Supplementary Material for "Simultaneous realization of nonreciprocal and ultra-strong coupling in cavity magnonics"

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I. EXPERIMENT AND SIMULATION RESULTS OF THE PHOTON MODE

Fig. S1(a) displays the experimental transmission spectra at 10.8 GHz under an applied magnetic field of 490 Oe. Using finite element simulations, we calculated the z-component microwave magnetic field distributions in the YIG at 10.8 GHz under 490 Oe for both forward (S_{21}) and reverse (S_{12}) propagation directions. As shown in Fig. S1(b) and (c), the energy flux exhibits outward divergence in the reverse (S_{12}) direction but inward convergence in the forward (S_{21}) direction.

II. ISOLATION RATIO

We calculated the isolation ratio (ISO) which is defined as $S_{21} - S_{12}$ so as to quantify the transmission asymmetry. Figure S2 compares the ISO spectra under positive ($+z$) and negative ($-z$) magnetic field orientations. The ISO exceeds 20 dB within the coupling bandwidth, demonstrating strong unidirectionality suitable for microwave isolation applications.

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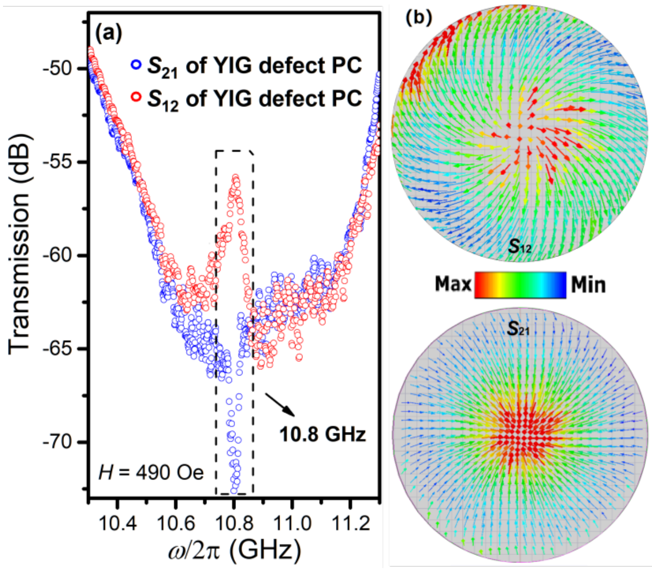

FIG. S1. (a) Experimental results. Red circles and blue circles represent the transmission spectra of S_{12} and S_{12}, respectively. (b) Simulation results of the distribution of microwave magnetic field of YIG at 10.8 GHz under an applied magnetic field of 490 Oe of S_{12}. (c) Simulation results of the distribution of microwave magnetic field of YIG at 10.8 GHz under an applied magnetic field of 490 Oe of S_{21}.

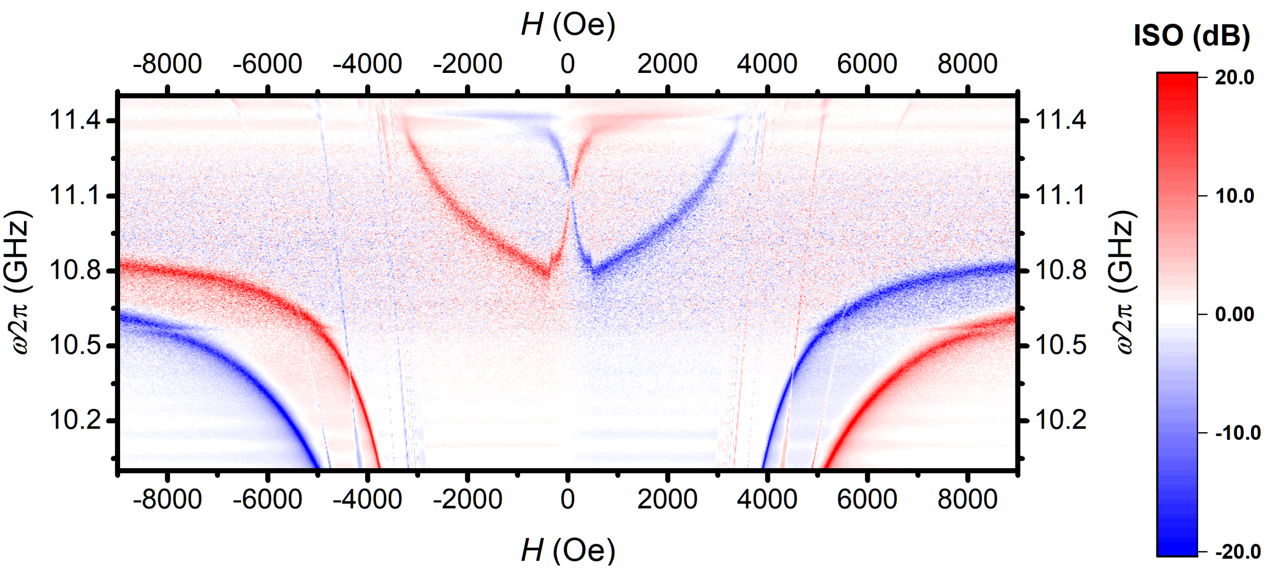

FIG. S2. ISO of the amplitude of the transmission coefficients

III. ULTRA-STRONG COUPLING INDUCED FROM THE YIG CYLINDER

The experimental setup schematic (inset of Fig. S3(a)) depicts a microwave probe connected to a vector network analyzer (VNA) for exciting the YIG resonator. The YIG cylinder functions as a microwave resonator, with its fundamental eigenmode observed at 12.2 GHz (Fig. S3(a)). This photonic mode hybridizes with the FMR mode through magnon-photon coupling. By sweeping the static magnetic field H, we monitored the evolution of reflection coefficient S_{11}. The characteristic anticrossing between FMR and photonic modes confirms strong coupling, as seen in the avoided level crossing (Fig. S3(b)). In Fig. S3(b), blue dots stand for the experiment data, black and red dashed lines represents FMR mode and photon mode of YIG cylinder, respectively. The coupling dispersion is well described by the modified Hopfield model. Figure S2(b) shows the hybridized modes (orange curves) with a coupling strength of 4 GHz, extracted from Hopfield model fitting. The lower hybridized mode branch (gray dashed ellipse in Fig. 3) provides the dominant contribution to the observed nonreciprocal coupling.

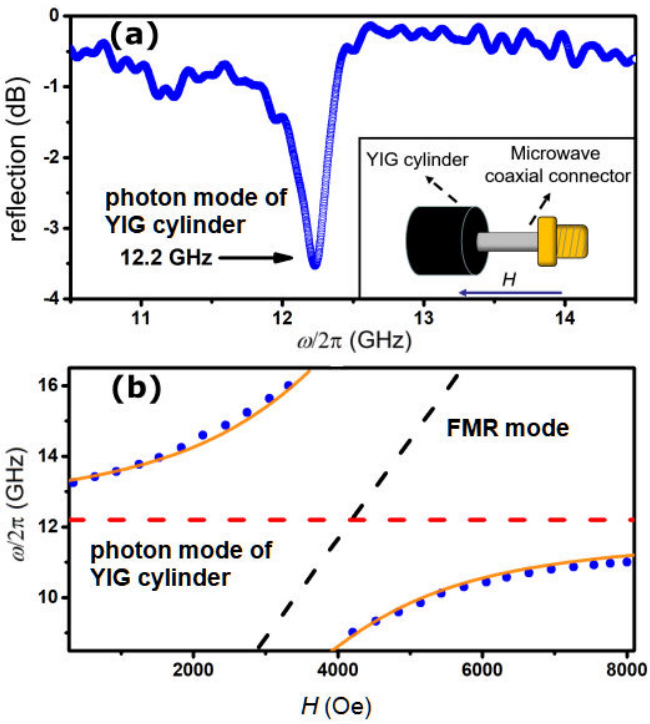

FIG. S3. (a) Microwave reflection coefficient S_{11} of the YIG cylinder at the magnetic field of 0. The inset stands for the experiment system. (b) The couplings in the frequency versus applied static magnetic field with the fitting curves. The experiment data are described as blue circles. Black dashed line indicates the FMR mode fitting with the Kittel equation; red dashed line indicates the resonance frequency of photon mode located at 12.2 GHz; orange curves are polarized modes.