Probing the Magnon-Magnon Coupling using Combinatorial Magneto-Optical Kerr and Faraday Effects

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Coherent conversion between microwave and optical photons are among the key challenges for long-distance coherent quantum information transfer. Recent advances in magnon hybrid systems provide new opportunities for coherent manipulation of microwave-optical transduction, where a facile and phase-coherent detection of the magnon dynamics in the context of magnon-photon and magnon-magnon couplings is required. Here, we demonstrate the magnetically-induced transparency (MIT) effect in Y2Fe5O12 (YIG)/Permalloy (Py) coupled bilayers. The measurement is achieved via stroboscopic detection of the coupled magnetization dynamics using a single wavelength that simultaneously probes the magneto-optical Kerr and Faraday effects of Py and YIG, respectively. Clear features of the MIT effect are evident from the deeply modulated ferromagnetic resonance of Py due to the perpendicular-standing-spin-wave of YIG. We develop a phenomenological model that nicely reproduces the observed MIT effect including the induced amplitude and phase evolution caused by the magnon-magnon coupling. Our work offers a new route towards studying phase-resolved spin dynamics and hybrid magnonic systems for future quantum manipulation of microwave and light.

INTRODUCTION

Hybrid magnonic systems are becoming rising contenders for coherent information processing [1–3], owing to their capability of connecting distinct physical platforms in quantum systems as well as the rich emerging physics for new functionalities [4–21]. Magnons have been demonstrated to efficiently couple to cavity quantum electrodynamics systems including superconducting resonators and qubits [4–8]; magnonic systems are therefore well-positioned for the next advances in quantum information. In addition, recent studies also revealed the potential of magnonic systems for microwave-optical transduction [22–25], which are promising for combining quantum information, sensing, and transduction. This is often achieved by making use of the magneto-optical Faraday effect to couple light and microwave with magnons [26]. Experimentally, the whisper gallery modes of YIG spheres have been utilized to provide a mode overlap between the microwave and light excitations. However, for on-chip integration and device applications, it is desirable to work with thin-film magnetic transducers towards complex quantum networks, which bulk ferromagnets are not suitable for.

To fully leverage the hybrid coupling phenomena with magnons, strong and tunable couplings between two magnonic systems have attracted considerable interests recently [27–30]. They can be considered as hosting hybrid magnonic modes in a “magnonic cavity” as opposed to microwave photonic cavity in cavity-magnon polaritons (CMPs) [1–3], which allows excitations of forbidden modes and high group velocity of spin waves owing to the state-of-the-art magnon bandgap engineering capabilities [28, 31]. The detuning of the two magnonic systems can be easily engineered by the thickness of the thin films, which set the wavenumbers and the corresponding exchange field. Furthermore, in such strongly coupled magnetic heterostructures, both magneto-optical Kerr and Faraday effects can be utilized for light modulation, in terms of light reflection by metals and/or transmission in insulators, respectively. In this architecture, the freedom of lateral dimensions is maintained for device fabrication and large-scale, on-chip integration.

To date, both magnon-photon and magnon-magnon couplings are predominantly investigated by the cavity ferromagnetic resonance (FMR) spectroscopy, i.e. microwave transmission and/or reflection measurements, typically involving a vector-network analyzer (VNA) or a microwave diode [4–11, 27–30]. Strong magnon-magnon couplings have been observed in yttrium iron garnet (Y2Fe5O12, YIG) coupled with ferromagnetic (FM) metals, where exchange spin waves were excited by a combined action of exchange, dampinglike, and/or fieldlike torques that are localized at the interfaces [27–30].

In this work, we investigate the magnon-magnon coupling in YIG/Permalloy (Py) bilayers by a phase-resolved, heterodyne optical detection method. We reveal the magnon coupling in the regime exhibiting the
FIG. 1. The dynamic Kerr and Faraday response at magnetic resonances. (a) Schematic illustration of the experimental setup. Modulated and linearly-polarized 1550-nm light enter the sample at a polarization angle (1); dynamic Faraday effect of the YIG causes the polarization to rotate (2); dynamic Kerr effect of the Py causes polarization to further rotate (3); the reflected light, upon the returning path, picks up again the Faraday effect and causes the polarization to further rotate (4), before entering light detection and analysis. The applied dc magnetic field is parallel to the ground-signal-ground (G-S-G) lines of the CPW. (b) Example PSSW spectra measured at 5.85 GHz, showing the individual optical signals, in-phase X (top) and quadrature Y (middle), and the total amplitude, $\sqrt{X^2 + Y^2}$ (bottom). (c) Plotting and the fitting of the observed PSSW modes versus the resonance fields.

magnetically-induced transparency (MIT) effect, akin to a “spin-wave induced suppression of FMR”. This effect is the magnetic analogy of electromagnetically induced transparency, which is a benchmark coherent phenomena observed in many hybrid systems. In this regime, the coupling between the two systems exceeds the dissipation of one mode but not the other, and, under such a condition, the magnon-magnon coupling leads to an abrupt suppression of the microwave transmission at a certain frequency range. In other words, a transparency window, whose linewidth is determined by the low-loss mode, can be observed in the broad resonance of the other lossy mode. Such “resonant transparency” is controlled by an external magnetic field. Our measurement is achieved via detecting the coupled magnetization dynamics of the insulating and metallic FMs using a single 1550-nm telecommunication wavelength. Unlike the ultrafast optical pump-probes [20], the method herein is a continue-wave (cw), stroboscopic technique in which the 1550-nm laser light is modulated at the FMR frequencies (in GHz range) simultaneously with the sample’s excitation. This feature makes the method effectively an optical “lock-in” type measurement, akin to the electrical lock-in detection [32][33]. In addition, by using one single light wavelength, i.e. at 1550-nm, it simultaneously probes the magneto-optical Kerr and Faraday effects from the Py and YIG, respectively. This makes our method particularly advantageous in the context of studying magnon-magnon coupling of hybrid insulator-metal FM systems, since it avoids the complication of using multiple wavelengths in the visible range for detecting respective metals and insulators. Finally, the phase information between the Py and YIG FMRs, as well as the YIG perpendicular standing spin waves (PSSWs) can be obtained by simultaneously analyzing both the Kerr and Faraday responses.

SAMPLES AND MEASUREMENTS

The commercial YIG films (from MTI Corporation) used in this work are 3-µm thick, single-sided grown on double-side-polished Gd$_3$Ga$_5$O$_{12}$ (GGG) substrates via liquid phase epitaxy (LPE). The Py films ($t_{Py} = 10$ nm and 30 nm) were subsequently deposited on the YIG films using magnetron sputtering following earlier recipes [30]. To ensure the strong coupling, we used in situ Ar gas rf-bias cleaning for 3 minutes, to clean the YIG surface before depositing the Py layer. Reference samples of YIG/SiO$_2$(3-nm)/Py(10-nm) YIG/Cu(3-nm)/Py(10-nm) were also prepared at the same growth condition.

Figure 1(a) illustrates the measurement configura-
tion. The modulated and linearly-polarized 1550-nm light passes through the transparent GGG substrates and detects the dynamic Faraday and Kerr signals upon their FMR excitation. As the light travels through the YIG bulk, the dynamic Faraday rotation due to the YIG FMR is picked up. Similarly, the dynamic Kerr rotation caused by the Py FMR is then picked up, when the light reaches the Py layer. The Py layer also serves as a mirror and reflects the laser light. Upon reflection, the dynamic Faraday effect from the YIG is picked up again, making the effective YIG thickness 6-μm, i.e. twice the film thickness. It should be noted that the Faraday rotations for the incoming and returning light add up as opposed to cancel, due to the inversion of both the chirality of the Faraday rotation and the projection of the perpendicular magnetization of YIG along the wavenumber direction, whose mechanism is akin to a commercial “Faraday rotator” often encountered in fiber optics.

The YIG/Py samples are chip-flipped on a coplanar waveguide (CPW) for microwave excitation and optical detection, as depicted in Fig. 1(a). An in-plane magnetic field, \( H \), along the \( y \)-direction saturates both the YIG and Py magnetizations. We scan the frequency (from 4 to 8 GHz) and the magnetic field, and then measure the optical responses using a lock-in amplifier’s in-phase \( X \) and quadrature \( Y \) channels as well as the microwave transmission \( (s_{21}) \) using a microwave diode. A detailed description of the measurement setup is in the Supplemental Materials (SM), Figure S-1.

RESULTS AND DISCUSSIONS

Optical detection of the FMRs and PSSWs

Figure 1(b) is an example trace of the optical rectification signal of the 10-nm-Py sample measured at 5.85 GHz, which shows the representative features of the detected signals and our system’s detecting capability. The complete fine-scan datasets are included in the SM, Fig S-2. The optical signals with the phase information are obtained by the lock-in’s in-phase \( X \) and quadrature \( Y \), following: \( X \propto m_zP_0 \cos (\phi_L - \phi_m) \) and \( Y \propto -m_zP_0 \sin (\phi_L - \phi_m) \), where \( m_z \) is the \( z \)-component of the dynamic magnetization (for YIG or Py), \( P_0 \) is the laser light intensity, \( \phi_L \) is the phase accumulated due to optical path length, and \( \phi_m \) is the magnetization phase, which includes contributions due to \( \phi_{MW} \) (the microwave path), \( \phi_h \) (possible phase delay between waveguide current and effective driving field, \( h_{rf} \)), and \( \phi_x \) (the phase of the magnetic response to the field) [32]. The \( \phi_L \) and \( \phi_{MW} \) are dependent on the optical and electrical paths, respectively, and the resulted path difference can be tuned by the fiber and microwave-cable lengths or using a microwave phase shifter [33]. It is noted that the fiber-optic system makes it particularly convenient to engineer the path difference by simply adding optical fibers at desirable lengths. The total amplitude is calculated by \( \sqrt{X^2 + Y^2} \) (bottom panel), which resembles the conventional microwave diode or the VNA measurements \( (s_{21}) [37-40] \).

In our measurements, the optical signals should have negligible effect from \( \phi_L, \phi_{MW}, \) and \( \phi_h \), which are solely geometrical. The YIG FMR at \( \sim 1.3 \) kOe is the signal from the Faraday effect due to the uniform YIG magnetization precession, detected as: \( X_{YIG} \propto m_z(YIG)P_0 \cos [\phi_L - \phi_{MW} - \phi_h - \phi_x(YIG)] \), and \( Y_{YIG} \propto -m_z(YIG)P_0 \sin [\phi_L - \phi_{MW} - \phi_h - \phi_x(YIG)] \). The Py FMR at \( \sim 0.6 \) kOe, on the other hand, is due to the Kerr effect, detected as: \( X_{Py} \propto m_z(Py)P_0 \cos [\phi_L - \phi_{MW} - \phi_h - \phi_x(Py)] \), and \( Y_{Py} \propto -m_z(Py)P_0 \sin [\phi_L - \phi_{MW} - \phi_h - \phi_x(Py)] \). In addition, the Py FMR is modulated by the YIG PSSWs’ spin-wave resonances (SWRs), forming the hybrid magnon modes, resulting in the observed MIT effect. The YIG PSSW signals near the Py FMR regime are much stronger than the off-resonance regime, which indicates a resonantly enhanced magnetization dynamics due to the coupling between the Py and YIG. In addition, the strong magnon-magnon coupling is also implied from the detecting mechanism of the PSSWs: due to the standing-wave nature, the Faraday optical response cancels out inside the YIG bulk except at the boundaries. The observed PSSW signals are thus dominated by the Py-YIG hybrid Kerr resonance at the interface, influenced by the magnon-magnon coupling with the bulk YIG PSSW modes.

The FMR modes corresponding to the spatially uniform magnetization precession are described by the Kittel formula: \( \omega^2/\gamma^2 = \mu_0^2H_{FMR}(H_{FMR} + M_s) \), where \( \omega \) is the mode frequency, \( \gamma/2\pi = (g_\text{eff}/2)/28 \) GHz/T is the gyromagnetic ratio, \( H_{FMR} \) is the resonance field and \( M_s \) is the magnetization. The spatially nonuniform YIG PSSW modes, on the other hand, are described by: \( \mu_0H_{ex} = (2A_{ex}/M_s)(n\pi/d_{YIG})^2 \), where the exchange field, \( H_{ex} \), defines the mode splitting between the PSSW modes and the uniform mode, \( A_{ex} \) is the exchange stiffness, and \( d_{YIG} \) is the YIG film thickness. A total of more than 30 PSSW modes can be identified for the 10-nm-Py sample. The quadratic increase of the exchange fields with the mode number \( n \) confirms the observation of the PSSWs. From the extracted resonance fields of each YIG mode, \( n \), see Fig. 1(c), we are able to determine the fitting parameters, yielding \( M_s = 0.197 \) T and \( A_{ex} = 3.76 \) pJ/m, which are in good agreement with the previously reported values [27-30].

Coupled YIG/Py resonance and the MIT effect

Figure 2(a) shows the optical signals \( X, Y \), and the total amplitude \( \sqrt{X^2 + Y^2} \) for the 30-nm-Py sample as a function of magnetic field, \( H \), and frequency, \( f \) from 4 - 8
FIG. 2. **Optically-detected FMR and PSSWs dispersions.** (a) The optically detected in-phase, $X$, quadrature, $Y$, and the amplitude ($\sqrt{X^2 + Y^2}$) for the 30-nm-Py sample as a function of the magnetic field and frequency. The color scale is normalized to an arbitrary value, but is the same for $X$, $Y$, and $\sqrt{X^2 + Y^2}$. The low frequency mode corresponds to the YIG FMR line, whereas the high frequency mode corresponds to the Py FMR line. Both the $X$ and $Y$ signals show clear phase evolution with the frequency. (b) The fine scan at smaller field and frequency steps, from 5.7 to 6.3 GHz, demonstrating the coupled resonances and the MIT effect.

GHz. Two Kittel dispersion can be observed for Py and YIG, the latter having a larger $H_{FMR}$ for the same frequency due to the smaller $M_s$. To locate the YIG PSSW modes, we show the zoom-in scan between 5.7 and 6.3 GHz and 0.2 to 0.9 kOe in Fig.2(b), which covers the Kittel dispersion of Py. We clearly observe the YIG PSSWs lines: within the broad Py FMR line, we find several narrow resonances, of which the dispersion is parallel to the YIG FMR, confirming the coupled YIG-Py resonances. For this frequency measurement window (4 - 8 GHz), clear phase evolution can be observed in the optical signals. The periods of the phase evolution are the same for both YIG and Py lines, due to the fixed path difference of the measurement geometry, i.e. $\phi_L - \phi_{MW} - \phi_h$. As seen from Fig.2(a) ($X$ and $Y$ datasets), the Py and YIG FMR lines also exhibit a small, but fixed phase offset, which could be due to either the intrinsic phase buildup from the Py-Kerr and YIG-Faraday effects, or a phase lag of the Py FMR with respect to the YIG FMR, caused by the coupled PSSWs’ “dragging” the hybrid YIG-Py resonances, i.e. from a finite $\phi_{X(Py)} - \phi_{X(YIG)}$. It is noted that this effect is unlikely due to the additional travelling distance inside the 3-µm YIG bulk, as this thickness is too small compared with the microwave wavelength.

Figure 2(b) shows a finer scan at a smaller frequency window (5.7 - 6.3 GHz) with smaller steps for both $f$ and $H$. We clearly identify the distinct PSSW modes strongly “chopping” the Py FMR line. In particular, the Py resonance is attenuated to nearly the background level (non-absorption condition) at the PSSW resonance dips. In the hybrid magnon-photon systems, the MIT effect arises when the coupling strength, $g/2\pi$ is larger than the photon dissipation rate $\kappa_p/2\pi$ but smaller than the magnon dissipation rate $\kappa_m/2\pi$ [9]. Here, we observe the analogous MIT effect, but in a “magnon-magnon” hybrid system. In other words, it is the hybrid magnon coupling with a “magnonic cavity” as opposed to a photonic cavity. Furthermore, such an MIT effect exhibits the multi-mode characteristics, in which the profiles and properties of each PSSW mode are greatly modified as compared to the free-space conditions, similar to the multi-mode coupling in the magnon-photon system [35]. The coupling strength of YIG/Py system is within the difference of the dissipation rates between the Py and YIG, due to their very different damping coefficients. We envisage, however, that a stronger coupling condition may
be fulfilled by combining an appropriately designed optical cavity such as the whispering gallery modes [23], or replacing the Py with a low damping ferromagnetic material with reduced dissipation rate [27]. Similar line-shapes are also obtained for the 10-nm-Py sample and the raw data traces are shown in the SM, Fig.S-3, with more PSSW modes becoming distinguishable due to the stronger magnon-magnon coupling at thinner Py thickness [30].

We also performed the same measurements for the reference samples, YIG/SiO$_2$/Py and YIG/Cu/Py, which are also summarized in the SM, Fig.S-4 and S-5. Despite the observation of the YIG and Py FMR modes, we do not measure any signal of YIG PSSW excitations from the optical data. This indicates that the excitation of YIG PSSW modes are dominated through the interfacial exchange coupling, rather than the dipolar interactions. In addition, the spin pumping effect and antidamping torque, observed earlier in much thinner YIGs ($\sim$ 100-nm), plays a negligible role here for thicker YIG (3-µm) samples since the torque decays with the square root of the YIG thickness [30].

**Phenomenological Model**

We developed a phenomenological model to interpret our results, which considers a series of YIG harmonic oscillators coupled with the Py oscillator, in which the measured complex optical signal, $V_O$, can be expressed as:

$$V_O = \frac{A e^{i(\phi_L - \phi_m)}}{i(H_{FMR} - H) - \Delta H_{Py} + \sum_j \frac{g^2}{(H_{YIG,SWR,j} - H) - \Delta H_{YIG,j}}}$$

where $A$ is the total signal amplitude, $H_{FMR}$ is the resonance field of Py and YIG-PSSWs, respectively, $\Delta H_{YIG(Py)}$ is the half-width-half-maximum linewidth, and $g$ is the interfacial exchange coupling strength. The example fitting to the experimental trace is shown in the SM, Fig.S-6. The fittings nicely reproduce the complex line-shapes arising from the coupled YIG PSSW modes and the Py FMR, including the relative phase variation of the PSSWs. Figure 3(a) and (b) show the modeled FMR and PSSW lines at a function of $H$ and $f$, which match very well with the experimental data shown in Fig.2. This model further allows extracting the YIG and Py magnon dissipation rates, e.g. at 6 GHz, $\kappa_{YIG} = 1.3$.
FIG. 4. Coupled Py-YIG hybrid magnon modes. (a) Example fitting of the hybrid YIG-Py magnon spectra for the 10-nm-Py sample, at a series of frequencies (5.85 - 6.10 GHz). The Py FMR dynamics can be extracted, yielding $\Delta H_{\text{Py}}$ and $H_{\text{Py FMR}}$ for the Py. (b) Subsequent analysis of each YIG PSSW mode’s dispersion within the Py FMR “umbrella”. At least 10 distinct PSSW modes can be extracted (marked by the arrows), yielding the $\Delta H_{\text{YIG}}$ and $H_{\text{YIG SWR}}$ for each marked PSSW, $j$ (1 - 10), under the Py FMR “umbrella”. (c) Example fitting results of $\Delta H$ and $H_{\text{FMR,SWR}}$ for Py and YIG PSSW [the highlighted resonance group in (b)]. From (d), we can extract the “resonance distance”, i.e. $\Delta H_{\text{res}} = [H_{\text{YIG SWR}} - H_{\text{Py FMR}}]$, at each frequency and for each PSSW mode $j$. Such a “resonance distance” $\Delta H_{\text{res}}$ corresponds to the degree of the overlapped resonances. (e) The $\Delta H_{\text{res}}$ at each $f$ and for all the PSSW series, is plotted against the corresponding YIG PSSW linewidth, $\Delta H_{\text{YIG}}$. 

Oe, $\kappa_{\text{Py}} = 35.0$ Oe, and the coupling strength: $g = 18.7$ Oe. The numbers satisfy the condition for observing the “MIT” effect: $\kappa_{\text{YIG}} < g < \kappa_{\text{Py}}$. A cooperativity is estimated as: $C = g^2 / \kappa_{\text{YIG}} \kappa_{\text{Py}} = 7.65$. It is noted that such cooperativity is between the Py uniform (Kittel) mode and YIG PSSW modes, thus is smaller than the earlier reported case with microwave-to-light conversion using the YIG uniform mode [24]. Because the coupling strength is much greater than the linewidth of the YIG PSSW modes, the linewidth of the induced MIT effect may be different from the PSSW modes. In order to examine the effect of MIT, we separate the global Py resonance and the PSSWs, and then fit each series of the PSSW modes. The fitting results are shown in Fig. 4. Due to our thick YIG films and the large linewidth contrast between YIG and Py ($\kappa_{\text{Py}}/\kappa_{\text{YIG}} \sim 27$), it is common to observe at least 7 ~ 8 distinct PSSW modes within the broad Py resonance profile, see Fig.4(a) and (b). Fitting each PSSW series to a phase-shifted Lorentzian function yields the resonance and linewidth dispersion for Py FMR and for each PSSWs, as shown in Fig.4(c) and (d). Due to the broad Py FMR profile, the involving PSSW modes may still be coupled differently, in terms of both amplitude and phase, to the Py “umbrella”. More detailed discussions on the phase evolution of the PSSWs are found in the SM, Fig.S-4. We define a “resonance distance”, $\Delta H_{\text{res}} = [H_{\text{YIG SWR}} - H_{\text{Py FMR}}]$, which represents their frequency detuning and the coupling efficiency.

In Fig.4(e), we plot the $\Delta H_{\text{res}}$ at each frequency and for all the PSSW series, with the corresponding YIG PSSW linewidth, $\Delta H_{\text{YIG}}$. We clearly observe an enhancement of the YIG linewidth, $\Delta H_{\text{YIG}}$, from $\sim 2$ Oe to $\sim 10$ Oe, spanning across the magnon-magnon coupling regime. This observation shows that the MIT linewidth is broadened due to the additional energy dissipation by coupling the YIG PSSW modes to the Py FMR mode, also known as the Purcell regime from the PSSWs point of view [2, 3, 9]. From the theoretical model in Eq.1, we also obtain a relationship between the enhanced YIG linewidth and the overlapped resonance of YIG and Py. The detailed derivation on the YIG resonance shift and the MIT linewidth broadening due to a finite $g$ is included in the SM. A theoretical fitting curve is obtained, yielding $g \sim 12.8$ Oe, which is similar to the lineshape fitting results of 18.7 Oe as discussed above.

Finally, the observed multiple PSSW modes provide unique opportunities for coherent information manipulation in our magnon coupled system. These standing wave modes along the thickness direction of the YIG thin film show significantly reduced linewidth compared with Py, and therefore can serve as the storage element in such a hybrid magnonic system. The coupling between these evenly distributed PSSWs and the spin waves in Py can form temporal dark modes [10] which can store the information at a time scale much longer than the spin wave lifetime in Py. Previously such evenly distributed resonances have only been reported in high-overtone microwave or mechanical resonators [36, 37] where the resonance frequencies are fixed for a given geometry. In our demonstration, the PSSWs also inherit the intrinsic tunability of magnons with their frequencies largely tunable by a bias magnetic field. Moreover, our demon-
Stratification of multimode MIT also opens up new possibilities for achieving multimode strong coupling in coupled magnonic systems, or even the so-called superstrong coupling regime, where the coupling strength is larger than the free spectral range (FSR, the resonance distance) of the PSSWs. In this new regime, the individual PSSW interacts with each other by strongly coupling to the common spin wave mode, enabling novel coherent dynamics.

**CONCLUSION**

In summary, using combinatorial magneto-optical Kerr and Faraday effects, we report the observation of the multi-mode magnetically-induced transparency in YIG/Py bilayers exhibiting magnon-magnon coupling. The use of the thin-film YIG system shows great potential in practical applications. For example, the series of standing wave magnon resonances in YIG may allow to build an evenly distributed resonance array in a single YIG device, which may lead to relevant applications such as memory and comb generation. In addition, compared with the so-far widely used hybrid magnonic systems that utilize the ferromagnetic resonances, our results pave the way towards building more complex hybrid systems with spin-waves.

Technologically, the measurement is achieved via simultaneous and stroboscopic detection of the coupled magnetization dynamics using a single wavelength, therefore avoids the possible artifacts due to multiple probes. We develop also a phenomenological model that nicely reproduces the experimental results including the induced amplitude and phase evolution caused by the magnon-magnon coupling. Our results not only offer a new route towards studying phase-resolved spin dynamics, but also suggest new prospects of utilizing magnetically coupled systems for future quantum hybrids in the context of quantum system manipulation.

Our work, performed in a planar structure as opposed to 3D cavities, also paves the way towards solving strong magnon-magnon couplings by the state-of-the-art spin-orbitronic toolkits, involving emerging materials such as antiferromagnets, 2D monolayers, and topological insulators.

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Supplemental Materials:

for Probing the Magnon-Magnon Coupling using Combinatorial Magneto-Optical Kerr and Faraday Effects

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1. Measurement setup:
The magnetization dynamics are detected optically by the magneto-optical Kerr and Faraday effects for Py and YIG, respectively, by measuring the out-of-plane component of precessing magnetization. A heterodyne method is adopted to enable precessional phase extraction using a setup illustrated in Fig. S-1. A single microwave source was used to simultaneously modulate the detecting laser light (optical path), and drive the FMR of the sample (electrical path) with a coplanar waveguide (CPW). The laser light was modulated at the microwave source frequency using an electro-optic intensity modulator. The modulated laser light can be polarized by either a fiber polarizer (used in combination with a polarization controller) or a free-space thin-film polarizer, before being focused onto the sample surface. We use an optical tap (∼10%), a GRIN lens, and another free-space polarizer to monitor the polarization during the whole measurements. The focused light spot is set to ∼40 µm in this work. A microwave diode was used simultaneously to measure the inductive FMR absorption through the CPW.

![Fig. S-1. Schematics of the measurement setup. After the rf splitter, the optical path (upper part) contains amplifier, 1550 nm infrared laser module, electro-optic modulator (EOM), polarizer, polarization controller, beam splitter (BS) and focusing lens; the electrical path (lower part) contains amplifier, mixer, coupler, spectrum analyzer, diode, and nanovoltmeter. (PBS = polarizing beam splitter, Cam = camera, bal.det = balancing detector, arb. func = arbitrary waveform generator.)](image)

For a heterodyne detection, the microwave signal along the electrical path was IQ-mixed with a low-frequency (100 kHz) signal provided by a waveform generator. The voltage amplitude, offset, and phase for the respective “I” and “Q” channels were optimized to ensure the power of the upper side-band of the microwave signal (which was subsequently used for FMR excitation) far exceeds those of the central and lower side-band (>20 dB). We use a directional coupler (−20 dB), and a real-time spectrum analyzer to monitor the central and side-bands throughout the whole measurement. The resultant, out-of-plane, dynamical Kerr and Faraday responses of the sample were then probed by the modulated light, sent into a balancing detector after polarization splitting, and analyzed by a lock-in amplifier.

2. Fine scan for the FMRs and PSSWs lineshapes:
The observation of the MIT effect and further quantitative analysis relies largely on the fine scan of the optical response as a function of both frequency and magnetic field. The complete fine scanned lineshapes for the 10-nm-Py sample are summarized in Fig.S-2. A total of more than 30 PSSW modes can be identified at a broad range of
frequencies. The frequency step used in the fine scan is 0.01 GHz.

FIG. S-2. The optically detected in-phase, $X$, quadrature, $Y$, and the amplitude, $\sqrt{X^2 + Y^2}$ for the 10-nm-Py sample as a function of the magnetic field and frequency, showing the frequency-dependent phase evolution.

3. FMR and PSSW dispersion of the 10-nm-Py sample, Py/SiO$_2$/YIG, and Py/Cu/YIG:
FIG. S-3. The optically detected in-phase, $X$, quadrature, $Y$, and the amplitude ($\sqrt{X^2+Y^2}$) for the 10-nm-Py sample as a function of the magnetic field and frequency.

FIG. S-4. The optically detected in-phase, $X$, quadrature, $Y$, and the amplitude ($\sqrt{X^2+Y^2}$) for the SiO$_2$-3nm/Py10-nm reference sample as a function of the magnetic field and frequency.

FIG. S-5. The optically detected in-phase, $X$, quadrature, $Y$, and the amplitude ($\sqrt{X^2+Y^2}$) for the Cu-3nm/Py10-nm reference sample as a function of the magnetic field and frequency.
Figures S-3, S-4, and S-5 show the fine-scanned optical signals $X$, $Y$, and the total amplitude for the 10-nm-Py sample, Py/SiO$_2$/YIG, and Py/Cu/YIG, as a function of the magnetic field and frequency. The YIG PSSWs and MIT effect due to the magnon-magnon coupling are clearly observed for the 10-nm-Py sample. No YIG PSSWs are observed in the Py/SiO$_2$/YIG and Py/Cu/YIG references, suggesting that the coupling is through the exchange interaction at the interface as opposed to the dipolar interaction. In addition, the Py Kerr signal is attenuated in the Py/Cu/YIG as compared to the Py/SiO$_2$/YIG, which is likely due to the metal refractive index of the inserted Cu layer.

4. Phenomenological Model and curve fitting example:

In the presence of a uniform microwave field, the magnetization dynamics of Py, which couples to the magnetization motion of YIG via interfacial exchange, can be expressed in the field domain by the quantum optics formula $[8, 9, 16]$ combined with the heterodyne detection mechanism $[33]$:

$$V_O = \frac{Ae^{i(\phi_L-\phi_m)}}{i(H_{FMR}^P - H) - \Delta H_P + \sum_j (H_{SWR,j} - H) - \Delta H_{YG,j}}$$

(S-1)

This equation is used to fit the entire lineshape of the optical signals, which is proportional to $\tilde{m}_P$ along with the optical detection amplitude, $A$, and an additional phase shift caused by the measurement $\phi_L - \phi_m$, introduced in terms of $e^{i(\phi_L-\phi_m)}$. Using Eq. S-1, Fig S-6(a) plots the hybrid lineshapes of the Py that is coupled to the YIG PSSW modes at the different Py-YIG resonance detuning, showing the amplitude and phase evolution of the coupled dynamics. The red curve, with a zero resonance detuning, denotes the MIT effect. Using a single $g$ value, the hybrid modes (1 - 7) already well display the amplitude and phase evolution caused by the different degrees of the coupling with the Py resonance. Away from the Py resonance, the lineshape appears to be much antisymmetric, whilst around the Py FMR, the hybrid mode appears to be more symmetric. These are in good agreement with the experimental observation. Fig. S-6(b) shows an example fit to the experimental data at 6 GHz.

![FIG. S-6. (a) Plotting the analytical result for modeling a single lineshape, from the phenomenological model and by considering 7 hybrid YIG PSSWs. (b) Example fitting result for the lineshape measured at 6 GHz.](image)

In order to quantitatively correlate the enhanced YIG linewidth with the overlapped resonance (resonance distance) of YIG and in the MIT regime. We further derive the formula S-1 as:

$$V_O = \frac{Ae^{i(\phi_L-\phi_m)}}{i(H_{FMR}^P - H) - \Delta H_P + \sum_j (H_{SWR,j} - H) - \Delta H_{YG,j}}$$

(S-2)
In the vicinity of the MIT regime, $H$ is close to $H_{YIG,SWR,j}^Y$. To consider the lineshape evolution within the range of \( \Delta H_{YIG,j} \), we can rewrite $H$ as $H = H_{YIG,SWR,j}^Y + \delta H$, with both $H_{YIG,SWR,j}^Y$ and $\delta H$ much smaller than the Py-YIG resonance distance, $\Delta H_{res} = H_{YIG,SWR,j}^Y - H_{FMR}^P$. Therefore:

$$V_O \approx \frac{A e^{i(\phi_L - \phi_m)}}{(H_{YIG,SWR,j}^Y - H_{FMR}^P) - i\Delta H_{Py} - \frac{g^2}{\delta H - i\Delta H_{YIG}}}$$

$$\approx \frac{A e^{i(\phi_L - \phi_m)}}{[\delta H - g^2(H_{YIG,SWR,j}^Y - H_{FMR}^P)^2 + [\Delta H_{Py}]^2] - i[\Delta H_{YIG,j} + g^2[\Delta H_{res}]^2 + [\Delta H_{Py}]^2]}.$$

(S-3)

where the $\delta H$ is the resonance field shift of the YIG SWR. As seen from Eq. S-3, the magnon-magnon coupling, characterized by the $g$ parameter, induce additional modulation for both the resonance field, $\delta H(g)$, and the YIG linewidth, $\Delta H_{YIG}(g)$:

$$\delta H(g) = \delta H - g^2 \frac{[H_{YIG,SWR,j}^Y - H_{FMR}^P]}{[H_{YIG,SWR,j}^Y - H_{FMR}^P]^2 + [\Delta H_{Py}]^2} = \delta H - g^2 \frac{[\Delta H_{res}]}{[\Delta H_{res}]^2 + [\Delta H_{Py}]^2},$$

$$\Delta H_{YIG}(g) = \Delta H_{YIG,j} + g^2 \frac{[\Delta H_{Py}]}{[H_{YIG,SWR,j}^Y - H_{FMR}^P]^2 + [\Delta H_{Py}]^2} = \Delta H_{YIG,j} + g^2 \frac{[\Delta H_{Py}]}{[\Delta H_{res}]^2 + [\Delta H_{Py}]^2}.$$

(S-4)

Therefore, the YIG linewidth is broadened by the coupling coefficient, $g^2$, multiplied by a Lorentzian function of $\Delta_{Py}$, and the maximum linewidth of the YIG SWR modes should be $\Delta H_{YIG,j} + g^2/\Delta_{Py}$. The result suggests that the linewidth broadening can be enhanced by either increase the $g$ or decrease the $\Delta_{Py}$. The corresponding data plotting and fitting are shown in the main text, Fig. 4(e).

5. YIG FMR analysis of the 30-nm-Py sample:

Figure S-7 shows the analysis of the YIG FMR properties of the 30-nm-Py sample. A $M_s$ value of YIG $\sim 0.199$ T is obtained from the resonance field, Fig. S-7(c), using the Kittel formula. This value is in good agreement with that obtained from the PSSW analysis in the main text. Fig S-7(d) plots the phase evolution with the frequency. Linear fits with the phase evolution, following $\Delta \phi_{opt/ele} = \frac{2\pi}{c} \Delta L_{opt/ele}$, yield an optical/electrical path difference, $\Delta L_{opt/ele} \sim 77.8$ cm.
FIG. S-7. (a) The optically detected in-phase, $X$, for the 30-nm-Py sample, with an analysis window shifted towards the YIG FMR dispersion regime (dashed-line pair). Summary of the linewidth (b), resonance field, $H_{res}$ and the corresponding Kittel fits (c), and the phase evolution with the frequency (d), are presented.