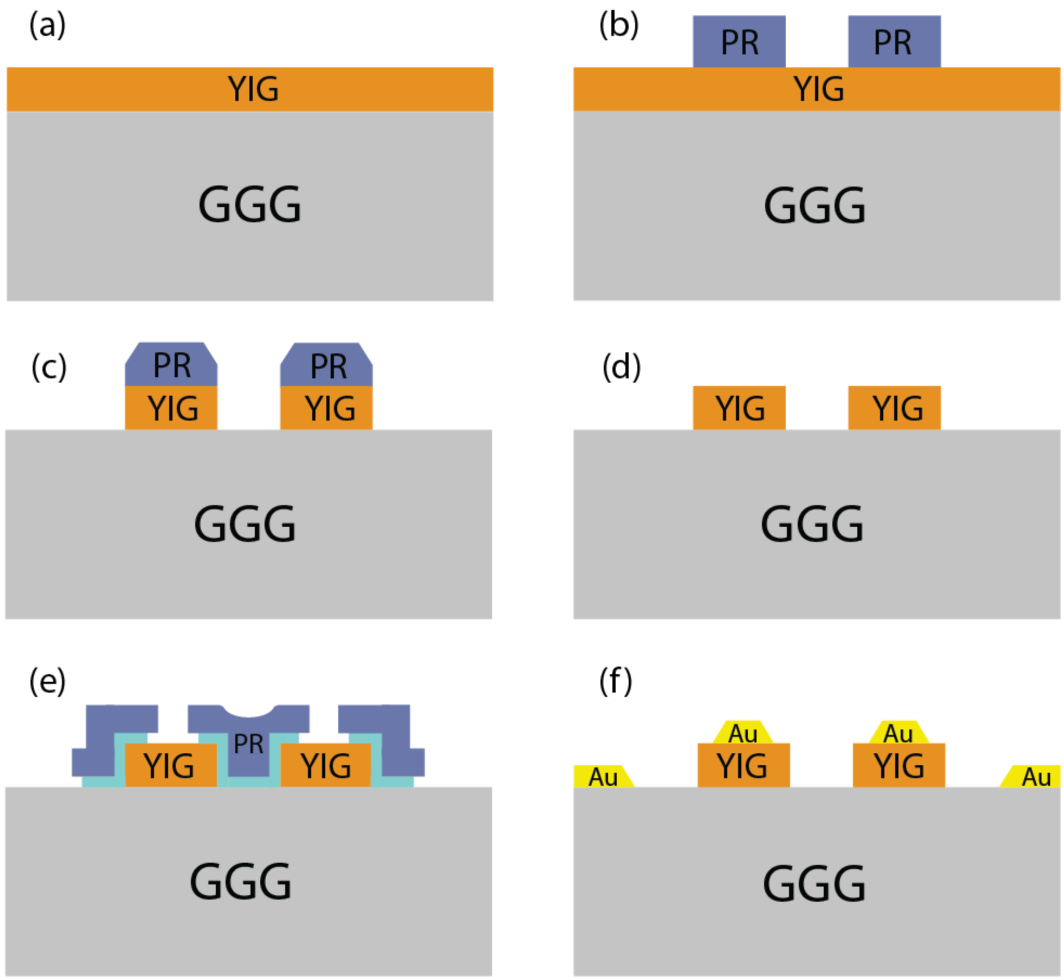
An Edge-Coupled Magnetostatic Bandpass Filter Supplementary Information

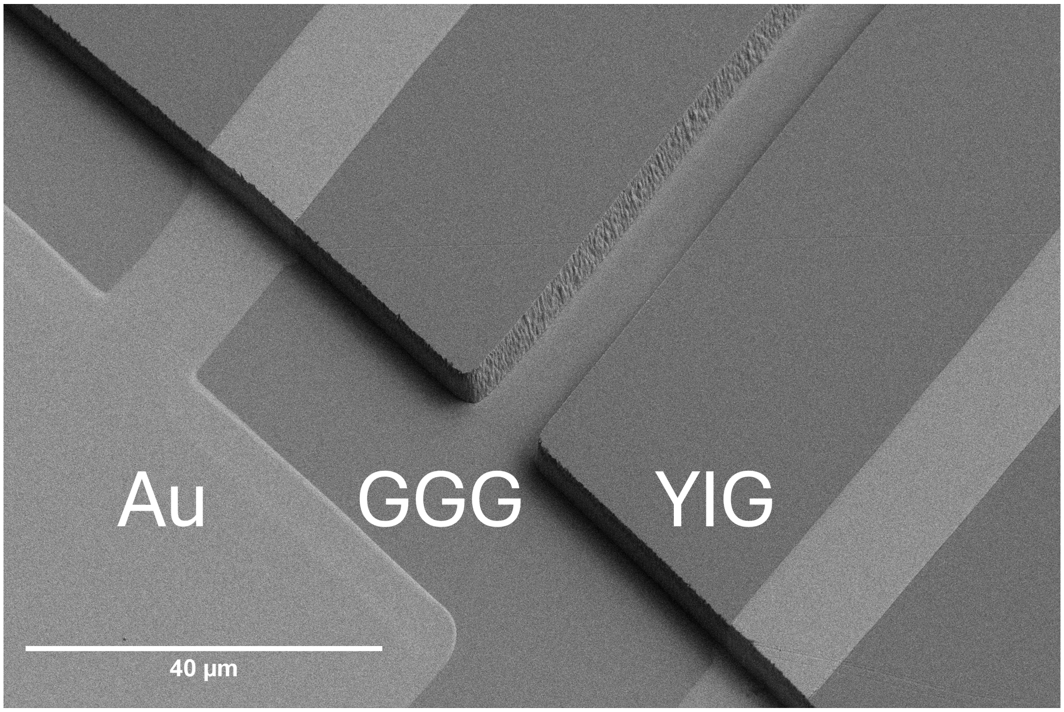
Connor Devitt[1*], Renyuan Wang[2*], Sudhanshu Tiwari[1], Sunil A. Bhave[1]
[1]OxideMEMS Lab, Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907 USA.
[2]FAST Labs, BAE Systems, Inc., Nashua, NH 03060 USA.
*e-mail: devitt@purdue.edu, renyuan.wang@baesystems.com

Supplementary Information 1: Fabrication

The fabrication process for the magnetostatic wave (MSW) bandpass filter is outlined in Supplementary Fig. 1 where steps (a)-(c) are adapted from [1]. A thick photoresist mask (SPR220-7.0) is patterned onto a $3\,\mu\mathrm{m}$ YIG film grown via liquid phase epitaxially (LPE) on a $500\,\mu\mathrm{m}$ GGG substrate. The YIG film is etched through at a rate of $36\,\mathrm{nm/min}$ using an optimized ion milling recipe for vertical sidewalls with sufficient intermittent cooling to prevent burning of the photoresist. Optimized lithography for the thick SPR photoresist is crucial to the filter's final performance since the inter-resonator coupling factors, M_{ij}, are sensitive to the physical separation of the etched YIG. With this process, we are able to fully etch resonator spacings as narrow as $3\,\mu\mathrm{m}$, setting the maximum achievable $M_{ij} \leq 1.37\%$ based on finite element simulation. After etching, the resist is removed and the sample is soaked in phosphoric acid at $80\,{}^{\circ}C$ to remove redeposited material. The gold electrodes are patterned through a bi-layer liftoff process using SPR220-7.0 and LOR 3B photoresists. Using a glancing angle e-beam evaporation, $300\,\mathrm{nm}$ of gold and a $10\,\mathrm{nm}$ titanium adhesion layer is conformally deposited over the etched YIG resonators. Finally, the sample is soaked in Remover PG overnight to complete the liftoff process. Supplementary Fig. 2 shows an SEM of a fabricated filter illustrating the vertically etched YIG with a spacing of $9.8\,\mu\mathrm{m}$ and conformal gold electrodes. Due to the combination of bi-layer liftoff and angled metal deposition, the gold electrodes are larger than designed and show a tapered thickness.



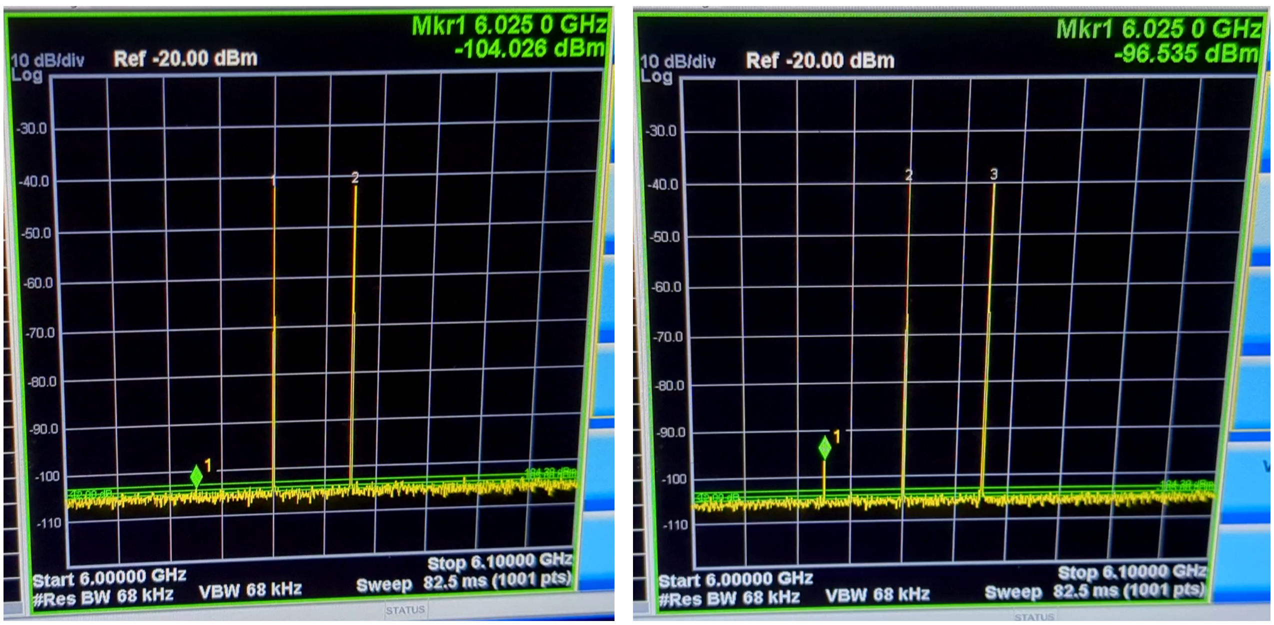
Supplementary Fig. 1. Fabrication process of the bandpass filter: **(a)** $3\,\mu\mathrm{m}$ liquid phase epitaxy (LPE) YIG film grown on 500µm GGG substrate. **(b)** 7.8µm thick photoresist (SPR220-7.0) patterned on YIG film as an etch mask. **(c)** 3µm ion mill etch of YIG film at a rate of $36\,\mathrm{nm/min}$. **(d)** Photoresist mask is removed and etched YIG is soaked in phosphoric acid at $80\,{}^{\circ}C$ for $20\,\mathrm{min}$. **(e)** Bi-layer photoresist (SPR220-7.0 and LOR 3B) mask for a liftoff is patterned onto the etched sample. **(f)** $10\,\mathrm{nm}$ Ti and $300\,\mathrm{nm}$ Au is deposited using glancing angle e-beam evaporation followed by a liftoff process.



Supplementary Fig. 2. SEM image of a 2-pole magnetostatic forward volume wave (MSFVW) bandpass filter showing vertically etched YIG resonators with an inter-resonator spacing of $9.8\,\mu\mathrm{m}$ and conformal gold electrodes over the edges of etched YIG.

Supplementary Information 2: Intermodulation Distortion Measurements

Two-tone intermodulation distortion measurements to characterize the filter IIP3 are performed using two Keysight E8257D signal generators with a frequency separation of $\Delta f = 15\,\mathrm{MHz}$. The two tones are combined using a wideband power divider whose output is connected to a GS probe at the filter input. A second GS probe at the filter output is connected to an Agilent PXA spectrum analyzer measuring the filter's spectrum. A two-stage calibration to remove all cable and system losses at every tone frequency and input power level is required to determine the IIP3. Supplementary Fig. 3 shows the raw uncalibrated 4-pole filter spectrum in the passband at two different input powers. The input tones are set at $6.04\,\mathrm{GHz}$ and $6.055\,\mathrm{GHz}$. For this particular measurement, only the lower intermodulation tone at $6.025\,\mathrm{GHz}$ in Fig $3b$ is above the noise floor.

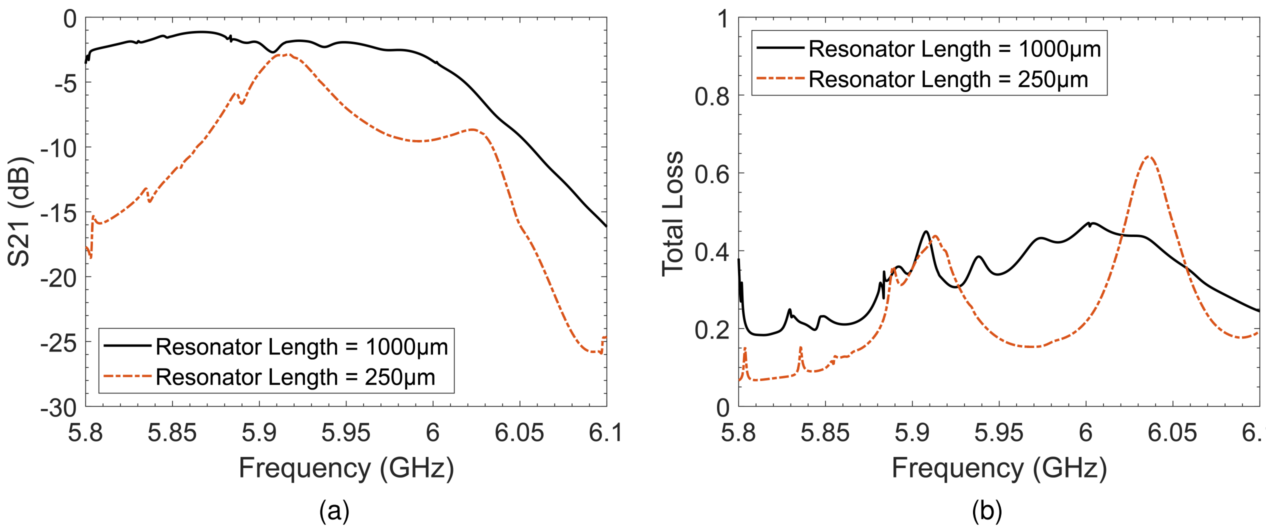


(a) (b)

Supplementary Fig. 3. Photograph of the raw 4-pole filter intermodulation distortion measurement spectrum taken from an Agilent PXA Spectrum Analyzer. The signal generator output power is set at **(a)** $7\,\mathrm{dBm}$ and **(b)** $9\,\mathrm{dBm}$.

Supplementary Information 3: Improving Filter Insertion Loss

Ansys HFSS finite element simulations are used to predict the performance of the MSFVW edge-coupled filters. The filter's out-of-band loss and insertion loss are shown to improve when using thicker gold electrodes. However, the measured insertion loss still remains high ($2.92\,\mathrm{dB}$ for the 2-pole filter). Using the thick gold electrodes, the coupled resonator structure is solved at the two fundamental resonance frequencies. The volume loss and surface loss are calculated for each material which shows that the loss is concentrated at the interface between the YIG and the gold transducer. By increasing the resonator length (and, by extension the transducer length), both the simulated interface loss of the coupled mode is reduced and the insertion loss improves. Supplementary Fig. 4 shows the simulated insertion loss and total loss $(1 - |S_{11}|^2 - |S_{21}|^2)$ at different resonator lengths.



Supplementary Fig. 4. Finite element simulation of a 2-pole edge-coupled MSFVW filter with resonator lengths of $250\,\mu\mathrm{m}$ and $1000\,\mu\mathrm{m}$ showing **(a)** insertion loss and **(b)** total loss.

References

[1] Y. Feng, S. Tiwari, S. A. Bhave *et al.*, "Micromachined Tunable Magnetostatic Forward Volume Wave Bandstop Filter," *IEEE Microwave and Wireless Technology Letters*, vol. 33, no. 6, pp. 807–810, Jun. 2023. [Online]. Available: https://ieeexplore.ieee.org/document/10111074/