nature portfolio

Peer Review File

An Edge-Coupled Magnetostatic Bandpass Filter

Reviewers' Comments:

Reviewer #1:

Remarks to the Author:

This manuscript reports an edge-coupled magnetostatic forward volume wave bandpass filter fabricated from YIG film grown on GGG substrate with inductive transducers. The parameters of the device including the bandwidth, the tunability, and the loss are quite impressive. However, this manuscript may not be compelling enough for publication in Nature Communications for the following reasons.

1.This manuscript in its current form is more suitable for IEEE journals due to the lack of significance to related fields. Magnetostatic bandpass filter with similar materials and performance has been reported years ago.

2.The authors mentioned that they used finite element simulation. However, I did not find any modeling descriptions or simulation results, not in the main text nor in the SI.

3. There are many gramma errors, such as:

On line 6 of the first paragraph of section II, “excite” should be “excites”;

Below Eq. (2), “reflects” should be “reflect”;

On line 1 on page 3, “represents” should be “represent”, and “frequency” should be added behind “resonance”;

On the last line of the first paragraph of section III on page 4, “with” should be added behind “agrees well”.

4. Fig. 7b and 7c should be in the form of a table.

Reviewer #3:

Remarks to the Author:

This paper demonstrates a novel design and fabrication (micromachining) of edge-coupled magnetostatic forward volume waves. The filter loss of 6.94dB is quite high, and the text explains that the loss is attributed to the gold transducers, however, to strengthen the paper more discussion about the YIG loss should be included. A path forward to reduce losses should also be discussed. Additionally, a spectrum of the two-tone linearity should be included to capture any potential limiting behavior of the device, especially at such device sizes. All other measurements show unique results for this novel filter topology.

PURDUE
UNIVERSITY

Connor Devitt
Elmore Family School of Electrical and
Computer Engineering, Purdue University
t. +1.215.485.2265
e. devitt@purdue.edu

Reviewer 1:

This manuscript reports an edge-coupled magnetostatic forward volume wave bandpass filter fabricated from YIG film grown on GGG substrate with inductive transducers. The parameters of the device including the bandwidth, the tunability, and the loss are quite impressive. However, this manuscript may not be compelling enough for publication in Nature Communications for the following reasons.

1. This manuscript in its current form is more suitable for IEEE journals due to the lack of significance to related fields. Magnetostatic bandpass filter with similar materials and performance has been reported years ago.

AUTHOR RESPONSE:

We respectfully disagree with the reviewer that our results lack significance for related fields. Nature family of journals recently emphasized engineering research results are becoming more pervasive and impact science and world more directly than ever before [1]. While magnetostatic wave bandpass filters have been demonstrated previously [2], [3], [4], [5], [6], [7], our manuscript details an innovative approach using multiple magnetically coupled YIG resonators towards a compact bandpass filter on a CHIP with the following advantages:

- A compact footprint of 870 µm x 740 µm (active area 520 µm x 360 µm) for a 4-pole filter which is competitive with state-of-the-art acoustic filters [8].
- Control over the filter bandwidth through design of the inter-resonator coupling M_{nm} which is lithographically defined during the ion milling step (see SI 1).
- Introduction of transmission zeros to the left or right of the passband to minimize spurious passbands and enhance selectivity.
- Independent control over the unit cell resonator allowing geometry optimization to maximize quality factor and coupling factor while minimizing spurious resonances.

Figure 1 (SEM is reproduced from Supplementary Information 1) illustrates the significant advancement of our technology. Our fabrication process gives precise control of the dimensions of the YIG resonators and the spacing between adjacent YIG mesas enabling an edge-coupled topology with miniaturized footprint, high selectivity, and suppressed spurious passbands.

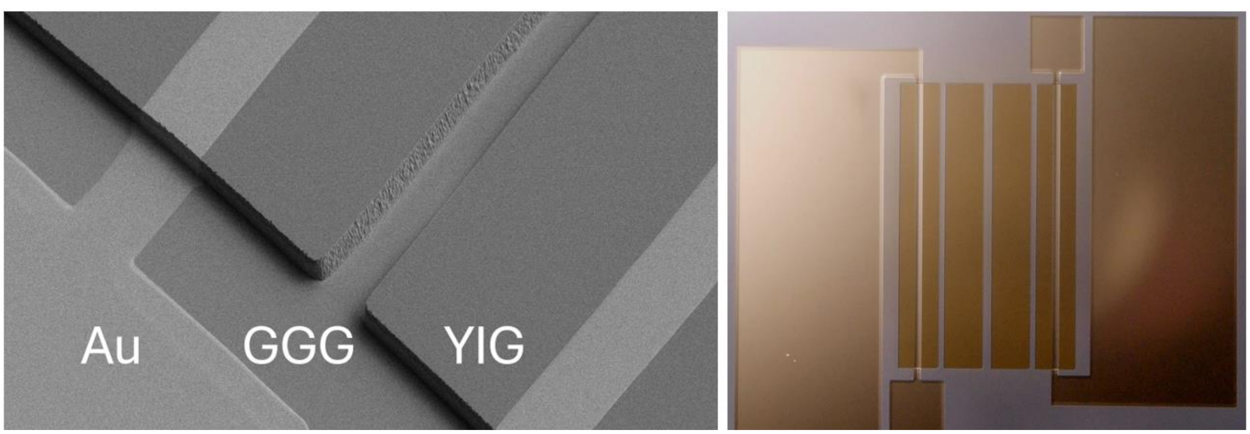

Figure 1: Left SEM shows two coupled YIG resonators with 9.8 µm gap and Au transducers in a 2-pole bandpass configuration. Right optical microphotograph is the 4-pole edge-coupled bandpass filter with dimensions 870 µm x 740 µm.

ACTION TAKEN:
The introduction section has been expanded to explicitly highlight the advantage of our filter technology.

In this paper, we show that planar YIG resonators can magnetically couple if they are fabricated in close proximity (Fig. 1b), analogous to the electrostatically coupled mechanical resonators in [2], [13] or coupled electromagnetic resonators [14], [15]. We demonstrate wafer-scale fabrication of magnetically coupled YIG filters in a highly compact footprint enabled by a surface micromachining process [6] detailed in Supplementary Information 1. Using multiple coupled resonators introduces additional design flexibility to optimize the unit cell resonator for high Q-factor, coupling, and good spurious suppression with independent control over the passband shape through the resonator coupling factors. A new class of compact coupled-resonator bandpass filters using magnetostatic waves in thin-film YIG is demonstrated.

2. The authors mentioned that they used finite element simulation. However, I did not find any modeling descriptions or simulation results, not in the main text nor in the SI.

   AUTHOR RESPONSE:
   We thank the reviewer for identifying this ambiguity. The filters and resonators were simulated using Ansys HFSS. Filter geometry, materials, and material thicknesses are provided in the "Bandpass Filter Design" section in the manuscript and Supplementary Information 1. The material properties of gold, GGG, and YIG are all widely available. The values used in our simulations will also be provided in our uploaded data repository on Zenodo upon manuscript publication.

   ACTION TAKEN:
   The bandpass filter design section been updated to clarify Ansys HFSS is used for finite element simulations and to provide the gold transducer geometry.

   at $w_{2,3} = 67\,\mu\mathrm{m}$ which was found to marginally improve insertion loss and higher order width mode suppression based on finite element simulation using Ansys HFSS. The $300\,\mathrm{nm}$ gold transducers are $10\,\mu\mathrm{m}$ wide over the $3\,\mu\mathrm{m}$ thick YIG mesas. At the probe launches, the gold signal pad is $94\,\mu\mathrm{m}$ wide with a $15\,\mu\mathrm{m}$ gap between the signal and ground pads.

3. There are many grammar errors, such as:
   a. On line 6 of the first paragraph of section II, "excite" should be "excites"
   b. Below Eq. (2), "reflects" should be "reflect"
   c. On line 1 on page 3, "represents" should be "represent", and "frequency" should be added behind "resonance"
   d. On the last line of the first paragraph of section III on page 4, "with" should be added behind "agrees well".

Birck Nanotechnology Center, Room 2027 ■ 1205 W. State St ■ West Lafayette, IN 47907-2035
(215) 485-2265 ■ devitt@purdue.edu ■ http://engineering.purdue.edu/oxidemems

AUTHOR RESPONSE:
We thank the reviewer and have corrected the errors in the manuscript.

ACTION TAKEN:
Line 73 has been updated.

resonators. With an out-of-plane DC magnetic bias, the RF magnetic field from the transducers excites MSFVW modes in the YIG mesa. Forward volume waves are a family of highly

Line 85 has been updated.

denoted as the spin wave manifold. When the planar dimensions of the thin YIG film are bounded, the magnetostatic waves reflect off the edges forming a standing waves with wave vectors approximately given by [17]–[21]:

Lines 138-139 have been updated.

by (5) where f_p and f_s represent the magnetic resonance and anti-resonance frequencies respectively.

Lines 199-200 have been updated.

between the chip and sensor. In this setup, the extrapolated $0\,\mathrm{Oe}$ intersection is at $\omega_m = \mu_0\gamma_m \cdot 1751\,\mathrm{Oe}$ which agrees well with the saturation magnetization of liquid phase epitaxy (LPE) YIG.

Additional small grammatical mistakes have been corrected.

filter from 4.5 GHz to 10.1 GHz while retaining a fractional bandwidth of 0.3%, an insertion loss of 6.94 dB, and a −35dB rejection level. We characterize the filter nonlinearity in the

[7]) and experimentally reported Q-factors exceeding 3000 [8], [9]. In state-of-the-art YIG sphere filters [10]–[12], polished YIG resonators are attached to a thermally conductive rod

significant improvement from 43% to only 12%. The average loss within the 3dB bandwidth exhibits a slight bias dependent improvement up to a 14.5% reduction. The insertion loss

4. Fig. 7b and 7c should be in the form of a table.

AUTHOR RESPONSE:
We thank the reviewer for this suggestion and have moved 7b and 7c into a separate compact table.

ACTION TAKEN:
Figures 7b and 7c have been combined into a single table.

Birck Nanotechnology Center, Room 2027 ■ 1205 W. State St ■ West Lafayette, IN 47907-2035
(215) 485-2265 ■ devitt@purdue.edu ■ http://engineering.purdue.edu/oxidemems

TABLE I
SUMMARY OF THE 4-POLE FILTER IIP3 MEASUREMENTS

	Stopband Low	Passband	Stopband High
High Tone	5.465 GHz	5.799 GHz	6.055 GHz
IIP3	≥ 37.95 dBm	-4.85 dBm	25.84 dBm

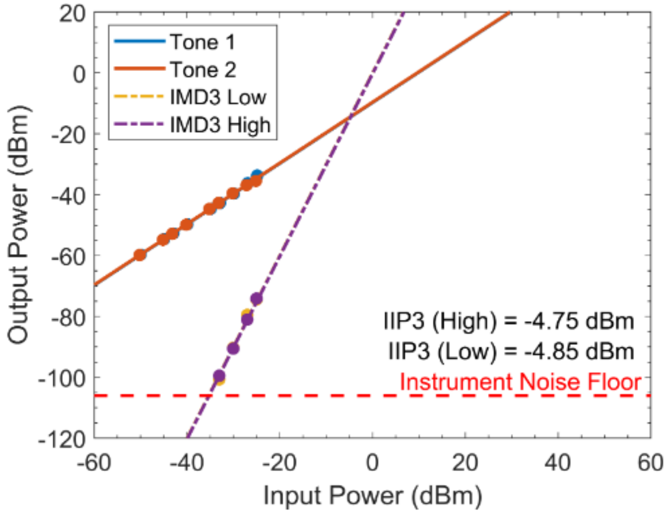

Fig. 7. Two-tone IIP3 measurement in the passband of a 4-pole filter at 3652 Oe bias. The two input tones are separated by 15 MHz with the high tone at 5.799 GHz.

The text has been updated to refer to Table I instead of figures 7b and 7c.

with a frequency separation of $\Delta f = 15$ MHz. The higher of the two tone frequencies for each region are listed in Table *I*. A wideband power divider combines the two tones while an Agilent PXA spectrum analyzer measures the resultant spectrum. A two-stage calibration is performed to remove all cable and system losses at every tone frequency and input power level. Far away from the passband, the filter is expected to be linear and no intermodulation products were observed. Based on the maximum output power of the signal generators and noise floor of the spectrum analyzer, the lower stopband IIP3 is estimated to be greater than 37.95 dBm at 3652 Oe. The passband shows the greatest nonlinearity with an IIP3 of -4.75 dBm at 3652 Oe as shown in Fig. 7. The measured IIP3 in each frequency region is summarized in Table *I*.

Reviewer 2:

This paper demonstrates a novel design and fabrication (micromachining) of edge-coupled magnetostatic forward volume waves.

1. The filter loss of 6.94dB is quite high, and the text explains that the loss is attributed to the gold transducers, however, to strengthen the paper more discussion about the YIG loss should be included. A path forward to reduce losses should also be discussed.

AUTHOR RESPONSE:
Increasing the gold thickness significantly reduces the out-of-band loss and improves measured filter insertion loss (to 2.92 dB for a 2-pole filter). The quoted 6.94 dB of insertion loss is for a 4-pole filter with 300nm gold electrodes (Fig. 5b). Due to the finite quality factor of each resonator, higher-order filters inherently have higher loss.

From the spectrum in Fig. 6b in the text, the total loss peaks at the location of each coupled magnetostatic mode for both gold thicknesses. In HFSS simulations, the contribution of each material towards the total loss is calculated at the two fundamental coupled magnetostatic wave modes. It is observed that the loss is concentrated at the interface between the YIG and Au. Through additional optimization using simulations, the interface loss can be reduced while by increasing the length of the YIG and insertion loss can be reduced below 2 dB for the 2-pole filter.

ACTION TAKEN:
The section discussing loss has been updated to state the remaining loss is concentrated at the Au/YIG interface. A proposed change to the resonator geometry is provided which results in lower simulated interface loss and insertion loss. Supplementary Information 3 has been added which shows this simulation result.

> 2.92 dB around 3660 Oe. From Fig. 6*b*, the total loss peaks at the resonance frequency of each magnetostatic mode. Using an HFSS simulation with 3 μm thick gold, each material's contribution to the total loss at the fundamental coupled modes is calculated. This analysis reveals that the remaining loss is concentrated at the interface between the YIG mesa and the gold transducer. By increasing the resonator length, both the simulated interface loss and insertion loss can be reduced.

2. Additionally, a spectrum of the two-tone linearity should be included to capture any potential limiting behavior of the device, especially at such device sizes. All other measurements show unique results for this novel filter topology.

AUTHOR RESPONSE:
We thank the reviewer for their comment and have included the spectrums from the intermodulation distortion measurement in Supplementary Information 2.

ACTION TAKEN:
Supplementary Information 2 has been included showing the raw uncalibrated filter spectrum at two different power levels for the 4-pole filter IIP3 measurements.

References:

[1] "Calling all engineers: Nature wants to publish your research," *Nature*, vol. 626, no. 7999, pp. 455–456, Feb. 2024, doi: 10.1038/d41586-024-00390-4.
[2] J. D. Adam, "An MSW Tunable Bandpass Filter," in *IEEE 1985 Ultrasonics Symposium*, San Francisco, CA, USA: IEEE, 1985, pp. 157–162. doi: 10.1109/ULTSYM.1985.198496.
[3] W. S. Ishak, "Magnetostatic wave technology: a review," *Proc. IEEE*, vol. 76, no. 2, pp. 171–187, Feb. 1988, doi: 10.1109/5.4393.

Birck Nanotechnology Center, Room 2027 ■ 1205 W. State St ■ West Lafayette, IN 47907-2035
(215) 485-2265 ■ devitt@purdue.edu ■ http://engineering.purdue.edu/oxidemems

[4] Y. Zhang *et al.*, “Nonreciprocal Isolating Bandpass Filter With Enhanced Isolation Using Metallized Ferrite,” *IEEE Trans. Microw. Theory Tech.*, vol. 68, no. 12, pp. 5307–5316, Dec. 2020, doi: 10.1109/TMTT.2020.3030784.
[5] G.-M. Yang, J. Wu, J. Lou, M. Liu, and N. X. Sun, “Low-Loss Magnetically Tunable Bandpass Filters With YIG Films,” *IEEE Trans. Magn.*, vol. 49, no. 9, pp. 5063–5068, Sep. 2013, doi: 10.1109/TMAG.2013.2253114.
[6] R. Marcelli, A. Lucibello, E. Proietti, and T. Koike, “Coupled Micromachined Magnetic Resonators for Microwave Signal Processing,” *Micromachines*, vol. 15, no. 2, Art. no. 2, Feb. 2024, doi: 10.3390/mi15020259.
[7] X. Du *et al.*, “Frequency tunable magnetostatic wave filters with zero static power magnetic biasing circuitry,” *Nat. Commun.*, vol. 15, no. 1, p. 3582, Apr. 2024, doi: 10.1038/s41467-024-47822-3.
[8] G. Giribaldi, L. Colombo, P. Simeoni, and M. Rinaldi, “Compact and wideband nanoacoustic pass-band filters for future 5G and 6G cellular radios,” *Nat. Commun.*, vol. 15, no. 1, p. 304, Jan. 2024, doi: 10.1038/s41467-023-44038-9.

Reviewers' Comments:

Reviewer #1:

Remarks to the Author:

The revised manuscript has been substantially improved following suggestions on the previous version. The added details in the paper allows for better understanding for the broader audience, therefore I recommend to publish this manuscript in Nature Communications as is.

Connor Devitt
Elmore Family School of Electrical and Computer Engineering, Purdue University
t. +1.215.485.2265
e. devitt@purdue.edu

July 24, 2024

Reviewer 1:
The revised manuscript has been substantially improved following suggestions on the previous version. The added details in the paper allows for better understanding for the broader audience, therefore I recommend to publish this manuscript in Nature Communications as is.

AUTHOR RESPONSE:
We thank the reviewer for their positive comment.

ACTION TAKEN:
We have expanded the abstract and introduction and added a methods section based on the editor's suggestion.