

A Wideband Tunable, Nonreciprocal Bandpass Filter Using Magnetostatic Surface Waves with Zero Static Power Consumption

Corresponding Author: Professor Roy Olsson

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Review Comments for

A Wideband Tunable, Nonreciprocal Bandpass Filter Using Magnetostatic Surface Waves with Zero Static Power Consumption

The manuscript presents an innovative demonstration of nonreciprocal bandpass filters implemented on thick (18 μm) YIG films grown on GGG substrates. The reported results are impressive and highlight significant advancements in magnetostatic wave-based filtering. However, the manuscript would benefit from a more thorough analysis of certain design choices. The paper explores several aspects of the device, including YIG thickness, transducer design (meander vs. straight lines), waveguide geometry, and surface planarization using BCB. While the rationale behind BCB planarization and the use of meander line transducers is well-articulated, the selection of YIG thickness and geometry—and their impact on device performance—require further elaboration. Below are specific comments and suggestions:

1. The selection of YIG thickness for the study needs to be explained with a more detailed analysis of its effect on non-reciprocity. The reference [30] cited in the manuscript details the non-reciprocity dependence as a function of the ratio of film thickness and wavelength. Was the thickness of 18 μm selected to keep these dependencies in mind?
2. Most of the analysis is only shown for 3 μm and 18 μm films. It would be beneficial to demonstrate the effects of varying YIG thickness from 3 to 18 μm or even higher and explain why 18 μm was chosen.
3. Since the authors claim that most of the performance metrics of the filter improve as we increase the thickness, is there no trade-off? Moreover, reference [27] provided in the manuscript suggests that the absorbed power (which I assume the authors relate to coupling) doesn't significantly change from 1 μm to 3 μm YIG. Can the author elaborate on this?
4. Perhaps the most impressive aspect of this manuscript is the non-reciprocity, which is achieved using a dual-hexagon shape of YIG that is 18 μm thick. Can the authors quantify how much the thickness of the YIG is helping? For example, if we use the same dual-hexagon shape on a 3 μm YIG, what level of non-reciprocity can we expect? Additionally, can the author detail how they arrived at this specific geometry and if it is optimal in terms of isolator performance? Have the authors tried other geometries?
5. The main manuscript mostly uses 18 μm but the fab images in the supplementary shows 15 μm which results in some confusion.
6. It is stated that a triangular YIG boundary prevents MSSW propagation on the bottom surface, but the mechanism is unclear. Could the authors elaborate on why a triangular YIG boundary is more effective at suppressing backside reflections compared to other boundary geometries?
7. An additional citation should be included for meander line MSSW transducers.
 - a. J. P. Parekh and H. S. Tuan, "Meander line excitation of magnetostatic surface waves," Proceedings of the IEEE, vol. 67, no. 1, pp. 182–183, Jan. 1979, doi: 10.1109/PROC.1979.11221.
8. In lines 225-226, the authors state that the meander line transducers allow control over the MSSW wavelength. However, they do not provide such a discussion in the text.
9. In lines 271-273, the authors state that the width of the yoke is reduced. Can the authors provide additional details on how this change reduces leakage flux? Additionally, which dimension in Fig. 1c corresponds to the width?
10. The authors claim the magnetic assembly shows zero continuous power consumption. However, the power consumption

- while tuning the magnetic bias and the tuning time is also of high interest. I suggest the authors include this information.
11. In Figure 5a, the authors show the magnetic flux density dependence on the applied current pulse amplitude. Can the authors comment on the degree of hysteresis in the field tuning? Additionally, the repeatability data from the magnetic bias circuit would be helpful.
 12. The iron-cobalt yoke material is typically lossy for electromagnetic waves. Can the authors comment on any differences in the isolator performance measured with and without the integrated magnetic assembly?
 13. The authors should cite the following recent SAW filter that showed frequency up to 8.63 GHz with insertion loss below 2 dB when discussing them in lines 330-335
a. Yang et al., "SV-SAW RF filters based on low-cost 128°Y LiNbO₃/SiO₂/poly-Si/Si substrate for 6G cmWave wireless communications," *Microsyst Nanoeng*, vol. 11, no. 1, p. 79, May 2025, doi: 10.1038/s41378-025-00949-9.
 14. In Fig. 1a, the authors state that the filtering isolator is placed before the PA to eliminate out-of-band signals and reflections. However, the PA itself will generate large out-of-band frequency products, and its output is sensitive to reflections. Can the authors detail why the filter is not placed between the PA and antenna? Can the authors also clarify why an isolator (instead of impedance matching sections, for example) is required to minimize signal reflections?
 15. Can the author add details explaining whether the isolator is absorptive or reflective? If the isolator is reflective, then the Tx system in Fig. 1a could amplify and re-transmit in-band reflections.
 16. In lines 42-43 and Fig. 1a, can the authors further explain the significance of attenuating reflected signals in the Rx path?
 17. In line 59: Should the text say "a zero-static-power magnetic bias circuit" instead of "zero static magnetic bias circuit"?
 18. There is an extra \cdot in the caption for Fig. 1 around "unidirectional \cdot magnetostatic wave"
 19. Typo in Y-label of Supplementary Figure 28.

Reviewer #2

(Remarks to the Author)

The authors made a critical advancement in fabrication, specifically a benzocyclobutene planarization process, that enabled the development of a 18 μm thick YIG filter tunable from 4 GHz to 17.7 GHz. In addition to the broad tuning range, the filter also demonstrates pronounced nonreciprocity, which expands the application space of this technology within RF frontends. In addition to the device demonstration, the authors implemented integrated magnetic bias circuitry, a critical step forward toward practical system integration. While this team previously demonstrated a similar technology, specifically a 3 μm thick YIG tunable filter, again with incorporated magnetic bias circuitry, the authors made a significant step forward advancing performance on both fronts. With respect to the filter the significantly thicker YIG film improved the power handling, filter selectivity, and bandwidth, while enabling the observed RF transmission nonreciprocity. In addition, the magnetic bias circuitry was designed to be more compact (reduced volume from 1.68 to 1.07 cm^3) with a larger magnetic field range (up to 5700 Gauss). The authors presented significant and comprehensive characterization of all aspects of the nonreciprocal, tunable filter and those results fully supported their findings. While related to their earlier work, this represents a major improvement enabled by a new fabrication method that allows for thicker YIG films than previously possible. This breakthrough not only benefits RF front-end applications but is also relevant to the broader YIG research community, including spintronics applications. Since this benzocyclobutene planarization process was central to enabling this device, I was happy to find that in the methods section the details of the fabrication were listed explicitly, such that others could exploit this approach in their own research. I also really enjoyed the final figure #6 which contrasts competing technologies with this study. I believe this work has high technical merit, and represents a significant step forward toward compact, low power nonreciprocal tunable filters based on YIG, and therefore should be accepted for publication. There should be more work like this—where the focus isn't just on a scientific demonstration, but on translating state-of-the-art magnetic technologies into real-world applications. This kind of research helps bridge the gap between novel materials science and practical RF systems, making the case for why advanced magnetics matter beyond the lab and serves a purpose.

Reviewer #3

(Remarks to the Author)

This paper presents a comprehensive study on the design and performance optimization of magnetostatic surface wave filters using inductive meander line transducers. Building upon the foundational concept introduced in the authors' earlier work [12], where transducers were fabricated on 3 μm thick YIG films, this study significantly extends the investigation by employing much thicker 18 μm YIG films. The transition to thicker films introduced new fabrication challenges, particularly in maintaining electrode continuity across significant surface topologies from the thick YIG films. The authors addressed these issues by developing a novel fabrication process, enabling successful device realization. The use of thicker YIG films led to notable improvements in filter linearity and bandwidth. Furthermore, the authors explored a wide range of transducer geometries, offering valuable insights into how design variations impact filter performance. In addition to the transducer advancements, the paper integrates the filters into a zero static power magnetic bias assembly. Comparing to the authors' previous work in [10], the bias assembly achieved a significantly enhanced tuning range (4–17.7 GHz), an over 50% improvement comparing to [10], while also reducing the assembly size through improved flux management and high-saturation magnetic materials. Overall, this is a well-executed and insightful study that meaningfully advances the field. That said, I do have several comments and questions that I hope the authors can address:

1. Line 21~22, line 38~39, I'm wondering if the authors can provide a more specific example to motivate the needs of having a non-reciprocal filtering device in the RF transceiver chain. Based on Fig. 1a, for a filter sits between Rx antenna and Rx LNA, the impedances at each interface are typically carefully engineered to ensure proper matching, optimize noise figure, ensure Rx stability. To my knowledge this is manageable. And on the Tx side, I could imagine a scenario where if there is some highly reflective objects near the antenna, the reflection could potentially de-stabilize the PA. And a non-reciprocal

device might help. However, are the linearity and power handling of magnetostatic wave based device sufficient to handle the power from the PAs?

2. Line 67, from what was described in the following sections, it seems it was the thicker YIG enhances nonreciprocity? Also in this context nonreciprocity is isolation?

3. Line 103~105: in general, when a wave is quantized in the transverse direction due to guiding, shouldn't the frequency of such spur be higher than the plane wave mode if the dispersion is normal (as opposed to anomalous dispersion commonly seen in FBAR devices). And MSSW exhibits normal dispersion? In addition, the wavevector of such spur should have a transverse component? My understanding is that the MSSW, MSFVW, MSBVW are derived under plane wave assumptions. When the wavevector has a transverse component, it seems the polarization of the MSSW would have to pick up something that's similar to MSBVW. Would an alternative interpretation be possible where there's some sort of MSSW and MSBVW hybridization happening leading to the frequency dropping below the MSSW manifold?

4. Line 130: is it possible to squeeze in chart on corresponding s_{21} ?

5. Fig.2: it seems the etching profile of YIG is highly tapered, and the electrode edges are rough. Can you comment on the effect of these on loss?

6. Line 155: "a is the width of the transducer". This might be a little confusing. One could potentially interpret "a" as the length of the arm of the meander line. Maybe add an annotation in one of the figures, and refer to it? Or rephrase?

7. Line 169: why a different "a" was chosen for the 18 μ m YIG device comparing to 3 μ m YIG devices, can you elaborate?

8. Line 185-187: the return loss should also be dependent on z_{12} , z_{21} , and z_{22} ? Maybe also provide values for these, when referring to return losses?

9. Line 203~205: "furthermore....", can this statement be quantified? Not sure if could find measurements or calculations on this in the manuscript.

10. Line 233~234, can the authors discuss what's the fundamental limit of the insertion loss? When two parallel design is used, the transducer input impedance is around 50 Ω ? Do the authors expecting better insertion loss than measured?

11. Line 240: "spurious mode around 8.8GHz" did the authors mean 8.4GHz?

12. Line 283~286: it seems the P1db were measured with VNA by varying the excitation power? It's a little hard to see in the figures in the supplement materials, but it would be interesting to see if the p1db vs. frequency? Might not provide much insights, but might be interesting.

13. Line 347: what is the purpose of annealing the ALD oxide hard mask? Improving selectivity? Anneal out pinholes? It is interesting that an ALD hard mask is used here. Can the authors comment on why ALD? Also, line:358, patterning of the aluminum transducers uses a PECVD oxide? Why oxide hard masks using different deposition methods are used for the two steps?

14. Line 354: it is not immediately clear which part of the BCB was patterned from first read. Maybe refer to one of the figures? And add some annotations?

15. Line 355: annealing the BCB to cure it and make it permanent?

16. Has the authors tried IP3 measurements?

Reviewer #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Review Comments for

A Wideband Tunable, Nonreciprocal Bandpass Filter Using Magnetostatic Surface Waves with Zero Static Power Consumption-Revision

The authors have made commendable progress in revising the manuscript, and most of the previous comments have been addressed satisfactorily. The discussion on YIG thickness selection is much improved and provides useful context. However, to further strengthen the manuscript and enhance its value to the broader community, it would be beneficial to include some quantitative analysis of the design choices.

For instance, the authors note that experimental data is currently limited to 3, 15, and 18 μ m YIG films due to availability constraints, and that no significant performance difference was observed between the 15 and 18 μ m samples. Given this, it remains unclear whether a 15 μ m or even a 10 μ m film—if available—might yield comparable results. While it is understandable that acquiring experimental data across the full 3–18 μ m range may not be feasible within a reasonable timeframe, a theoretical or simulation-based analysis could help understand the continuous behavior of device performance as a function of YIG thickness.

As a suggestion, Figures 2(a) and 2(b) could be regenerated for additional thickness values within this range to examine whether the observed improvements are monotonic or tend to saturate. Similarly, Figure 3(a) might also be updated accordingly. At present, the manuscript implies that only two thickness options—3 μ m and 18 μ m—are viable. To guide future development of YIG films with intermediate thicknesses, it would be helpful to understand whether increasing

thickness continues to offer benefits or if an optimal balance exists. This insight would be valuable in informing the direction of subsequent research efforts.

In addition to the above, the following minor comments may also be considered:

1. Since the manuscript includes measurements using 18 μm -thick YIG, it would be helpful if Supplementary Figure 19a also presented the internal magnetic field for this thickness.
2. In Figure 1a, the labels “DAC” and “ADC” appear to be reversed. For clarity, “DAC” should be placed in the Tx path.

Reviewer #2

(Remarks to the Author)

This revised version strengthens the manuscript, which was already compelling in the first round for its high-quality device physics and clear relevance to adaptive signal-filtering applications. The integration of compact, low-power magnetic bias circuitry advances the work’s practical viability and system-level significance. Clarifications regarding YIG thickness selection and geometry-driven nonreciprocity provide more clarity, while the inclusion of quantitative data on tuning dynamics, repeatability, power handling, and linearity demonstrates the device’s technological maturity. The expanded fabrication details, improved organization, and polished presentation make this a well-executed and impactful paper that is more than suitable for publication.

Reviewer #3

(Remarks to the Author)

The authors have presented a significant body of work, and addressed all my comments. I do not have further comments.

Reviewer #4

(Remarks to the Author)

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

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Reviewer #1 (Remarks to the Author):

Review Comments for A Wideband Tunable, Nonreciprocal Bandpass Filter Using Magnetostatic Surface Waves with Zero Static Power Consumption

The manuscript presents an innovative demonstration of nonreciprocal bandpass filters implemented on thick (18 μm) YIG films grown on GGG substrates. The reported results are impressive and highlight significant advancements in magnetostatic wave-based filtering. However, the manuscript would benefit from a more thorough analysis of certain design choices. The paper explores several aspects of the device, including YIG thickness, transducer design (meander vs. straight lines), waveguide geometry, and surface planarization using BCB. While the rationale behind BCB planarization and the use of meander line transducers is well-articulated, the selection of YIG thickness and geometry—and their impact on device performance—require further elaboration. Below are specific comments and suggestions:

Answer to the reviewer:

We sincerely appreciate the reviewer's positive and encouraging comments on our work. The reviewer's constructive feedback has been extremely helpful in identifying areas where further clarification and elaboration could enhance the manuscript. In the revised version, we have expanded the discussion on the rationale for selecting specific YIG thicknesses and geometries, and we have provided additional analysis on how these parameters influence device performance.

1. The selection of YIG thickness for the study needs to be explained with a more detailed analysis of its effect on non-reciprocity. The reference [30] cited in the manuscript details the non-reciprocity dependence as a function of the ratio of film thickness and wavelength. Was the thickness of 18 μm selected to keep these dependencies in mind?

Answer to the reviewer:

We thank the reviewer for this insightful comment regarding the selection of YIG thickness and its relation to nonreciprocity. The 15–18 μm YIG film used in this study was not chosen based on an optimization process but rather due to commercial YIG availability constraints. This thickness range represents the thickest high-quality YIG-on-GGG films currently available from commercial vendors, in contrast to the much more common 3 μm films.

Nevertheless, the observed enhancement in nonreciprocity for the 15–18 μm films aligns well with the theoretical understanding described in reference [30], where nonreciprocity is shown to increase with the ratio of film thickness to magnetostatic surface wave (MSSW) wavelength. Although the thickness was not specifically selected to satisfy this condition, our experimental results are consistent with this dependence. As also noted in [30], we expect that even greater nonreciprocity could be achieved in future devices using thicker YIG films, should such materials become available.

2. Most of the analysis is only shown for 3 μm and 18 μm films. It would be beneficial to demonstrate the effects of varying YIG thickness from 3 to 18 μm or even higher and explain why 18 μm was chosen.

Answer to the reviewer:

We appreciate the reviewer's valuable comment regarding the exploration of YIG film thickness variation. In our current study, we focused on 3 μm and 15-18 μm YIG films primarily due to the high materials cost and limited commercial availability of intermediate thicknesses. Each wafer costs over \$20,000, which makes it financially impractical to include multiple additional thicknesses within this work. Moreover, despite our efforts to procure YIG films with intermediate thicknesses, the manufacturer (MTI corporation) was unable to provide YIG-on-GGG wafers between 3 μm and 18 μm .

Nevertheless, this study systematically investigates the influence of YIG thickness through both experimental comparison (3 μm vs. 18 μm) and theoretical analysis. We examined several key parameters affected by thickness, including dispersion characteristics, power handling capability, nonreciprocity, linearity, and propagation loss. These analyses collectively offer a framework that can be extended to predict and optimize the performance of YIG filters with intermediate or even greater thicknesses in future work.

The following sentences have been added to the revised manuscript:

Discussion Section:

Although only one thin YIG film (3 μm) and one thick YIG film (15 - 18 μm) were examined in this study due to limits on commercially available YIG thicknesses, the BCB planarization fabrication method demonstrated here can be readily adapted to YIG films of other thicknesses. Furthermore, this work provides the first comprehensive experimental and theoretical analysis of the thickness effect in microfabricated YIG films. The methodologies used here, including dispersion relation, power handling, linearity, nonreciprocity, and propagation loss, can be directly applied to future investigations of YIG devices with intermediate or alternative thicknesses.

3. Since the authors claim that most of the performance metrics of the filter improve as we increase the thickness, is there no trade-off? Moreover, reference [27] provided in the manuscript suggests that the absorbed power (which I assume the authors relate to coupling) doesn't significantly change from 1 μm to 3 μm YIG. Can the author elaborate on this?

Answer to the reviewer:

We appreciate the reviewer's thoughtful comments and the opportunity to clarify this point. In the study by V. Castel et al. [27], the absorbed power did not appear to increase significantly with YIG film thickness primarily because the measurements were performed near the saturation level of the available RF power. Nevertheless, their results did show that the magnitude of the absorbed power increased with frequency below the saturation point, which is consistent with the fact that absorbed power scales with the effective volume of YIG interacting with the microwave field. Therefore, in general, the coupling efficiency (or absorption efficiency) is expected to increase with YIG film thickness, as a thicker film provides a larger interaction volume for MSSW excitation.

Regarding the trade-offs associated with increasing YIG thickness, several important challenges arise. As discussed in detail in this study, the primary limitation is the increased difficulty in microfabrication, which we addressed through the proposed BCB planarization process.

Additionally, demagnetization effects become more pronounced in thicker films. As shown in Supplementary Note #6 (comparison of YIG filters with dual-waveguide and single-waveguide designs), stronger demagnetizing fields in thicker YIG reduces the effective channel width and central internal field, degrading the uniformity of the MSSW mode. The integration of two parallel waveguides into a single, wider structure partially mitigates this issue.

Another observed trade-off is that increasing YIG thickness raises the minimum operating frequency of the tunable filter. In this work, the minimum frequency with acceptable insertion loss is approximately 4 GHz, which is higher than the ~ 3.3 GHz achieved in previous works using 3 μm thick YIG films [R1-3-1]. The underlying mechanism for this frequency shift remains under investigation and will be explored in future studies.

[R1-3-1] X. Du et al., "Frequency tunable magnetostatic wave filters with zero static power magnetic biasing circuitry," Nature Communications, vol. 15, no. 1, p. 3582, 2024.

4. Perhaps the most impressive aspect of this manuscript is the non-reciprocity, which is achieved using a dual-hexagon shape of YIG that is 18 μm thick. Can the authors quantify how much the thickness of the YIG is helping? For example, if we use the same dual-hexagon shape on a 3 μm YIG, what level of non-reciprocity can we expect? Additionally, can the author detail how they arrived at this specific geometry and if it is optimal in terms of isolator performance? Have the authors tried other geometries?

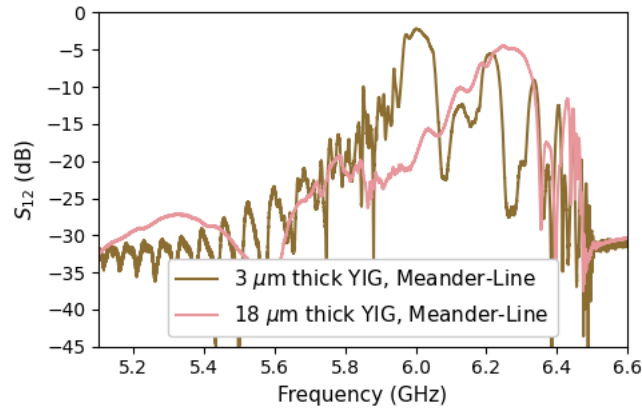
Answer to the reviewer:

We appreciate the reviewer's thoughtful comments and recognition of the significance of the observed nonreciprocity. To quantify the effect of YIG thickness on nonreciprocity, we compared the performance of meander-line transducer filters fabricated on 3 μm and 18 μm YIG films. As shown in Figure 1-4-1 (Fig. 3c in the main text), both filters exhibit distinct passbands in the forward transmission (S_{12}). However, in Figure 1-4-2 (Supplementary Figure 11), the backward transmission (S_{21}) differs markedly: the 3 μm filter shows less than 5 dB attenuation, whereas the 18 μm filter exhibits strong suppression, indicating pronounced nonreciprocal behavior.

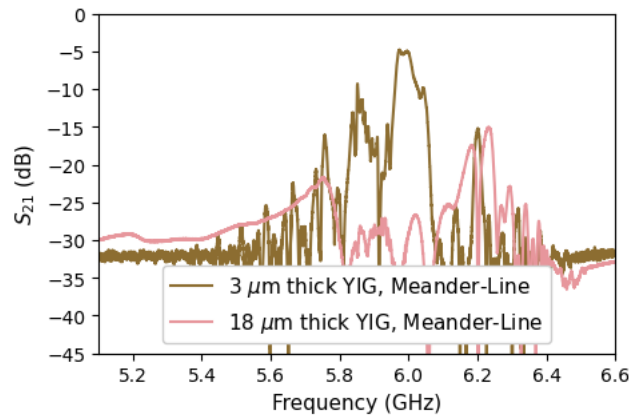
The difference arises from the underlying propagation mechanisms. In the 3 μm -thick YIG filter, the device functions similarly to a resonator, where the two straight edges act as reflective boundaries [R1-4-1, R1-4-2]. The magnetostatic surface waves (MSSWs) are reflected back and forth between the edges, forming standing or circulating wave patterns that yield nearly reciprocal transmission.

In contrast, the 18 μm -thick YIG filter no longer supports such resonant circulation. The spin waves excited at one port propagate primarily in a single direction and experience minimal reflection. One key factor is the increased sidewall roughness of the thicker YIG film, as visible in the optical micrographs (Fig. 2c and Fig. 2d). The roughened edges, which result from the greater etching depth required for thick YIG, act as scattering centers that suppress spin-wave reflection. This phenomenon is consistent with previous studies that used rough and lossy edge terminations [R1-4-3, R1-4-4, R1-4-5, R1-4-6], nonuniform magnetic fields [R1-4-7], or additional spin wave absorbers [R1-4-8, R1-4-9, R1-4-5] to minimize reflection and enhance nonreciprocity. Furthermore, increasing the film thickness enhances surface confinement and unidirectionality of MSSWs on a single surface, further amplifying nonreciprocal transmission.

Regarding the geometry, we appreciate the reviewer's question. While the dual-hexagon geometry used here effectively promotes unidirectional propagation, it has not been fully optimized. Other geometries may also enhance nonreciprocity, such as rotated YIG slabs [R1-4-10], or tapered edges (cut at an oblique angle to the propagation direction to scatter reflected waves) [R1-4-11 and R1-4-12]. These alternatives will be investigated in future work to identify optimal designs for isolator performance.



Response Figure 1-4-1 (Fig. 3c in the main text): Comparison of measured S_{12} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss.



Response Figure 1-4-2 (Supplementary Figure 11): Comparison of measured S_{21} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss.

- [R1-4-1] K. W. Chang and W. Ishak, "Magnetostatic surface wave straight-edge resonators," *Circuits, systems and signal processing*, vol. 4, pp. 201–209, 1985.
- [R1-4-2] 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 27 2024, doi: 10.1038/s41467-024-47822-3.
- [R1-4-3] N. Kanazawa et al., "Spin wave absorber generated by artificial surface anisotropy for spin wave device network," *AIP Advances*, vol. 6, no. 9, 2016.
- [R1-4-4] J. H. Collins, D. M. Hastie, J. M. Owens, and C. V. Smith, Jr., "Magnetostatic wave terminations," *Journal of Applied Physics*, vol. 49, no. 3, pp. 1800–1802, 1978, doi: 10.1063/1.324870.
- [R1-4-5] V. L. Taylor, J. C. Sethares, and C. V. Smith, "MSW Terminations," in *1980 Ultrasonics Symposium*, 5–7 Nov. 1980 1980, pp. 562–570, doi: 10.1109/ULTSYM.1980.197461.
- [R1-4-6] H. Glass, L. Adkins, and F. Stearns, "Attenuation layer for magnetostatic wave (MSW) absorbers," *IEEE Transactions on Magnetics*, vol. 20, no. 5, pp. 1235–1237, 2003.
- [R1-4-7] W. Faber, "Terminations for magnetostatic waves," *Electronics Letters*, vol. 16, no. 12, pp. 452–453, 1980, doi: 10.1049/el:19800318.

- [R1-4-8] K. Shimada et al., "Extremely flat transmission band of forward volume spin wave using gold and yttrium iron garnet," *Journal of Physics D: Applied Physics*, vol. 50, no. 27, p. 275001, 2017.
- [R1-4-9] J. Krug and P. Edenhofer, "Broadband terminations for magnetostatic surface waves," *Electronics Letters*, vol. 19, no. 23, pp. 971–972, 1983, doi: doi:10.1049/el:19830660.
- [R1-4-10] J. Wu, X. Yang, S. Beguhn, J. Lou, and N. X. Sun, "Nonreciprocal tunable low-loss bandpass filters with ultra-wideband isolation based on magnetostatic surface wave," *IEEE transactions on microwave theory and techniques*, vol. 60, no. 12, pp. 3959-3968, 2012.
- [R1-4-11] H. Yu et al., "Magnetic thin-film insulator with ultra-low spin wave damping for coherent nanomagnonics," *Scientific reports*, vol. 4, no. 1, p. 6848, 2014.
- [R1-4-12] W. Ishak, "Magnetostatic surface wave devices for UHF and L band applications," *IEEE Transactions on Magnetics*, vol. 19, no. 5, pp. 1880-1882, 1983, doi: 10.1109/TMAG.1983.1062691.

The following sentences have been added to the revised manuscript:

YIG Filter with Meander-Line Transducers Section:

Moreover, Supplementary Note #4 also compares the nonreciprocity of 3 μm and 18 μm thick YIG meander-line filters. It highlights that, with increasing film thickness and the resulting roughened sidewalls, the YIG structure no longer supports resonant circulation. Instead, the spin waves excited at one port predominantly propagate in a single direction, leading to enhanced nonreciprocal behavior.

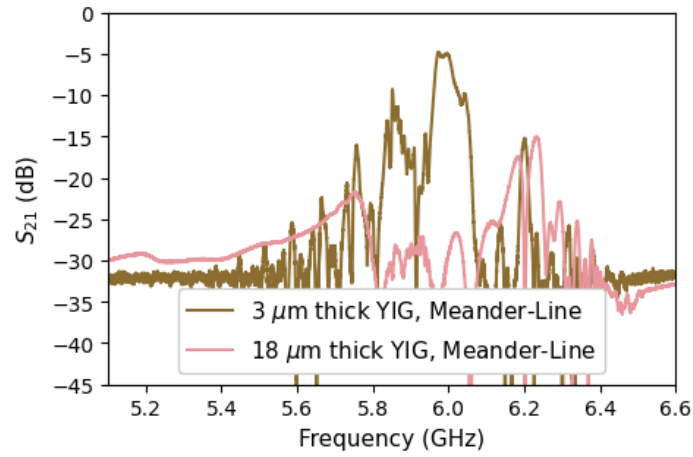
Supplementary Note #4: Comparison of YIG Filters with Straight Line and Meander-Line Transducers:

Supplementary Figure 11 highlights the improved nonreciprocity observed in the 18 μm thick YIG filters with meander-line transducers compared to their 3 μm thick counterparts. As shown in Fig. 3c, both filters exhibit distinct passbands in the forward transmission (S_{12}). However, in Supplementary Figure 11, the backward transmission (S_{21}) differs markedly: the 3 μm filter shows less than 5 dB attenuation, whereas the 18 μm filter exhibits strong suppression, indicating pronounced nonreciprocal behavior.

The difference arises from the underlying propagation mechanisms. In the 3 μm -thick YIG filter, the device functions similarly to a resonator, where the two straight edges act as reflective boundaries [6, 8]. The magnetostatic surface waves (MSSWs) are reflected back and forth between the edges, forming circulating wave patterns that yield nearly reciprocal transmission.

In contrast, the 18 μm -thick YIG filter no longer supports such resonant circulation. The spin waves excited at one port propagate primarily in a single direction and experience minimal reflection. One key factor is the increased sidewall roughness of the thicker YIG film, as visible in the optical micrographs (Fig. 2c and Fig. 2d). The roughened edges, which result from the greater etching depth required for thick YIG, act as scattering centers that suppress spin-wave reflection. This phenomenon is consistent with previous studies that used rough and lossy edge terminations [9-12], nonuniform magnetic fields [13], or additional spin wave absorbers [11, 14, 15] to minimize reflection and enhance nonreciprocity. Furthermore, increasing the film thickness

enhances surface confinement and unidirectionality of MSSWs on a single surface, further improving nonreciprocal transmission.



Supplementary Figure 11. Comparison of measured S_{21} frequency responses between the 3 μm and 18 μm thick YIG meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss. The S_{12} frequency response comparison is shown in Fig. 3 in the main text.

5. The main manuscript mostly uses 18 μm but the fab images in the supplementary shows 15 μm which results in some confusion.

Answer to the reviewer:

We appreciate the reviewer's insightful comment regarding the apparent inconsistency between the 15 μm and 18 μm YIG film thicknesses. The variation arises from the manufacturer's limited control over the exact film thickness during the liquid-phase epitaxy growth process. In our initial fabrication trial, a smaller 15 μm YIG-on-GGG wafer was procured and used that to demonstrate the process flow presented in Supplementary Note #2 (Thick YIG fabrication process). For subsequent device fabrication and measurements reported in the main manuscript, we ordered a larger wafer of the same specification; however, due to manufacturing tolerances, the resulting film thickness was approximately 18 μm .

Overall, the performance difference between 15 μm and 18 μm YIG films is negligible for the scope of this study. Thus, this minor variation does not affect the validity or interpretation of the reported results.

The following sentences have been added to the revised manuscript:

Methods Section:

MSSW filter fabrication: Initially, a $\langle 111 \rangle$ oriented 15-18 μm thick YIG was grown on a GGG substrate using liquid epitaxy, prepared by MTI Corporation, with a ferromagnetic resonance linewidth of 0.5–2.0 Oe. The difference between 15 μm and 18 μm YIG films is minimal and does not significantly influence the device performance. The YIG film used in Supplementary Note #2 (Thick YIG fabrication process) was approximately 15 μm thick, while all other experiments in the main text utilized the 18 μm film.

6. It is stated that a triangular YIG boundary prevents MSSW propagation on the bottom surface, but the mechanism is unclear. Could the authors elaborate on why a triangular YIG boundary is more effective at suppressing backside reflections compared to other boundary geometries?

Answer to the reviewer:

We thank the reviewer for the comments regarding the role of the triangular YIG boundary in enhancing nonreciprocity. The triangular boundary improves nonreciprocal behavior through two primary mechanisms.

First, the oblique edges of the triangular YIG structure suppress standing-wave formation by scattering the propagating magnetostatic surface waves (MSSW) into directions that follow the magnetostatic backward volume wave (MSBVW) condition. The MSSWs propagate in-plane and perpendicular to the magnetic field, whereas the MSBVWs correspond to magnetostatic waves propagating in-plane but parallel to the magnetic field, typically at lower frequencies than MSSW. Because the scattered waves lie within the stopband of the MSBVW, they rapidly decay, leading to energy dissipation along the oblique boundary and the absence of standing-wave resonances. Similar techniques have been demonstrated in rotated YIG slabs [R1-6-1], which showed improved MSSW nonreciprocity by suppressing reflections, or tapered edges cut at an oblique angle to the propagation direction [R1-6-2 and R1-6-3].

Second, within the triangular regions, much of the YIG material lies near the etched sidewalls around two ends. The increased roughness of these sidewalls introduces additional damping and attenuation of the MSSWs, thereby preventing reflection toward the bottom interface and suppressing wave circulation within the structure. This serves as an additional loss mechanism that further strengthens unidirectional propagation.

Moreover, the triangular YIG boundaries help reduce coupling to higher-order width modes, mitigating spurious modes below the passband, as illustrated in Fig. 4e and utilized in prior magnetostatic-wave studies [R1-6-4].

Overall, the hexagonal device geometry effectively promotes unidirectional propagation and suppresses higher-order width mode spurs. The nonreciprocal MSSWs cannot circulate inside the cavity and instead either dissipate along the lossy sidewalls or convert into MSBVWs that quickly decay, since MSBVWs cannot exist at these frequencies. Although the geometry has not yet been fully optimized, the observed backward transmission approaching the noise floor indicates that this structure already provides near-optimal suppression of undesired reflections and spurious responses.

[R1-6-1] J. Wu, X. Yang, S. Beguhn, J. Lou, and N. X. Sun, "Nonreciprocal tunable low-loss bandpass filters with ultra-wideband isolation based on magnetostatic surface wave," *IEEE transactions on microwave theory and techniques*, vol. 60, no. 12, pp. 3959-3968, 2012.

[R1-6-2] H. Yu et al., "Magnetic thin-film insulator with ultra-low spin wave damping for coherent nanomagnonics," *Scientific reports*, vol. 4, no. 1, p. 6848, 2014.

[R1-6-3] W. Ishak, "Magnetostatic surface wave devices for UHF and L band applications," *IEEE Transactions on Magnetics*, vol. 19, no. 5, pp. 1880-1882, 1983, doi: 10.1109/TMAG.1983.1062691.

[R1-6-4] W. S. Ishak, "Magnetostatic wave technology: a review," *Proceedings of the IEEE*, vol. 76, no. 2, pp. 171-187, 1988, doi: 10.1109/5.4393

We added the following sentences to the revised manuscript for better clarity:

YIG Filter with Meander Line Transducers Section:

By modifying the YIG edge from a straight edge to a triangular shape, the MSSWs on the top surface are effectively blocked from reflecting to the bottom surface, reducing internal MSSW circulation within the YIG waveguide. The oblique edges of the triangular YIG structure suppress standing-wave formation by scattering the propagating MSSW into directions that follow the MSBVW condition. Because these scattered waves lie within the stopband of the MSBVW, they rapidly decay [37-39]. Additionally, in the triangular regions, a large portion of the YIG lies near the etched sidewalls at both ends. The increased surface roughness of these sidewalls introduces extra damping and attenuation of MSSWs, preventing reflection toward the bottom interface and further reducing internal wave circulation [40-43]. This added loss mechanism enhances unidirectional propagation, leading to a significant improvement in nonreciprocity ($|S_{12} - S_{21}|$).

7. An additional citation should be included for meander line MSSW transducers.
a. J. P. Parekh and H. S. Tuan, "Meander line excitation of magnetostatic surface waves," Proceedings of the IEEE, vol. 67, no. 1, pp. 182–183, Jan. 1979, doi: 10.1109/PROC.1979.11221.

Answer to the reviewer:

We appreciate the reviewer's helpful suggestion to include this important reference. The cited work by Parekh and Tuan has now been added to the manuscript in two relevant locations to properly acknowledge the foundational study on meander line excitation of magnetostatic surface waves.

YIG Filter with Meander-Line Transducers Section :

Meander-line transducers have been proposed in previous studies, showing improved radiation impedance compared to single straight-line transducers through theoretical calculations [33, 34], and demonstrating low insertion loss in filters utilizing 3 μm thick YIG [12].

As discussed earlier, meander-line transducers exhibit wavelength selectivity, providing enhanced excitation efficiency when the transducer period corresponds to an odd integral multiple of the MSSW wavelength, resulting in a higher radiation impedance [33,34]. This property enables more effective control over the excited MSSW modes compared with straight-line transducers.

[34] J. P. Parekh and H. S. Tuan, "Meander line excitation of magnetostatic surface waves," Proceedings of the IEEE, vol. 67, no. 1, pp. 182–183, 1979, doi: 10.1109/PROC.1979.11221.

8. In lines 225-226, the authors state that the meander line transducers allow control over the MSSW wavelength. However, they do not provide such a discussion in the text.

Answer to the reviewer:

We appreciate the reviewer's insightful comment regarding the discussion on how the meander line transducers control the MSSW wavelength. Prior studies have demonstrated the wavelength-selective nature of periodic meander line transducers. Both theoretical analyses and experimental results have shown that meander line structures significantly enhance MSSW excitation efficiency compared to straight transducers, particularly at frequencies where the meander line period is an odd integral multiple of the magnetostatic surface wavelength [R1-8-1, R1-8-2]. This selective coupling behavior can also be explained by the theoretical formulation of the radiation resistance of a meander-line transducer, expressed as [R1-8-2]:

$$T_m = \frac{R_m}{R_1 \times l} = \left[\frac{\sin\left(\frac{W_T k_y}{2}\right)}{\frac{W_T k_y}{2}} \right]^2 \left[\frac{\sin\left(\frac{p N k_y}{2}\right)}{\cos\left(\frac{p k_y}{2}\right)} \right]^2 \quad (1)$$

Here, T_m is the transducer specific radiation impedance per unit length, R_m is the radiation impedance, and R_1 is a function of YIG parameters and ground-plane spacing and is independent of transducer parameters, l is the length of the meander-line transducer's arm, which also serves as the width of the YIG waveguide, W_T is the width of the transducer, p is the pitch, and N is the number of arms in the meander-line.

[R1-8-1] J. Sethares, "Magnetostatic surface-wave transducers," IEEE Transactions on Microwave Theory and Techniques, vol. 27, no. 11, pp. 902–909, 1979.

[R1-8-2] J. Parekh and H. Tuan, "Meander line excitation of magnetostatic surface waves," Proceedings of the IEEE, vol. 67, no. 1, pp. 182–183, 2005.

The following sentences have been added to the revised manuscript:

YIG Filter with Meander-Line Transducers Section :

As discussed earlier, meander-line transducers exhibit wavelength selectivity, providing enhanced excitation efficiency when the transducer period corresponds to an odd integral multiple of the MSSW wavelength, resulting in a higher radiation impedance [33,34]. This property enables more effective control over the excited MSSW mode compared with straight-line transducers.

9. In lines 271-273, the authors state that the width of the yoke is reduced. Can the authors provide additional details on how this change reduces leakage flux? Additionally, which dimension in Fig. 1c corresponds to the width?

Answer to the reviewer:

We appreciate the reviewer's question. The reduced leakage flux is achieved by reducing the surface area of the yoke. Ideally, the flux generated by the permanent magnets (NdFeB and AlNiCo) should be confined within the yokes and directed exclusively through the tapered pole pieces. However, the relative permeability of the air surrounding the yokes are ~ 1 (rather than 0). Therefore, a large portion of the flux escapes from other surfaces of the yokes, such as the top, bottom, and back, rather than being guided to the pole pieces. This part of the flux is defined as leakage flux.

Using ANSYS Maxwell simulations, we found that larger yokes generally have more leakage flux, as the increased surface area provides more paths for flux to leak into air. So, by reducing the width of the yokes to 2 mm, which is the vertical dimension of the rectangular yoke base in Fig. 1c, while keeping the pole pieces area unchanged, the overall surface area of the yoke is decreased. This effectively reduces leakage flux without compromising the flux concentration at the pole tips.

We have incorporated these clarifications into the manuscript to improve understanding.

Integrated Devices Section:

In this study, the surface area of the yoke pieces has been reduced by narrowing the width of the yoke, corresponding to the vertical dimension of the rectangular yoke base in Fig. 1c.

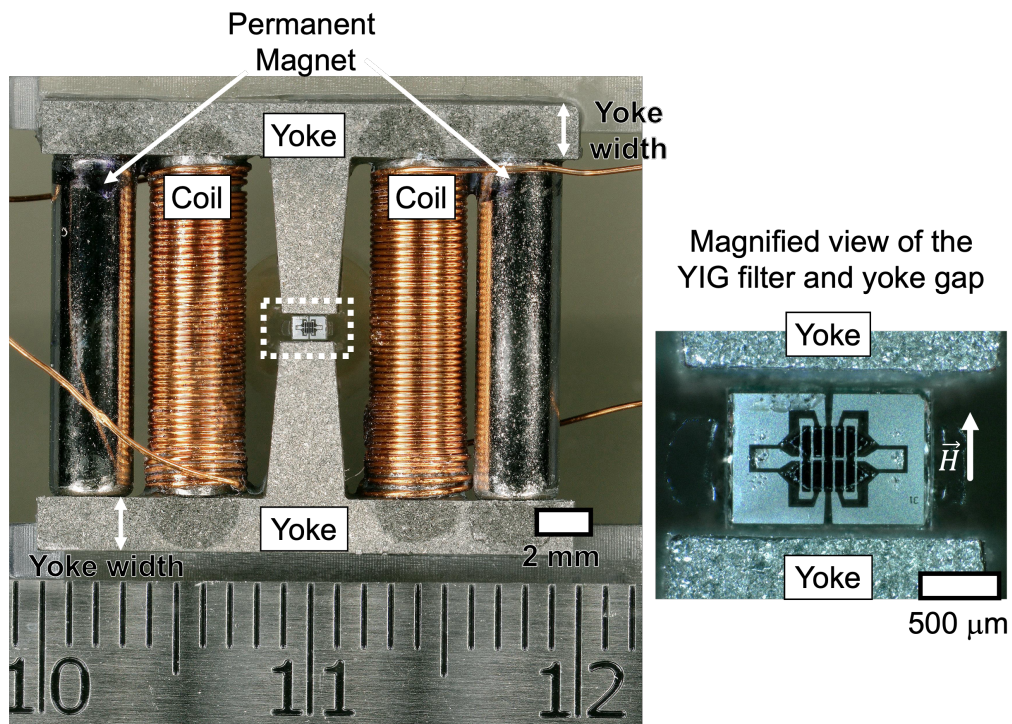


Figure 1 (c) Optical microscope image of the fabricated device assembly with a magnified view of the white box region showing the YIG filter and yoke gap.

10. The authors claim the magnetic assembly shows zero continuous power consumption. However, the power consumption while tuning the magnetic bias and the tuning time is also of high interest. I suggest the authors include this information.

Answer to the reviewer:

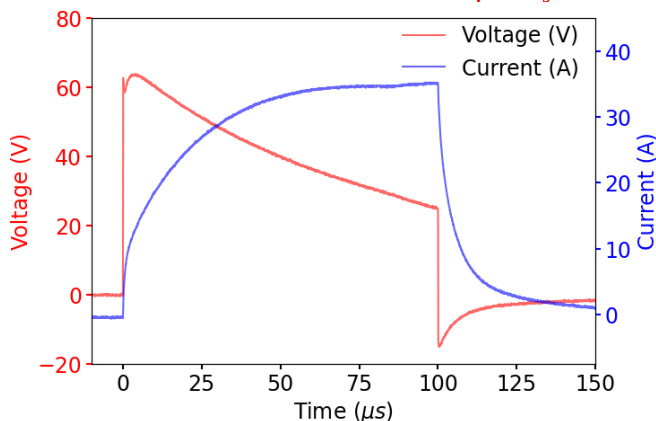
We thank the reviewer for the question regarding the time and energy requirements. Supplementary Note #13 has been added.

Integrated Devices Section:

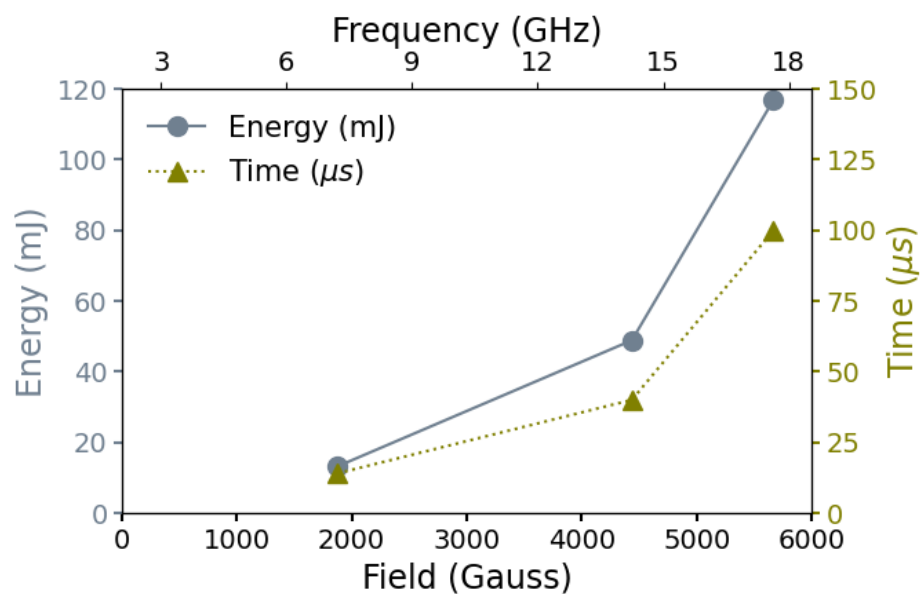
Supplementary Note #13 details the time and energy requirements for frequency tuning of the integrated device. The maximum switching duration is approximately 100 μs , requiring approximately 116 mJ to tune across the full 4–18 GHz range (0–5700 Gauss).

Supplementary Note #13: Time and Energy Requirements for Frequency Tuning

Supplementary Figure 33 presents the measured coil voltage and current during capacitor discharge for switching from 0 Gauss, where the filter doesn't respond due to the lack of a bias magnetic field, to the maximum field and frequency of around 5700 Gauss or 18 GHz. The maximum switching duration is approximately 100 μs , requiring about 116 mJ to tune across the full 18 GHz range (0–5700 Gauss). For smaller tuning spans, both the switching time and energy consumption decrease. For example, tuning from zero bias field to 15 GHz (0–4500 Gauss) requires a 40 μs pulse and 48 mJ, while tuning from zero bias field to 7 GHz (0–1800 Gauss) requires only a 14 μs pulse and 13 mJ. **Supplementary Figure 34** summarizes the energy and time requirements for tunable filters from the minimum frequency to different frequencies.



Supplementary Figure 33. Coil's voltage and current during capacitor discharge. This short discharge current pulse was applied to the coil and magnetizes or demagnetizes the AlNiCo magnets.



Supplementary Figure 34. Energy and time requirements for tunable filter switching from 0 Gauss, where the filter does not respond to RF excitation, to a target frequency or magnetic field.

11. In Figure 5a, the authors show the magnetic flux density dependence on the applied current pulse amplitude. Can the authors comment on the degree of hysteresis in the field tuning? Additionally, the repeatability data from the magnetic bias circuit would be helpful.

Answer to the reviewer:

We thank the reviewer for the question regarding the repeatability of the tunable filters. Supplementary Note #14 has been added.

Integrated Devices Section:

Supplementary Note #14 examines the repeatability of the tunable filter programming. Although the AlNiCo magnet exhibits hysteresis, the filter demonstrates excellent frequency tuning repeatability when a reset (demagnetization) process is performed prior to setting the desired frequency.

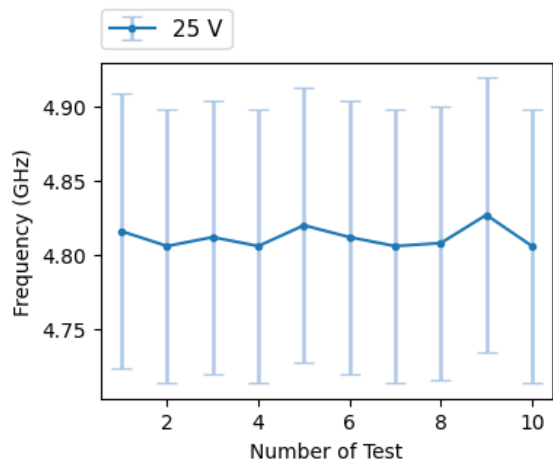
Supplementary Note #14: Repeatability of Frequency Tuning

The tunable filter's non-volatile magnetic bias circuit is based on a programmable AlNiCo magnet, which exhibits magnetic hysteresis. This hysteresis introduces uncertainty in frequency tuning. To minimize this effect and improve tuning consistency, the AlNiCo magnet is fully demagnetized before each tuning operation, enabling highly repeatable results.

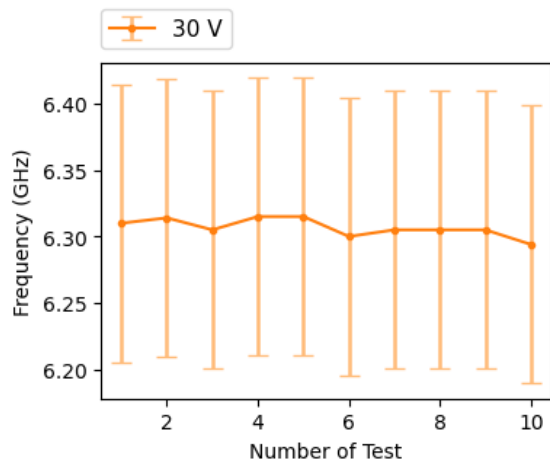
A separate magnetic bias circuit was implemented on a printed circuit board (PCB), to which the YIG filter was flip chip bonded. The center frequency was measured using a vector network analyzer (VNA). To accommodate the size of the YIG filters and bonding pads, the gap between the two magnetic yokes was slightly increased. Consequently, the frequency tuning range of this prototype filter is smaller than that of the device described in the main text, and the same voltage pulses yield slightly lower center frequencies.

Supplementary Figure 35 shows the measurement results detailing the repeatability of the programming. The filter was first demagnetized by discharging a capacitor charged to -60 V through the coil for $100\text{ }\mu\text{s}$, followed by magnetization using $100\text{ }\mu\text{s}$ voltage pulses of different amplitudes. This process was repeated ten times to evaluate repeatability. The measured center frequencies are highly consistent, with over 90% of the measured values for a given voltage falling within $\pm 10\%$ of the filter's 3 dB bandwidth. Thus, only a small amount of the filter 3 dB bandwidth must be allocated to account for the small frequency inaccuracy in the filter programming.

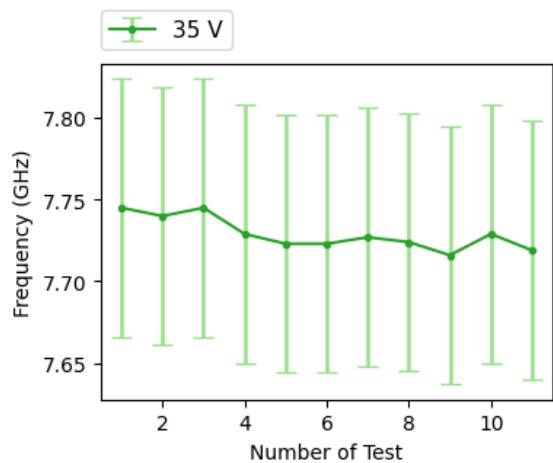
These results demonstrate the high repeatability and stability of the tunable filter's non-volatile magnetic bias circuit, confirming that controlled demagnetization effectively mitigates hysteresis effects and enables reliable frequency tuning across multiple cycles.



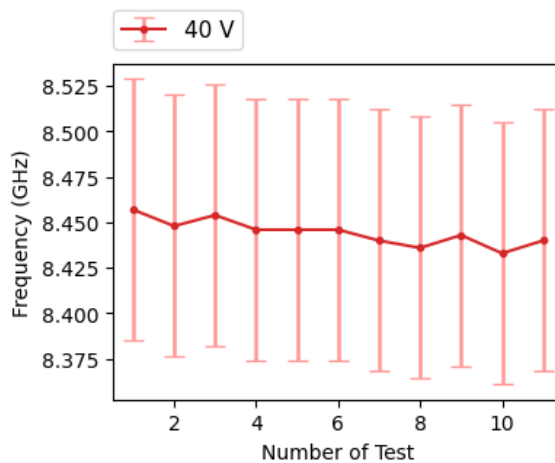
(a)



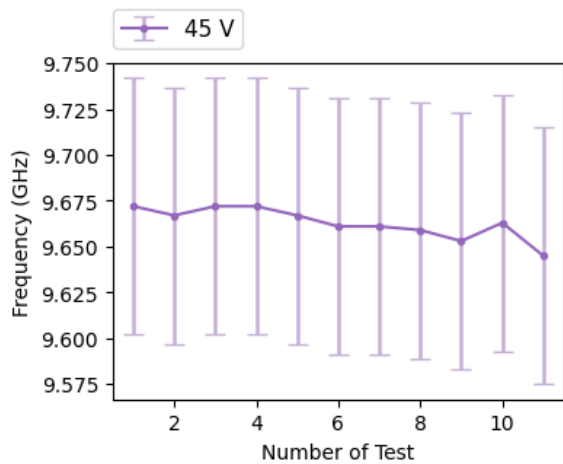
(b)



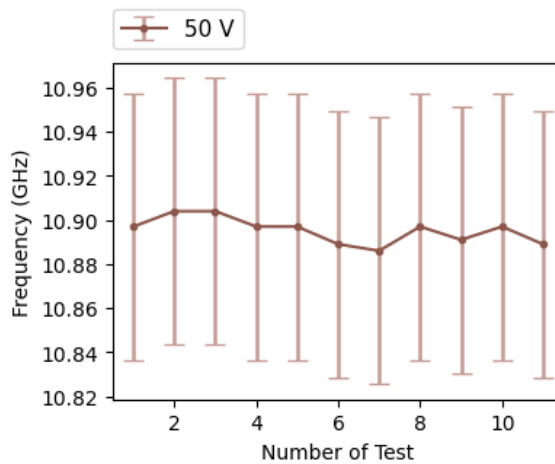
(c)



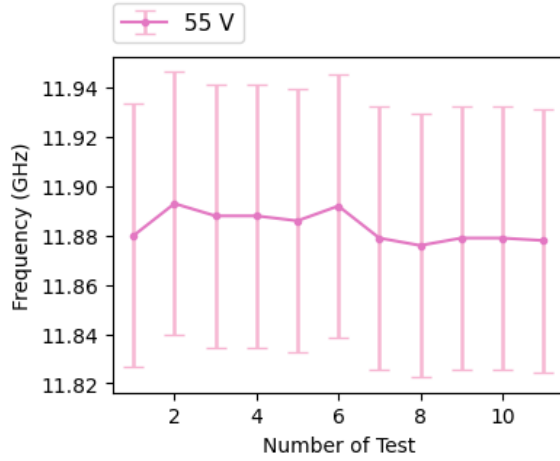
(d)



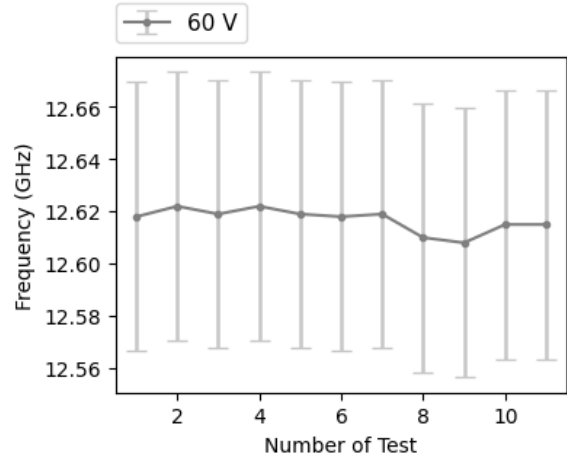
(e)



(f)



(g)



(h)

Supplementary Figure 35. Repeatability analysis of the tunable filter programming. Each measurement begins with a -60 V, 100 μ s current pulse to fully demagnetize the device, followed by a 100 μ s positive pulse of (a) 25 V, (b) 30 V, (c) 35 V, (d) 40 V, (e) 45 V, (f) 50 V, (g) 55 V, and (h) 60 V to magnetize the filter to different levels. The bars indicate the 3 dB bandwidth of the filter, which is much wider than the frequency deviation with programming cycles.

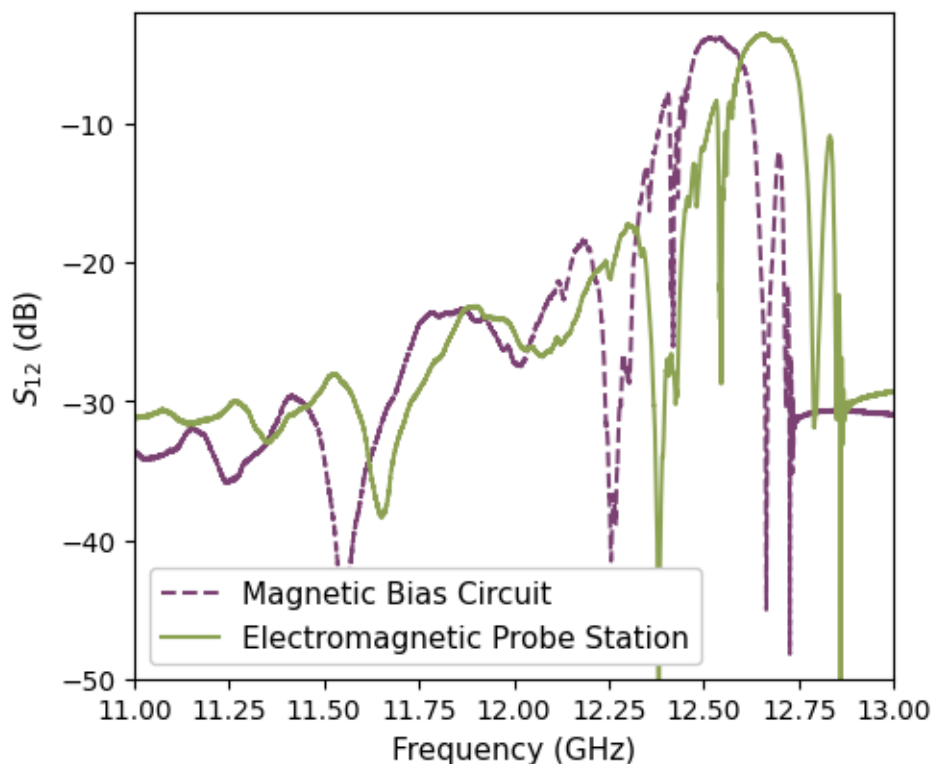
12. The iron-cobalt yoke material is typically lossy for electromagnetic waves. Can the authors comment on any differences in the isolator performance measured with and without the integrated magnetic assembly?

Answer to the reviewer:

We thank the reviewer for the insightful comment regarding the effect of the integrated magnetic assembly on isolator performance. The MSSW in this device are confined entirely within the YIG layer; thus, magnetic materials positioned sufficiently far from the YIG do not influence the transmission characteristics.

As shown in Response Figure 1-12-1, the frequency responses measured using the integrated magnetic bias circuit and a conventional magnetic probe station are nearly identical under an applied field of approximately 3500 G. The small frequency offset observed arises from magnetic field calibration precision rather than a physical performance difference.

In our earlier work [R1-12-1], we found that a yoke with a very small thickness (≈ 0.5 mm) could generate a slightly nonuniform magnetic field, leading to increased insertion loss. In the present configuration, however, no such nonuniformity was observed, and the resulting transmission and isolation performance remained unchanged.



Response Figure 1-12-1: Comparison of the S_{12} frequency response of the filter inside the magnetic bias circuit and on a magnetic probe station. The applied magnetic field is around 3500 Gauss.

[R1-12-1] 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 27 2024, doi: 10.1038/s41467-024-47822-3.

13. The authors should cite the following recent SAW filter that showed frequency up to 8.63 GHz with insertion loss below 2 dB when discussing them in lines 330-335
a. Yang et al., "SV-SAW RF filters based on low-cost 128°Y LiNbO₃/SiO₂/poly-Si/Si substrate for 6G cmWave wireless communications," *Microsyst Nanoeng*, vol. 11, no. 1, p. 79, May 2025, doi: 10.1038/s41378-025-00949-9.

Answer to the reviewer:

We thank the reviewer for the suggestion. The following sentence has been changed.

Discussion Section :

(3) Low insertion loss. Even though SAW filters have been demonstrated with low insertion loss [59], state-of-the-art SAW delay lines with low loss are generally limited to below 6 GHz and exhibit insertion losses around 7 dB [60].

[59] K. Yang et al., "SV-SAW RF filters based on low-cost 128° Y LiNbO₃/SiO₂/poly-Si/Si substrate for 6G cmWave wireless communications," *Microsystems & Nanoengineering*, vol. 11, no. 1, p. 79, 2025.

14. In Fig. 1a, the authors state that the filtering isolator is placed before the PA to eliminate out-of-band signals and reflections. However, the PA itself will generate large out-of-band frequency products, and its output is sensitive to reflections. Can the authors detail why the filter is not placed between the PA and antenna? Can the authors also clarify why an isolator (instead of impedance matching sections, for example) is required to minimize signal reflections?

Answer to the reviewer:

We appreciate the reviewer's thoughtful comment and we fully agree that, ideally, the nonreciprocal filter would be placed between the PA and antenna to suppress both reflected and out-of-band signals generated by the PA. However, in this work, the current device's power handling capability is limited to approximately 11 dBm, which is significantly lower than the >20 dBm output power typically required at the PA output stage. Improving the power handling capacity of the nonreciprocal filter is a key focus of our future research so that it can be directly integrated between the PA and antenna.

Despite being positioned before the PA, the nonreciprocal filter still offers several important advantages. An important consideration for using an isolator rather than impedance matching is the very wide frequency tuning range covered in this paper. The output impedance of RF transceiver components varies over such wide frequency ranges, challenging impedance matching techniques. In broadband transmitter architectures (e.g., 4–18 GHz), both the digital-to-analog converter (DAC) and wideband PA exhibit nonideal impedance characteristics—PAs such as QPB0220J, ZVA-18443TC+, or AVA-6183MPS-DG+ typically have input return losses that vary between 10–20 dB, while DACs can exhibit frequency-dependent output mismatch that degrade spurious-free dynamic range (SFDR). The nonreciprocal bandpass filter effectively isolates the DAC from the PA by absorbing reflected signals and blocking out-of-band energy, thus stabilizing the impedance environment and preventing distortion or feedback. Moreover, since the DAC and the PA may reside on separate chips, high-frequency transmission lines or interconnects between them can introduce additional impedance mismatch.

While a passive impedance-matching network could, in principle, improve matching, it is extremely challenging to design a broadband network that maintains consistent impedance across such a wide frequency range (4–18 GHz). The nonreciprocal filter therefore provides a unique advantage—it not only performs frequency-selective transmission but also absorbs unwanted reflections, offering simultaneous filtering and isolation in a single compact element.

The following sentences have been added to the revised manuscript:

Discussion Section:

In the transmit path, the nonreciprocal bandpass filter effectively isolates the DAC from the PA by absorbing backward-propagating energy and suppressing out-of-band components. This absorptive isolation stabilizes the impedance between stages, minimizing distortion and feedback. The filter thus provides a compact and efficient solution that simultaneously achieves frequency selective transmission and reflection absorption. Although placing the nonreciprocal filter between the PA and antenna could further enhance system stability, this configuration requires higher

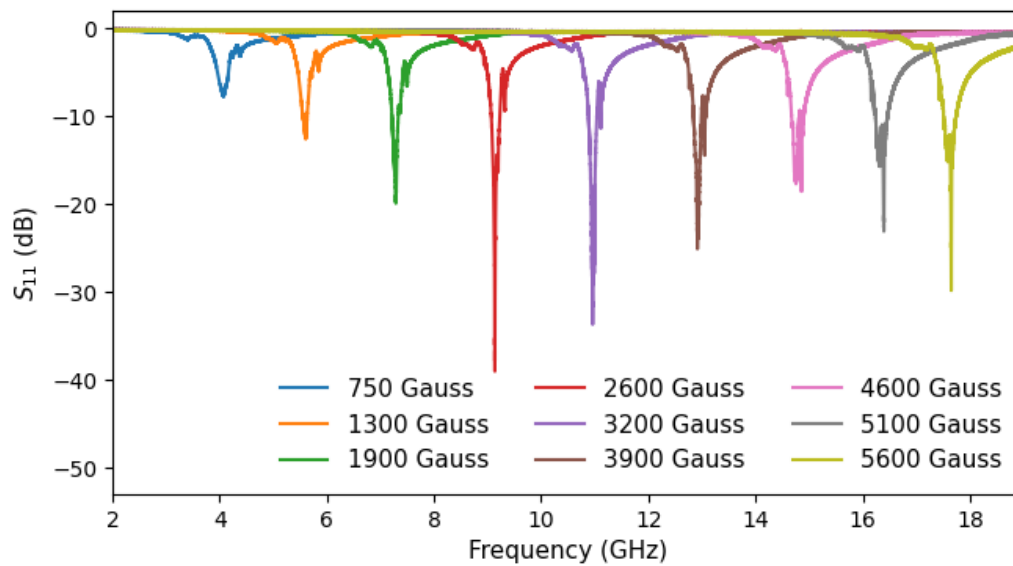
power handling capability. Future work will therefore focus on increasing the device's power tolerance from the current ~ 11 dBm to above 20 dBm to enable direct integration at the PA output.

15. Can the author add details explaining whether the isolator is absorptive or reflective? If the isolator is reflective, then the Tx system in Fig. 1a could amplify and re-transmit in-band reflections.

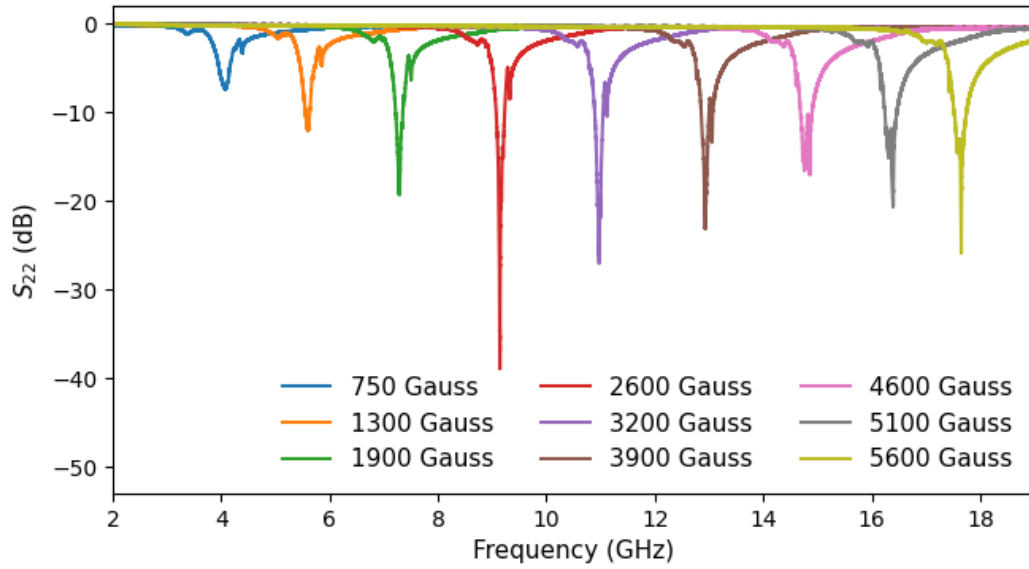
Answer to the reviewer:

We thank the reviewer for the insightful question. As shown in **Response Figure 1-15-1**, the nonreciprocal filter operates as an absorptive isolator rather than a reflective one. Both S_{11} and S_{22} exhibit deep notches at the center frequency, indicating minimal reflection at either port. The filter couples most of the incident RF energy at the center frequency into MSSW. For forward transmission (S_{12}), the MSSW propagates through the YIG and efficiently couples back to the electromagnetic mode at the output port. In contrast, for backward propagation (S_{21}), the filter rejects that frequency; the MSSW energy dissipates at the YIG edge or scatters into MSBVW, which rapidly decay.

Thus, the device absorbs rather than reflects the backward-propagating energy, preventing in-band reflections and ensuring stable operation of the Tx system. This absorptive behavior allows the filter to function effectively as a self-isolating, nonreciprocal component suitable for RF front-end applications.



(a)



(b)

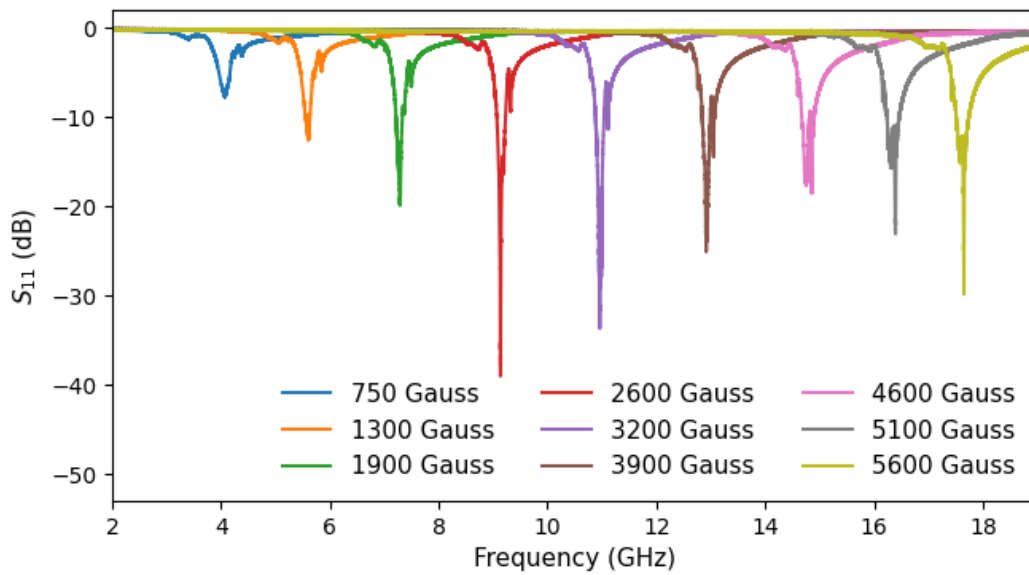
Response Figure 1-15-1: Measured (a) S_{11} and (b) S_{22} frequency responses with the magnetic field supplied by the zero static power consumption magnetic bias circuit.

The following sentences have been added to the revised manuscript:

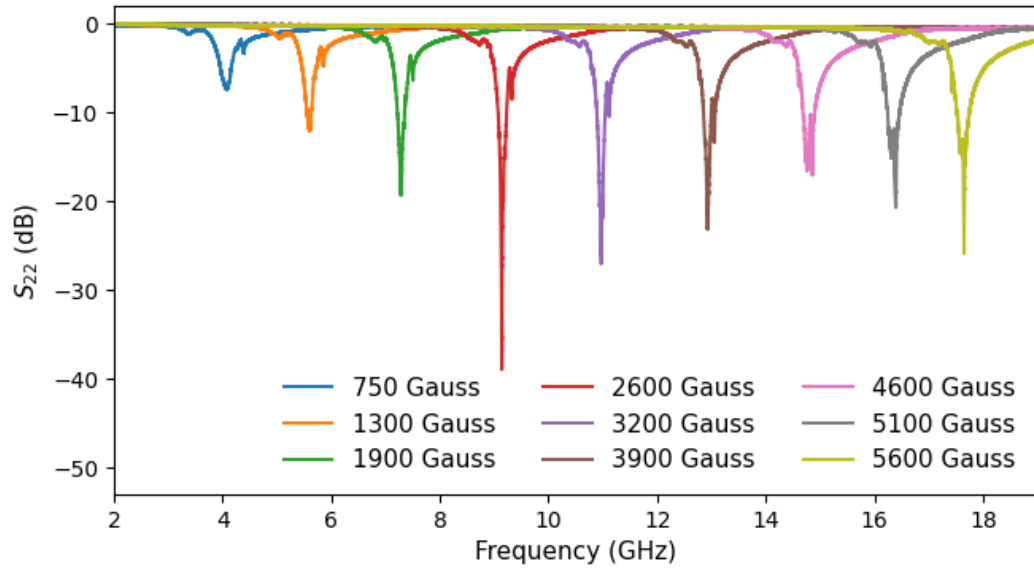
Discussion Section :

By incorporating the nonreciprocal filter, reflected in-band signals from the amplifier or antenna are absorbed within the device rather than reflected, ensuring that unwanted energy is dissipated internally and does not re-enter the signal chain. This is confirmed by the high return loss (S_{11}) observed at the filter's output port.

Supplementary Note #12: Integrated Filter:



(b)



(c)

Supplementary Figure 31. Measured (b) S_{11} , and (c) S_{22} , frequency responses with the magnetic field supplied by the zero static power consumption magnetic bias circuit.

16. In lines 42-43 and Fig. 1a, can the authors further explain the significance of attenuating reflected signals in the Rx path?

Answer to the reviewer:

We appreciate the reviewer's insightful question. The attenuation of reflected signals in the Rx path is crucial to maintaining receiver stability and minimizing distortion, especially in wideband systems. Even though impedance matching can be excellent at a single frequency, it becomes very challenging to maintain consistent matching over a broad frequency range such as 4–18 GHz. For instance, wideband LNAs typically exhibit input return losses between 8–15 dB across this range (e.g., PMA2-183LN+ or ZX60-06203ALN+), which translates to noticeable impedance variation. Similarly, wideband antennas often exhibit voltage standing wave ratios (VSWR) between 1.8–2.5, as seen in models such as ANT-BHA-1-18, OmniLOG PRO 10200, or UWB0618-1000.

These mismatches cause partial signal reflections that travel back toward the receiver input, forming standing waves and effectively increasing the noise floor. The reflected power can also re-enter the LNA and induce ripple or oscillations, degrading sensitivity and linearity. Therefore, the ability of the nonreciprocal filter to absorb and attenuate reflected signals in the Rx path ensures stable impedance conditions, suppresses undesired feedback, and preserves signal fidelity across the entire operating bandwidth.

The following sentences have been added to the revised manuscript:

Discussion Section:

This nonreciprocal bandpass filter plays an important role in both the transmit and receive paths, as illustrated in Fig. 1(a). In the receive path, wideband LNAs and wideband antennas often exhibit significant impedance mismatches across the 4–18 GHz range, resulting in partial reflections that can form standing waves. The reflected power can re-enter the LNA input, causing ripple and oscillations, ultimately degrading receiver sensitivity. By incorporating the nonreciprocal filter, reflected in-band signals from the amplifier are absorbed within the device rather than reflected back to the antenna, ensuring that unwanted energy is dissipated internally and does not re-enter the signal chain.

17. In line 59: Should the text say “a zero-static-power magnetic bias circuit” instead of “zero static magnetic bias circuit”?

Answer to the reviewer:

We appreciate the reviewer’s suggestion. The following sentence has been changed.

Introduction Section:

The entire device occupies a compact footprint of just 20.0 mm × 16.7 mm × 3.2 mm and consists of two key components: a nonreciprocal Yttrium Iron Garnet (YIG) bandpass filter and a zero-static-power magnetic bias circuit.

18. There is an extra \cdot in the caption for Fig. 1 around “unidirectional ·magnetostatic wave”

Answer to the reviewer:

We appreciate the reviewer’s suggestion. The following sentence has been changed.

Figure 1 Caption:

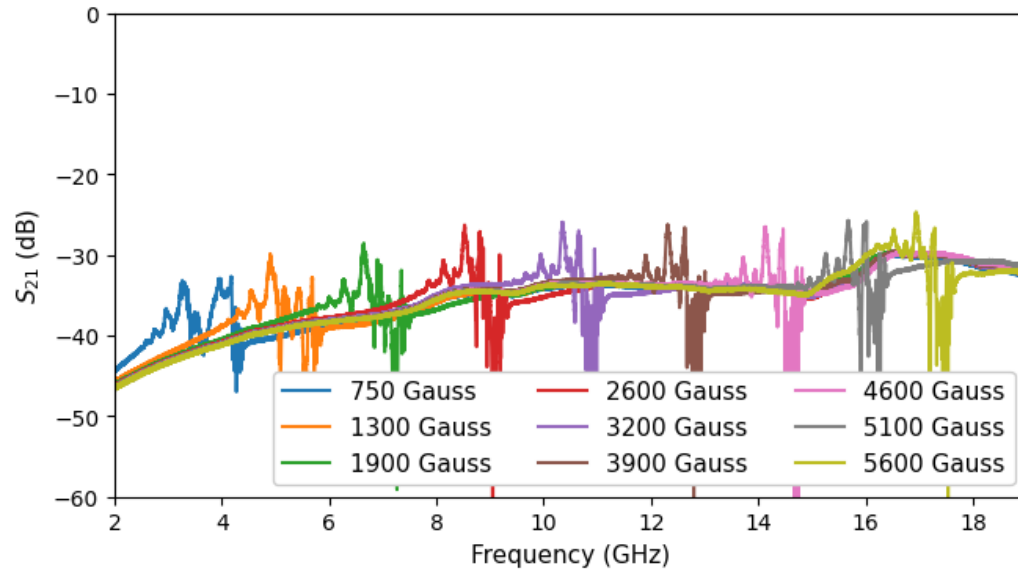
An input aluminum meander-line transducer excites a unidirectional magnetostatic wave (MSW), which propagates through the YIG and is reconverted back to an electrical signal at the output transducer.

19. Typo in Y-label of Supplementary Figure 28.

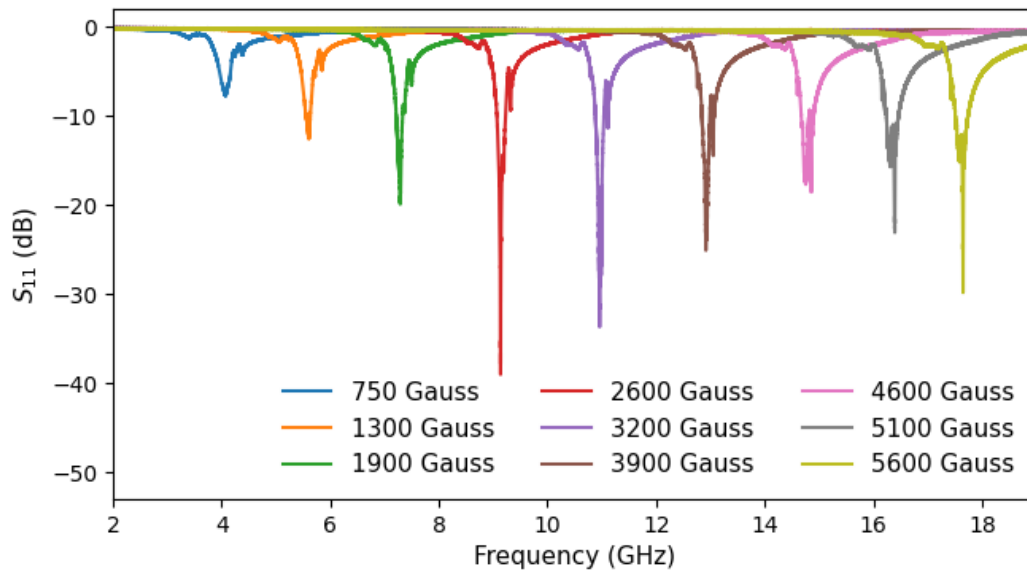
Answer to the reviewer:

We appreciate the reviewer's careful observation and thank them for pointing this out. The typo in the Y-axis label of Supplementary Figure 28 (now 31) has been corrected in the revised version of the manuscript.

Supplementary Figure #12: Integrated Filter:



(a)



(b)

Supplementary Figure 31. Measured **(a)** S_{21} and **(b)** S_{11} frequency responses with the magnetic field supplied by the zero static power consumption magnetic bias circuit.

Reviewer #2 (Remarks to the Author):

The authors made a critical advancement in fabrication, specifically a benzocyclobutene planarization process, that enabled the development of a 18 μm thick YIG filter tunable from 4 GHz to 17.7 GHz. In addition to the broad tuning range, the filter also demonstrates pronounced nonreciprocity, which expands the application space of this technology within RF frontends. In addition to the device demonstration, the authors implemented integrated magnetic bias circuitry, a critical step forward toward practical system integration. While this team previously demonstrated a similar technology, specifically a 3 μm thick YIG tunable filter, again with incorporated magnetic bias circuitry, the authors made a significant step forward advancing performance on both fronts. With respect to the filter the significantly thicker YIG film improved the power handling, filter selectivity, and bandwidth, while enabling the observed RF transmission nonreciprocity. In addition, the magnetic bias circuitry was designed to be more compact (reduced volume from 1.68 to 1.07 cm^3) with a larger magnetic field range (up to 5700 Gauss). The authors presented significant and comprehensive characterization of all aspects of the nonreciprocal, tunable filter and those results fully supported their findings. While related to their earlier work, this represents a major improvement enabled by a new fabrication method that allows for thicker YIG films than previously possible. This breakthrough not only benefits RF front-end applications but is also relevant to the broader YIG research community, including spintronics applications. Since this benzocyclobutene planarization process was central to enabling this device, I was happy to find that in the methods section the details of the fabrication were listed explicitly, such that others could exploit this approach in their own research. I also really enjoyed the final figure #6 which contrasts competing technologies with this study. I believe this work has high technical merit, and represents a significant step forward toward compact, low power nonreciprocal tunable filters based on YIG, and therefore should be accepted for publication. There should be more work like this—where the focus isn't just on a scientific demonstration, but on translating state-of-the-art magnetic technologies into real-world applications. This kind of research helps bridge the gap between novel materials science and practical RF systems, making the case for why advanced magnetics matter beyond the lab and serves a purpose.

Answer to the reviewer:

We appreciate the recognition from the reviewer.

Reviewer #3 (Remarks to the Author):

This paper presents a comprehensive study on the design and performance optimization of magnetostatic surface wave filters using inductive meander line transducers. Building upon the foundational concept introduced in the authors' earlier work [12], where transducers were fabricated on 3 μm thick YIG films, this study significantly extends the investigation by employing much thicker 18 μm YIG films. The transition to thicker films introduced new fabrication challenges, particularly in maintaining electrode continuity across significant surface topologies from the thick YIG films. The authors addressed these issues by developing a novel fabrication process, enabling successful device realization. The use of thicker YIG films led to notable improvements in filter linearity and bandwidth. Furthermore, the authors explored a wide range of transducer geometries, offering valuable insights into how design variations impact filter performance. In addition to the transducer advancements, the paper integrates the filters into a zero static power magnetic bias assembly. Comparing to the authors' previous work in [10], the bias assembly achieved a significantly enhanced tuning range (4–17.7 GHz), an over 50% improvement comparing to [10], while also reducing the assembly size through improved flux management and high-saturation magnetic materials. Overall, this is a well-executed and insightful study that meaningfully advances the field. That said, I do have several comments and questions that I hope the authors can address:

Answer to the reviewer:

We sincerely thank the reviewer for the thoughtful and encouraging assessment of our work. We truly appreciate the recognition of our efforts in advancing both the device fabrication and system integration aspects of YIG-based magnetostatic surface wave filters. We are grateful for the opportunity to further clarify and expand upon several of the points raised in the following responses.

.

1. Line 21~22, line 38~39, I'm wondering if the authors can provide a more specific example to motivate the needs of having a non-reciprocal filtering device in the RF transceiver chain. Based on Fig. 1a, for a filter sits between Rx antenna and Rx LNA, the impedances at each interface are typically carefully engineered to ensure proper matching, optimize noise figure, ensure Rx stability. To my knowledge this is manageable. And on the Tx side, I could imagine a scenario where if there is some highly reflective objects near the antenna, the reflection could potentially de-stabilize the PA. And a non-reciprocal device might help. However, are the linearity and power handling of magnetostatic wave based device sufficient to handle the power from the PAs?

Answer to the reviewer:

We thank the reviewer for the insightful question.

The attenuation of reflected signals in the Rx path is crucial to maintaining receiver stability and minimizing distortion, especially in wideband systems. Even though impedance matching can be excellent at a single frequency, it becomes extremely challenging to maintain consistent matching over a broad frequency range such as 4–18 GHz. For instance, wideband LNAs typically exhibit input return losses between 8–15 dB across this range (e.g., PMA2-183LN+ or ZX60-06203ALN+), which translates to noticeable impedance variation. Similarly, wideband antennas often exhibit voltage standing wave ratios (VSWR) between 1.8–2.5, as seen in models such as ANT-BHA-1-18, OmniLOG PRO 10200, or UWB0618-1000.

These mismatches cause partial signal reflections between the LNA and antenna, forming standing waves and effectively increasing the noise floor. The reflected power can also re-enter the LNA and induce gain ripple or oscillations, degrading sensitivity and linearity. Therefore, the ability of the nonreciprocal filter to absorb and attenuate reflected signals in the Rx path ensures stable impedance conditions, suppresses undesired feedback, and preserves signal fidelity across the entire operating bandwidth.

Moreover, for the transmit path, we fully agree that, ideally, the nonreciprocal filter would be placed between the PA and antenna to suppress both reflected and out-of-band signals generated by the PA. However, in this work, the current device's power handling capability is limited to approximately 11 dBm, which is significantly lower than the >20 dBm output power typically required at the PA output stage. Improving the power handling capacity of the nonreciprocal filter is a key focus of our future research so that it can be directly integrated between the PA and antenna.

Despite being positioned before the PA, the nonreciprocal filter still offers several important advantages. In broadband transmitter architectures (e.g., 4–18 GHz), both the digital-to-analog converter (DAC) and wideband PA exhibit nonideal impedance characteristics—PAs such as QPB0220J, ZVA-18443TC+, or AVA-6183MPS-DG+ typically have input return losses between 10–20 dB, while DACs can exhibit frequency-dependent output mismatches that degrade spurious-free dynamic range (SFDR). The nonreciprocal bandpass filter effectively isolates the DAC from the PA by absorbing reflected signals and blocking out-of-band energy, thus stabilizing the impedance environment and preventing distortion or feedback. Moreover, since the DAC and the PA may reside on separate chips, high-frequency transmission lines or interconnects between them can introduce additional impedance mismatches.

The following sentences have been added to the revised manuscript:

Discussion Section :

This nonreciprocal bandpass filter plays an important role in both the transmit and receive paths, as illustrated in Fig. 1(a). In the receive path, wideband LNAs and wideband antennas often exhibit significant impedance mismatches across the 4–18 GHz range, resulting in partial reflections that form standing waves. The reflected power can re-enter the LNA input, causing ripple and oscillations, ultimately degrading receiver sensitivity. By incorporating the nonreciprocal filter, reflected in-band signals from the amplifier or antenna are absorbed within the device rather than reflected, ensuring that unwanted energy is dissipated internally and does not re-enter the signal chain. In the transmit path, the nonreciprocal bandpass filter effectively isolates the DAC from the PA by absorbing backward-propagating energy and suppressing out-of-band components. This absorptive isolation stabilizes the impedance between stages, minimizing distortion and feedback. The filter thus provides a compact and efficient solution that simultaneously achieves frequency selective transmission and absorptive isolation. Although placing the nonreciprocal filter between the PA and antenna could further enhance system stability, this configuration requires higher power handling capability. Future work will therefore focus on increasing the device's power tolerance from the current ~11 dBm to above 20 dBm to enable direct integration at the PA output.

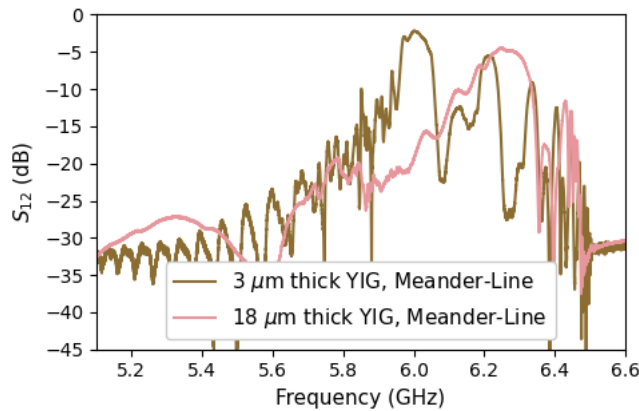
2. Line 67, from what was described in the following sections, it seems it was the thicker YIG enhances nonreciprocity? Also in this context nonreciprocity is isolation?

Answer to the reviewer:

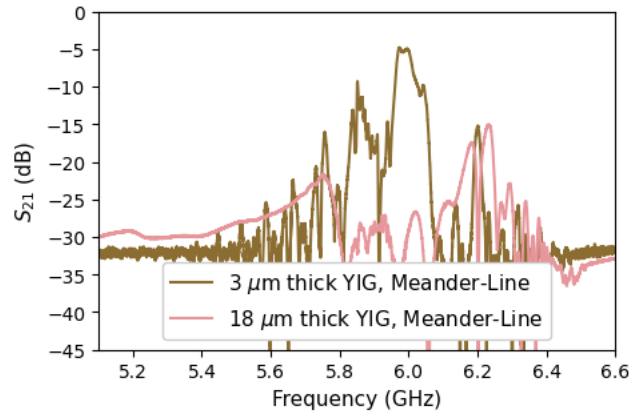
We appreciate the reviewer's question. Thicker YIG enhances nonreciprocity. To quantify the effect of YIG thickness on nonreciprocity, we compared the performance of meander-line transducer filters fabricated on 3 μm and 18 μm YIG films. As shown in Response Figure R2-2-1 (Fig. 3c in the main text), both filters exhibit distinct passbands in the forward transmission (S_{12}). However, in Response Figure R2-2-2 (Supplementary Figure 11), the backward transmission (S_{21}) differs markedly: the 3 μm filter shows less than 5 dB attenuation, whereas the 18 μm filter exhibits strong suppression, indicating pronounced nonreciprocal behavior.

The difference arises from the underlying propagation mechanisms. In the 3 μm -thick YIG filter, the device functions similarly to a resonator, where the two straight edges act as reflective boundaries [R2-2-1, R2-2-2]. The magnetostatic surface waves (MSSWs) are reflected back and forth between the edges, forming circulating wave patterns that yield nearly reciprocal transmission.

In contrast, the 18 μm -thick YIG filter no longer supports such resonant circulation. The spin waves excited at one port propagate primarily in a single direction and experience minimal reflection. One key factor is the increased sidewall roughness of the thicker YIG film, as visible in the optical micrographs (Fig. 2c and Fig. 2d). The roughened edges, which result from the greater etching depth required for thick YIG, act as scattering centers that suppress spin-wave reflection. This phenomenon is consistent with previous studies that used rough and lossy edge terminations [R2-2-3, R2-2-4, R2-2-5, R2-2-6], nonuniform magnetic fields [R2-2-7], or additional spin wave absorbers [R2-2-8, R2-2-9, R2-2-5] to minimize reflection and enhance nonreciprocity. Furthermore, increasing the film thickness enhances surface confinement and unidirectionality of MSSWs on a single surface, further amplifying nonreciprocal transmission.



Response Figure R2-2-1 (Fig. 3c in the main text): Comparison of measured S_{12} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss.



Response Figure R2-2-2 (Supplementary Figure 11): Comparison of measured S_{21} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss.

- [R2-2-1] K. W. Chang and W. Ishak, "Magnetostatic surface wave straight-edge resonators," *Circuits, systems and signal processing*, vol. 4, pp. 201–209, 1985.
- [R2-2-2] 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 27 2024, doi: 10.1038/s41467-024-47822-3.
- [R2-2-3] N. Kanazawa et al., "Spin wave absorber generated by artificial surface anisotropy for spin wave device network," *AIP Advances*, vol. 6, no. 9, 2016.
- [R2-2-4] J. H. Collins, D. M. Hastie, J. M. Owens, and C. V. Smith, Jr., "Magnetostatic wave terminations," *Journal of Applied Physics*, vol. 49, no. 3, pp. 1800–1802, 1978, doi: 10.1063/1.324870.
- [R2-2-5] V. L. Taylor, J. C. Sethares, and C. V. Smith, "MSW Terminations," in *1980 Ultrasonics Symposium*, 5–7 Nov. 1980 1980, pp. 562–570, doi: 10.1109/ULTSYM.1980.197461.
- [R2-2-6] H. Glass, L. Adkins, and F. Stearns, "Attenuation layer for magnetostatic wave (MSW) absorbers," *IEEE Transactions on Magnetics*, vol. 20, no. 5, pp. 1235–1237, 2003.
- [R2-2-7] W. Faber, "Terminations for magnetostatic waves," *Electronics Letters*, vol. 16, no. 12, pp. 452–453, 1980, doi: 10.1049/el:19800318.
- [R2-2-8] K. Shimada et al., "Extremely flat transmission band of forward volume spin wave using gold and yttrium iron garnet," *Journal of Physics D: Applied Physics*, vol. 50, no. 27, p. 275001, 2017.
- [R2-2-9] J. Krug and P. Edenhofer, "Broadband terminations for magnetostatic surface waves," *Electronics Letters*, vol. 19, no. 23, pp. 971–972, 1983, doi: 10.1049/el:19830660.
- [R2-2-10] J. Wu, X. Yang, S. Beguhn, J. Lou, and N. X. Sun, "Nonreciprocal tunable low-loss bandpass filters with ultra-wideband isolation based on magnetostatic surface wave," *IEEE transactions on microwave theory and techniques*, vol. 60, no. 12, pp. 3959–3968, 2012.
- [R2-2-11] H. Yu et al., "Magnetic thin-film insulator with ultra-low spin wave damping for coherent nanomagnonics," *Scientific reports*, vol. 4, no. 1, p. 6848, 2014.
- [R2-2-12] W. Ishak, "Magnetostatic surface wave devices for UHF and L band applications," *IEEE Transactions on Magnetics*, vol. 19, no. 5, pp. 1880–1882, 1983, doi: 10.1109/TMAG.1983.1062691.

We appreciate the reviewer's comment regarding the use of the term "isolation" in Line 67. In this context, "isolation" was intended to refer to out-of-band rejection, describing the performance improvement achieved with the meander-line transducer. To improve clarity, the term has been replaced with "out-of-band rejection" in the revised manuscript.

Introduction Section:

Additionally, the meander-line aluminum transducers further enhance nonreciprocity and out-of-band rejection, suppress spurious modes, and produce a flatter passband response.

3. Line 103~105: in general, when a wave is quantized in the transverse direction due to guiding, shouldn't the frequency of such spur be higher than the plane wave mode if the dispersion is normal (as opposed to anomalous dispersion commonly seen in FBAR devices). And MSSW exhibits normal dispersion? In addition, the wavevector of such spur should have a transverse component? My understanding is that the MSSW, MSFVW, MSBVW are derived under plane wave assumptions. When the wavevector has a transverse component, it seems the polarization of the MSSW would have to pick up something that's similar to MSBVW. Would an alternative interpretation be possible where there's some sort of MSSW and MSBVW hybridization happening leading to the frequency dropping below the MSSW manifold?

Answer to the reviewer:

We thank the reviewer for the insightful and technically precise question.

Regarding the frequency shift due to transverse quantization, we agree that for waves with normal (positive) dispersion, introducing a transverse quantization component $k_x = n\pi/w$ increases the total wavevector magnitude $k = \sqrt{k_x^2 + k_y^2}$, and the frequency would normally increase, as observed in acoustic, optical, or electromagnetic waveguides. However, spin-wave dispersion in magnetostatic systems is neither isotropic nor uniformly normal. For MSSW, and in particular for backward-volume (BV) type modes, parts of the dispersion are anomalous: the frequency decreases with increasing k for certain propagation directions or polarization configurations. When a transverse mode introduces an additional k_x component parallel to the magnetization (as in the stripe waveguide geometry), this reduces the effective dipolar energy contribution, thereby shifting the mode frequency downward. This behavior contrasts with systems exhibiting purely normal dispersion.

Concerning the role of MSSW dispersion and anisotropy, we agree that the pure magnetostatic surface spin wave (MSSW, or Damon–Eshbach mode) shows normal, forward dispersion when propagating strictly perpendicular to the magnetization in an extended film. However, in a laterally confined structure, propagation is no longer purely transverse to the magnetization—the quantized component k_x is now partly parallel to the direction of magnetization, M_0 . Because spin-wave dispersion is strongly anisotropic, the presence of this $k_x \parallel M_0$ component mixes in a backward-volume-like character. As a result, while the fundamental MSSW mode remains largely surface-localized, higher-order transverse modes (with larger k_x) exhibit progressively lower frequencies, consistent with the trends shown in Fig. 2 (a) or reference papers [R 2-3-1 and R2-3-2].

Finally, regarding the hybridization interpretation, the reviewer's suggestion is indeed physically meaningful and consistent with prior discussions in the magnons literature [R 2-3-1 and R2-3-2]. When the propagation direction becomes oblique to the magnetization, or when lateral confinement introduces a finite $k_x \parallel M_0$, the dynamic magnetization precession acquires both surface and volume characteristics. The resulting dipolar coupling hybridizes the MSSW and MSBVW modes, forming mixed MSSW–MSBVW eigenmodes. This hybridization provides an intuitive explanation for the observed frequency downshift of confined MSSW modes relative to the ideal plane-wave MSSW manifold.

[R2-3-1] Chumak, A. V., A. A. Serga, and B. Hillebrands. "Magnonic crystals for data processing." *Journal of Physics D: Applied Physics* 50.24 (2017): 244001.

[R2-3-2] V. E. Demidov and S. O. Demokritov, "Magnonic waveguides studied by microfocus Brillouin light scattering," *IEEE Transactions on Magnetics*, vol. 51, no. 4, pp. 1-15, 2015

To improve clarity, the following sentences have been modified:

Thickness Scaled Yttrium Iron Garnet (YIG) Section:

When the film has finite width, the wavevector in the width (z) direction becomes quantized, leading to discrete standing wave modes. Because the transverse quantization introduces a wavevector component parallel to the magnetization, the effective dipolar energy is reduced, causing these confined modes to appear at lower frequencies than the corresponding plane-wave MSSW mode. This finite-width confinement allows MSSWs to occur below ω_{min} , entering the volume wave frequency range.

4. Line 130: is it possible to squeeze in chart on corresponding s_{21} ?

Answer to the reviewer:

We appreciate the reviewer's suggestion. However, figures are already quite dense, and adding additional S_{21} data would make them difficult to read. To more clearly illustrate the difference in nonreciprocal behavior between the thick and thin films, we have included a detailed comparison of S_{21} and S_{12} in Supplementary Note 4. The following sentences have also been added to the revised manuscript to direct readers to this additional data:

YIG Filter with Meander-Line Transducers Section:

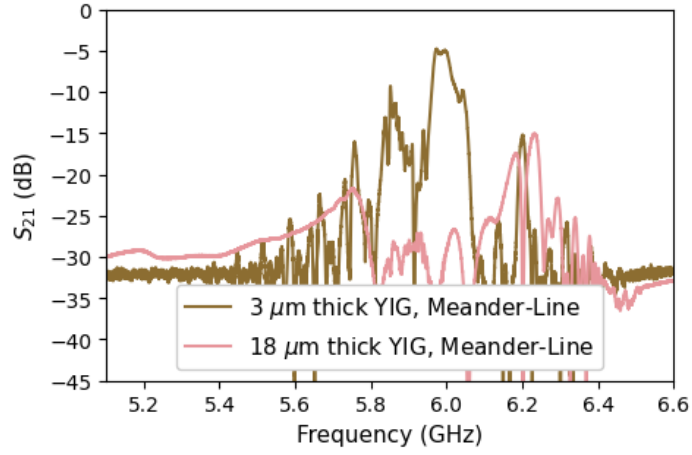
Moreover, Supplementary Note #4 also compares the nonreciprocity of 3 μm and 18 μm thick YIG meander-line filters. It highlights that, with increasing film thickness and the resulting increased sidewall roughness, the YIG structure no longer supports resonant circulation. Instead, the spin waves excited at one port predominantly propagate in a single direction, leading to enhanced nonreciprocal behavior.

Supplementary Note #4: Comparison of YIG Filters with Straight Line and Meander-Line Transducers:

Supplementary Figure 11 highlights the improved nonreciprocity observed in the 18 μm thick YIG filters with meander-line transducers compared to their 3 μm thick counterparts. As shown in Fig. 3c, both filters exhibit distinct passbands in the forward transmission (S_{12}). However, in Supplementary Figure 11, the backward transmission (S_{21}) differs markedly: the 3 μm filter shows less than 5 dB attenuation, whereas the 18 μm filter exhibits strong suppression, indicating pronounced nonreciprocal behavior.

The difference arises from the underlying propagation mechanisms. In the 3 μm -thick YIG filter, the device functions similarly to a resonator, where the two straight edges act as reflective boundaries [6, 8]. The magnetostatic surface waves (MSSWs) are reflected back and forth between the edges, forming circulating wave patterns that yield nearly reciprocal transmission.

In contrast, the 18 μm -thick YIG filter no longer supports such resonant circulation. The spin waves excited at one port propagate primarily in a single direction and experience minimal reflection. One key factor is the increased sidewall roughness of the thicker YIG film, as visible in the optical micrographs (Fig. 2c and Fig. 2d). The roughened edges, which result from the greater etching depth required for thick YIG, act as scattering centers that suppress spin-wave reflection. This phenomenon is consistent with previous studies that used rough and lossy edge terminations [9-12], nonuniform magnetic fields [13], or additional spin wave absorbers [11, 14, 15] to minimize reflection and enhance nonreciprocity. Furthermore, increasing the film thickness enhances surface confinement and unidirectionality of MSSWs on a single surface, further increasing nonreciprocal transmission.



Supplementary Figure 11. Comparison of measured S_{21} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss. The S_{12} frequency response comparison is shown in Fig. 3 in the main text.

5. Fig.2: it seems the etching profile of YIG is highly tapered, and the electrode edges are rough. Can you comment on the effect of these on loss?

Answer to the reviewer:

We thank the reviewer for this thoughtful observation. The tapered etching profile of the YIG arises from the nature of the hot phosphoric acid etching process, which produces slanted sidewalls rather than perfectly vertical ones. In our study, this tapered geometry is not detrimental. In fact, it is intentionally leveraged to reduce sidewall reflections of MSSW and to suppress standing-wave formation within the YIG film. This suppression helps enhance the device's nonreciprocity by minimizing internal wave circulation. Therefore, while the sidewall taper is a byproduct of the wet etching process, it also contributes positively to the observed unidirectional propagation characteristics. That said, we acknowledge that the precise relationship between sidewall geometry and propagation loss warrants further investigation. A more systematic analysis of different sidewall profiles would help quantify their effects on insertion loss, and we plan to address this in future work.

Regarding the roughness of the electrode edges, this is partially due to the aluminum etching process used to define the YIG and electrode patterns. While our current measured insertion loss is very small and can be less than 3 dB in some frequency ranges, we agree that smoother electrode edges could further reduce insertion loss. The optimization of the metallization and etching processes to achieve smoother edges will also be pursued in future studies.

6. Line 155: “a is the width of the transducer”. This might be a little confusing. One could potentially interpret “a” as the length of the arm of the meander line. Maybe add an annotation in one of the figures, and refer to it? Or rephrase?

Answer to the reviewer:

We appreciate the reviewer’s helpful suggestion. To avoid confusion, we have replaced the symbol “a” with W_T to clearly denote the width of the transducer. Corresponding text in the manuscript has been revised accordingly. The following sentences have been updated in the revised manuscript.

YIG Filter with MeanderLine Transducers Section :

A previous study determined the radiation resistance for a meander-line transducer as follows [33]:

$$T_m = \frac{R_m}{R_1 \times l} = \left[\frac{\sin\left(\frac{W_T k_y}{2}\right)}{\frac{W_T k_y}{2}} \right]^2 \left[\frac{\sin\left(\frac{p N k_y}{2}\right)}{\cos\left(\frac{p k_y}{2}\right)} \right]^2 \quad (1)$$

Here, T_m is the transducer specific radiation impedance per unit length, R_m is the radiation impedance, and R_1 is a function of YIG parameters and ground-plane spacing and is independent of transducer parameters, l is the length of the meander-line transducer’s arm, which also serves as the width of the YIG waveguide, W_T is the width of the transducer, p is the pitch, and N is the number of arms in the meander-line.

The same YIG waveguide shape and transducers are utilized for both designs, except the 3 μm thick YIG filter has $W_T = 5 \mu m$, while the 18 μm thick YIG filter has $W_T = 10 \mu m$.

7. Lien 169: why a different “a” was chosen for the 18 μ m YIG device comparing to 3 μ m YIG devices, can you elaborate?

Answer to the reviewer:

We appreciate the reviewer’s question and the opportunity to clarify this point. In this study, a 10 μ m transducer width was used for all 18 μ m-thick YIG filters, while a 5 μ m transducer width was used for all 3 μ m-thick YIG filters.

Although the benzocyclobutene (BCB) planarization layer effectively smooths the YIG surface and reduces the step height at the YIG edges, a noticeable topographical step still remains. The aluminum transducer must transition from the BCB surface to the top of the YIG, and this height difference can cause discontinuities or breaks in narrow electrodes. Using a wider transducer helps mitigate this issue by providing better step coverage and improved metal continuity, thereby enhancing overall fabrication yield.

8. Line 185-187: the return loss should also be dependent on z_{12} , z_{21} , and z_{22} ? Maybe also provide values for these, when referring to return losses?

Answer to the reviewer:

We appreciate the reviewer’s insightful comment. The intent of the original sentence was to emphasize that the meander-line YIG filter exhibits a larger Z_{11} value, primarily due to the three arms of meander line, which contributes to improved impedance matching and consequently a higher return loss at certain frequencies.

We fully agree that the return loss depends not only on Z_{11} , but also on the other impedances parameters. A complete understanding of return loss indeed requires consideration of the full impedance matrix. To clarify this, we have revised the manuscript to explicitly acknowledge this dependency.

YIG Filter with MeanderLine Transducers Section :

The maximum filter input impedance, Z_{11} , values are 40.9 dB and 33.2 dB for the meander-line and straight-line YIG filters, respectively. The minimum return losses, **determined by the full impedance matrix**, are 21.5 dB and 10.4 dB for the meander-line and straight-line YIG filters, respectively.

9. Line 203~205: “furthermore....”, can this statement be quantified? Not sure if could find measurements or calculations on this in the manuscript.

Answer to the reviewer:

We appreciate the reviewer’s valuable suggestion. The original statement was intended to compare the insertion loss performance between the single large YIG waveguide filter and the two-parallel YIG waveguide configuration. Supplementary Note #6 has quantified this comparison using measurement data. Specifically, the insertion loss increased from 2.9 dB to 4.2 dB at 6.3 GHz, from 3.1 dB to 4.9 dB at 8.8 GHz, and from 3.8 dB to 6.5 dB at 11.8 GHz.

The corresponding sentences in the manuscript have been revised for clarity as follows:

YIG Filter with MeanderLine Transducers Section :

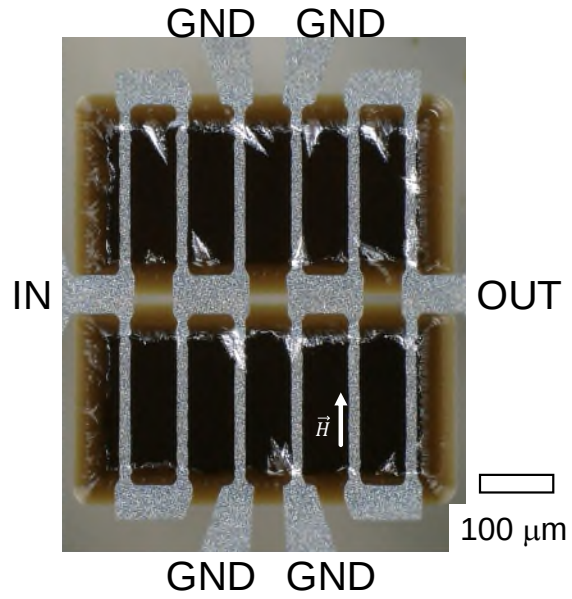
Furthermore, the use of a larger YIG waveguide in the two-parallel design contributes to **1-3 dB** lower insertion loss by reducing sidewall propagation loss. Supplementary Note #6 compares the performance of two-parallel meander-line filters with single and dual YIG waveguides, showing that wider YIG waveguides exhibit lower insertion loss and reduced demagnetization effects.

Supplementary Note #6: Comparison of YIG Filters with Dual Waveguide and Single Waveguide Designs

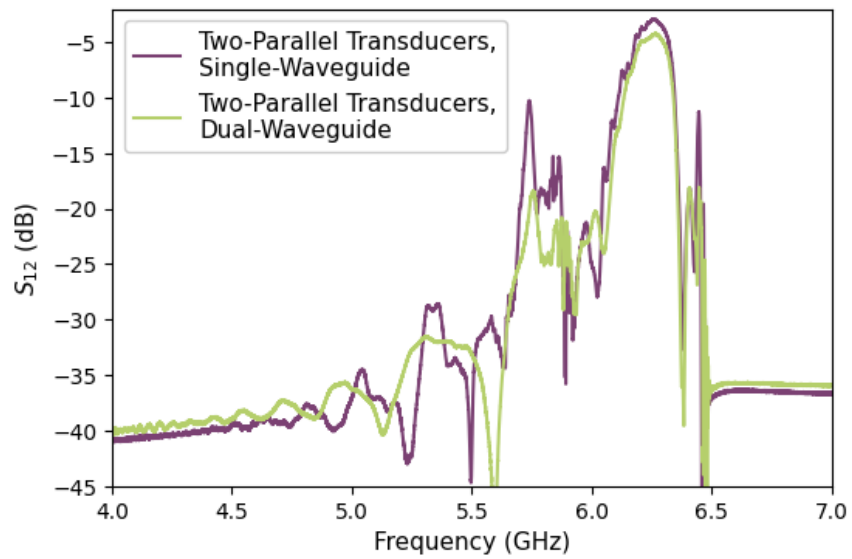
Supplementary Figure 15 shows a two-parallel meander-line filter featuring dual YIG waveguides, where each YIG waveguide follows the same design as the single meander-line filter. Compared to the two-parallel meander-line filter with a single YIG waveguide (**Fig. 3e**), the dual YIG waveguide configuration positions the center bridge section of the meander-line above the BCB/GGG where there is no YIG. As a result, the dual YIG waveguide filter reduces the contact between the bridge section of the meander-line to the YIG waveguide and reduces the excitation of magnetostatic backward volume waves (MSBVWs).

Supplementary Figure 15, 16, and 17 provide a comparative analysis of the frequency responses of two-parallel meander-line YIG filters with single and dual YIG waveguides under magnetic bias fields of 1500, 2500, and 3500 Gauss, respectively. The single-waveguide filter exhibits more pronounced spurious modes in both S_{12} and S_{11} .

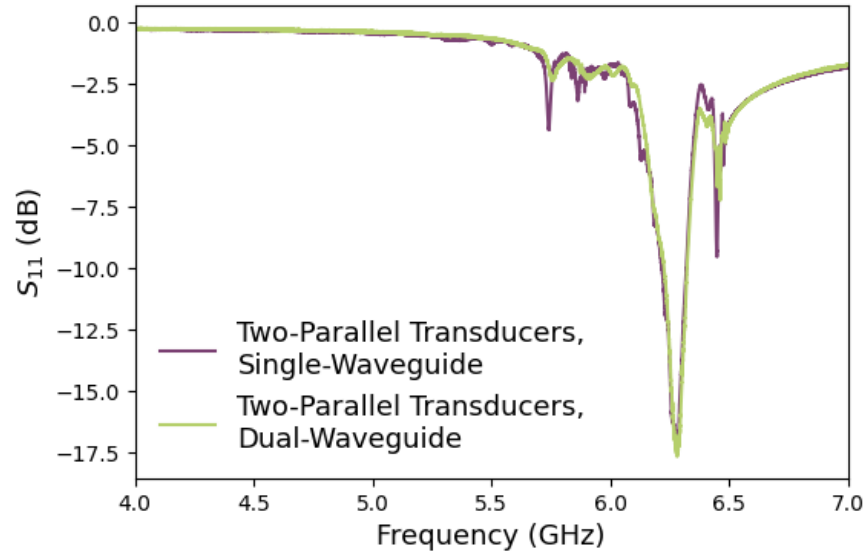
By moving the bridge section away from the YIG, the dual-waveguide configuration effectively suppresses the large spurious peaks that occur at frequencies slightly below the passband: 5.7 GHz (1500 Gauss), 8.7 GHz (2500 Gauss), and 11.5 GHz (3500 Gauss). However, the dual-waveguide design was not adopted in this study primarily due to its higher insertion loss. Specifically, the insertion loss increased from 2.9 dB to 4.2 dB at 6.3 GHz, from 3.1 dB to 4.9 dB at 8.8 GHz, and from 3.8 dB to 6.5 dB at 11.8 GHz. The increase in insertion loss can also be observed in the Smith chart analysis, where the dual-waveguide filter exhibits a smaller resonance circle, indicating weaker resonances. This increased loss is suspected to arise from the larger total edge region of the YIG waveguides in the dual-waveguide design. In contrast, the single-waveguide configuration minimizes the edge region, thereby reducing edge-related MSSW scattering and MSSW propagation loss.



Supplementary Figure 15. Optical microscope image of a two parallel meander-line transducer dual-waveguide YIG filter with pitch of 70 μm and width of 200 μm .

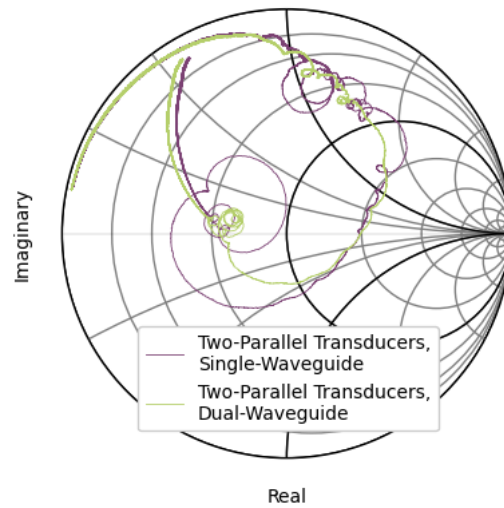


(a)



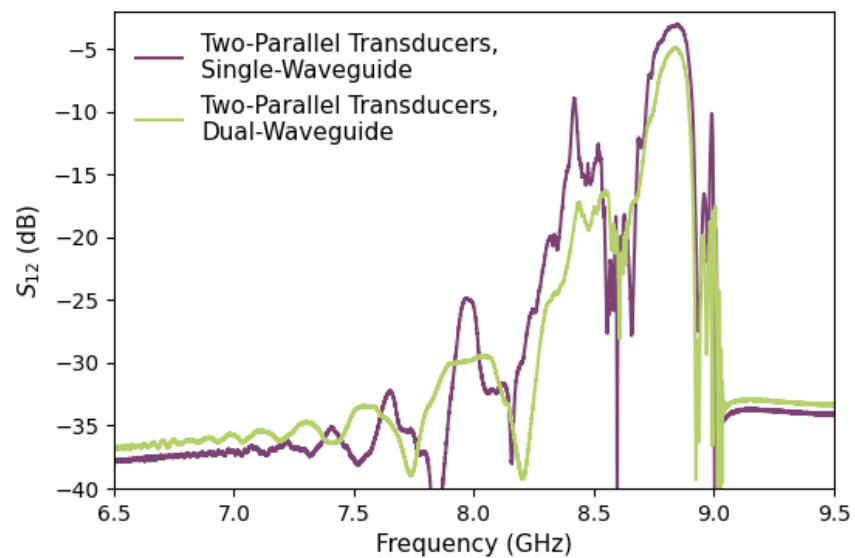
(b)

Complex Plane

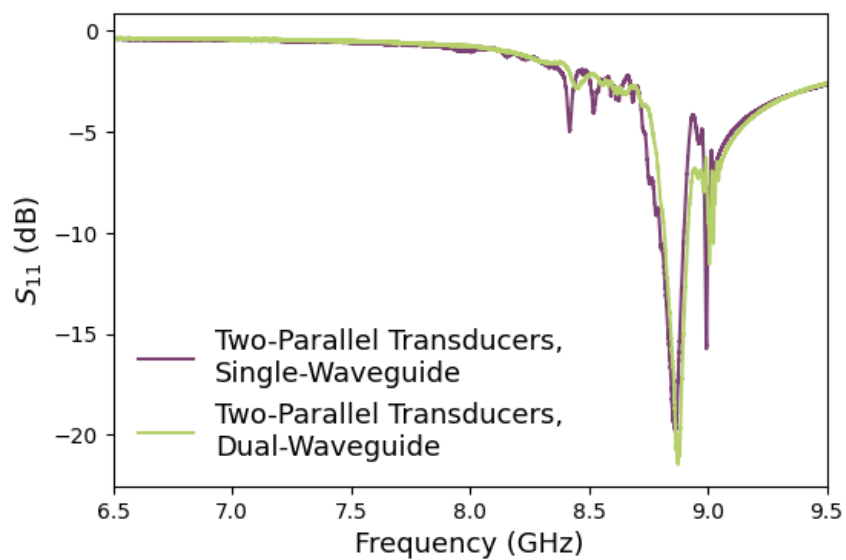


(c)

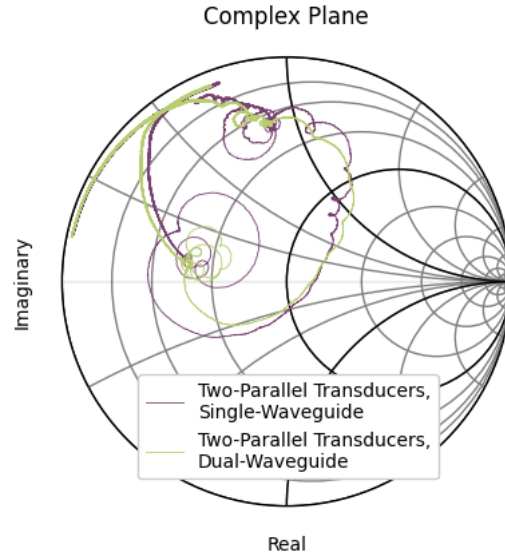
Supplementary Figure 16. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer dual and single waveguide YIG filters under applied magnetic flux densities of approximately 1500 Gauss.



(a)

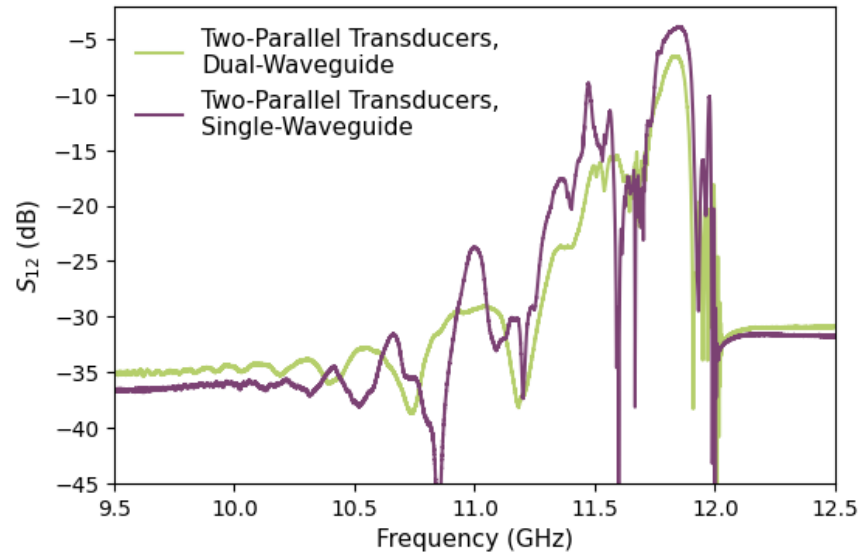


(b)

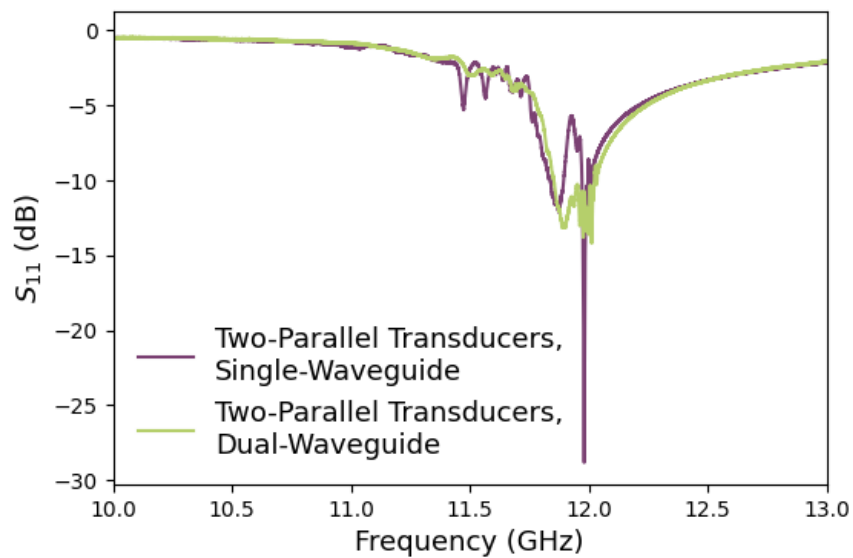


(c)

Supplementary Figure 17. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer dual and single waveguide YIG filters under applied magnetic flux densities of approximately 2500 Gauss.

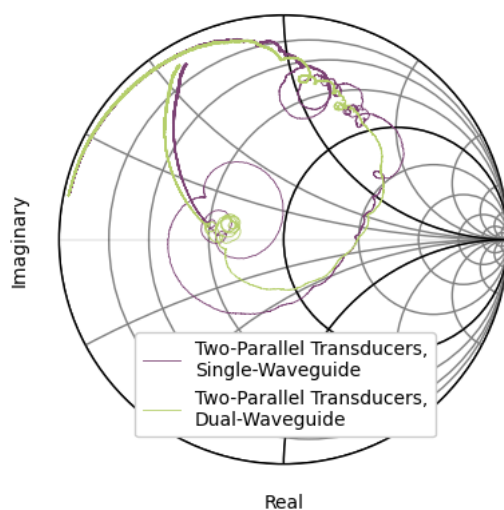


(a)



(b)

Complex Plane



(c)

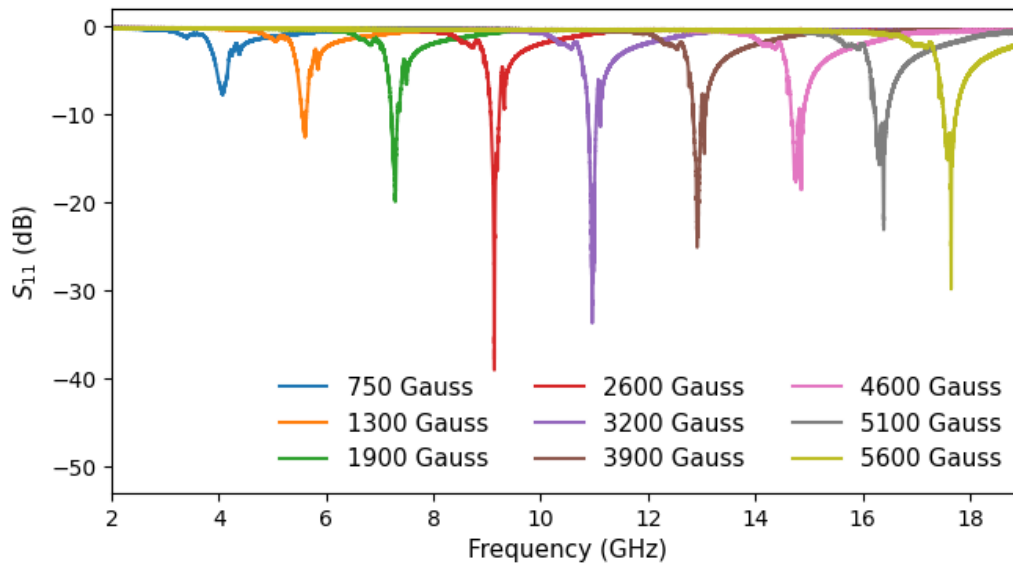
Supplementary Figure 18. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer dual and single waveguide YIG filters under applied magnetic flux densities of approximately 3500 Gauss.

10. Line 233~234, can the authors discuss what's the fundamental limit of the insertion loss? When two parallel design is used, the transducer input impedance is around 50ohm? Do the authors expecting better insertion loss than measured?

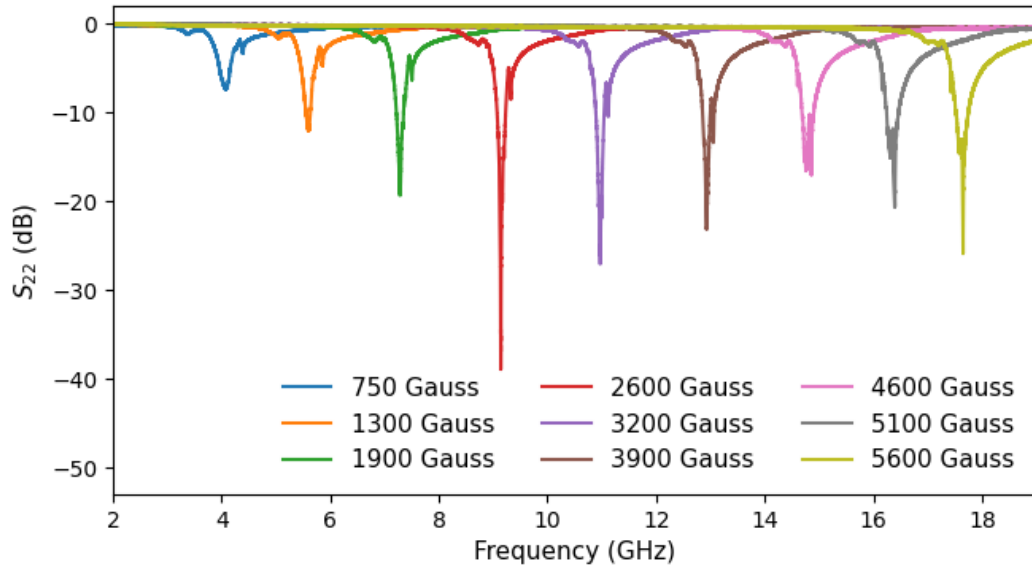
Answer to the reviewer:

We appreciate the reviewer's insightful question. The fundamental limit of the insertion loss in our YIG-based nonreciprocal filters is primarily determined by the intrinsic spin-wave propagation loss, which is governed by the Gilbert damping coefficient (α) of the YIG material. However, in our micromachined and patterned devices, additional contributions such as surface roughness, etch-induced defects, and magnetostatic nonuniformities can increase the effective damping and, consequently, the insertion loss. Future work focused on improving YIG material quality could further reduce this loss toward the intrinsic limit.

Regarding the two-parallel filter design, Supplementary Fig. 31 (c) shows the impedance characteristics of the dual-hexagon YIG filter. The measured input impedance is well matched to 50 Ω across a broad range (4–18 GHz), with the best matching occurring around 9 GHz, where the insertion loss reaches 2.9 dB.



(b)



(c)

Supplementary Figure 31. Measured (b) S_{11} (output port) and (c) S_{22} (Input port) frequency responses with the magnetic field supplied by the zero static power consumption magnetic bias circuit.

11. Line 240: “spurious mode around 8.8GHz” did the authors mean 8.4GHz?

Answer to the reviewer:

We appreciate the suggestion from the reviewer. It should be 8.4 GHz. The following sentence has been changed:

YIG Filter with Meander Line Transducers Section:

Fig. 4d depicts a dual-hexagon YIG design that enhances nonreciprocity and suppresses the spurious mode **around 8.4 GHz**, while maintaining a nearly constant insertion loss.

12. Line 283~286: it seems the P1db were measured with VNA by varying the excitation power? It's a little hard to see in the figures in the supplement materials, but it would be interesting to see if the p1db vs. frequency? Might not provide much insights, but might be interesting.

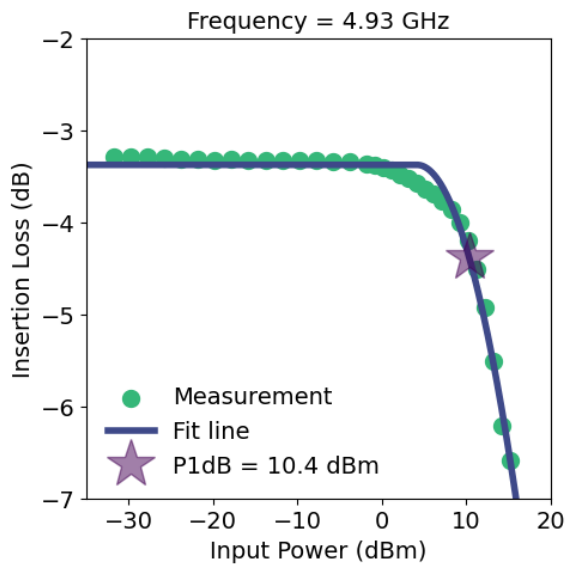
Answer to the reviewer:

We appreciate the reviewer's thoughtful suggestion. The P1dB measurements were indeed performed using a vector network analyzer (VNA) by gradually increasing the input power. To further illustrate the power-handling characteristics of the tunable filter, we have added a P1dB versus frequency plot to the Supplementary Information. This plot summarizes the measured P1dB values at eight different center frequencies, showing that the saturation power increases slightly with frequency.

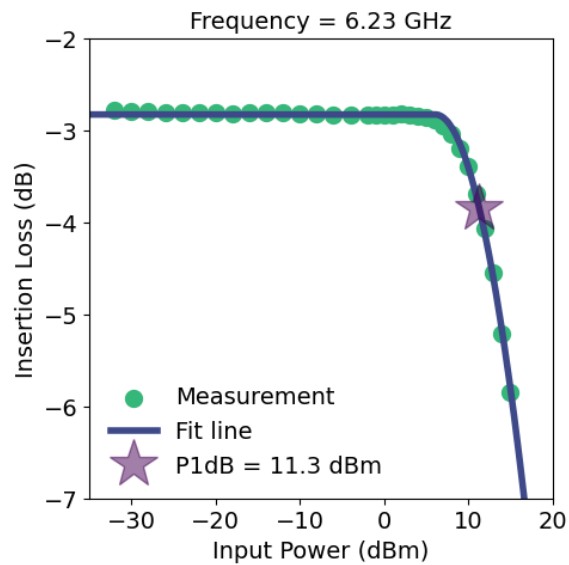
Supplementary Note #10: Power Handling Characteristics Section :

Supplementary Figures 25, 26, and 27 present a comparative analysis of the frequency responses of the filter with different input power levels, ranging from -30 dBm to 16 dBm. The filter under test is an 18 μm thick dual-hexagon-shaped YIG filter with two-parallel meander-line transducers. It features a waveguide width of 200 μm , a transducer pitch of 70 μm , and a transducer width of 10 μm .

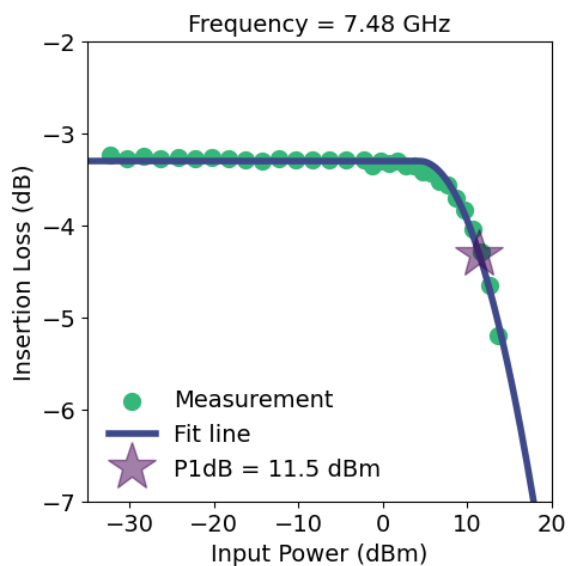
The filter response remains unchanged up to an input power of approximately 8 dBm. The measured input 1 dB compression points (P1dB) are 10.4 dBm, 11.3 dBm, 11.5 dBm, 12.0 dBm, 12.0 dBm, 11.9 dBm, 14.3 dBm, and 13.5 dBm at 4.9 GHz, 6.2 GHz, 7.5 GHz, 9.1 GHz, 10.2 GHz, 11.9 GHz, 13.3 GHz, and 14.7 GHz, respectively. This large power handling capability has been significantly improved from a filter implemented using a straight-line transducer in a 3 μm thick YIG film, with P1dB of -17 dBm to -14 dBm reported in a previous study [6]. **Supplementary Figure 28** reports the power handling of a meander-line transducer filter realized in a 3 μm thick YIG film with P1dB near 0 dBm. The design of this type of filter was reported in [16]. It can be concluded that the enhanced power handling is attributed primarily to the increased YIG thickness. Moreover, the filter reported in this work maintains consistent out-of-band rejection and nonreciprocity characteristics across the tested power range.



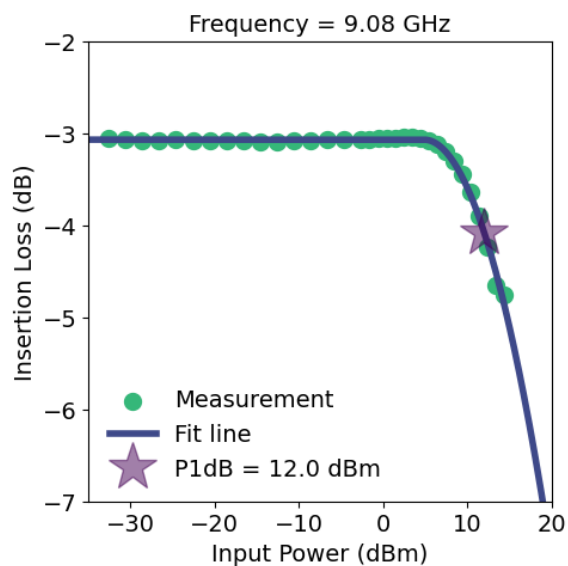
(a)



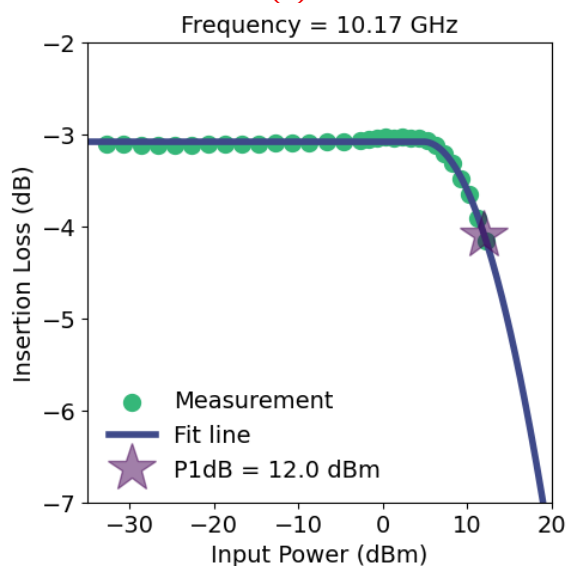
(b)



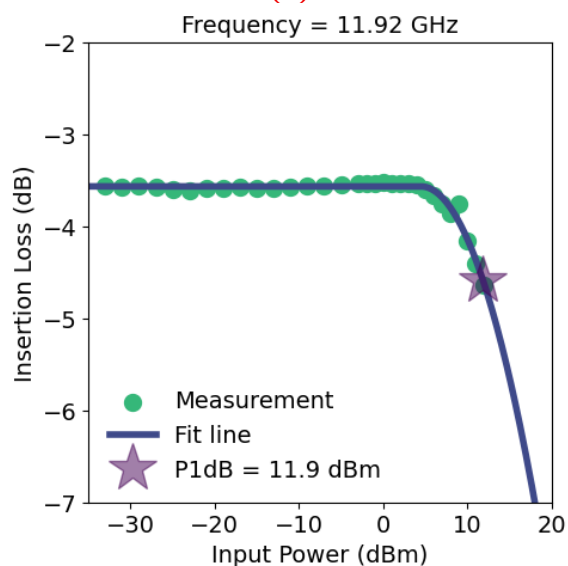
(c)



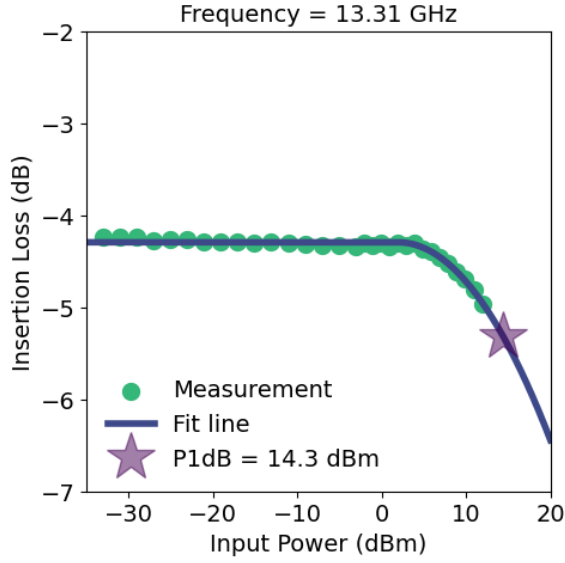
(d)



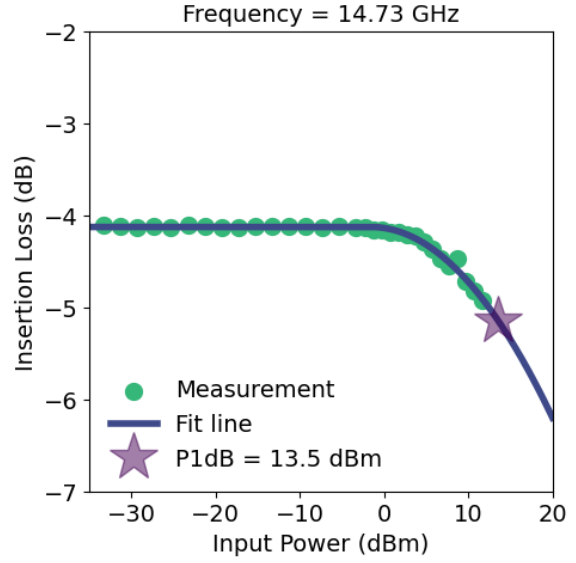
(e)



(f)

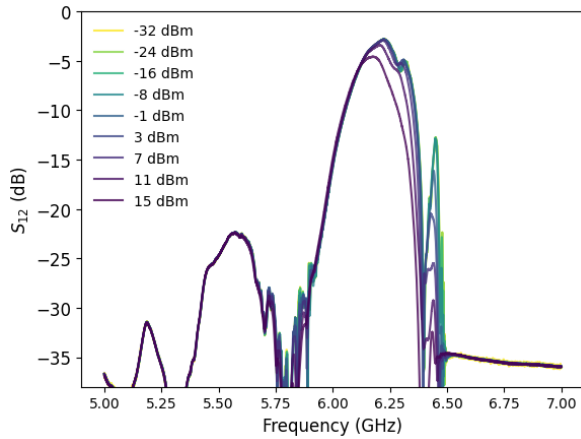


(g)

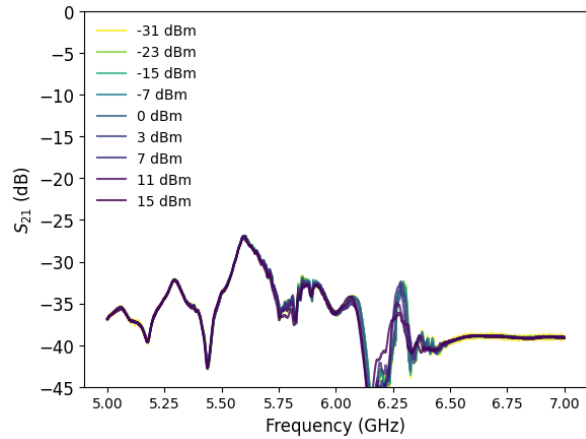


(h)

Supplementary Figure 25. Comparison of the insertion loss with different input powers with bias field of (a) ~1000 Gauss, (b) ~1500 Gauss, (c) ~2000 Gauss, (d) ~2500 Gauss, (e) ~3000 Gauss, (f) ~3500 Gauss, (g) ~4000 Gauss, (h) ~4500 Gauss.

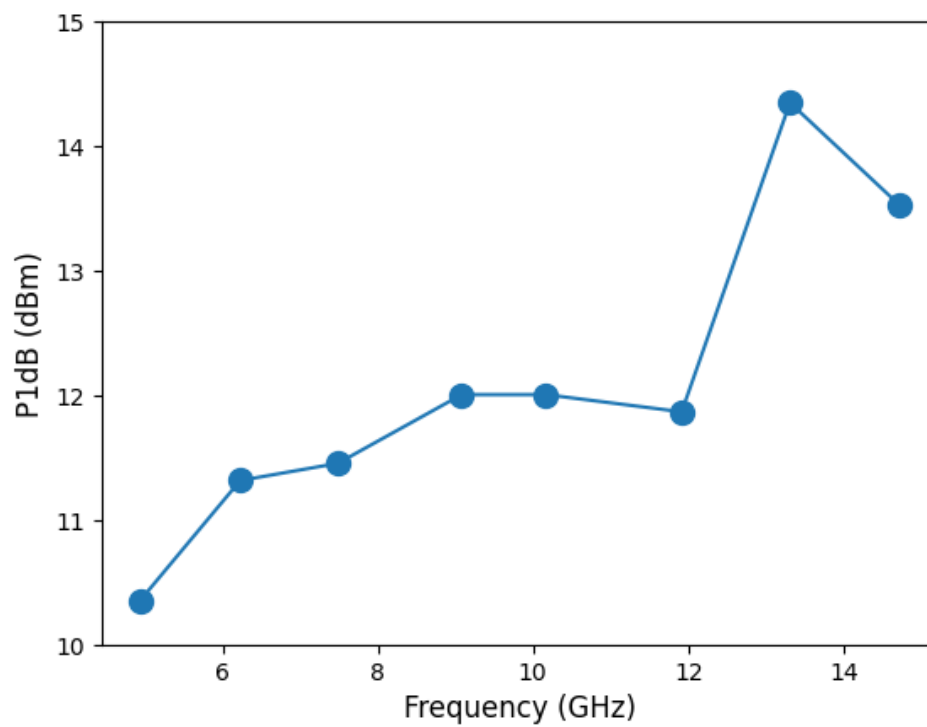


(a)

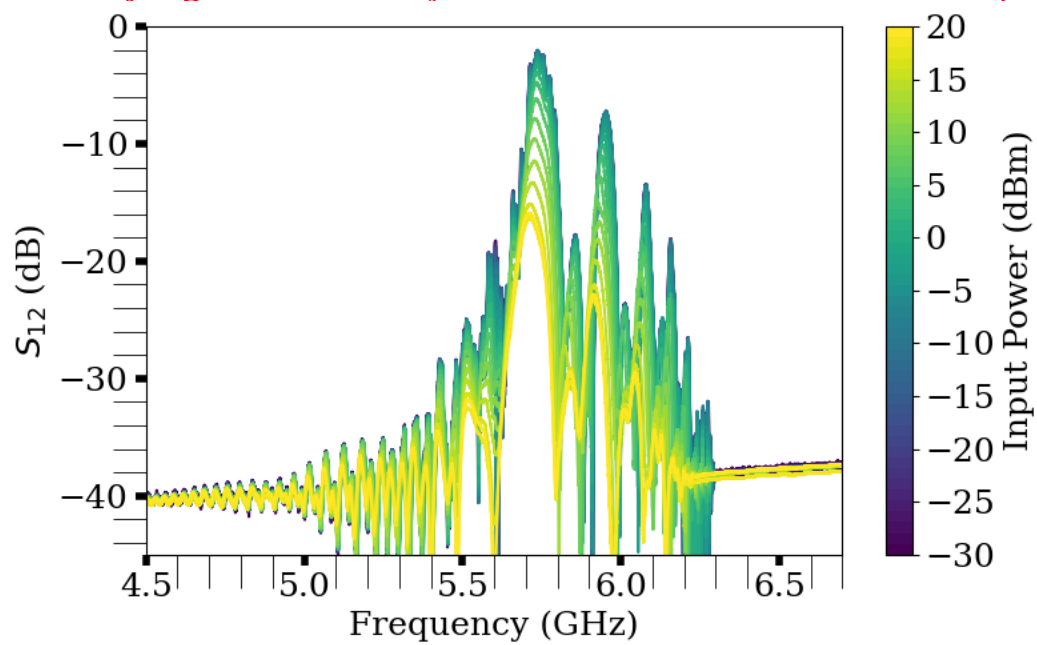


(b)

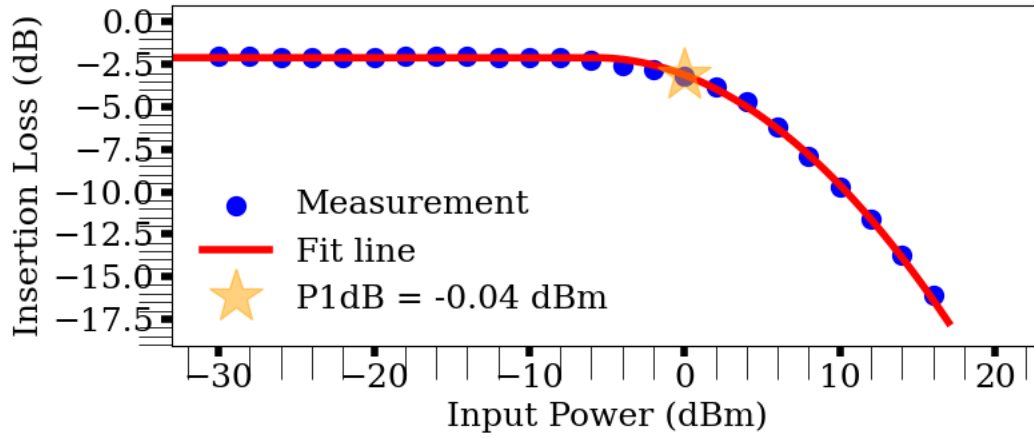
Supplementary Figure 26. Comparison of the measured (a) S_{12} and (b) S_{21} frequency responses with different input power with a bias field of ~1500 Gauss.



Supplementary Figure 27. Summary of the P1dB results as a function of frequency.



(a)



(b)

Supplementary Figure 28. Comparison of the measured (a) S_{12} frequency responses and (b) insertion loss with different input power at 5.8 GHz. This 3 μm thick YIG meander-line filter was previously reported in [16].

13. Line 347: what is the purpose of annealing the ALD oxide hard mask? Improving selectivity? Anneal out pinholes? It is interesting that an ALD hard mask is used here. Can the authors comment on why ALD? Also, line:358, patterning of the aluminum transducers uses a PECVD oxide? Why oxide hard masks using different deposition methods are used for the two steps?

Answer to the reviewer:

We appreciate the reviewer's question regarding the use and processing of the oxide hard masks.

The ALD-grown oxide hard mask was annealed primarily to enhance its adhesion to the YIG surface. ALD was specifically chosen because it provides higher quality, which is essential for achieving high selectivity and maintaining mask integrity during the prolonged wet etching process required for the 18 μm -thick YIG films.

In contrast, for the aluminum transducer patterning, the etching depth and selectivity requirements are less stringent. Therefore, a PECVD oxide hard mask was used in that step. Although PECVD oxide has a higher deposition rate, it typically exhibits lower quality and more pinholes compared to an ALD oxide, making it unsuitable for deep YIG etching, but adequate for defining the shallow aluminum transducers.

14. Line 354: it is not immediately clear which part of the BCB was patterned from first read. Maybe refer to one of the figures? And add some annotations?

Answer to the reviewer:

We appreciate the reviewer's helpful suggestion. The photosensitive BCB used in this work behaves similarly to a negative photoresist: it undergoes cross-linking upon UV exposure. During the photolithography process, the regions of BCB not covering the YIG are exposed to UV light and become cross-linked, while the BCB directly on top of the YIG is shielded from exposure and therefore remains uncrosslinked. This uncrosslinked BCB is subsequently removed during the development step using AP3000 developer, effectively leaving openings above the YIG regions. The revised description in the Methods section is now as follows:

Methods Section:

Following spin coating, the BCB layer was exposed to UV light and patterned using AP3000 developer. The regions of BCB not covering the YIG were crosslinked upon UV light exposure and remained, while the unexposed BCB directly on top of the YIG was dissolved in the developer (see Fig. 1d).

15. Line 355: annealing the BCB to cure it and make it permanent?

Answer to the reviewer:

We appreciate the reviewer's question. Yes, the purpose of annealing the BCB is to fully cure it and form a stable, permanent dielectric layer. For clarity, the corresponding description in the Methods section has been revised as follows:

Methods Section:

The patterned BCB was then thermally annealed at 350 °C for 2 hours to complete cross-linking and fully cure the film, forming a stable dielectric layer.

16. Has the authors tried IP3 measurements?

Answer to the reviewer:

We appreciate the reviewer's suggestion. The IIP3 measurement results have been added as Supplementary Note #11: In-Band Linearity.

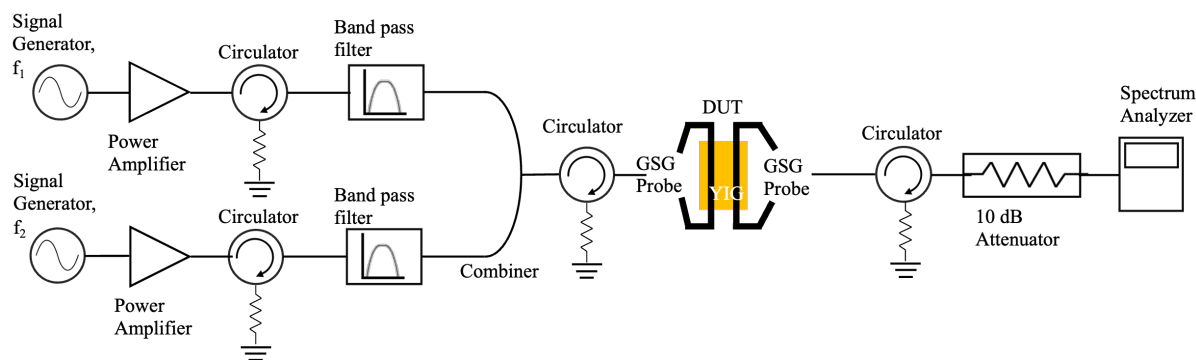
Integrated Device Section:

Supplementary Note #11 also shows the in-band linearity of the filter, which exhibits an input-referred third order intermodulation intercept point (IIP3) of more than +26 dBm.

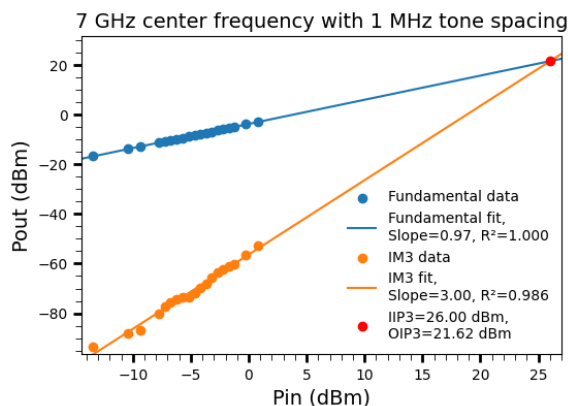
Supplementary Note #11: In-Band Linearity:

The in-band third order intermodulation intercept point (IIP3) measurement setup followed the procedure described in a previous report [6], as shown in **Supplementary Figure 29**. Two-tone signals (f_1 and f_2) were generated using two signal generators (Keysight P5024B). The combined signal was first amplified by a Mini-circuits ZX60-24-S+ amplifier. To suppress unwanted harmonics and spurious tones, two bandpass filters (Mini-circuits ZBSS-12G-S+) and two circulators (DiTom Microwave DMC6018) were employed to clean the amplified signals. The two tones were then combined using a power combiner (Krytar 6020265), passed through an additional circulator, and applied to the device under test (the YIG filter). The output of the YIG filter was routed through another circulator and a 10 dB attenuator before being connected to a spectrum analyzer (Keysight P5024B).

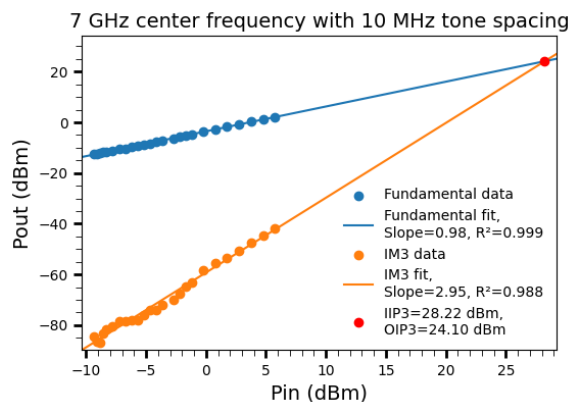
Supplementary Figure 30 presents the resulting in-band IIP3 data measured at 7 GHz and 11 GHz for tone spacings of 1 MHz, 10 MHz, and 100 MHz. For 1 MHz and 10 MHz tone spacings the third order intermodulation (IM3) products fall fully within the filter passband. Over all conditions the IIP3 remains above +26 dBm, a significant improvement over prior reports [5, 6, 17] demonstrating the improved linearity associated with realizing filters in the thicker YIG films.



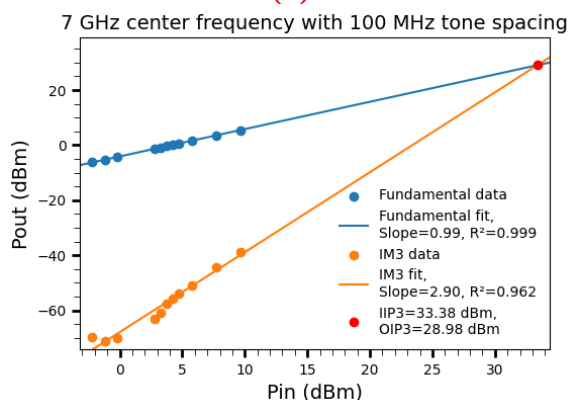
Supplementary Figure 29. In-band third order intermodulation intercept point (IIP3) measurement setup schematic.



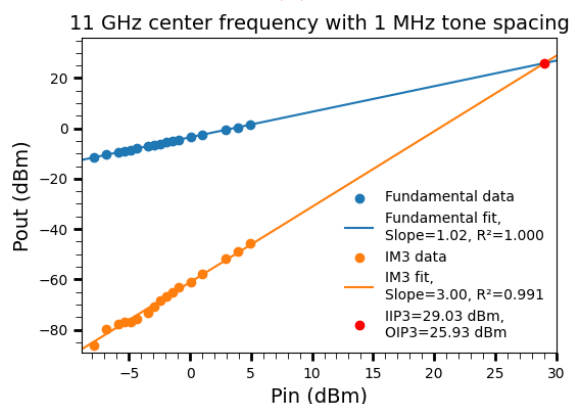
(a)



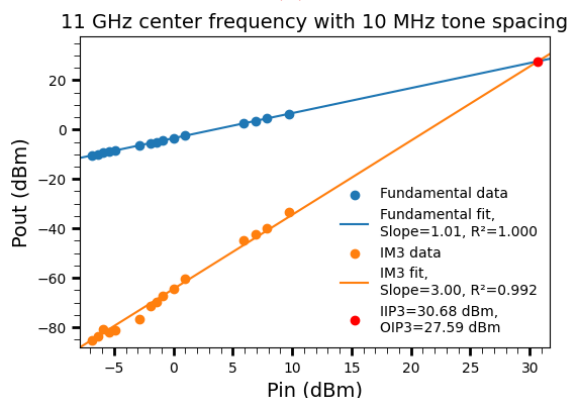
(b)



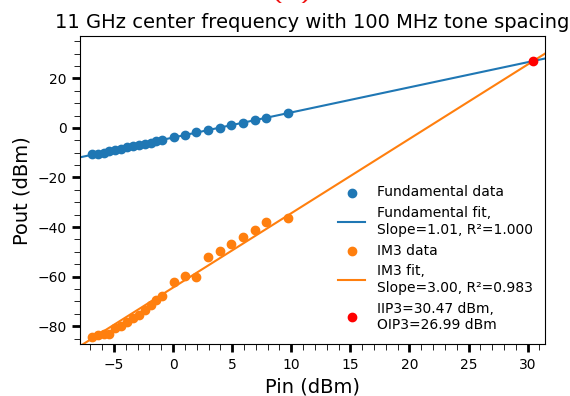
(c)



(d)



(e)



(f)

Supplementary Figure 30. In-band input third order intercept point (IIP3). The device is measured at (a, b, and c) 7 GHz and (d, e, and f) 11 GHz with tone spacings of (a and d) 1 MHz, (b and e) 10 MHz, and (c and f) 100 MHz.

Reviewer #4 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

REVIEWERS' COMMENTS

Reviewer #1 (Remarks to the Author):

Review Comments for A Wideband Tunable, Nonreciprocal Bandpass Filter Using Magnetostatic Surface Waves with Zero Static Power Consumption-Revision

The authors have made commendable progress in revising the manuscript, and most of the previous comments have been addressed satisfactorily. The discussion on YIG thickness selection is much improved and provides useful context. However, to further strengthen the manuscript and enhance its value to the broader community, it would be beneficial to include some quantitative analysis of the design choices.

For instance, the authors note that experimental data is currently limited to 3, 15, and 18 μm YIG films due to availability constraints, and that no significant performance difference was observed between the 15 and 18 μm samples. Given this, it remains unclear whether a 15 μm or even a 10 μm film—if available—might yield comparable results. While it is understandable that acquiring experimental data across the full 3–18 μm range may not be feasible within a reasonable timeframe, a theoretical or simulation-based analysis could help understand the continuous behavior of device performance as a function of YIG thickness.

As a suggestion, Figures 2(a) and 2(b) could be regenerated for additional thickness values within this range to examine whether the observed improvements are monotonic or tend to saturate. Similarly, Figure 3(a) might also be updated accordingly. At present, the manuscript implies that only two thickness options—3 μm and 18 μm —are viable. To guide future development of YIG films with intermediate thicknesses, it would be helpful to understand whether increasing thickness continues to offer benefits or if an optimal balance exists. This insight would be valuable in informing the direction of subsequent research efforts.

Answer to the reviewer:

We sincerely appreciate the reviewer's positive and encouraging comments on our revised manuscript, as well as the thoughtful suggestions for further strengthening the analysis of YIG thickness effects. We fully agree that incorporating additional thickness values within the 3–18 μm range can provide deeper insight and offer useful guidance for future device development. To address the reviewer's points, we have expanded our analysis in several ways:

Figure 2(a) already contains multiple dispersion curves and is visually dense. To still provide the quantitative insight the reviewer requested, we have instead added a dedicated comparison of dispersion behavior across different thicknesses in Supplementary Note #1: Magnetostatic Surface Wave Dispersion Relationship, where the curves can be displayed clearly without visual congestion.

Figure 2(b) has now been updated to include calculated results for multiple YIG thicknesses (3, 6, 9, 12, 15, and 18 μm). This allows the reader to directly compare how device performance evolves with thickness and confirms that the trend remains monotonic across this range.

Following the reviewer's suggestion, we have added a 10 μm YIG case to Fig. 3(a). This intermediate thickness helps illustrate the continuous transition between thin-film and thick-film behavior, making the overall trend more apparent to the reader.

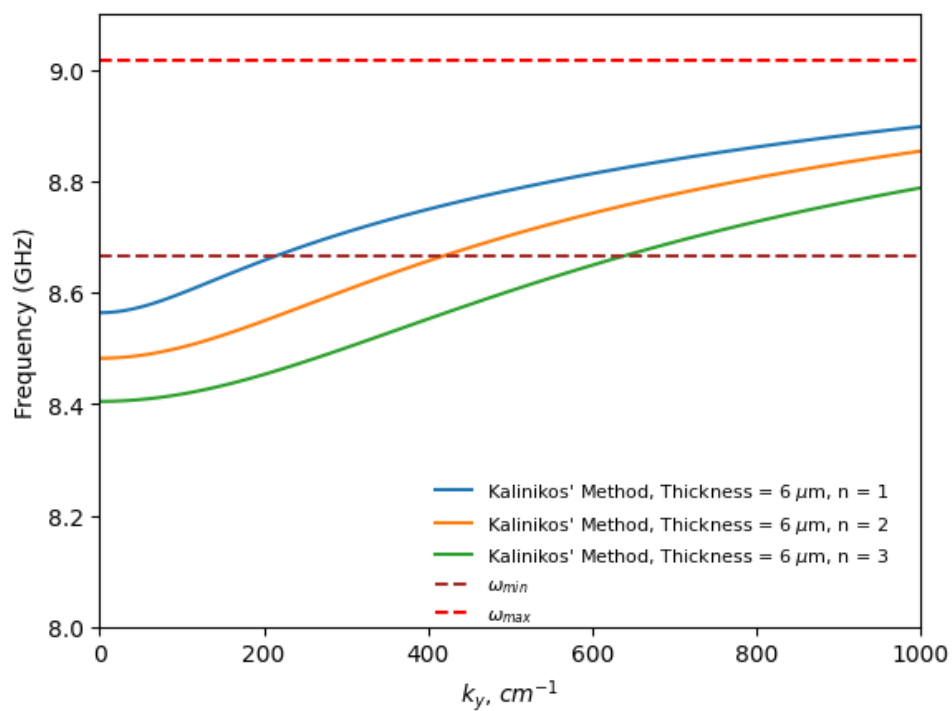
These suggests that there is no abrupt change in behavior between 3 and 18 μm . We believe this provides valuable context for guiding the fabrication of future YIG films with intermediate thicknesses.

Thickness Scaled Yttrium Iron Garnet (YIG) Filter Section:

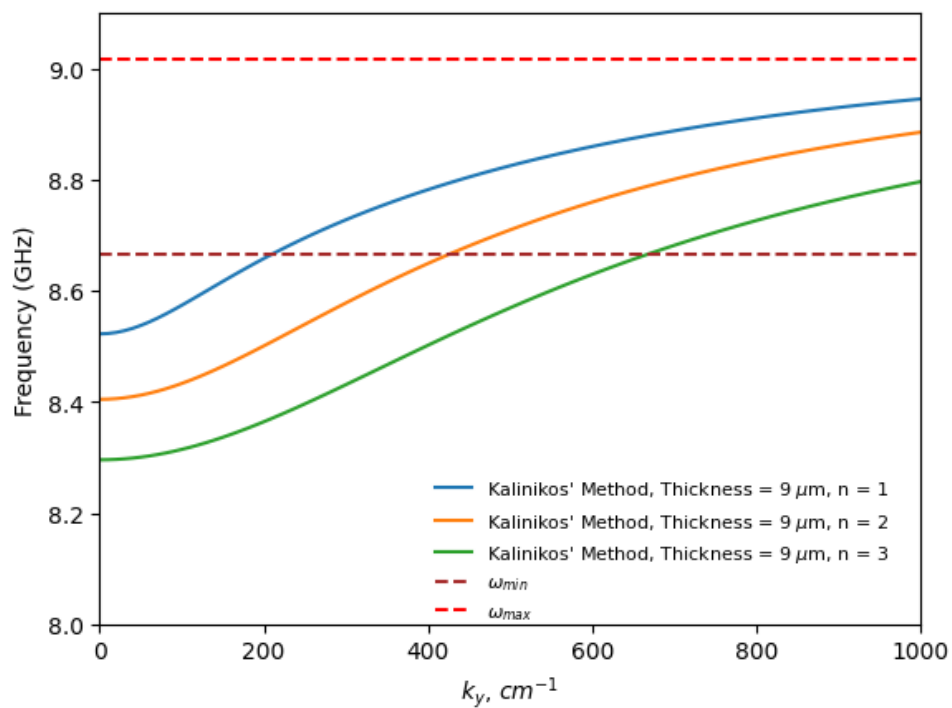
Fig. 2a shows the calculated dispersion relationship for 3 μm and 18 μm thick YIG films using the equations from [31], with demagnetization effect neglected. The calculation details and the results for other thicknesses can be found in Supplementary Note #1.

Supplementary Note #1: Magnetostatic Surface Wave Dispersion Relationship:

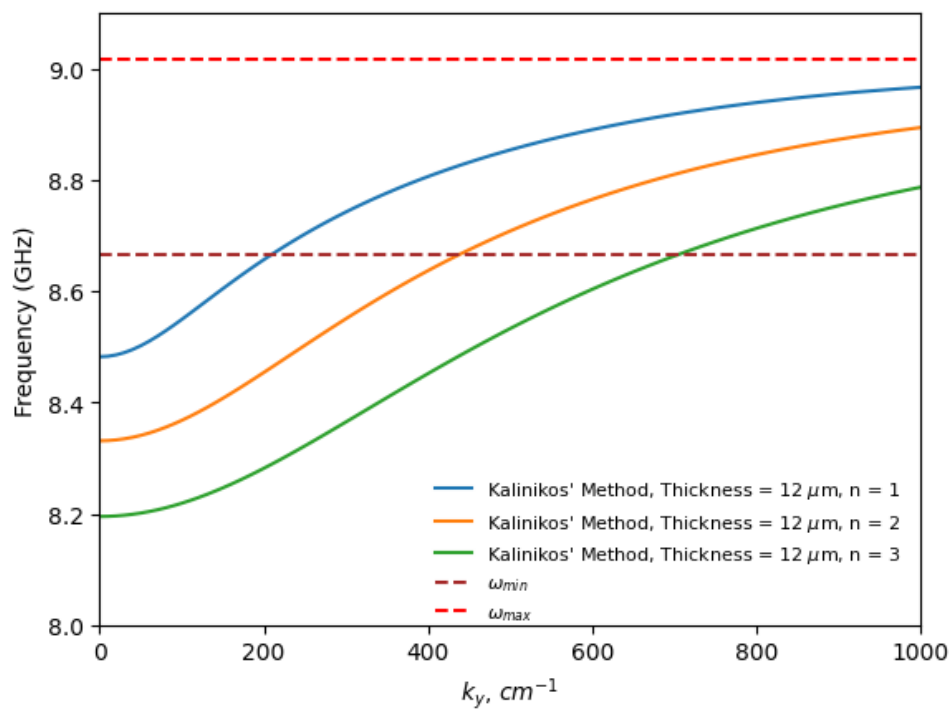
Supplementary Figure 3 compares YIG thicknesses ranging from 6 μm to 15 μm . The thickness dependence is monotonic. As the YIG layer becomes thicker, width-related effects become more pronounced, with higher-order modes exhibiting greater frequency separation from lower-order modes, and with the wavenumber rising more sharply with frequency at small wavenumbers. Future studies can determine the optimal thickness trade-off based on the specific performance requirements.



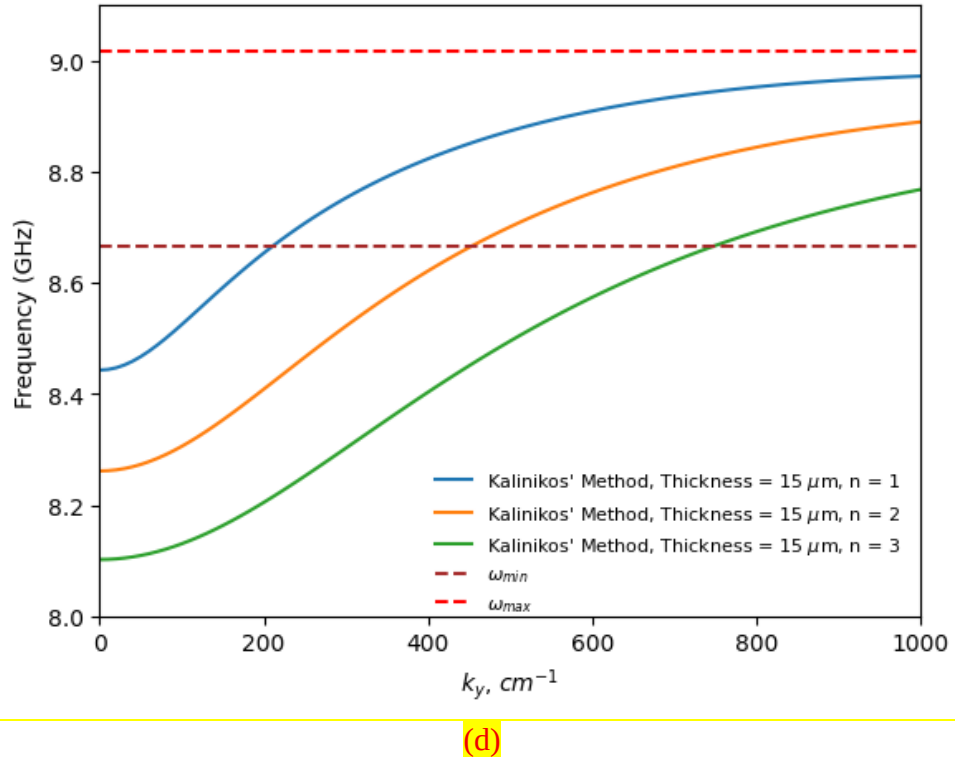
(a)



(b)



(c)



Supplementary Figure 3. Comparison of (a) 6 μm , (b) 9 μm , (c) 12 μm , (d) 15 μm thick YIG dispersion relationship using Kalinikos' method. The YIG waveguide width is 200 μm . The applied magnetic field is 2325 Gauss.

Thickness Scaled Yttrium Iron Garnet (YIG) Filter Section:

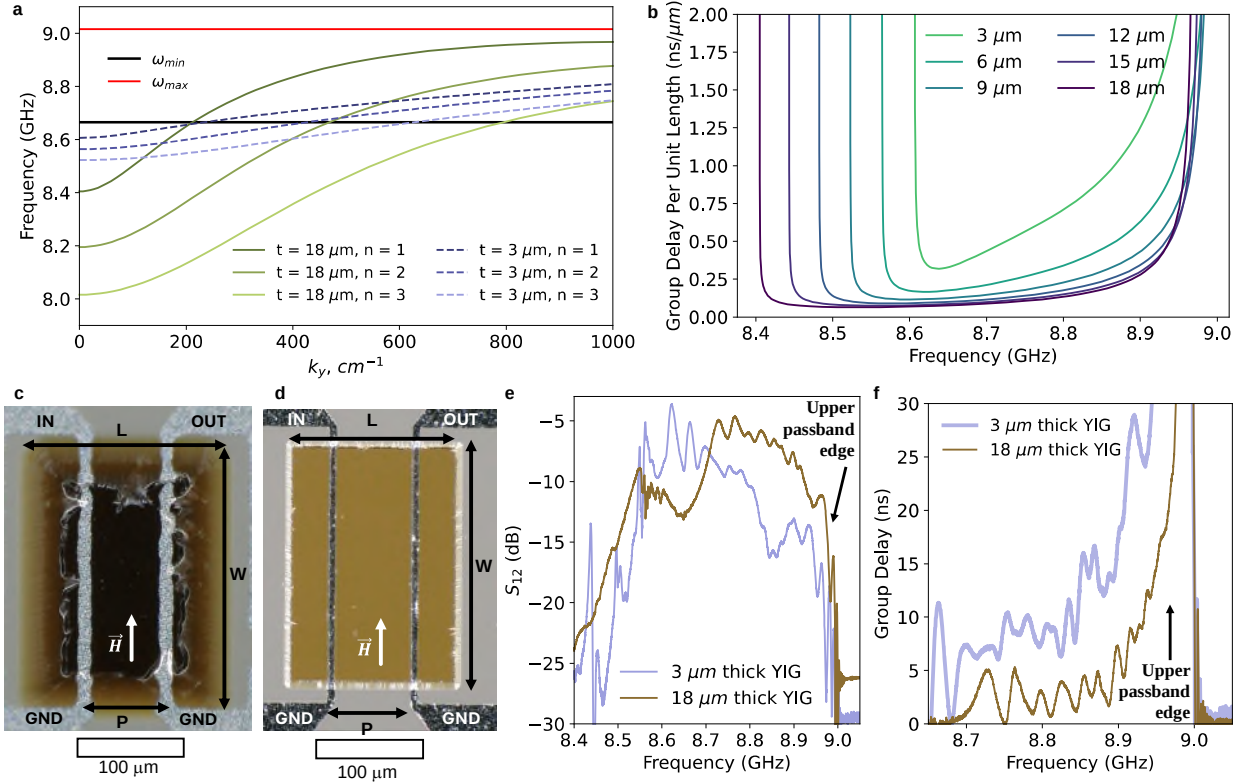


Fig. 2 Thickness effect on YIG filters. (a) Comparison of the dispersion relationships for 3 μm and 18 μm thick YIG films under a 2325 Gauss bias field for different width modes (n). The ω_{min} and ω_{max} frequencies represent the minimum and maximum allowable frequencies for an infinitely wide YIG film with a ground plane located at an infinite distance. (b) Calculated group delay per micrometer for the first width mode across different YIG film thicknesses with a bias field of 2325 Gauss. (c) Optical image of the fabricated YIG filter with an 18 μm thick film using BCB planarization. BCB is transparent and is not visible; aluminum transducers are 10 μm wide. (d) Optical image of the YIG filter with a 3 μm thick film. No BCB is used due to the thin YIG layer. Aluminum transducers are 5 μm wide. (e) Measured S_{12} frequency response with applied magnetic flux density of around 2500 Gauss. (f) Measured S_{12} group delay with applied magnetic flux density of around 2500 Gauss.

YIG Filter with Meander Line Transducers Section

Applying the previously calculated dispersion relation into equation (1), the T_m for different YIG thickness with meander-line transducers can be determined, as shown in Fig. 3a.

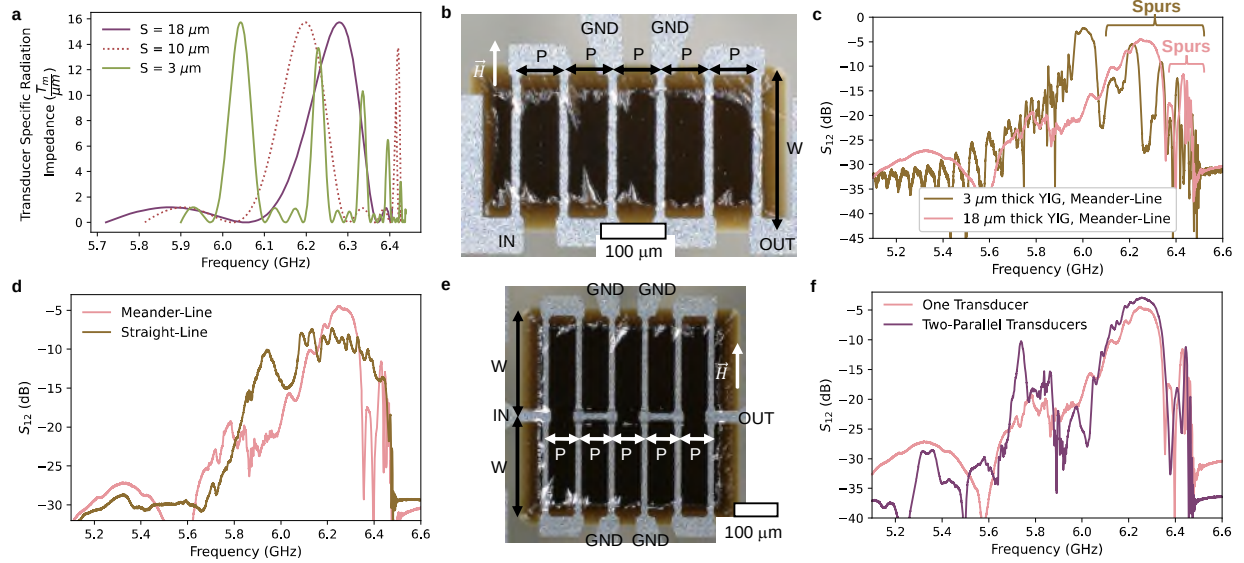


Fig. 3 YIG filters with meander-line transducers. (a) Comparison of the calculated transducer specific radiation impedance for meander-line transducers on 3 μm , 10 μm , and 18 μm thick YIG films (first width mode, $n = 1$) at ~ 1500 Gauss. (b) Optical microscope image of a YIG filter with a meander-line transducer with a pitch of 70 μm and width of 200 μm . (c) Comparison of measured S_{12} frequency responses between the 3 μm and 18 μm meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss. (d) Comparison of measured S_{12} frequency responses between the meander-line and straight-line transducer 18 μm thick YIG filters under applied magnetic flux densities of approximately 1500 Gauss. (e) Optical image of a YIG filter with two parallel meander-line transducers with a pitch of 70 μm and width of 200 μm . (f) Comparison of measured S_{12} frequency responses between filters with two parallel meander-line transducers and a single meander-line transducer at around 1500 Gauss.

Discussion Section

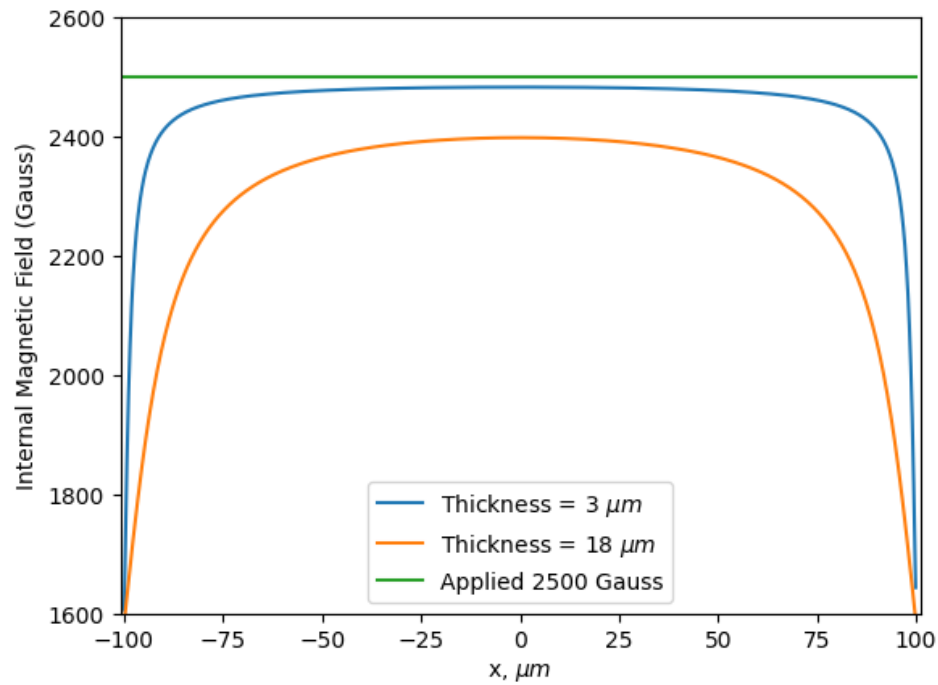
Although only one thin YIG film (3 μm) and one thick YIG film (15 - 18 μm) were examined in this study due to limits on commercially available YIG thicknesses, the BCB planarization fabrication method demonstrated here can be readily adapted to YIG films of other thicknesses. Furthermore, this work provides the first comprehensive experimental and theoretical analysis of the thickness effect in microfabricated YIG films. The theoretical calculation results show no abrupt transitions as thickness varies. Instead, all thickness effects evolve gradually. Moreover, the methodologies used here, including the dispersion relation, power handling, linearity, nonreciprocity, and propagation loss, can be directly applied to future investigations of YIG devices with intermediate or alternative thicknesses.

In addition to the above, the following minor comments may also be considered:

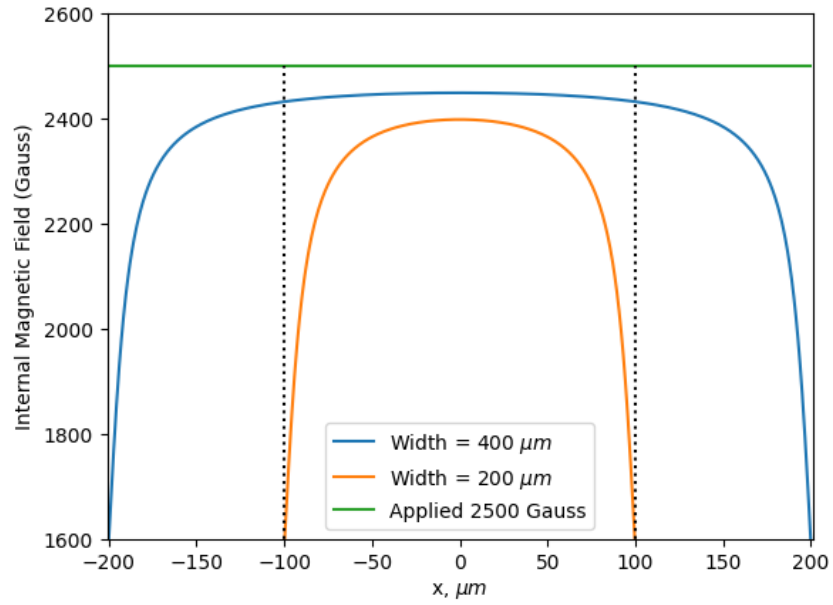
1. Since the manuscript includes measurements using 18 μm -thick YIG, it would be helpful if Supplementary Figure 19a also presented the internal magnetic field for this thickness.

Answer to the reviewer:

We sincerely appreciate the reviewer's helpful suggestion. We have updated Supplementary Figure 19 (now 20) to present the internal magnetic field corresponding to the 18 μm -thick YIG film, ensuring consistency with the thickness used in the experimental measurements reported in the manuscript.



(a)



(b)

Supplementary Figure 20. Theoretical distribution of the internal static magnetic field across the width of a YIG waveguide. **(a)** Comparison between YIG waveguides with thickness of $3 \mu\text{m}$ and $18 \mu\text{m}$, both with a fixed width of $200 \mu\text{m}$. **(b)** Comparison between waveguide widths of $200 \mu\text{m}$ and $400 \mu\text{m}$, with a fixed thickness of $18 \mu\text{m}$. The green line indicates the value of the applied external magnetic field.

2. In Figure 1a, the labels “DAC” and “ADC” appear to be reversed. For clarity, “DAC” should be placed in the Tx path.

Answer to the reviewer:

We sincerely appreciate the reviewer’s careful examination of the figure and for pointing out this labeling issue. The placement of “DAC” and “ADC” in Figure 1(a) has now been corrected so that “DAC” appears in the transmit (Tx) path and “ADC” appears in the receive (Rx) path

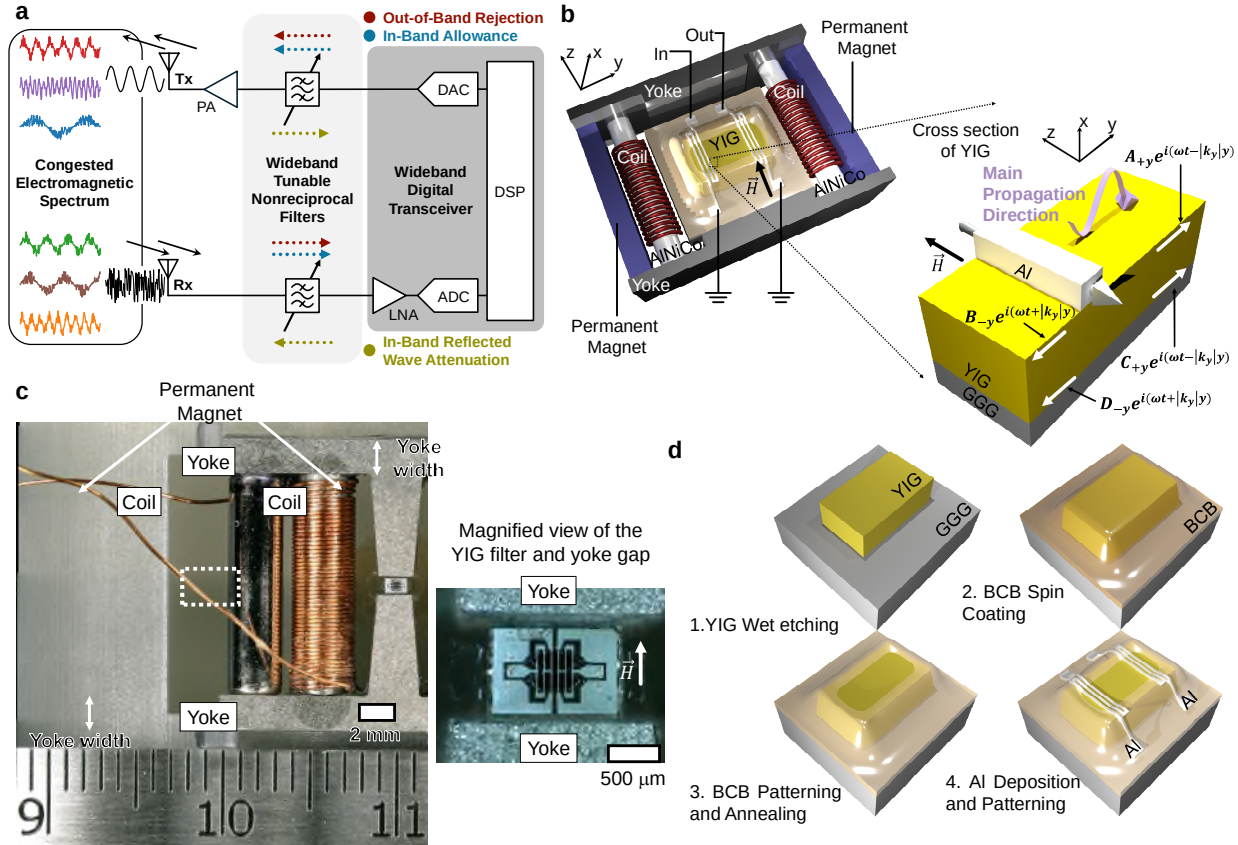


Fig. 1 Overview of the wideband tunable nonreciprocal filter. (a) Block diagram of a transceiver system incorporating wideband tunable, nonreciprocal filters. **(b)** 3D schematic of the filter, which integrates a YIG (yttrium iron garnet) filter with a zero-static-power magnetic bias circuit. An input aluminum meander-line transducer excites a unidirectional magnetostatic wave (MSW), which propagates through the YIG and is reconverted back to an electrical signal at the output transducer. The magnetic bias structure includes two permanent magnets, two shunt magnets wound with coils, and magnetically permeable yokes that focus the magnetic flux at the filter. **(c)** Optical microscope image of the fabricated device assembly with a magnified view of the white box region showing the YIG filter and yoke gap. **(d)** Fabrication process flow of the YIG filter, incorporating an innovative benzocyclobutene (BCB) planarization technique for thickness-scaled YIG filters.

Reviewer #2 (Remarks to the Author):

This revised version strengthens the manuscript, which was already compelling in the first round for its high-quality device physics and clear relevance to adaptive signal-filtering applications. The integration of compact, low-power magnetic bias circuitry advances the work's practical viability and system-level significance. Clarifications regarding YIG thickness selection and geometry-driven nonreciprocity provide more clarity, while the inclusion of quantitative data on tuning dynamics, repeatability, power handling, and linearity demonstrates the device's technological maturity. The expanded fabrication details, improved organization, and polished presentation make this a well-executed and impactful paper that is more than suitable for publication.

Answer to the reviewer:

We sincerely thank the reviewer for the thoughtful and encouraging assessment of our work.

Reviewer #3 (Remarks to the Author):

The authors have presented a significant body of work, and addressed all my comments. I do not have further comments.

Answer to the reviewer:

We sincerely thank the reviewer.

Reviewer #4 (Remarks to the Author):

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.