# Strong On-Chip Microwave Photon–Magnon Coupling Using Ultralow-Damping Epitaxial $Y_3Fe_5O_{12}$ Films

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Yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) is one of the best magnetic materials for magnon-based quantum information science (QIS) because of its extremely low damping loss. For scalable on-chip QIS devices, ultralow-damping YIG films at mK temperatures are desired. However, almost all epitaxial YIG films are grown on rare-earth-containing garnet substrates which cause very large damping at low temperatures, hindering the use of YIG films for QIS studies. We report ultralow damping at 2 K in epitaxial $Y_3Fe_5O_{12}$ thin films grown on a diamagnetic $Y_3Sc_2Ga_3O_{12}$ (YSGG) substrate that contains no rare-earth elements (Figs. 1a-1b). The extremely low damping of the YIG epitaxial films on diamagnetic YSGG substrates at very low temperatures is highly promising for QIS studies. As an initial step in this regard, we integrate the YIG/YSGG films with superconducting resonators for the study of coupling between magnons in a YIG film and microwave photons emitted by a superconducting coplanar waveguide resonator (Fig. 1c). We observe strong coupling between magnons in patterned YIG thin films and microwave photons in a superconducting Nb resonator at 2 K (Fig. 1d). This is the first demonstration that ultralow-damping YIG epitaxial films on YSGG can be integrated with superconductor resonators to achieve strong microwave photon-magnon coupling at few Kelvin temperatures. Such ultralow-damping YIG films offer advantages over metallic ferromagnets for on-chip hybrid quantum systems that incorporate magnonic conduits, microwave superconductor resonators, and superconductor qubits for QIS applications that operate in the mK regime.

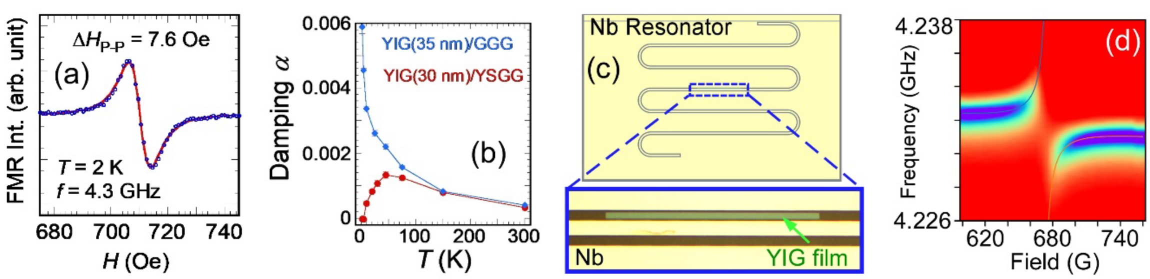


Figure 1. (a) Derivative FMR spectrum of a YIG(30 nm)/YSGG film at 2 K driven by a microwave frequency of 4.3 GHz. (b) Damping constants for the YIG(30 nm)/YSGG film (red) and a conventional YIG(35 nm)/GGG film (blue) at 2-300 K. (c) Photograph of a hybrid device with a Nb resonator and a YIG film strip in the gap between the center line and the ground plane. (d) Avoided crossing of microwave transmission in the hybrid device at $T = 2$ K, demonstrating strong coupling between microwave photons and magnons in the YIG film.

[1] S. D. Guo, D. Russell, J. Lanier, H. T. Da, P. C. Hammel, and F. Y. Yang, Nano Lett. **23**, 5055 (2023).

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# Supplementary Pages

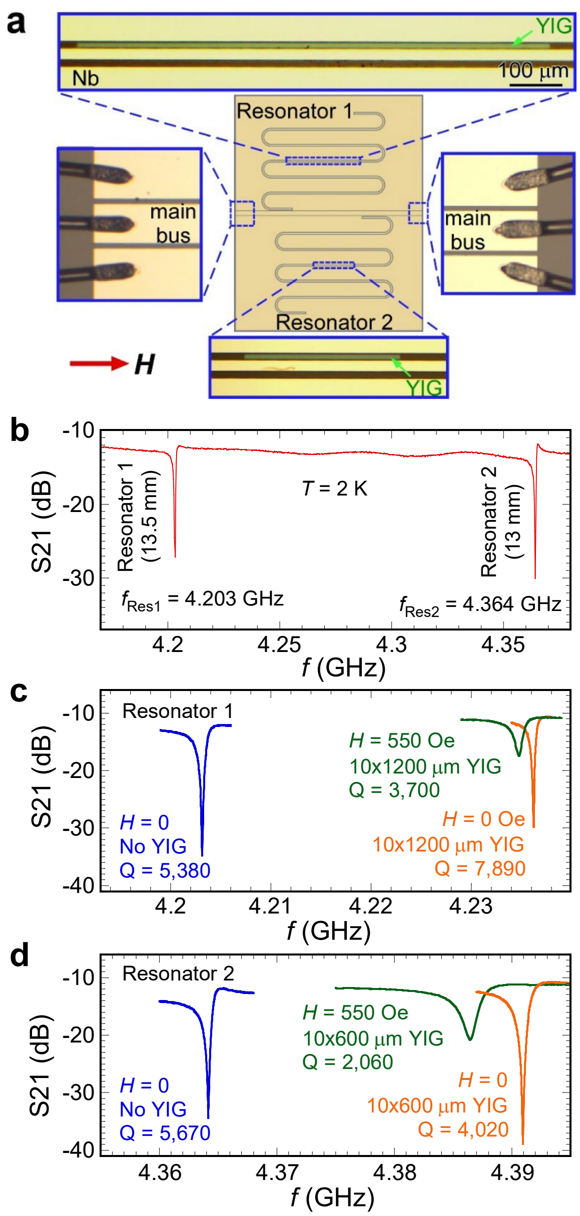


Figure 2. Microwave transmission of Nb CPW resonators with or without YIG strips on YSGG and magnetic field at $T$ = 2 K. **a**, Schematic of Nb resonator device with YIG strips placed within their gaps. The size of the whole device is $3.5 \times 4.4$ mm$^2$. The lengths of the two Nb resonators are 13 mm and 13.5 mm. Insets: optical microscope images of selected areas with the same magnification. The YIG strips shown (color contrast augmented) are $10 \times 900$ µm$^2$ (top) and $10 \times 300$ µm$^2$ (bottom). **b**, Microwave transmission (S21) spectrum of two Nb resonators without a YIG strip in their gaps. The two sharp dips (resonances) at 4.364 and 4.203 GHz correspond to the resonance frequencies of the 13 mm and 13.5 mm resonators, respectively. **c**, Microwave transmission spectra of the 13.5 mm resonators without YIG at zero field (blue), with a $10 \times 1200$ µm$^2$ YIG strip at zero field (orange), and with a $10 \times 1200$ µm$^2$ YIG strip in the presence of a 550 Oe in-plane magnetic field (green) as illustrated in **a**. **d**, Microwave transmission spectra of the 13 mm resonators without YIG at zero field (blue), with a $10 \times 600$ µm$^2$ YIG strip at zero field (orange), and with a $10 \times 600$ µm$^2$ YIG strip at 550 Oe (green).