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# Phase-controlled pathway interferences and switchable fast-slow light in a cavity-magnon polariton system

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## Abstract

We study the phase controlled transmission properties in a compound system consisting of a 3D copper cavity and an yttrium iron garnet (YIG) sphere. By tuning the relative phase of the magnon pumping and cavity probe tones, constructive and destructive interferences occur periodically, which strongly modify both the cavity field transmission spectra and the group delay of light. Moreover, the tunable amplitude ratio between pump-probe tones allows us to further improve the signal absorption or amplification, accompanied by either significantly enhanced optical advance or delay. Both the phase and amplitude-ratio can be used to realize in-situ tunable and switchable fast-slow light. The tunable phase and amplitude-ratio lead to the zero reflection of the transmitted light and an abrupt fast-slow light transition. Our results confirm that direct magnon pumping through the coupling loops provides a versatile route to achieve controllable signal transmission, storage, and communication, which can be further expanded to the quantum regime, realizing coherent-state processing or quantum-limited precise measurements.

## I. INTRODUCTION

Interference, due to superposed waves, plays a paramount role in explaining many classical and quantum physical phenomena. Based on the phase-difference-induced interference patterns, ultra-precise interferometers have been created, impacting the development of modern physics and industry [1]. In addition to the phases, waves or particles propagating through different pathways can also introduce interference patterns. Among various types of multiple-paths-induced interference, the Fano resonance [2] and its typical manifestations, the electromagnetically-induced-transparency (EIT) and electromagnetically-induced-absorption (EI-ABS) [3, 4], are the most well-known ones. The Fano resonance and EIT-like (or EI-ABS-like) line-shapes are not only experimentally observed in quantum systems but also in various classical harmonic-resonator systems. Quantum examples include quantum dots [5], quantum wells [6], superconducting qubits [7–10], as well as Bose-Einstein condensates [11]. Classical examples [12] include coupled optical cavities [13–16], terahertz resonators [17, 18], microwave resonators [19, 20], mechanical resonators [21, 22], optomechanical systems [23]. However, whether in quantum or in classical systems, the Fano resonance, EIT or EI-ABS like spectra are normally experimentally realized

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separately. The switchable electromagnetically induced transparency and absorption, as well as fast and slow light, have been proposed using dressed superconducting qubits [8], hybrid optomechanical system [24, 25], dark-mode breaking [26–28], and so on. Especially, there appears growing interest to control the EIT and EI-ABS by introducing exceptional points [29–31]. Photon stops [32, 33], chiral EIT [34], and infinite slow light [33] have recently been realized around exceptional points. Motivated by their potential applications in rapid transitions between fast and slow light, which facilitate coherent state storage and retrieval, it is highly desirable to have experimental realizations of in-situ tunable and switchable absorption, transparency, and even amplification.

Meanwhile, cavity magnon-polaritons in an yttrium iron garnet (YIG) sphere-cavity coupled system has attracted much attention due to its strong [35–42] and even ultra-strong couplings [43–45]. The compatibility and scalability with microwave and optical light enable magnons to be a versatile interface for different quantum devices [46–51]. At low-temperatures, strong coupling between magnons, superconducting resonators and qubits have been demonstrated [52–56]. Subsequently, the EIT-like magnon-induced-transparency (MIT) or the EI-ABS like magnon-induced-absorption (MI-ABS) of the transmitted cavity field were observed for different external coupling conditions [57]. The underlying mechanism is attributed to interferences between two transition pathways, i.e., the direct cavity pathway and the cavity-magnon-cavity pathway, to transmit the probe field.

In addition to the coupling strength [57] and frequency detuning [58–60] between coupled modes, phases play a vital role in wave interference control. We thus focus on the controllability of pathway interferences through the phase difference between the cavity probe tone and the magnon pump tone, which is introduced by the coupling loops technology [61–64]. The direct magnon pump is becoming important in realizing the light-wave interface [46–48], enhancing the Kerr nonlinearity [65–67], and has also been adopted to observe the magnetostriction induced quantum entanglement [68–72], among other applications.

Together with the cavity probe tone, a magnon pump tone introduces a controllable relative phase to the system, and thus the path interference can be real-time controlled. Changing the two-tone phase difference, we can *switch the cavity probe spectra from the original magnon-induced transparency instantly to the magnon-induced absorption, or even the Fano line shape*. Furthermore, the tunable pump-probe amplitude ratio allows us to further improve the signal absorption, transparency or amplification, accompanied by a significant enhancement by nearly *two orders of*

*magnitude* of the optical advance or delay time compared to the case without magnon pump [57]. Specially, the tunable phase and amplitude ratio also lead to the zero reflection of the transmitted light, which is accompanied by an abrupt transition of delay time. Our results confirm that direct magnon pumping provides a versatile route to control signal transmission, storage, and communication, and can be further expanded to coherent state processing in the quantum regime.

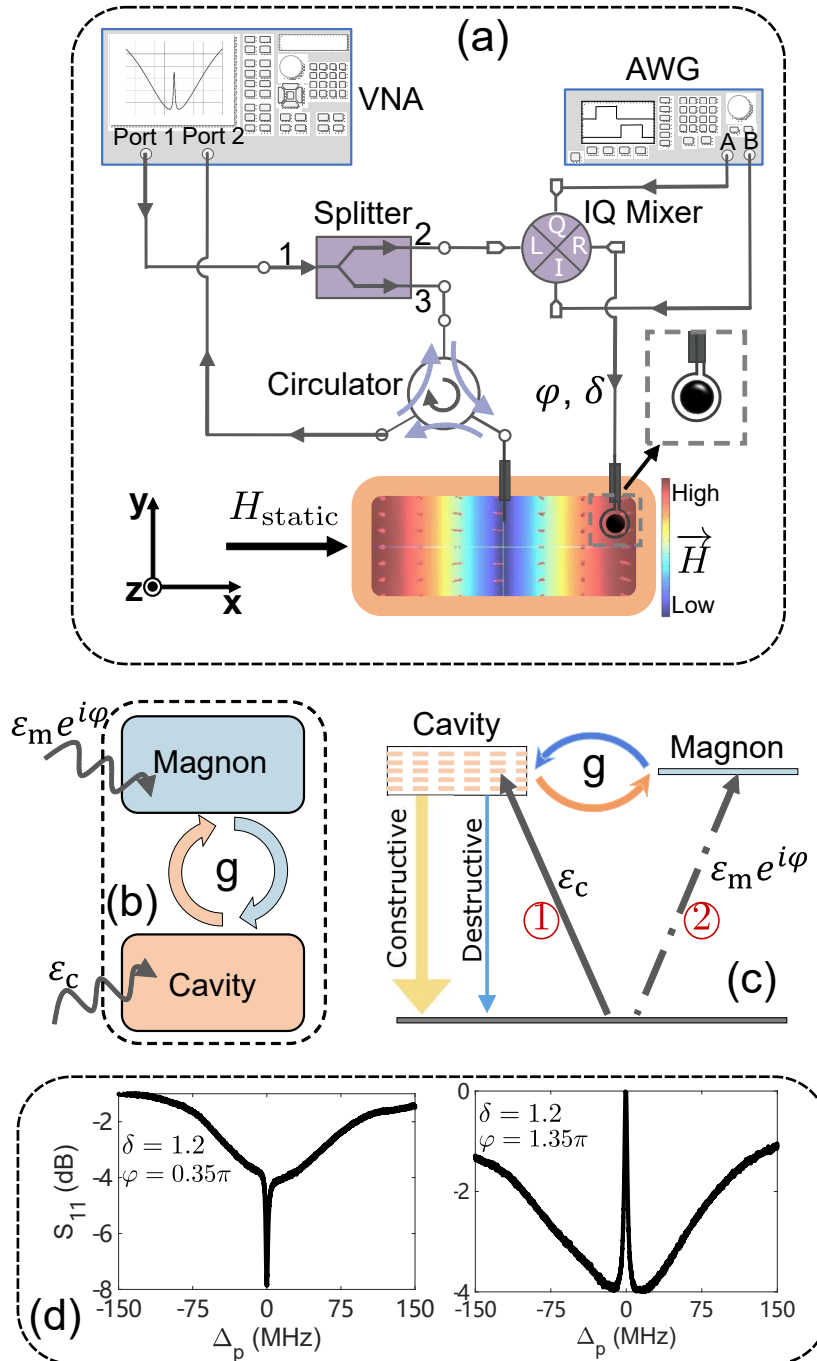


FIG. 1. Measurement setup and phase-induced interference mechanism diagrams. (a) The system consisting of a 3D copper cavity and a yttrium iron garnet (YIG) sphere, which is coherently pumped by the coupling loops shown as a black coil surrounding the YIG sphere. The red arrows and colors indicate the magnetic field directions and amplitudes of the  $TE_{101}$  mode distribution, respectively. The YIG sphere is placed at the area with maximum magnetic field distribution inside a 3D Copper cavity box to obtain a strong cavity-magnon coupling. A small hole at the cavity sidewall is assembled with a standard SubMiniature version A connector (SMA connector), allowing us to do the reflection measurement  $S_{11}$  of the probe field, i.e., such SMA connector works as both the signal input and readout port. A beam of coherent microwave comes out from port 1 of the vector network analyzer (VNA) and split into two beams, working as the magnon pump tone and the cavity probe tone. Here, we use an in-phase/quadrature mixer (I/Q mixer) and an arbitrary waveform generator (AWG) to control and tune the phase difference  $\varphi$  and pump-probe amplitude ratio  $\delta = \varepsilon_m/\varepsilon_c$  between the pump and probe tones. The interfering results are extracted by the circulator and finally transferred to port 2 of the VNA. (b) Diagram showing the relative phase between the magnon pump and cavity probe in the cavity-magnon coupled system. (c) The corresponding energy level diagram. Two transition pathways to the higher energy level: ① probe-tone-induced direct excitation, and ② pump-tone excites magnons and then coherently transfers there to cavity photons. (d) Measurements of the reflection spectra  $S_{11}$  versus the detuning  $\Delta_p = \omega_c - \omega_p = \omega_m - \omega_p$ . The relative phase difference between pump and probe tones can be developed to realize an in-situ switchable constructive and destructive interference, presented as magnon-induced-absorption (MI-ABS) with  $\varphi = 0.35\pi, \delta = 1.2$  and -transparency (MIT) with  $\varphi = 1.35\pi, \delta = 1.2$ .

## II. EXPERIMENTAL SETUP

As shown in Fig. 1(a), our system consists of a 3D copper (Cu) cavity with an inner dimension of  $40 \times 20 \times 8 \text{ mm}^3$  and an yttrium iron garnet (YIG) sphere with a 0.3 mm diameter. A static magnetic field  $H_{\text{static}}$  applied in the  $xy$  plane tunes the magnon frequency. The simulated cavity mode magnetic field distribution is shown at the bottom of Fig. 1(a), where the arrows and colors indicate the cavity mode magnetic field directions and amplitudes. The YIG sphere is placed near the magnetic field antinode of the cavity  $TE_{101}$  mode. The magnetic components (along the  $z$  axis) of the microwave field at this antinode is perpendicular to the static magnetic bias field.

Here, we are only interested in the low excited states of the Kittel mode, in which all the spins

precess in phase. Under the Holstein-Primakoff transformation, such collective spin mode can be simplified to a harmonic resonator, which introduces the magnon mode. In our setup, the cavity mode couples to the magnon mode with coupling strength  $g = 7.6$  MHz, which is larger than the magnon decay rate  $\kappa_m = 1.2$  MHz, but smaller than the cavity decay rate  $\kappa_c = 113.9$  MHz.

In our experiment, a beam of coherent microwave is emitted from port 1 of a vector network analyzer (VNA) and then divided through a splitter into two beams, one of which is used to probe the cavity (probe tone) and another beam is used to pump the magnon (pump tone) by incorporating the coupling loop technique, which is schematically shown in the dashed rectangle of Fig. 1(a). The probe tone is injected into the cavity through antenna 1, which induces the cavity external decay rate  $\kappa_{c1} = 21.8$  MHz. The pump tone is injected through antenna 2, which introduces the magnon external decay rate  $\kappa_{m1} = 0.6$  MHz. Note that the phase  $\varphi_c = 0$  and amplitude  $\varepsilon_c$  of the probe tone are fixed (i.e., working as a reference), and the phase  $\varphi$  and amplitude  $\varepsilon_m$  of the magnon pump tone are tunable and controlled by an arbitrary wave generator (AWG) with an in-phase/quadrature mixer (I/Q mixer).

### III. MODEL

By considering the cavity-magnon coupling, as well as the pump and probe tones [model in Fig. 1(b)], the system Hamiltonian becomes

$$\begin{aligned}
H = & \omega_c a^\dagger a + \omega_m m^\dagger m + g(a^\dagger m + m^\dagger a) \\
& + i\sqrt{2\eta_c \kappa_c} \varepsilon_c (a^\dagger e^{-i\omega_p t} - a e^{i\omega_p t}) \\
& + i\sqrt{2\eta_m \kappa_m} \varepsilon_m (m^\dagger e^{-i\omega_p t - i\varphi} - m e^{i\omega_p t + i\varphi}).
\end{aligned} \tag{1}$$

Here,  $a^\dagger$  ( $a$ ) and  $m^\dagger$  ( $m$ ) are the creation (annihilation) operators for the microwave photon and the magnon at frequencies  $\omega_c$  and  $\omega_m$ , respectively, and we have chosen units with  $\hbar = 1$ . The magnon frequency  $\omega_m$  linearly depends on the static bias field  $H_{\text{static}}$  and is tunable within the range of a few hundred MHz to about 45 GHz;  $\varepsilon_c$  ( $\varepsilon_m$ ) is the microwave amplitude applied to drive the cavity (magnon). Here, we introduce the coupling parameter

$$\eta_c = \kappa_{c1}/\kappa_c, \tag{2}$$

$$\eta_m = \kappa_{m1}/\kappa_m \tag{3}$$

to classify the working regime of the cavity (the magnon). The parameter  $\eta_c$  ( $\eta_m$ ) classifies three working regimes for the cavity (magnon) into three types: over-coupling regime for  $\eta_c$  ( $\eta_m$ )  $>$   $1/2$ ; critical-coupling regime for  $\eta_c$  ( $\eta_m$ )  $= 1/2$ ; and under-coupling regime for  $\eta_c$  ( $\eta_m$ )  $<$   $1/2$ . In our experiment, the cavity works in the under-coupling regime ( $\eta_c < 1/2$ ) and the magnon works in the critical coupling regime ( $\eta_m = 1/2$ ).

Experimentally, the reflection signal from the cavity is circulated and then transferred to port 2 of the VNA to carry out the spectroscopic measurement, which corresponds to the steady-state solution of the Hamiltonian Eq. (1). The transmission coefficient  $t_p$  of the probe field is defined as the ratio of the output field amplitude  $\varepsilon_{\text{out}}$  to the input field amplitude  $\varepsilon_c$  at the probe frequency  $\omega_p$ :  $t_p = \varepsilon_{\text{out}}/\varepsilon_c$ . With the input-output boundary condition,

$$\varepsilon_{\text{out}} = \varepsilon_c - \sqrt{2\eta_c\kappa_c} \langle a \rangle, \quad (4)$$

we can solve the transmission coefficient  $t_p$  of the probe field as [73]

$$t_p = t_{\text{probe}} + t_{\text{pump}}, \quad (5)$$

with

$$t_{\text{probe}} = 1 - \frac{2\eta_c\kappa_c (i\Delta_p + \kappa_m)}{(i\Delta_p + \kappa_c)(i\Delta_p + \kappa_m) + g^2}, \quad (6)$$

$$t_{\text{pump}} = \frac{ig\sqrt{2\eta_c\kappa_c}\sqrt{2\eta_m\kappa_m}\delta e^{-i\varphi}}{(i\Delta_p + \kappa_c)(i\Delta_p + \kappa_m) + g^2}. \quad (7)$$

Here  $\Delta_p$  is the detuning between the probe frequency  $\omega_p$  and either the cavity resonant frequency  $\omega_c$  or the magnon frequency  $\omega_m$ . In our experiment, the cavity is resonant with the cavity, i.e.,

$$\Delta_p = \omega_c - \omega_p = \omega_m - \omega_p; \quad (8)$$

and

$$\delta = \varepsilon_m/\varepsilon_c \quad (9)$$

is the pump-probe amplitude ratio. Equation (5) clear shows that the transmission coefficient can be divided into two parts:

1.  $t_{\text{probe}}$  in Eq. (6), the contribution from the cavity probe tone, represents the traditional pathway-induced interference;
2.  $t_{\text{pump}}$  in Eq. (7), the contribution from the magnon pump field, affects the interference and modifies the transmission of the probe field.



As shown in Fig. 1(c), there exist two transition pathways for the cavity: the probe-tone-induced direct excitation, and the photons transferred from magnon excitations. When the cavity decay rate (analog to broadband of states) is much larger than the magnon decay rate (analog to a narrow discrete quantum state in other quantum systems), Fano-interference happens and has been successfully used to explain the MIT and MI-ABS phenomenon in cavity magnon-polariton systems [57]. Besides pathways-induced interference, the steered phase  $\varphi$  of the wave provides another useful way to generate and especially control the interferences, as shown in Fig. 1(d).

We emphasize that in this paper we focus on *how the phase difference  $\varphi$  and pump-probe ratio  $\delta = \varepsilon_m/\varepsilon_c$  affect the interference, and we explore its potential applications, such as controllable field transmission and in-situ switchable slow-fast light*. The  $S_{11}$  spectrum and group-time delay measurement are carried out on the VNA and then fitted by

$$T = |t_p| \quad (10)$$

and

$$\tau = -\frac{\partial [\arg(t_p)]}{\partial \Delta_p}, \quad (11)$$

respectively.

#### IV. PHASE INDUCED INTERFERENCE AND CONTROLLABLE MICROWAVE FIELD TRANSPORT

We first study how the phase of the magnon pump tone affects the transmission of the cavity probe field. In Fig. 2 (a), we present experimental results of the transmission, when the pump-probe ratio is  $\delta = \varepsilon_m/\varepsilon_c = 1.7$ . In this setup, the phase  $\varphi$  is continuously increased from 0 to  $2\pi$  using an I/Q mixer, and is shown in the  $x$ -axis of Fig. 2 (a). Then we conduct the  $S_{11}$  measurements and the recorded spectra are plotted versus the detuning frequencies  $\Delta_p$ . The colors represent the relative steady-state output amplitude (in dB units) at different frequency and pump-probe ratios. Figure 2(a) shows that the interference mainly happens around  $\Delta_p = 0$  and can be controlled in-situ by changing the phase  $\varphi$ .

As shown in Fig. 2(b), where  $\varphi$  is set to  $0.35\pi$ , destructive interference happens and an obvious dip appears around  $\Delta_p = 0$ . This behavior can be regarded as magnon-induced-absorption

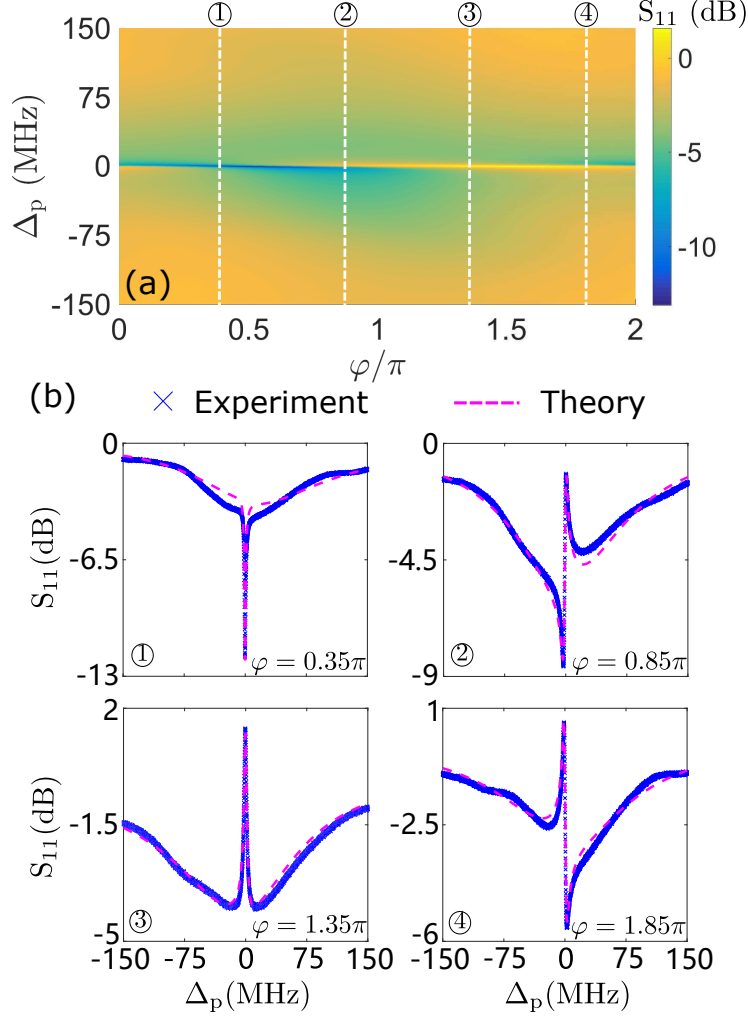


FIG. 2.  $S_{11}$  spectrum versus relative phase difference  $\varphi$ . (a) Measured transmission spectrum  $S_{11}$  versus phase  $\varphi$  and detuning  $\Delta_p$ . The colors indicate the transmitted amplitudes in dB units. (b) Measured output spectrum  $S_{11}$  with phases: ①  $\varphi = 0.35\pi$ , ②  $\varphi = 0.85\pi$ , ③  $\varphi = 1.35\pi$ , and ④  $\varphi = 1.85\pi$ . Here, the pump-probe amplitude ratio is fixed at  $\delta = 1.7$ . Red-solid lines are the corresponding theoretical results.

(MI-ABS). However, if we set  $\varphi = 1.35\pi$ , constructive interference happens and an obvious amplification window appears around  $\Delta_p = 0$ . This behavior can be described as magnon-induced-amplification (MI-AMP). When  $\varphi$  is set to  $0.85\pi$  or  $1.85\pi$ , sharp and Fano-interference-like asymmetry spectra are observed even when the cavity and magnon are exactly resonant.

Although the interference originates from the coherent cavity-magnon coupling, Fig. 2 clearly shows that *the phase  $\varphi$  plays a key role in realizing an in-situ tunable and controllable interference (e.g., constructive or destructive interference)*, which can be further engineered to control the probe field transmission. Note that in previous studies [57] MI-ABS was only observed in the

cavity over-coupling regime (i.e.,  $\eta_a > 1/2$ ) and MIT was only observed in the cavity under-coupling regime (i.e.,  $\eta_a < 1/2$ ). In contrast to this, here we realize a phase-dependent and switchable MI-ABS and MIT, *as well as* MI-AMP in a fixed under-coupling regime ( $\eta_c = 0.19$  in our experiment). We emphasize that the destructive interference-induced MI-ABS is a unique result of phase modulation. The observed asymmetric Fano-lineshapes could be useful to realize Fano-interference sensors or precise measurements, using the magnon pump method realized in our work.

## V. AMPLITUDE RATIO OPTIMIZED MAGNON-INDUCED-ABSORPTION

Recall the magnon pump transmission coefficient  $t_{\text{pump}}$  in Eq. (7). There, the phase  $\varphi$  determines the type of interference, e.g., constructive or destructive. However, the pump-probe ratio  $\delta = \varepsilon_m/\varepsilon_c$  also affects the degree of interference, and thus can be used to control the probe field transmissions  $t_p$ . As shown in Fig. 3(a), a color map is used to present the experiment results. Along the  $x$ -axis, the amplitude ratio  $\delta$  is continuously increased from 0 to 6.5, by changing the overall voltage amplitude applied to the I and Q ports of an I/Q mixer. Then we conduct the  $S_{11}$  measurements and the steady-state output field amplitudes are plotted versus the frequency detuning  $\Delta_p$ . The colors in Fig. 3(a) represent the relative strength of the steady-state output field (in dB units) at a different frequency. Here, the chosen phase  $\varphi = 0.35\pi$  results in MITs when  $\delta < 0.32$ , while MI-ABSs dominate the output response in the regime  $\delta > 0.32$ . We then study how the pump-probe ratio  $\delta$  affects the central absorption window of the  $S_{11}$  spectra.

Figure 3(a) shows that interference occurs around  $\Delta_p = 0$  and is in-situ controlled by changing the pump-probe ratio  $\delta$ . The center blue-colored area represents an ideal absorption (transmission  $T < 0.01$ ) of the probe field.

Figure 3 (b) shows the extreme values of the transmission coefficients around  $\Delta_p = 0$  versus the pump-probe ratio  $\delta$ . In the yellow area, we find the local maximum values of the MITs, and the local minimum values are found for MI-ABSs in the blue area. An obvious dip appears around  $\delta = 3$  and the minimum transmission value is less than 1% (voltage amplitude ratio), which corresponds to an optimized and ideal probe field absorption.

Figure 3(c) shows the evolution process from MIT to MI-ABS by gradually increasing the pump-probe ratio  $\delta$ . When  $\delta = 0$ , corresponding to case ① of Fig. 3(c), our scheme recovers the traditional MIT case when no magnon pump is applied. When the magnon pump is introduced

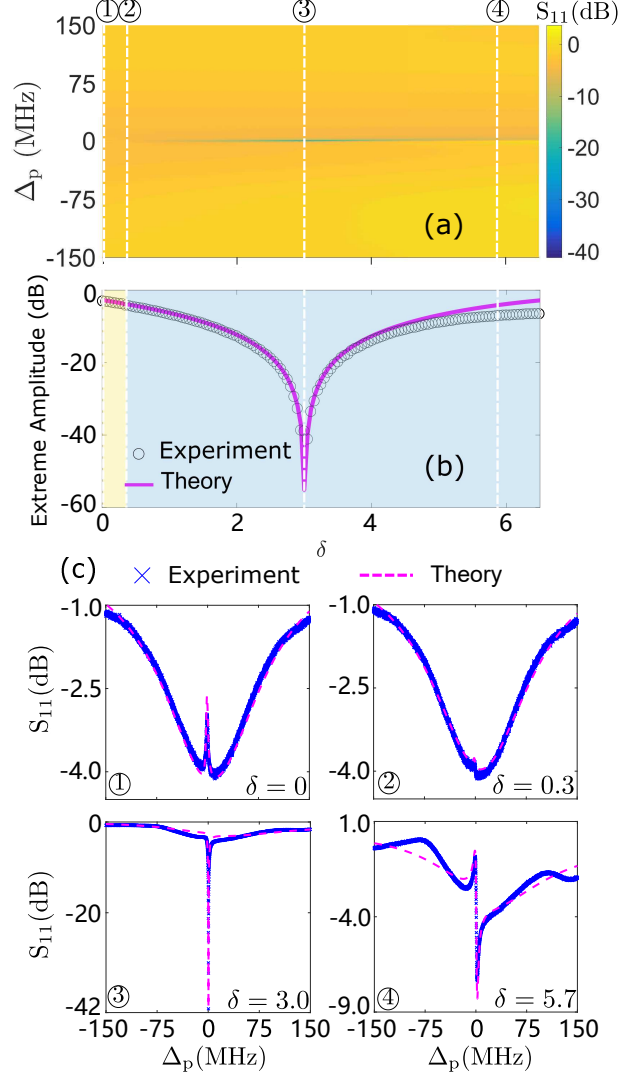


FIG. 3. Measured transmission spectrum  $S_{11}$  versus pump-probe amplitude ratio  $\delta$  with phase fixed at  $\varphi = 0.35\pi$ . (a) Measured output spectrum versus amplitude ratio  $\delta$  and detuning  $\Delta_p$ . The colors indicate transmitted power in dBs. (b) The extreme values of the  $S_{11}$  transmission spectra of the output field versus the amplitude ratio parameter  $\delta$ . In the light-yellow (light-blue) regime, the extreme values represent the maximum (minimum) transmission amplitudes of the peaks (dips) around  $\Delta_p = 0$ . (c) Measured transmission spectrum  $S_{11}$  with amplitude ratio: ①  $\delta = 0$ , ②  $\delta = 0.3$ , ③  $\delta = 3.0$ , and ④  $\delta = 5.7$ . Red-solid lines are the corresponding theoretical results.

and its strength is continuously increased, the transparency window disappears and is replaced by an obvious absorption dip, as shown in cases ② and ③ of Fig. 3(c). With an even larger pump-probe ratio, the MI-ABS dips become asymmetry gradually, such as the spectrum in the case ④ of Fig. 3(c). Comparing with other results in Fig. 3(c), we can find that the experimental data

do not fit so well with the theory in the case ④ of Fig. 3(c). This is induced by the additional cavity-antenna 2 coupling. Due to the existence of this tiny coupling, the magnon pump signal also pumps the cavity. With a modest magnon pump strength, the additional cavity pump does not affect the system seriously, so that the theory fits the experiment data well. With a relatively strong magnon pump, the side effects of the additional cavity pump become larger, though it does not change the line shape. Therefore, the experiment data and theory do not fit so well when the magnon pump is relatively strong [73]. Similar phenomena can also be observed in the case ④ of Fig. 4(c).

We emphasize one main result of this paper: *the absorption dips appear with an under-coupling coefficient of  $\eta_a = 0.19$  in our experiment. However, absorptions only happen in the over-coupling regime in traditional cases.* Moreover, Figs. 3(a) and (c) show that  $\delta$  can be used to switch the transmission behavior from the magnon-induced transparency to the magnon-induced absorption. Note that the type of interference, destructive interference or constructive interference, depends on the value of the phase  $\varphi$ . However, the interference intensity is determined and optimized by the pump-probe ratio  $\delta$ . As shown in Fig. 3(c), the dip of  $S_{11}$  is 42 dB lower than the baseline. The dip amplitude is quite close to zero, which indicates that a zero reflection is generated by the destructive interference.

## VI. AMPLITUDE RATIO OPTIMIZED MAGNON-INDUCED-AMPLIFICATION

We now study how the amplitude ratio of  $\delta = \varepsilon_m/\varepsilon_c$  affects the MI-AMP. In this case, the phase is fixed at  $\varphi = 1.35\pi$ , where constructive interference dominates the transmission of the output field. As shown in Fig. 4(a), a color map is used to present the measurement results. Along the  $x$ -axis, the pump-probe ratio  $\delta$  is continuously increased from 0 to 6.5. Then we conduct the  $S_{11}$  measurement, and the steady-state transmission spectra are plotted versus the frequency detuning parameter  $\Delta_p$ . The colors in Fig. 4(a) represent the transmission amplitudes of the steady-state output field (in dB units) at different frequencies. We then study how the amplitude  $\delta$  affects the center amplification window of the  $S_{11}$  spectra.

Figure 4(a) clearly shows that constructive interference happens around  $\Delta_p = 0$  and are in-situ controlled by changing the pump-probe ratio  $\delta$ . Magnon-pump induced constructive interference happens when the probe field is nearly resonant with the cavity (also the magnon), and amplification windows appear. Around  $\Delta_p = 0$ , the color changes from light-blue to orange when the

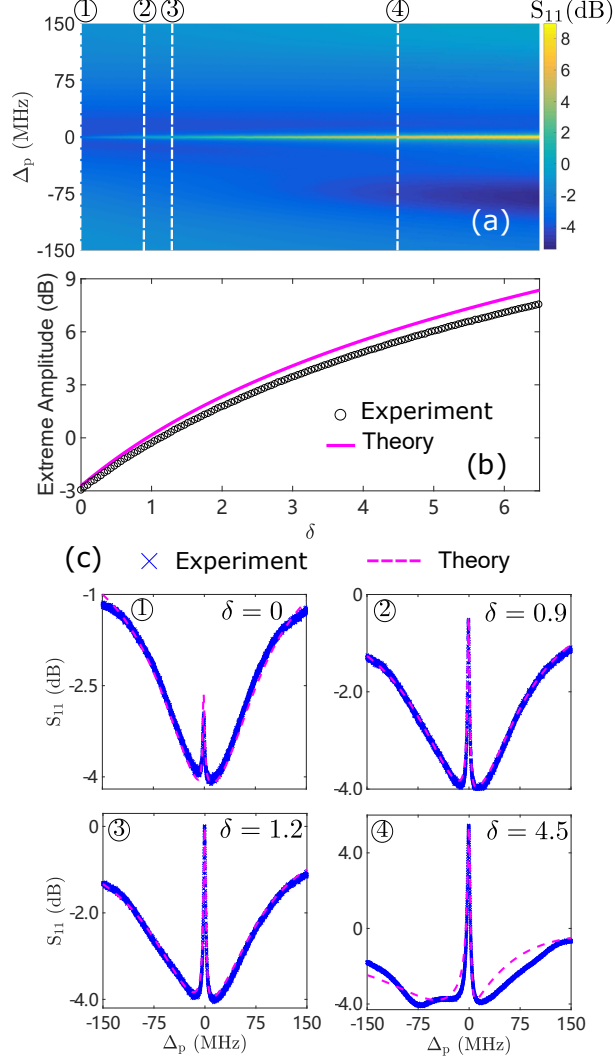


FIG. 4. Measured transmission spectrum  $S_{11}$  versus pump-probe amplitude ratio  $\delta = \varepsilon_m/\varepsilon_c$  with phase fixed at  $\varphi = 1.35\pi$ . (a) Measured output spectra  $S_{11}$  versus amplitude ratio  $\delta$  and frequency detuning  $\Delta_p$ . The colors indicate the transmitted amplitude in dB units. (b) The extreme values of the  $S_{11}$  transmission spectra of the output field versus the amplitude ratio parameter  $\delta$ . The extreme values represent the maximum transmission amplitude of the peaks around  $\Delta_p = 0$ . (c) Measured transmission spectra  $S_{11}$  with amplitude ratios: ①  $\delta = 0$ , ②  $\delta = 0.9$ , ③  $\delta = 1.2$ , and ④  $\delta = 4.5$ . The red-solid lines are the corresponding theoretical results.

pump-probe ratio  $\delta$  increases from 0 to 6.5. This indicates that the higher amplification can be obtained with a larger pump-probe ratio  $\delta$ .

Figure 4(b) shows how the peak values in the amplification window change versus the amplitude ratio  $\delta$ . The amplification coefficient is monotonously dependent on the increment of the

pump-probe ratio  $\delta$ . Although the maximum pump-probe ratio is  $\delta = 6.5$  in our experiment, we emphasize that a higher transmission gain can be obtained using a larger pump power.

Figure 4(c) clearly shows the evolution of the transmission spectrum from MIT to MI-AMP when we gradually increase the pump-probe ratio  $\delta$ . When  $\delta < 1.2$ , an obvious transparency window appears. When  $\delta = 1.2$ , the peak value of the transparency window equals the value of the baseline, showing the ideal MIT phenomenon. Further increasing the pump strength, we can observe MI-AMP. When  $\delta = 4.5$ , an obvious amplification window appears, producing MI-AMP.

Note that the phase is fixed at  $\varphi = 1.35\pi$  to produce constructive interference. When the amplitude ratio is set to  $\delta = 0$ , i.e., no magnon pump, our scheme also recovers the traditional case without a magnon pump and only MIT is observed. This result is, of course, the same as case ① in Fig. 3(c). We point out another main result that *the pump-probe ratio  $\delta$  can be used to realize and control the magnon-induced amplifications*. Figures 4(a) and (c) show that  $\delta$  can be used to switch the system response from MIT to MI-AMP. Note that the interference type, such as constructive interference discussed here, depends on the value of the phase  $\varphi$ ; however, the interference intensity is determined and optimized by the pump-probe ratio  $\delta$ .

## VII. SWITCHABLE FAST- AND SLOW-LIGHT BASED ON THE PHASE AND AMPLITUDE RATIO

The group delay or advance of light always accompanies electromagnetic-induced-transparency (EIT) or electromagnetic-induced-absorption (EI-ABS). In this experiment, we show that the group delay (slow light) and group advance (fast light) can also be realized in our cavity magnon-polariton system. Similar to the discussions above, the phase  $\varphi$  is the key parameter that determines the interference type, e.g., destructive or constructive. Therefore, the phase  $\varphi$  provides a tunable and in-situ-switched group advance or delay of the probe field. The extreme values of the delay time are measured and presented in Fig. 5, choosing the same phases  $\varphi = 0.35\pi$  and  $\varphi = 1.35\pi$ , which were also used in Figs. 3 and 4, respectively.

In Fig. 5(a), the phase is set to  $\varphi = 0.35\pi$ . When we increase the pump-probe ratio  $\delta$ , a longer advance time is achieved, but immediately changes to time delay when  $\delta > 3.0$ . Further increasing  $\delta$  reduces the delay time. In Fig. 5(c), we present the phase of transmission signals at different probe frequencies with  $\delta = 2.7$  (case ①) and  $\delta = 3.3$  (case ②). The phase changes drastically around  $\Delta_p = 0$  with opposite directions. The drastic changes of the phase result in a long advance

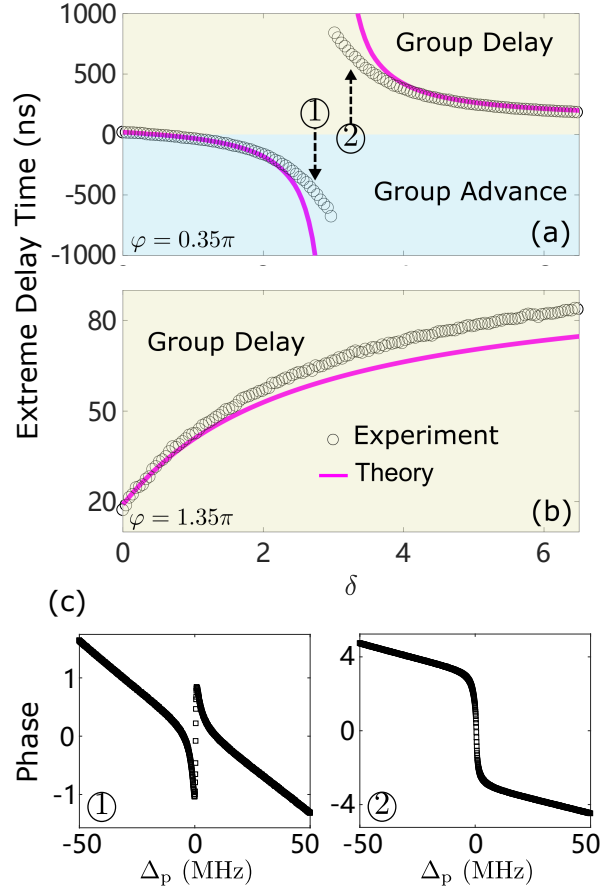


FIG. 5. Measured time delay versus pump-probe ratio  $\delta$  for the phase  $\varphi = 0.35\pi$  (a); and  $\varphi = 1.35\pi$  (b). Light yellow area indicates the group-delay regime, and the light blue area indicates the group-advance regime. (c) Measured unwrapped phase versus frequency detuning  $\Delta_p$  with  $\delta = 2.7$  (point ① in (a)) and  $\delta = 3.3$  (point ② in (a)) for  $\varphi = 0.35\pi$ .

or delay time, while the phase change direction reversal results in the sharp transition from time advance to time delay. Accompanying the sharp transition in Fig. 5(a), we observe the longest either delay or advance times. Therefore, the pump-probe ratio  $\delta$  allows to *optimize and switch the probe microwave from fast to slow light, or inversely*. Comparing the abrupt transition in Fig. 5(a) with the zero reflection discussed in Section V, we find that the delay time abrupt transition and the zero reflection occur at the same parameter setup. It is notable that the discontinuity and abrupt transition are always accompanied by the zero reflection in coupled resonator systems. In Fig. 5(b), we set the phase to  $\varphi = 1.35\pi$  and mainly observe constructive interference. In this case, the time delay monotonously increases with the pump-probe ratio  $\delta$ . Note that the pump-probe ratio used in Fig. 5(b) is not its limitation, therefore longer delay times can be achieved by further increasing



TABLE I. Summary of magnon-induced-transparency (MIT), -absorption (MI-ABS), -amplification (MI-AMP) and Fano resonance observed experimentally for different values in parameter space.

		Amplitude Ratio $\delta$					
		0 - 0.3	0.3	0.3 - 1.2	1.2	1.2 - 3.0	> 3.0
Phase $\varphi$	$0.35\pi$	MIT	NULL	MI-ABS	MI-ABS	MI-ABS	Fano
	$1.35\pi$	MIT	MIT	MIT	MIT (perfect)	MI-AMP	MI-AMP

$\delta$ .

Figure 5 also shows that when the amplitude ratio  $\delta \leq 3.0$ , the delay time is a negative number which corresponds to fast-light with  $\varphi = 0.35\pi$ , and the positive delay time corresponds to slow-light with  $\varphi = 1.35\pi$ . Thus the phase parameter  $\varphi$  can also be used to switch fast and slow light. When  $\delta = 0$ , i.e., no magnon pump, our scheme recovers the traditional MIT and only a 16 ns delay time is achieved. By applying the magnon pump and optimizing  $\varphi$  and  $\delta$ , *the time delay, as well as advance, can be enhanced by nearly two orders of magnitude compared with the case without magnon pump.* For our scheme, the pump-probe amplitude ratio and phase difference mediated path interference can result in the zero reflection, which is accompanied with a delay time abrupt transition. In our experiment, Fig. 5(a) clearly shows such abrupt transition and greatly enhanced fast-slow light around this point. We can find that the experimental data deviates from the theoretical result around the abrupt transition. This is mainly induced by the imperfect system setups, such as limited output precision of AWG, imperfectness of the IQ mixer and unstable magnon frequency [73].

## VIII. CONCLUSION

We experimentally study how the magnon pump affects the probe field transmission, and the observed results are summarized in Table. I. Two parameters, the relative phase  $\varphi$  and the pump-probe ratio  $\delta$  between pump and probe tones, are studied in detail. The main results of this work are as follows:

- the unconventional MI-ABS of the transmitted microwave field is observed with the cavity in the under-coupling condition;

- the magnon pump induced amplification (MI-AMP) phenomena is realized in our experiment;
- asymmetric Fano-resonance-like spectra are observed even when the cavity is resonant with the magnon;
- by tuning the phase of the magnon pump, we can easily switch between MIT, MI-ABS and MI-AMP;
- by tuning the pump and probe ratio, the MI-ABS and MI-AMP can be further optimized, accompanied by greatly enhanced advanced or slow light by nearly two orders of magnitude;
- the tunable phase and amplitude ratio can lead to the zero reflection of the transmitted light and abrupt fast-slow light transitions.;
- both the  $\varphi$  and  $\delta$  can be used to carry out the in-situ switch of fast and slow light.

Our results confirm that direct magnon pumping through the coupling loops provides a versatile route to achieve controllable signal transmission, storage, and communication, which can be further expanded to coherent state processing in the quantum regime. Furthermore, by exploiting multi-YIG spheres or multi-magnon modes systems, the amplification or absorption bandwidth can be increased, resulting in a broadband coherent signal store device. The sharp peak and asymmetric Fano-lineshape indicate that our platform has great potential in the application of high-precision measurement of weak microwave fields [74, 75]. Our two-tone pump scheme and phase-tunable interference can also be accomplished in other coupled-resonator systems, such as optomechanical resonators, which explores effects of mechanical pump on light transmission [76–84], and even in circuit-QED systems, in which controlling photon transmission through a circuit-QED system [85–88].

After this work was completed, we become aware of a study presenting an infinite group delay and abrupt transition in a magnonic non-Hermitian system [33].

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