissipation rates of magnon 1 and magnon 2, respectively. g_{13} or g_{23} is the coupling strength between the cavity and magnon 1 or magnon 2, respectively. $|\Omega|$ is the effective detuning. κ_{int} is the intrinsic dissipation rate of the cavity (without additional ports). κ_1 , κ_2 , and κ_3 are the dissipation rates introduced by antenna 1, antenna 2, and antenna 3, respectively.

2*Probe method	System parameters (MHz)								
	$\gamma_1/2\pi$	$\gamma_2/2\pi$	$g_{13}/2\pi$	$g_{23}/2\pi$	$ \Omega /2\pi$	$\kappa_{\text{int}}/2\pi$	$\kappa_1/2\pi$	$\kappa_2/2\pi$	$\kappa_3/2\pi$
Cavity-readout	1.11	1.11	9.77	9.61	2.7	Tunable	0	0	$\approx \kappa_{\text{int}}$
Magnon-readout	2.22	2.22	6.65	6.41	2.7	1.5	0.45	0.92	Tunable

FIG. 2. (a) The magnon-readout results with different cavity dissipation rates κ in the unit of 2π MHz. The circles and the squares represent the experiment data of spectra S_{11} and S_{22} , respectively. The solid lines and the dash-dotted lines are the fitting results obtained with the original-experiment Hamiltonian. The triangles mark the resonant-dip positions in the original-anti- $\mathcal{PT}$ -Hamiltonian-solved spectra, as shown in (b). (b) Spectra S_{11} and S_{22} solved by the original anti- $\mathcal{PT}$ Hamiltonian in Eq. (1). The triangles indicate the resonant dips in the spectra. (c) Cavity-readout result in anti- $\mathcal{PT}$ -symmetry phase (upper panel) and in anti- $\mathcal{PT}$ -symmetry-broken phase (lower panel). The circles are experimental data and the solid lines are theoretical predictions from the original-experiment Hamiltonian with best-fit parameters.

data demonstrate that the approximations are sufficient and indicate that we successfully construct anti- $\mathcal{PT}$ symmetry in a magnon-cavity-magnon coupled system.

In addition to the magnon-readout method, we can also probe the system through antenna 3 by the cavity-readout method. As shown in Fig. 2(c), although the measured data can be fitted well with the spectra given by the original-experiment Hamiltonian (see Sec. F in Supplemental Material [38] for detailed experimental data), the results cannot prove that we successfully construct an anti- $\mathcal{PT}$ system. Because the cavity mode c is eliminated in the large-dissipation-rate approximation, we cannot compare the measurement results with those obtained with the anti- $\mathcal{PT}$ Hamiltonian. Compared with the cavity-readout method, we find that the well-developed magnon-readout technique allows us to verify the validity of adiabatic elimination of the cavity field.

We now discuss the spontaneous phase transition of the anti- $\mathcal{PT}$ system. In our experiments, the coupling rates between magnons and the cavity are fixed values, and are around $2\pi \times 6.5$ MHz. To observe the anti- $\mathcal{PT}$ symmetry phase transition, we need to increase the effective coupling rate $\Gamma = g^2/\kappa$ by decreasing the overall dissipation rate of the cavity κ , where $\kappa = \kappa_{\text{int}} + \kappa_1 + \kappa_2 + \kappa_3$ in magnon-readout method, where κ_{int} is the intrinsic dissipation rate of the cavity (without additional ports) and κ_1 , κ_2 , and κ_3 are the dissipation rates introduced by antenna 1, antenna 2, and antenna 3, respectively. With different cavity dissipation rates, we obtain the corresponding transmission spectra S_{11} and S_{22} , as shown in Fig. 2(a). When

the cavity dissipation rate κ is large, the corresponding effective coupling rate is smaller than the effective magnon detuning (i.e., $\Gamma < \Omega$). The system works in the anti- $\mathcal{PT}$ -symmetry-broken phase, and the separation between the two dips in the spectrum is larger than the full width at half maximum (FWHM). Using the definition of the EP, we can obtain the corresponding cavity dissipation rate $\kappa_0 = 2\pi \times 15.8$ MHz. Continuously decreasing the cavity dissipation across the EP results in two main counterintuitive phenomena: (i) on decrease of the cavity loss, the measured spectra show mode attraction; (ii) on increase of the effective coupling strength between the magnon modes, we observe energy attraction instead of mode splitting. These two counterintuitive phenomena are basically induced by the broken-anti- $\mathcal{PT}$ -symmetry phase transition. When our system works in the anti- $\mathcal{PT}$ -symmetry phase, the separation between the two dips is smaller than the FWHM. To formulate the relationship between the dip separation and the FWHM, we can define the combined spectrum by $\bar{S} = (S_{11} + S_{22})/2$ (see Sec. D in Supplemental Material [38] for details).

The anti- $\mathcal{PT}$ -symmetry-broken-induced level attraction can be expressed even more clearly by examining the eigenvalues of different dissipation rates κ . In our experiment, the line shapes of reflection coefficients S_{11} and S_{22} are not the normally Lorentzian ones when the cavity dissipation rate is not large enough. It is not suitable to extract the real part (resonant frequency) or the imaginary part (line width) of the eigenenergies of the system by directly fitting the reflection spectra. We extract the eigenvalues by

FIG. 3. (a) The real part and (b) the imaginary part of the eigenvalues as a function of κ . The shadowed area with $\kappa > 2\pi \times 15.8$ MHz indicates the parametric regime of the anti- $\mathcal{PT}$ -symmetry-broken phase.

diagonalizing the effective Hamiltonian with experimental parameters and plot the real and imaginary parts as a function of κ in Figs. 3(a) and 3(b), respectively (see Sec. E in Supplemental Material [38] for details). The experimental data in Fig. 3(a) reveal that the exceptional point occurs at $\kappa_0 = 2\pi \times 15.8$ MHz, which corresponds to dissipative coupling rate $\Gamma = 2\pi \times 2.7$ MHz. According to Eq. (1), the two real parts of the eigenvalues should be $\pm 2\pi \times 2.7$ MHz when the cavity dissipation rate κ approaches infinity. As shown in Fig. 3(a), the real parts of the eigenvalues corresponding to $\kappa = 2\pi \times 105$ MHz are approximately $\pm 2\pi \times 2.7$ MHz, which are compatible with the theoretical results. When we decrease κ , the difference between the two real parts becomes smaller and is reduced to zero at the EP. The theory predicts that there should be two different imaginary parts in the anti- $\mathcal{PT}$ -symmetry regime, and a single value of the imaginary part in the symmetry-broken regime. We also observe this phenomenon in our experiment, as shown in Fig. 3(b). Figures 3(a) and 3(b) clearly show that when the cavity dissipation rate is decreased (i.e., the effective coupling strength between the two magnon modes is increased), anti- $\mathcal{PT}$ symmetry is broken on crossing the EP and the counterintuitive energy-level attraction happens. The deviation of the experimental data from the theoretical prediction is caused by the finite detuning between the two magnon modes and the cavity mode.

IV. CONCLUSION AND OUTLOOK

In conclusion, we successfully construct anti- $\mathcal{PT}$ symmetry in a magnon-cavity-magnon coupled system without any gain medium. We then directly measure the energy

transmission spectra from the magnon side by applying the coupling-loop technique. The magnon-readout results clearly show that the anti- $\mathcal{PT}$ symmetry is broken at the phase transition point (i.e., the EP), accompanied by a counterintuitive energy-attraction phenomenon instead of the energy repulsion widely reported in strongly coupled resonator systems [19–22]. Encircling around such an exceptional point in the future may allow us to observe various topological operations based on nonadiabatic transitions. The negative frequencies (negative-energy modes) in an anti- $\mathcal{PT}$ symmetric Hamiltonian equivalent to harmonic oscillators with negative mass also have a close connection to evasion of quantum measurement back-action [14]. By comparison with the cavity-readout results, we uncover the ability of the magnon-readout method in exploring multimagnon-cavity coupled systems. Our experiment illustrates the power of the magnon-readout method and provides motivation for further explorations of macroscopic quantum phenomena and the fundamental limit of quantum sensing based on EPs [12].

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