

Supplementary Information

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

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Supplementary Note #1: Magnetostatic Surface Wave Dispersion Relationship

Kalinikos et al. calculated the dispersion relationship of spin waves taking into account both the dipole and exchange interactions and surface pinning conditions. This relationship can be written as [1, 2]:

$$f^2 = \gamma^2 [H + M_s(1 - P + \alpha k^2)] \left[H + M_s \left(P \frac{k_y^2}{k^2} + \alpha k^2 \right) \right] \quad (S1)$$

where $P = 1 - (1 - \exp(-kS))/(kS)$, $k^2 = k_z^2 + k_y^2$, $\gamma = 2.8$ MHz/Gauss which is the gyromagnetic ratio, H is the magnetic field applied in Gauss, and $M_s = 1780$ Gauss is the saturation magnetization of YIG, $\alpha = 5.18 \times 10^{-18} \text{m}^2$ which is the exchange stiffness, and S is the film thickness. The coordinate system is shown in Fig. 1 (c), where k_z is in the width (z) direction and k_y is in the length (y) or magnetostatic surface wave (MSSW) propagation direction.

Ignoring the effects of internal static magnetic field non-uniformity caused by edge demagnetization in the stripe waveguide, spin-wave confinement can be understood as the quantization of plane spin waves. For MSSW propagating in infinitely wide YIG films, k_z is zero and k_y can vary continuously. For MSSW propagating inside a stripe waveguide, the k_z component must be discrete. This results in the formation of resonant standing waves across the waveguide width. These discrete values k_x^n are governed by the boundary conditions of the dynamic magnetization at the waveguide edges, which depends on the thickness-to-width ratio $\frac{S}{W}$. When $\frac{S}{W} \ll 1$, the magnetic wall boundary conditions can be given by [2]:

$$k_x^n = \frac{n\pi}{W}, n = 1, 2, 3, \dots \quad (S2)$$

Another method to calculate the MSSW dispersion is reported by O'Keeffe et al [3], which can be expressed by:

$$\begin{aligned} \exp(2MS) = & \frac{\Omega_m M + \Omega_k + (\Omega_H^2 - \Omega^2)(M - N)}{\Omega_H M - \Omega_k + (\Omega_H^2 - \Omega^2)(M + N)} \\ & \times \frac{\Omega_m M - \Omega_k + (\Omega_H^2 - \Omega^2)(M - N \tanh(Nt))}{\Omega_m M + \Omega_k + (\Omega_H^2 - \Omega^2)(M + N \tanh(Nt))} \end{aligned} \quad (S3)$$

Inside the film, we have

$$M^2 = k_z^2 = \frac{\left(\frac{n\pi}{W}\right)^2}{\mu_1} + k_y^2 \quad (\text{S4})$$

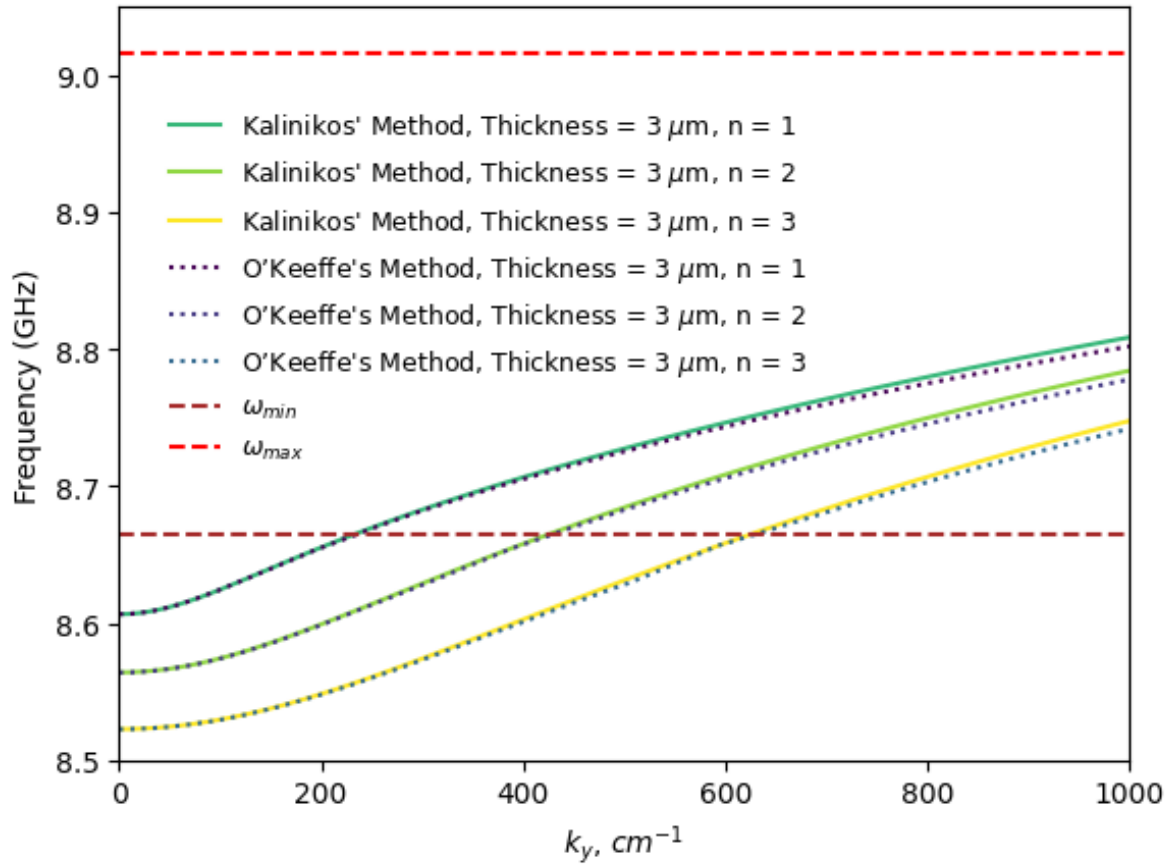
and outside

$$N^2 = k_z^2 = \left(\frac{n\pi}{W}\right)^2 + k_y^2 \quad (\text{S5})$$

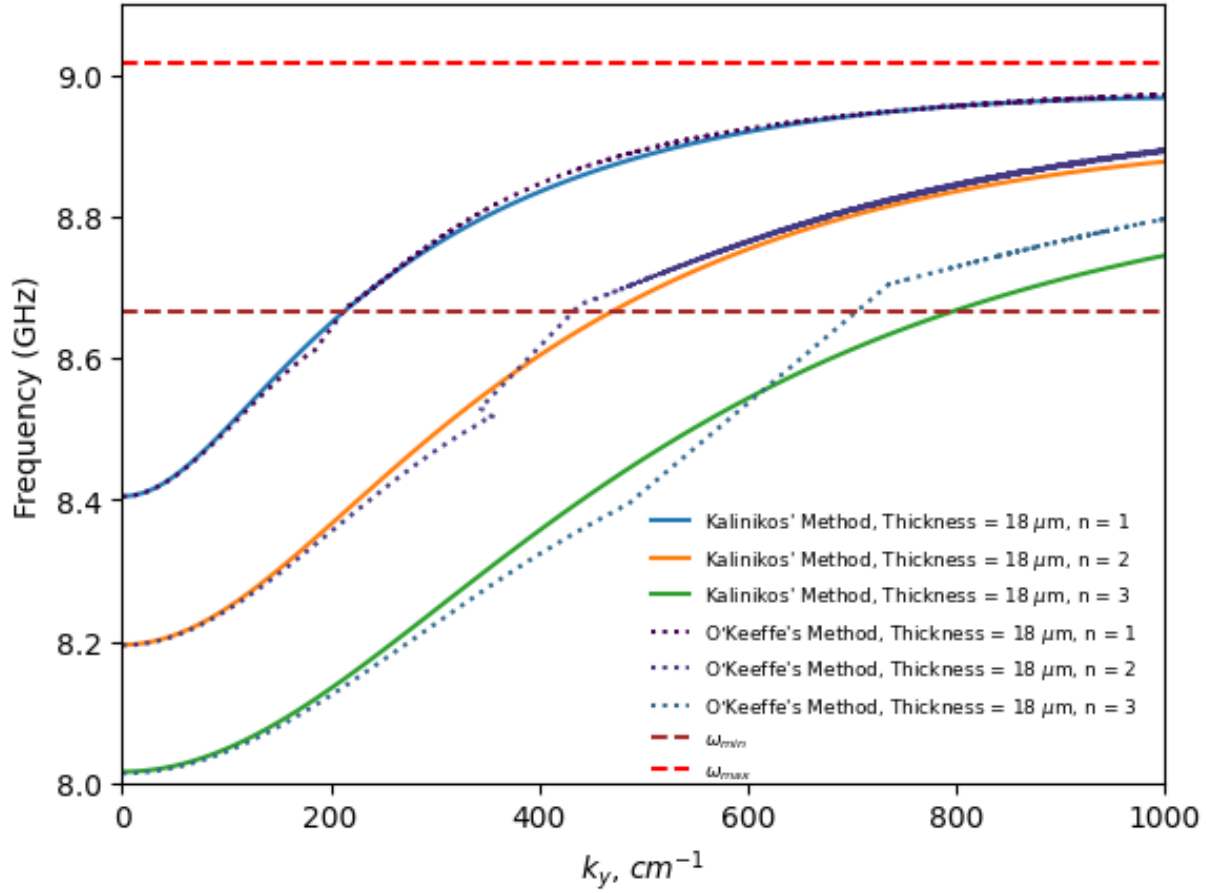
where $\mu_1 = 1 - \Omega_H/(\Omega^2 - \Omega_H^2)$, $\Omega = \omega/\gamma 4\pi M_s$, $\Omega_H = H/4\pi M_s$, and t is the distance between the YIG film and a ground plane, which is infinite here.

Supplementary Figures 1 and 2 compare the two methods applied to both 3 μm and 18 μm thick YIG films. For O’Keeffe’s method applied to the 18 μm thick YIG film, the M^2 term in the dispersion relation for higher-order width modes changes rapidly from positive to negative near the ω_{min} frequency, which complicates the calculation. To address this, a straight-line approximation was used to estimate the corresponding frequency near the ω_{min} frequency. Despite this complexity, both Kalinikos’ and O’Keeffe’s methods exhibit very similar trends overall, although Kalinikos’ approach incorporates more physical effects.

One effect included in Kalinikos’ method is the exchange interaction. This interaction can be neglected under two conditions: (1) when the YIG film thickness (S) and waveguide width (W) are of the same order, and (2) when both S and W are significantly larger than the YIG exchange length, $\lambda_{ex} \approx 13$ nm. The critical waveguide width, above which exchange dynamics become negligible, can be estimated by $w_{cr} = 2.2S + 6.7\lambda_{ex} \approx 40$ μm [4]. In this case, the waveguide width is 200 μm —well above w_{cr} —so the exchange interaction can be ignored.

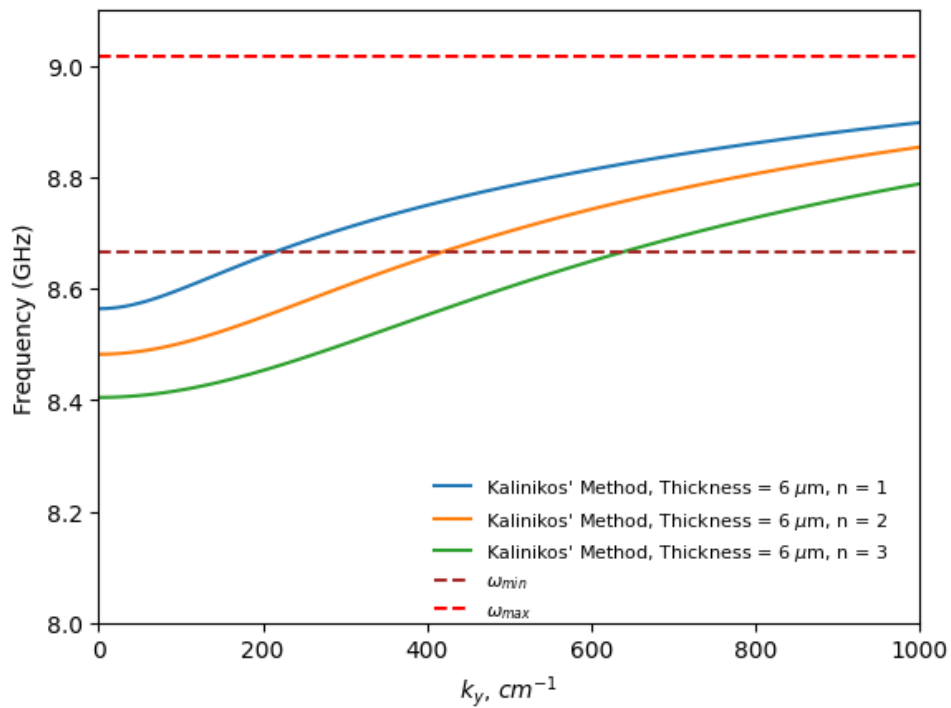


Supplementary Figure 1. Comparison of the 3 μm thick YIG dispersion relationship between Kalinikos' method and O'Keeffe's method. The YIG waveguide width is 200 μm . The applied magnetic field is 2325 Gauss.

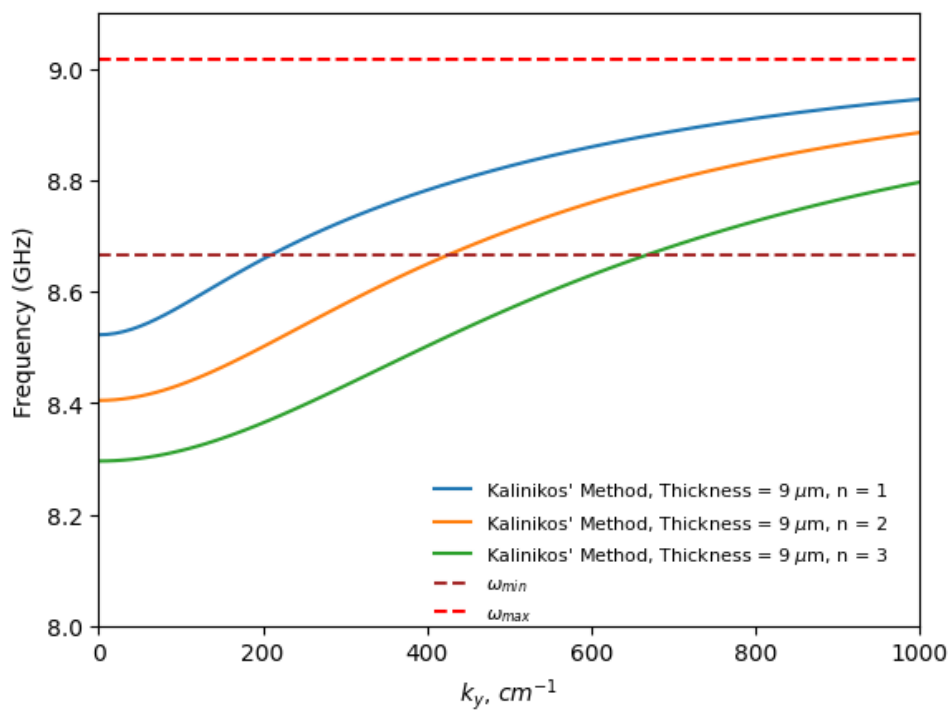


Supplementary Figure 2. Comparison of the 18 μm thick YIG dispersion relationship between Kalinikos' method and O'Keefe's method. The YIG waveguide width is 200 μm . The applied magnetic field is 2325 Gauss.

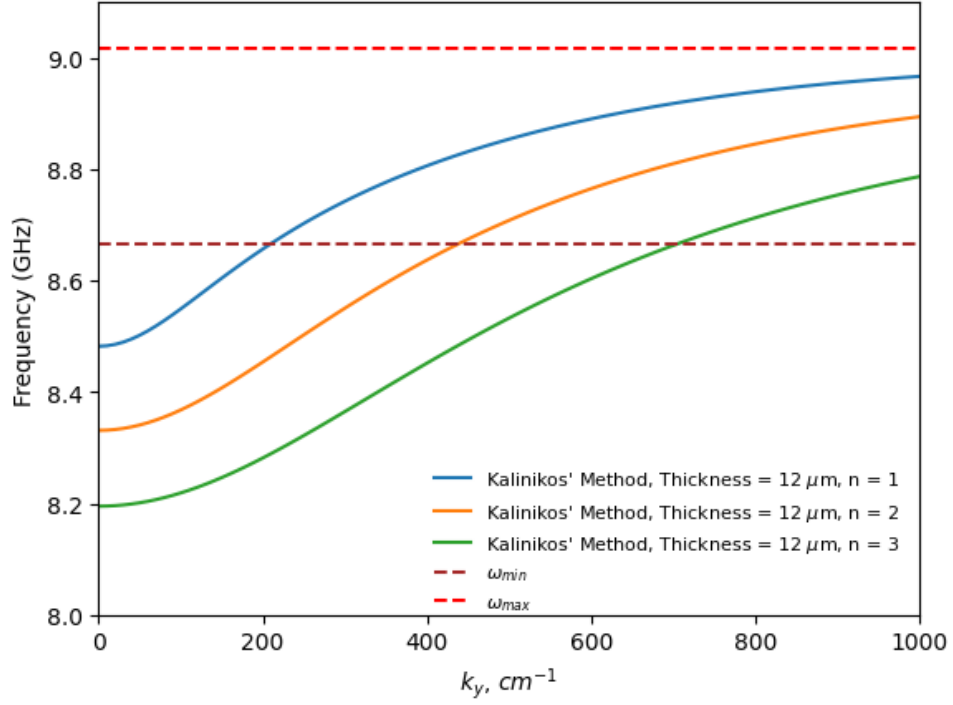
Supplementary Figure 3 compares YIG thicknesses ranging from 6 μm to 15 μm . The thickness dependence is monotonic. As the YIG layer becomes thicker, width-related effects become more pronounced, with higher-order modes exhibiting greater frequency separation from lower-order modes, and with the wavenumber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



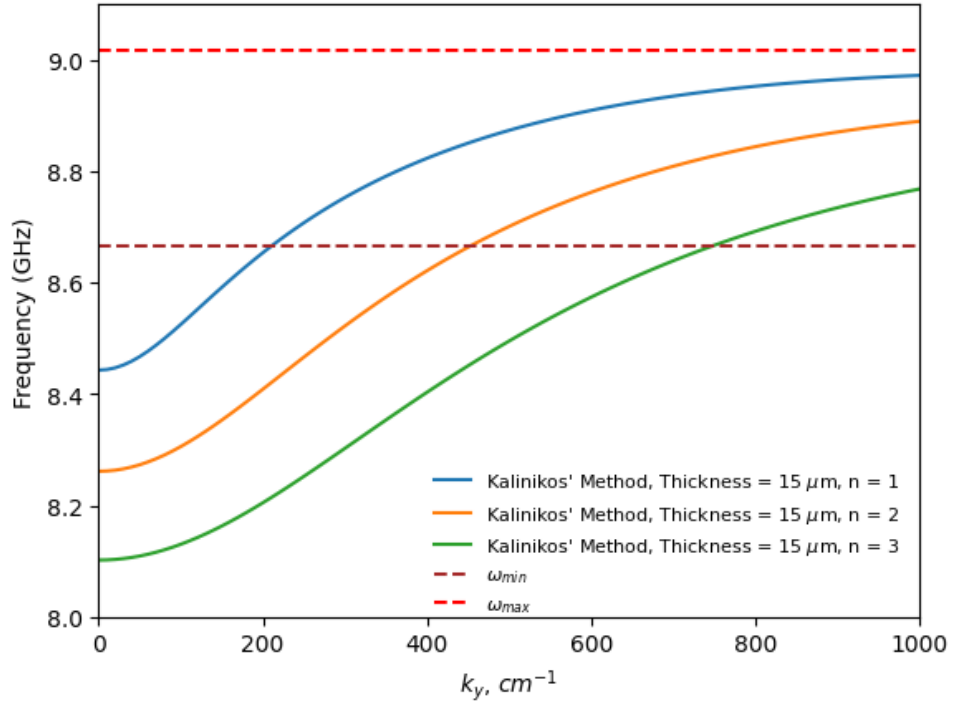
(a)



(b)



(c)



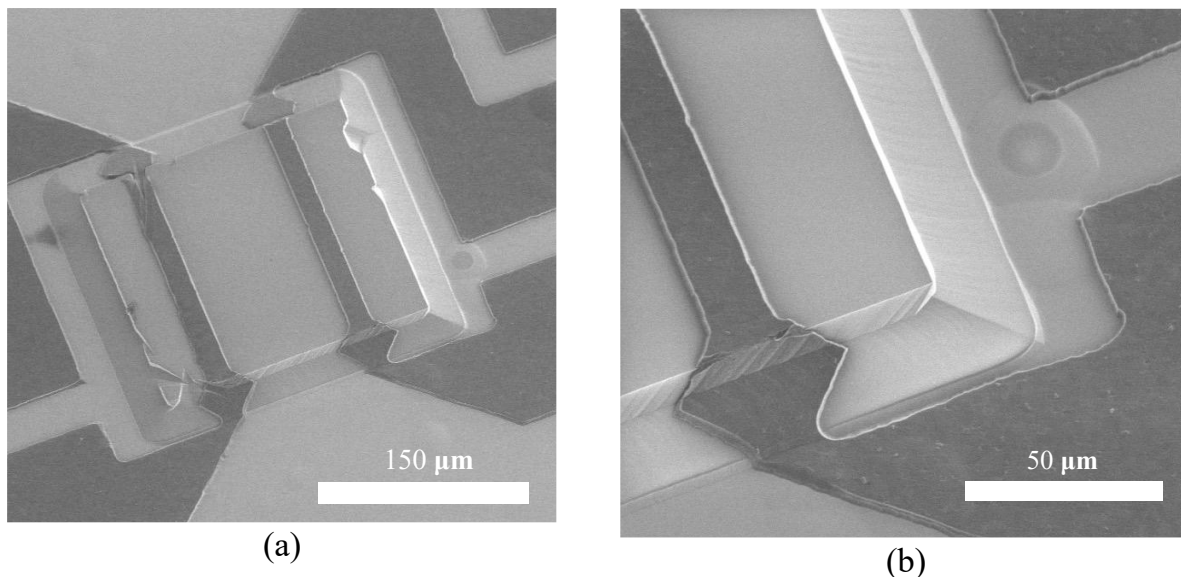
(d)

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.

Supplementary Note #2: Thick YIG Fabrication Process

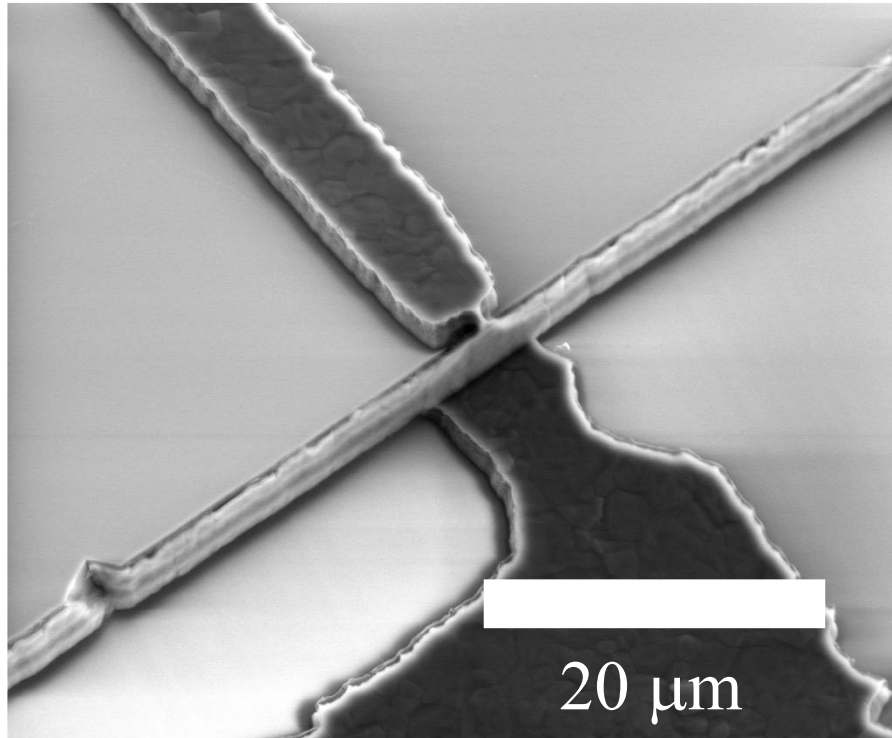
Previous studies have primarily utilized conventional MSSW filters fabricated by patterning metal transducers, either through lift-off or subtractive etching, on top of etched YIG cavities [5, 6]. Typically, the YIG film is first patterned using wet etching or ion milling. If etching is used, a metal layer is deposited on the YIG surface, followed by photolithography to define the metal pattern, and then metal etching. Alternatively, in a lift-off process, a photoresist is first spin-coated, the metal is deposited, and then the excess is lifted off. These methods work well for thin YIG films, typically around 3 μm thick. However, when scaling up to thicker YIG films—such as 18 μm —the process encounters several challenges.

Supplementary Figure 4 presents an example of a device where the conventional process was successful, though the overall fabrication yield was extremely low. The steep sidewalls of the thick YIG waveguide are clearly visible in the images. To aid aluminum (visible as black regions) in conformally coating the YIG sidewalls, diamond-shaped features were added near the waveguide edges. These structures help guide the metal over the steep sidewalls and prevent breakage during the etching process, which improves the yield slightly. In this successful device, the YIG sidewalls appear clean, indicating complete removal of aluminum from undesired regions. Additionally, the width of the aluminum transducers is increased to 20 μm , which contributed to a slight improvement in fabrication yield.



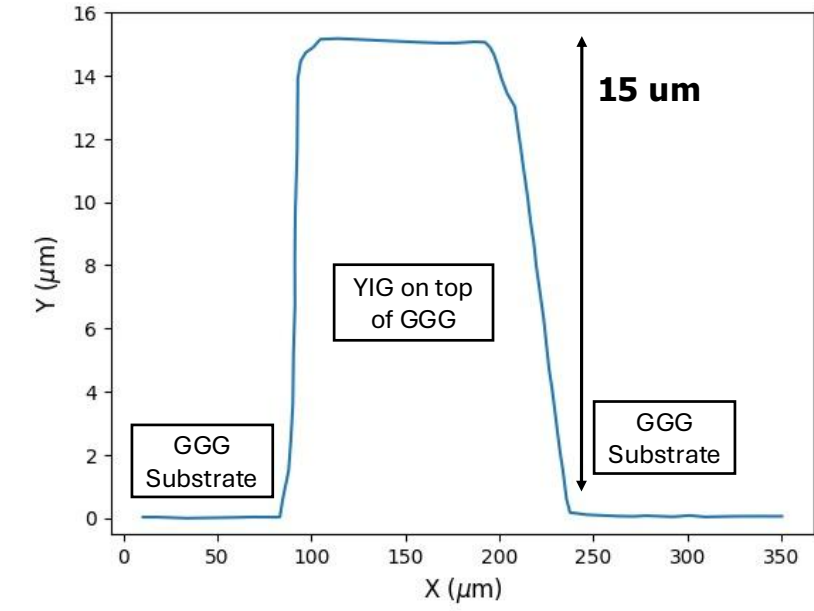
Supplementary Figure 4. (a-b) Scanning electron microscope (SEM) image of a successful thick YIG filter using a previous fabrication process without BCB. The thickness of the YIG is 15 μm . The aluminum transducer width is 20 μm . The width of the YIG is 200 μm and the length is 220 μm . The pitch of the transducer is 110 μm .

Supplementary Figure 5 shows another example device where the conventional fabrication method failed—a common outcome for most devices using this approach. In this case, the aluminum layer (black regions) barely connects to the aluminum deposited on top of the YIG waveguide. This poor connection introduces a large series resistance in the aluminum transducers, significantly hindering efficient excitation of the MSSW. Additionally, a substantial amount of residual aluminum remains on the YIG sidewalls. This not only causes electrical shorting between the input and output transducers—thereby degrading out-of-band rejection—but also obstructs current flow into the transducer located on top of the YIG.

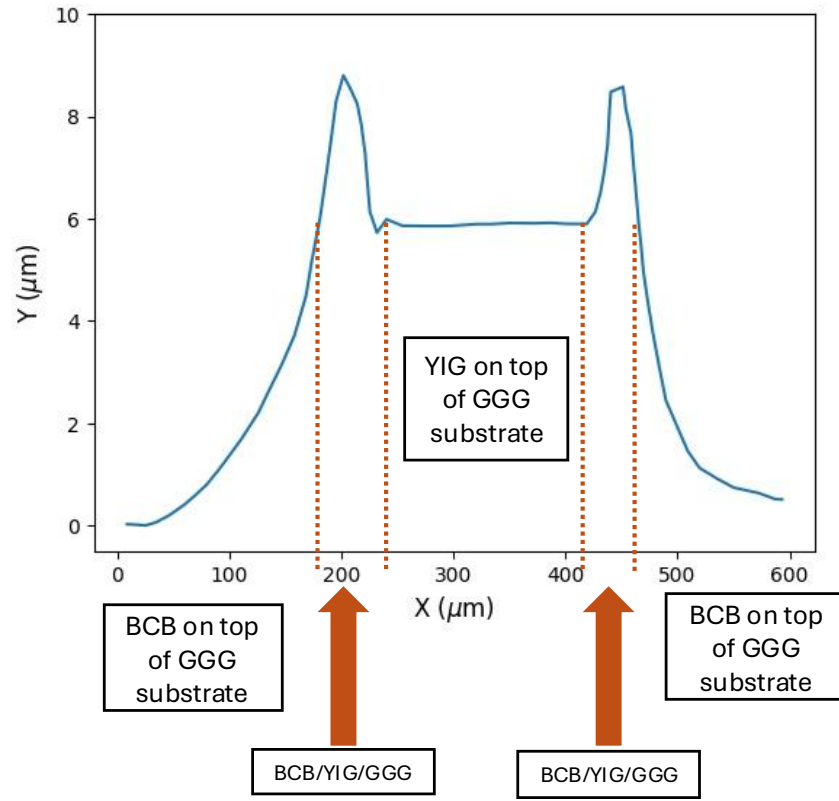


Supplementary Figure 5. SEM image of a failed YIG filter. The aluminum layer (dark regions) makes poor contact with the aluminum deposited on top of the YIG waveguide, leading to a weak electrical connection. Significant residual aluminum is also visible on the YIG sidewalls, contributing to electrical shorts and degraded device performance.

The key to the previously described problem lies in the steep sidewall of the YIG waveguide. A KLA Tencor P7 2D profilometer was used to measure the YIG sidewall before and after Benzocyclobutene (BCB) patterning and annealing, as shown in the **Supplementary Figure 6**. The use of BCB changes the 15 μm steep sidewall into a much more gradual sidewall with a height difference around 7 μm.



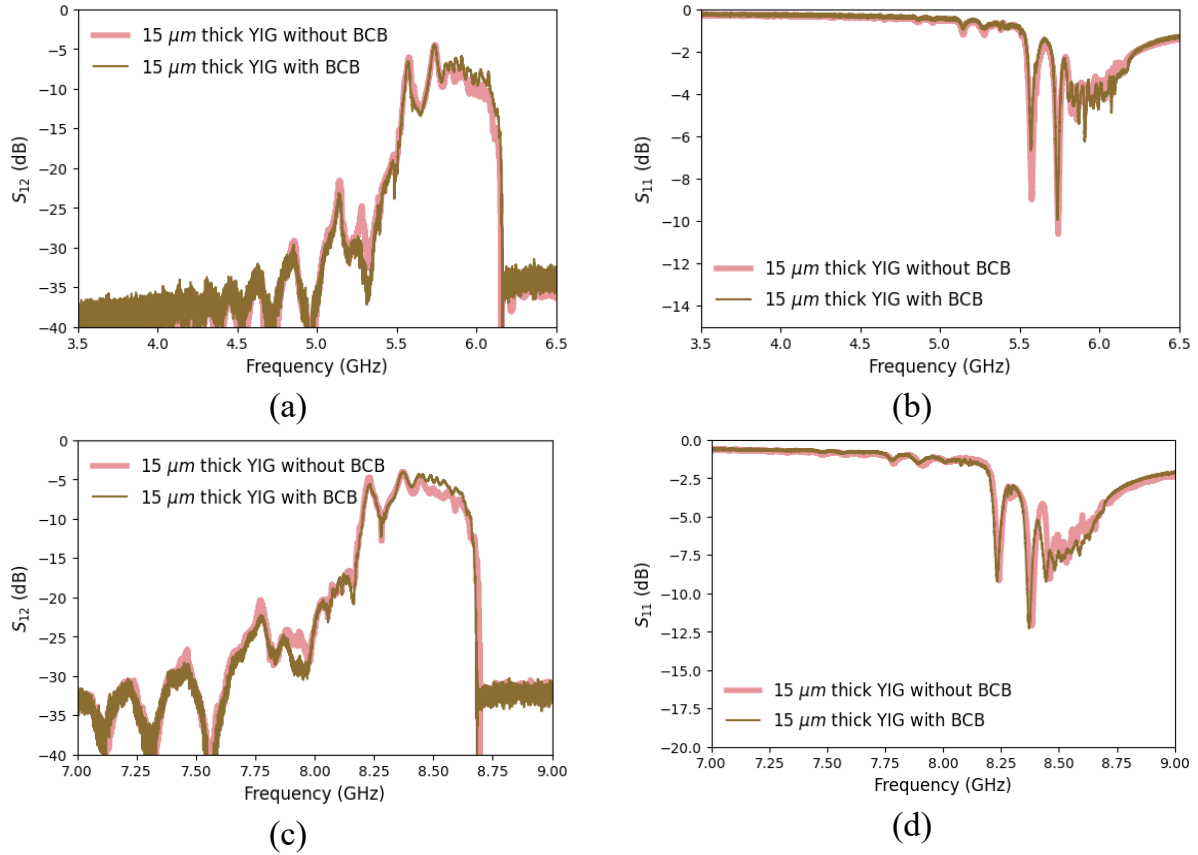
(a)



(b)

Supplementary Figure 6. Profilometer measurement of the YIG (a) before BCB spin coating and (b) after BCB patterning and annealing.

Supplementary Figure 7 compares the frequency responses of two YIG filters: one fabricated with BCB planarization and the other using the previous method without any BCB layers. The fabrication process for YIG filters with BCB planarization shows significantly higher yield. Both devices share identical transducer layouts and YIG geometries, and they exhibit nearly identical frequency responses. This indicates that the introduction of the BCB layer does not contribute to additional RF loss or alter MSSW propagation. Previous studies have demonstrated that BCB is an excellent polymer for high-frequency RF applications, offering a minimal loss tangent [7].

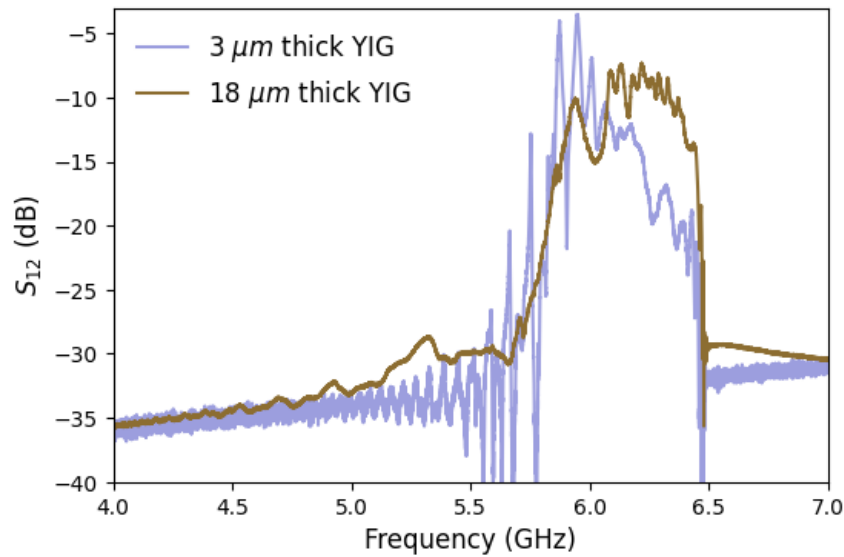


Supplementary Figure 7. Comparison of measured **(a and c)** S_{12} and **(b and d)** S_{11} frequency responses between YIG filters with and without the BCB planarization technique. The aluminum transducer width is 20 μm. The width of the YIG is 200 μm and the length is 220 μm. The pitch of the transducer is 110 μm. The thickness of the YIG is 15 μm. The applied magnetic field is around **(a and b)** 1500 Gauss, and **(c and d)** 2500 Gauss.

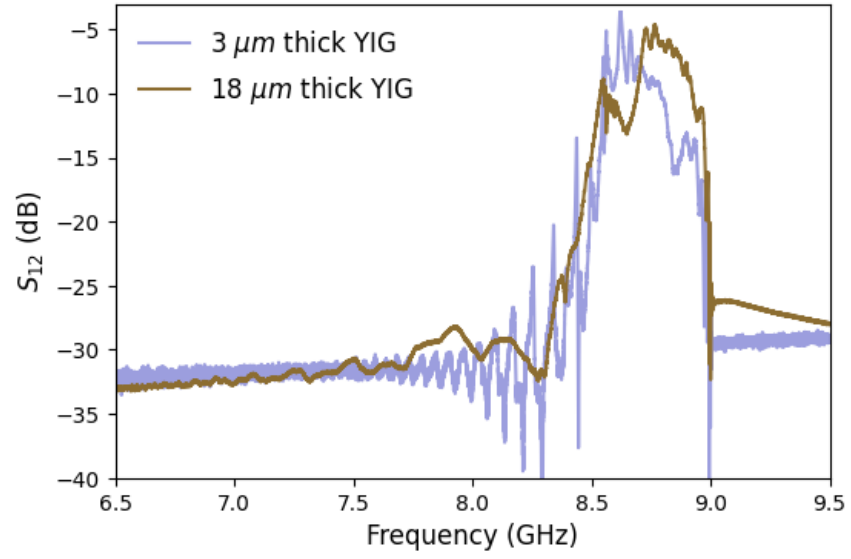
Overall, this fabrication process not only boosted the overall yield for the 18 μm thick film YIG filter but also facilitates more intricate transducer designs, such as meander-line transducers, which require the aluminum transducer traversing the YIG waveguide multiple times.

Supplementary Note #3: Comparison of YIG Filters with 3 μm and 18 μm Thicknesses

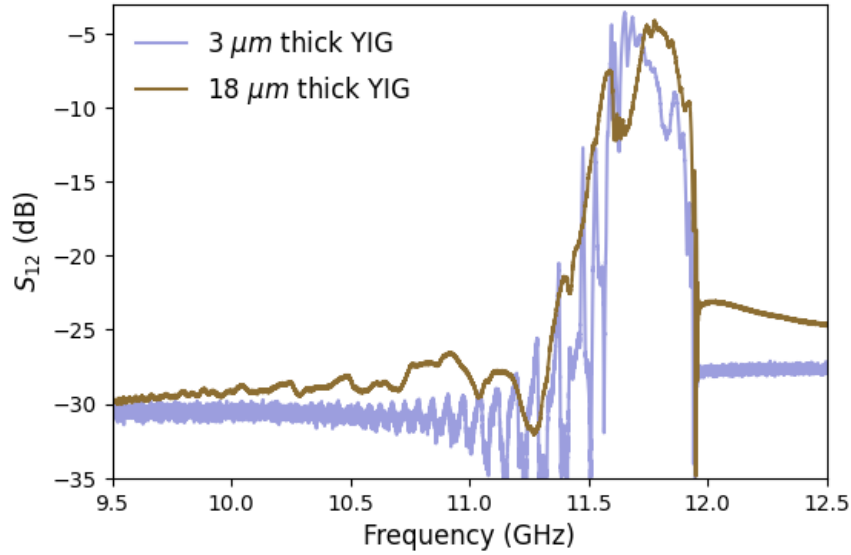
Supplementary Figure 8 compares the frequency responses of YIG filters with thicknesses of 3 μm and 18 μm tuned to three different frequencies. Both filters share the same waveguide width of 200 μm , length of 140 μm , and transducer pitch of 70 μm representing the center-to-center distance between the two aluminum transducers. A straight-line aluminum transducer design is used in both cases. For the 3 μm thick YIG filter, the aluminum transducer width is 5 μm , while a wider 10 μm transducer is used for the 18 μm thick YIG filter. The narrower transducer in the 3 μm filter helps to reduce insertion loss, particularly at 6 GHz. Overall, both filters demonstrate comparable insertion losses, especially at higher frequencies. However, the 18 μm thick YIG filter exhibits a much sharper filter skirt at the upper frequency edge, attributed to differences in their MSSW dispersion characteristics.



(a)



(b)



(c)

Supplementary Figure 8. Comparison of measured S_{12} frequency responses between the 3 μm and 18 μm thick YIG filters under applied magnetic flux densities of approximately (a) 1500 Gauss, (b) 2500 Gauss, and (c) 3500 Gauss.

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

Supplementary Figures 9, 10, and 11 present a comparative analysis of the frequency responses of 18 μm thick YIG filters featuring straight-line and meander-line transducers under three different applied magnetic flux densities of 1500, 2500, 3500 Gauss, respectively. Both filters share the same waveguide width of 200 μm , transducer pitch of 70 μm , and transducer width of 10 μm . The waveguide length of the meander-line YIG filter is 420 μm , as shown in the **Fig. 3b**. The waveguide length of the straight-line YIG filter is 140 μm , as shown in the **Fig. 2c**. The straight-line YIG filter is the same one detailed in the **Supplementary Note #3**.

At 6 GHz, the meander-line YIG filter exhibits superior performance, with an insertion loss of 4.4 dB compared to 7.4 dB for the straight-line configuration. The maximum Z_{11} values are 40.9 dB and 33.2 dB for the meander-line and straight-line YIG filters, respectively. The corresponding minimum return losses are 21.5 dB and 10.4 dB for meander-line and straight-line YIG filters, respectively. Smith chart analysis (**Supplementary Figure 9c**) shows that the meander-line filter provides a higher radiation impedance and improved impedance matching to a 50 Ω port impedance, contributing to its reduced insertion loss.

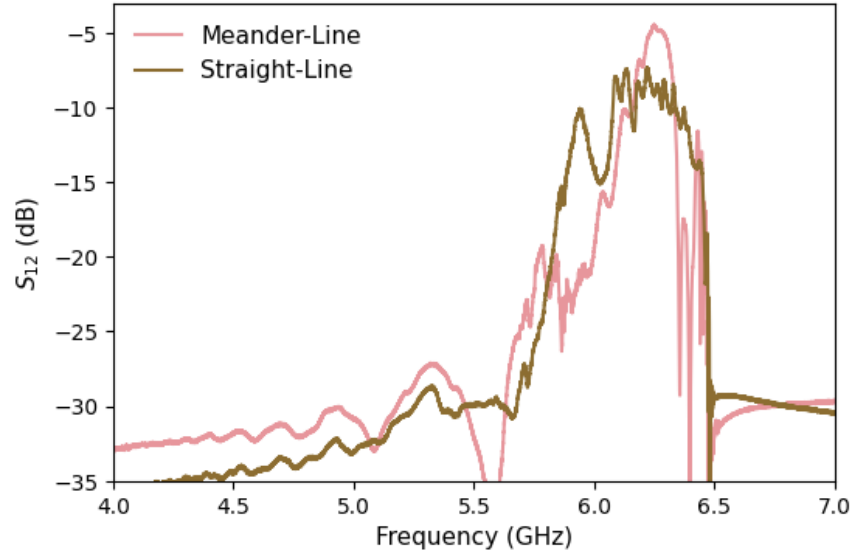
However, as frequency increases, radiation impedance also increases, as observed in the Smith plots of **Supplementary Figure 9c, 10c, and 11c**. This leads to over-coupling in the meander-line filter and results in greater insertion loss. At 11.8 GHz under an applied field of ~ 3500 Gauss, the meander-line filter exhibits a peak Z_{11} of 47.4 dB, compared to 42.1 dB for the straight-line filter, leading to significant impedance mismatch with the 50 Ω filter terminations and a corresponding increase in insertion loss to 8.3 dB, versus 4.1 dB for the straight-line configuration.

Supplementary Figure 12 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 12**, 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.

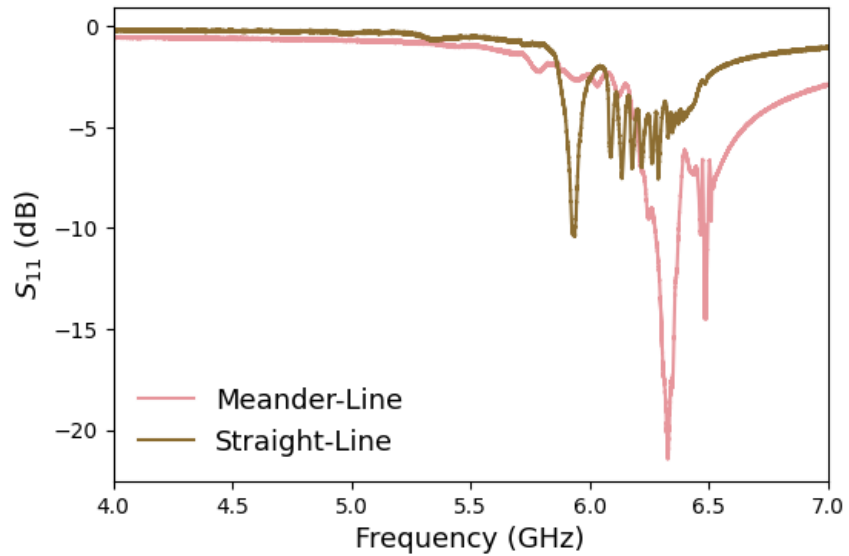
The difference arises from the underlying propagation mechanisms. In the 3 μm -thick YIG filter, the device functions similarly to a resonator, where the two straight edges act as reflective boundaries[6, 8]. The magnetostatic surface waves (MSSWs) are reflected back and forth between the edges, forming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

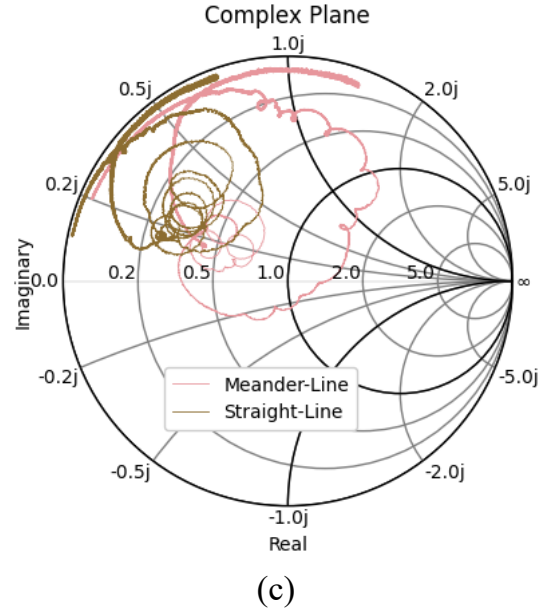
minimal reflection. One key factor is the increased sidewall roughness of the thicker YIG film, as visible in the optical micrographs (Fig. 2c and Fig. 2d). The roughened edges, which result from the greater etching depth required for thick YIG, act as scattering centers that suppress spin-wave reflection. 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.



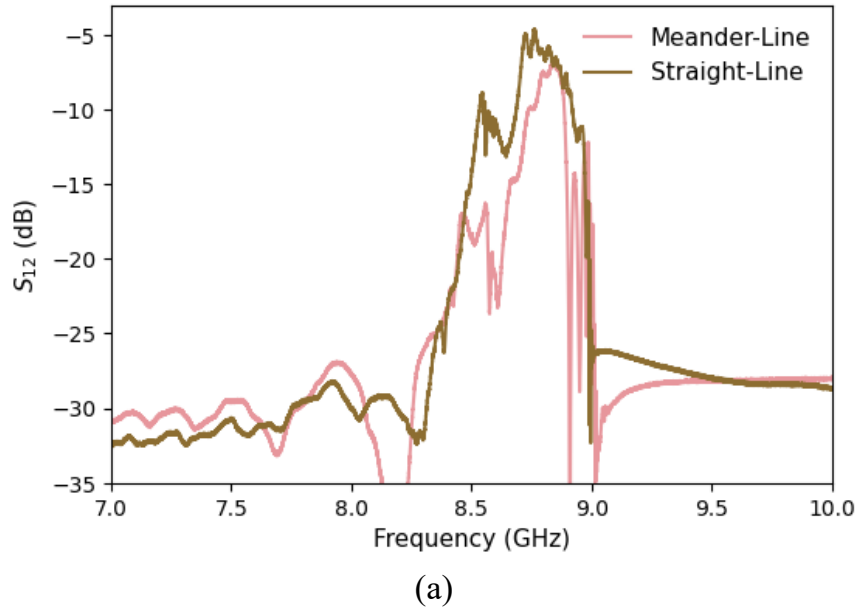
(a)

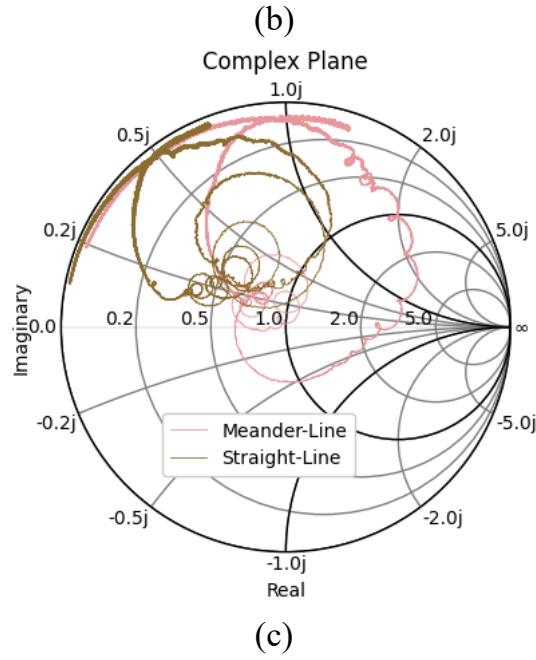
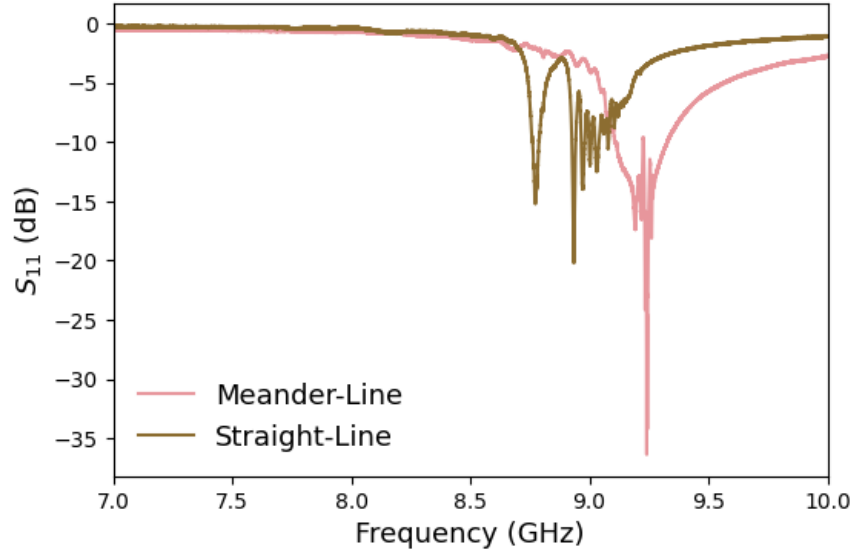


(b)

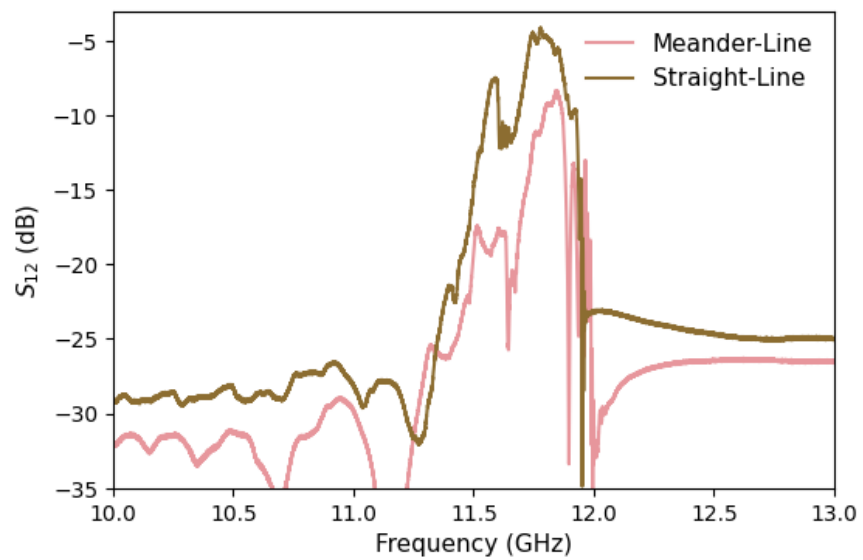


Supplementary Figure 9. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between meander-line and straight-line transducer YIG filters under applied magnetic flux densities of approximately 1500 Gauss.

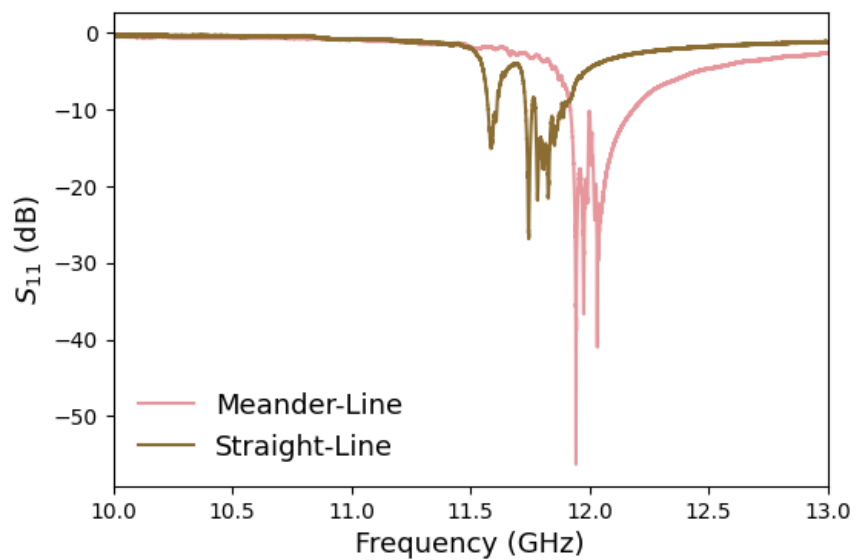




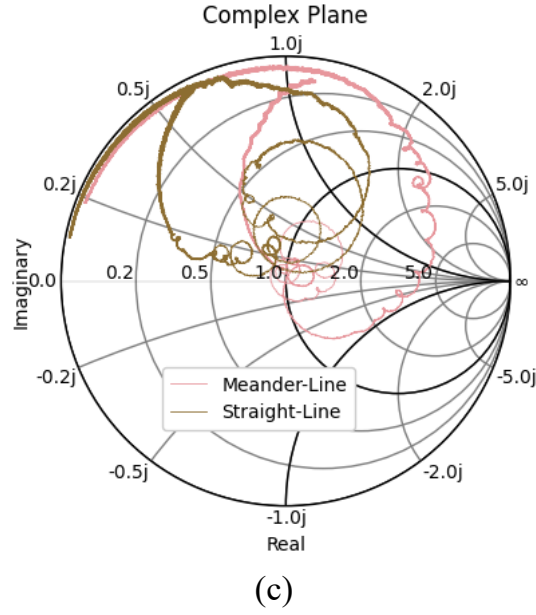
Supplementary Figure 10. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between meander-line and straight-line transducer YIG filters under applied magnetic flux densities of approximately 2500 Gauss.



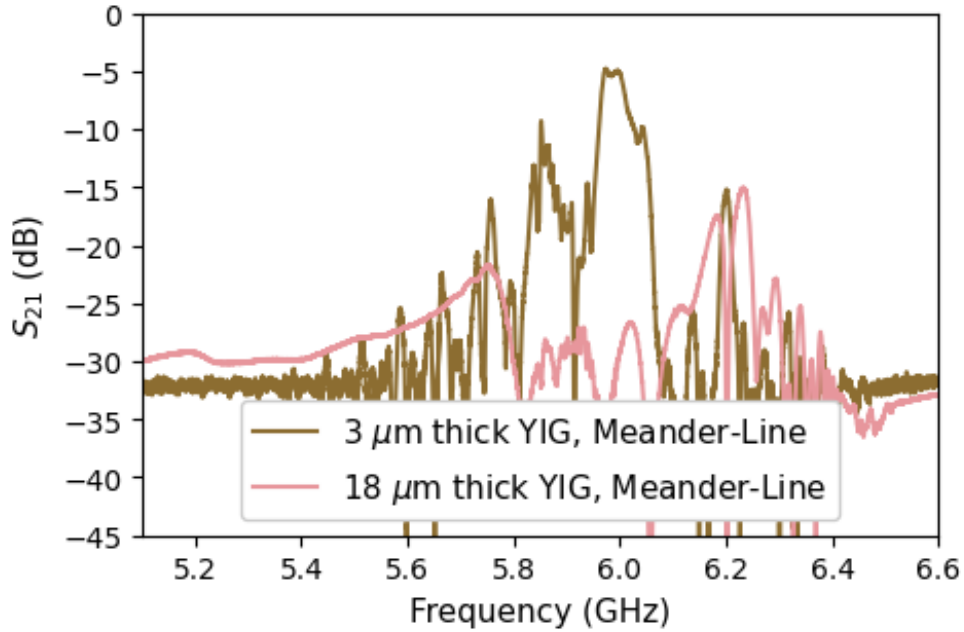
(a)



(b)



Supplementary Figure 11. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between meander-line and straight-line transducer YIG filters under applied magnetic flux density of approximately 3500 Gauss.



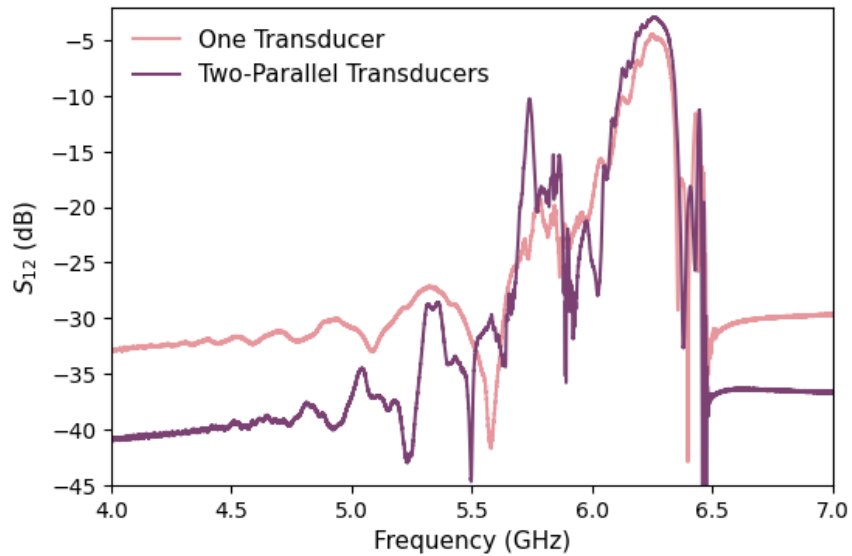
Supplementary Figure 12. Comparison of measured S_{21} frequency responses between the 3 μm and 18 μm thick YIG meander-line transducer filters under applied magnetic flux densities of approximately 1500 Gauss. The S_{12} frequency response comparison is shown in Fig. 3 in the main text.

Supplementary Note #5: YIG Filters with Two Parallel Transducers

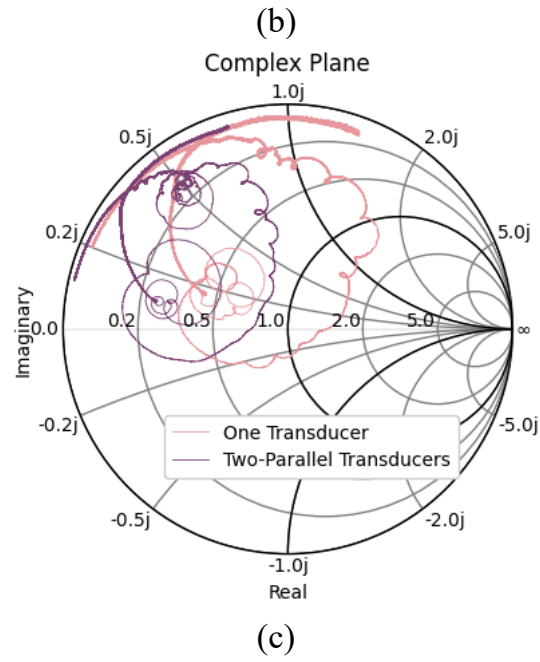
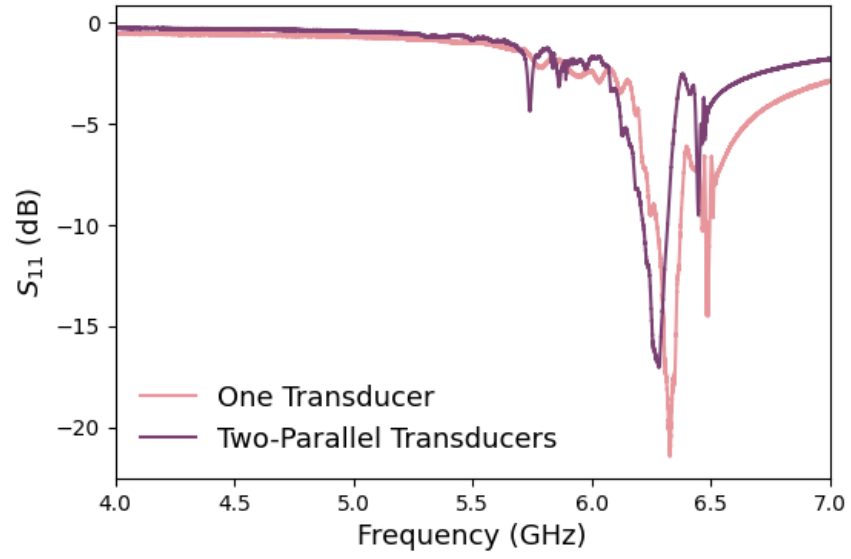
Supplementary Figure 13, 14, and 15 present a comparative analysis of the frequency responses of 18 μm thick YIG filters featuring one meander-line and two-parallel meander-line transducers under three different applied magnetic flux densities of 1500, 2500, 3500 Gauss, respectively. Both filters share an identical transducer pitch of 70 μm , transducer width of 200 μm , and YIG waveguide length of 420 μm . The two-parallel meander-line filter has a total width approximately double that of the single meander-line design (200 μm), plus the width of the central bridge section, as illustrated in **Fig. 3e**. The single meander-line transducer YIG filter is the same one detailed in **Supplementary Note #4**.

At 6.3 GHz, the inclusion of a parallel transducer branch reduces the peak Z_{11} from 40.9 dB to 33.5 dB, improving impedance matching and decreasing the insertion loss from 4.4 dB to 2.9 dB. This better matching is confirmed by the Smith chart analysis in **Supplementary Fig. 13c**. At higher frequencies, this benefit becomes even more significant. For instance, at 11.8 GHz, the insertion loss drops from 8.3 dB (single meander-line) to 3.8 dB (two-parallel), due to better impedance matching, as seen in **Supplementary Figure 14c and 15c**.

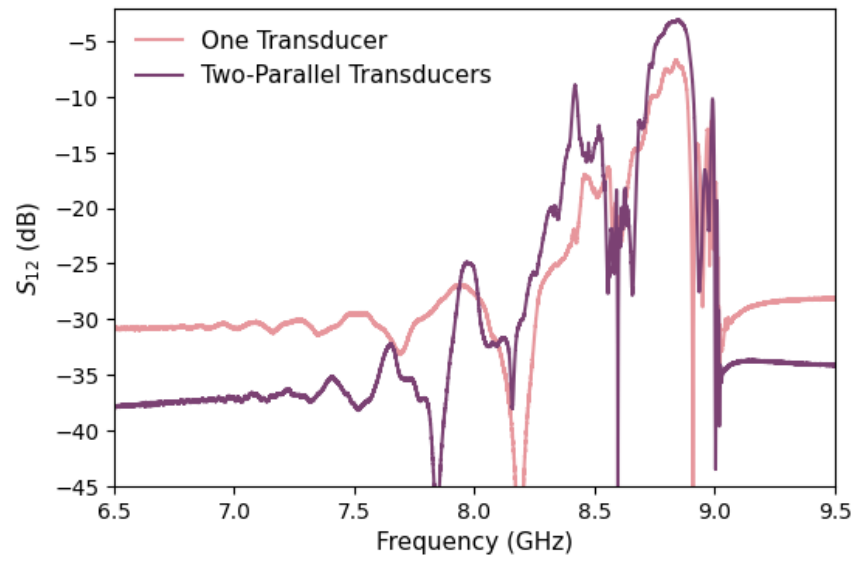
However, a drawback of the parallel configuration is the emergence of pronounced spurious modes at slightly lower frequencies—approximately 5.7 GHz (1500 Gauss), 8.7 GHz (2500 Gauss), and 11.5 GHz (3500 Gauss). These undesired responses are likely introduced by the center bridge section, which can also excite magnetostatic backward volume waves (MSBVWs).



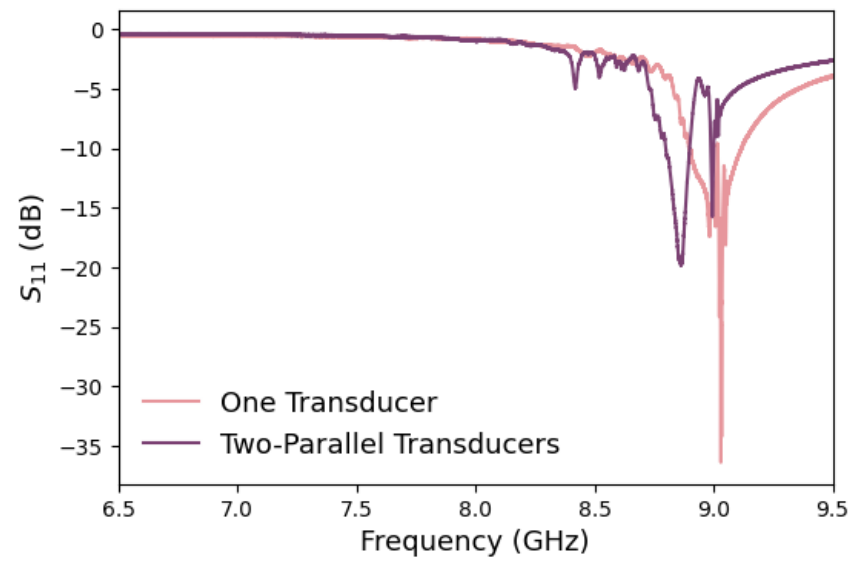
(a)



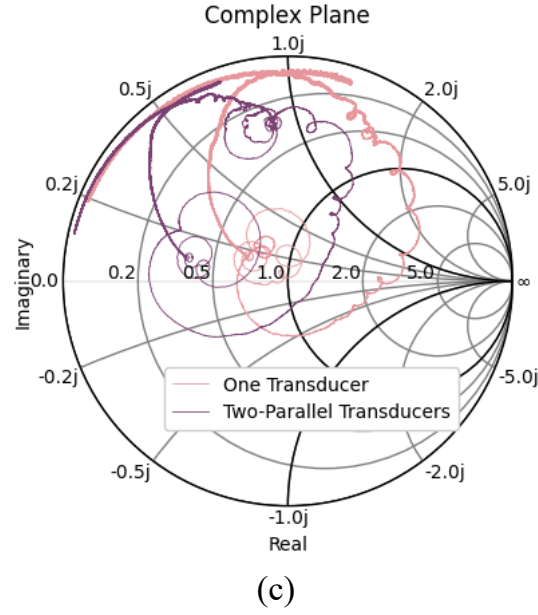
Supplementary Figure 13. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer and a single meander-line transducer YIG filters under applied magnetic flux densities of approximately 1500 Gauss.



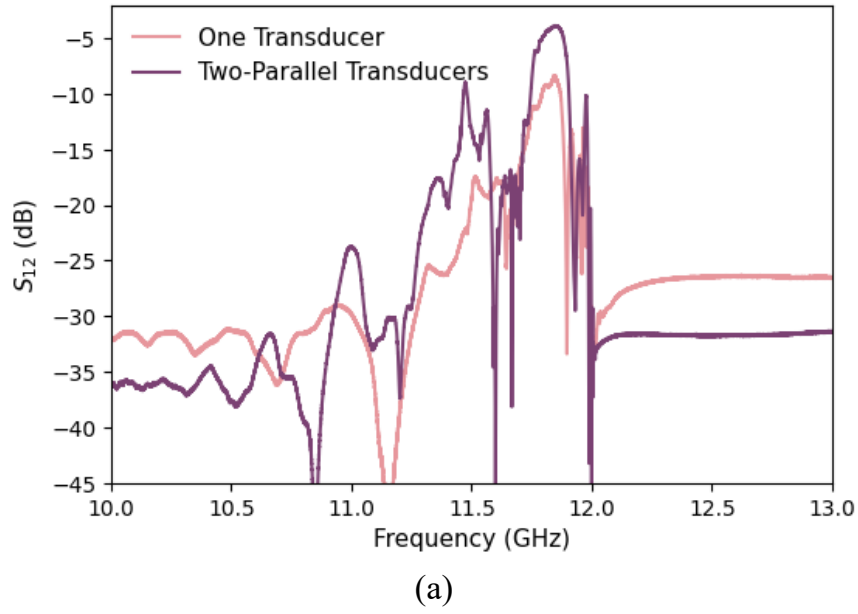
(a)

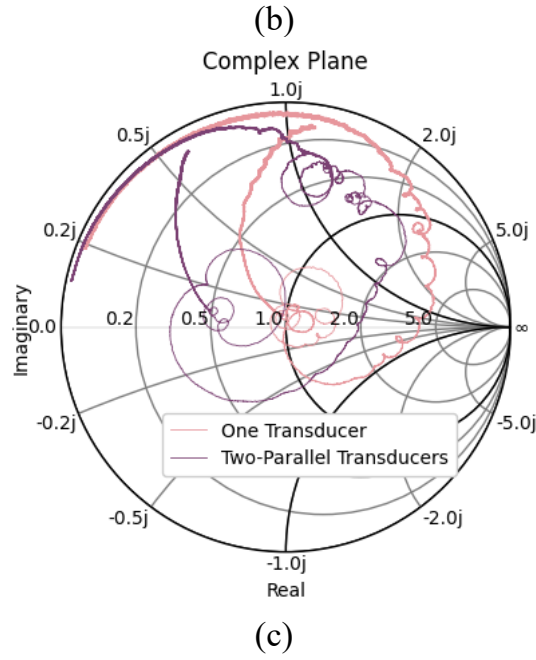
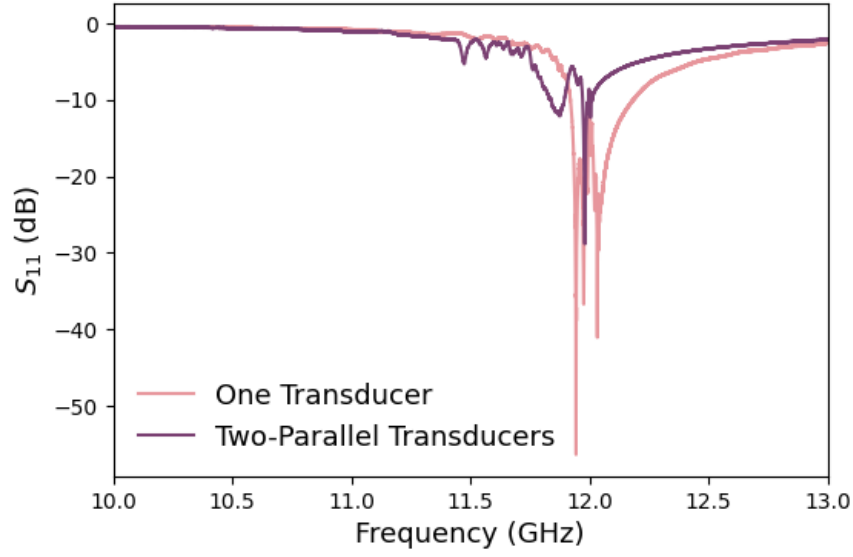


(b)



Supplementary Figure 14. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer and a single meander-line transducer YIG filters under applied magnetic flux densities of approximately 2500 Gauss.





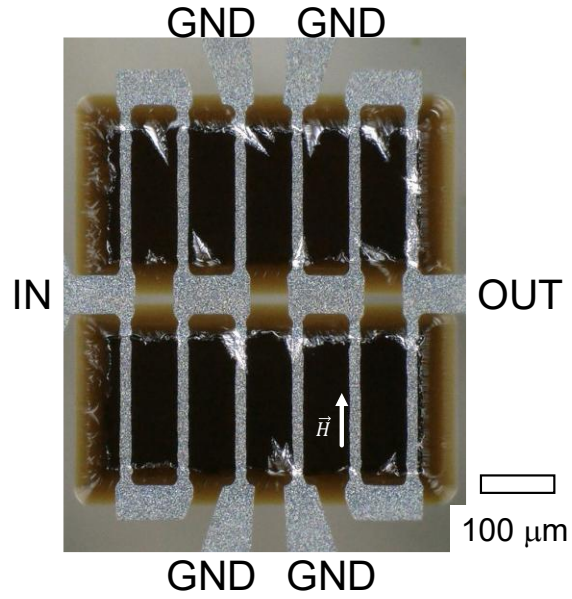
Supplementary Figure 15. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer and a single meander line transducer YIG filters under applied magnetic flux densities of approximately 3500 Gauss.

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

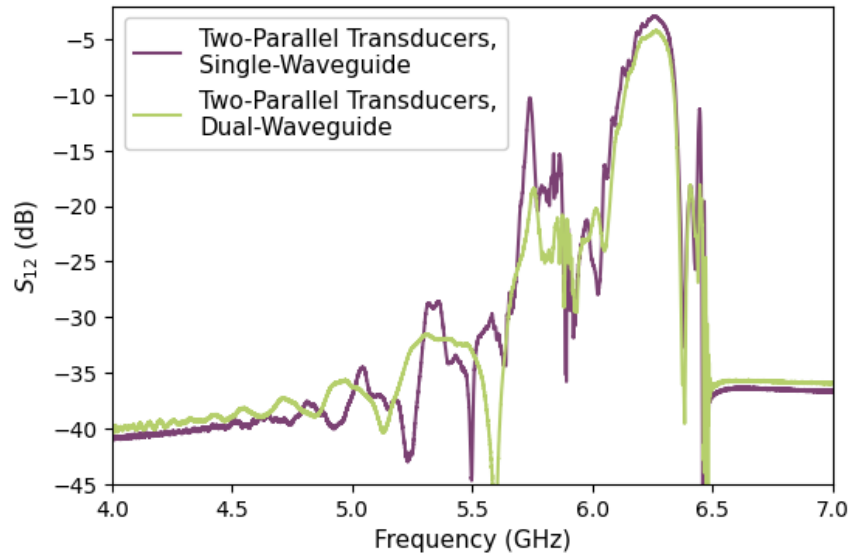
Supplementary Figure 16 shows a two-parallel meander-line filter featuring dual YIG waveguides, where each YIG waveguide follows the same design as the single meander-line filter. Compared to the two-parallel meander-line filter with a single YIG waveguide (**Fig. 3e**), the dual YIG waveguide configuration 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 17, 18, and 19 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} .

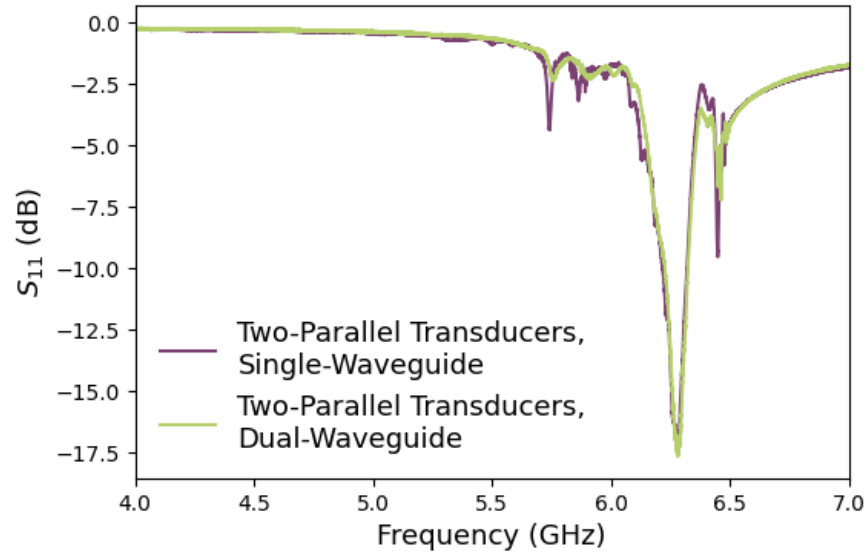
By moving the bridge section away from the YIG, the dual-waveguide configuration effectively suppresses the large spurious peaks that occur at frequencies slightly below the passband: 5.7 GHz (1500 Gauss), 8.7 GHz (2500 Gauss), and 11.5 GHz (3500 Gauss). However, the dual-waveguide design was not adopted 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 16. Optical microscope image of a two parallel meander-line transducer dual-waveguide YIG filter with pitch of 70 μm and width of 200 μm .

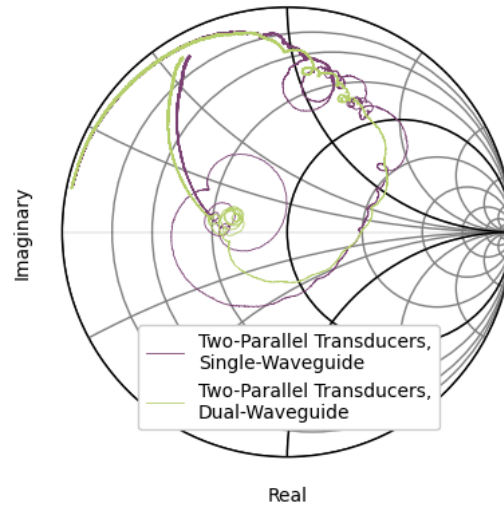


(a)



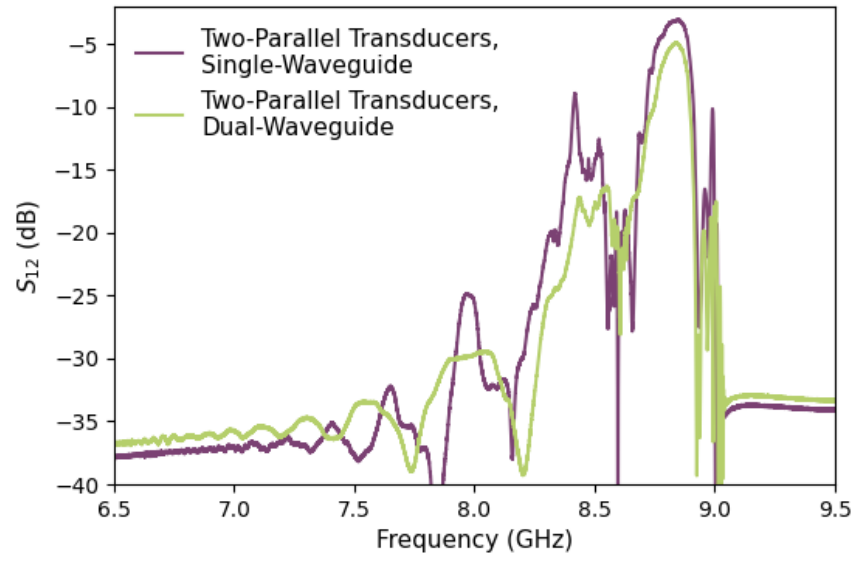
(b)

Complex Plane

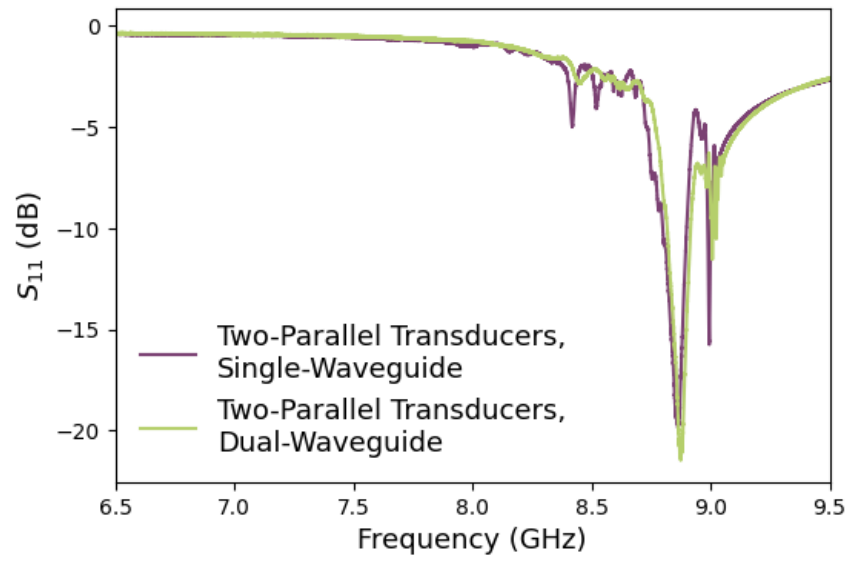


(c)

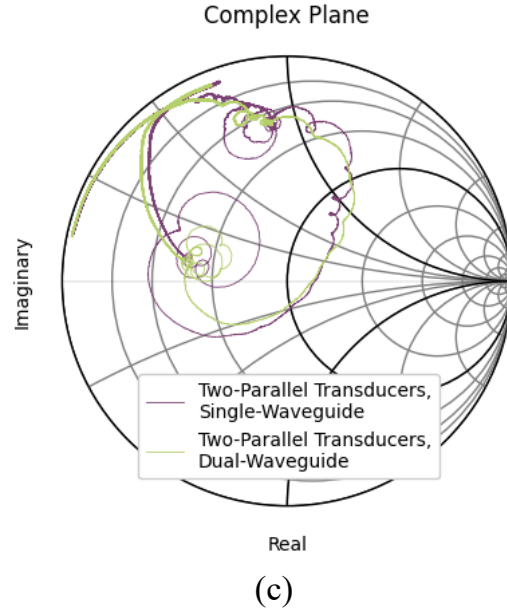
Supplementary Figure 17. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer dual and single waveguide YIG filters under applied magnetic flux densities of approximately 1500 Gauss.



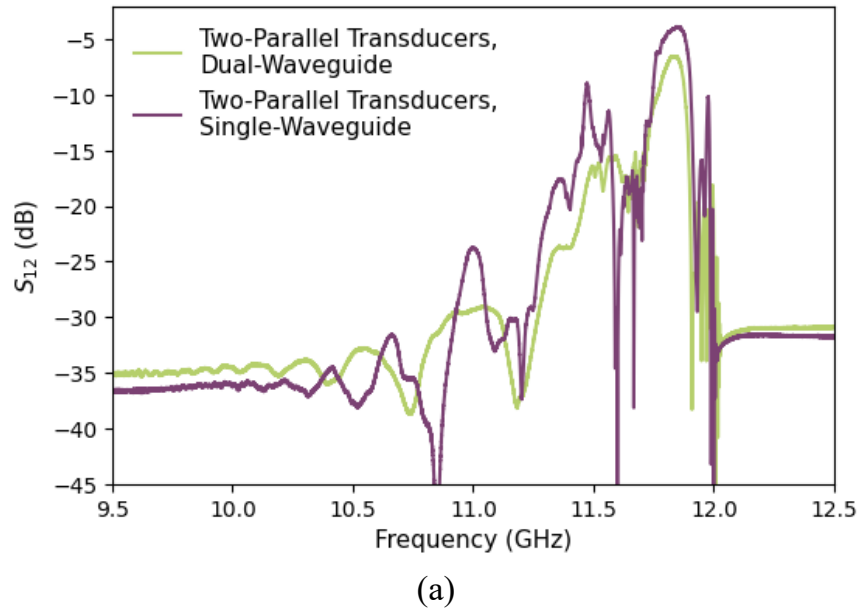
(a)

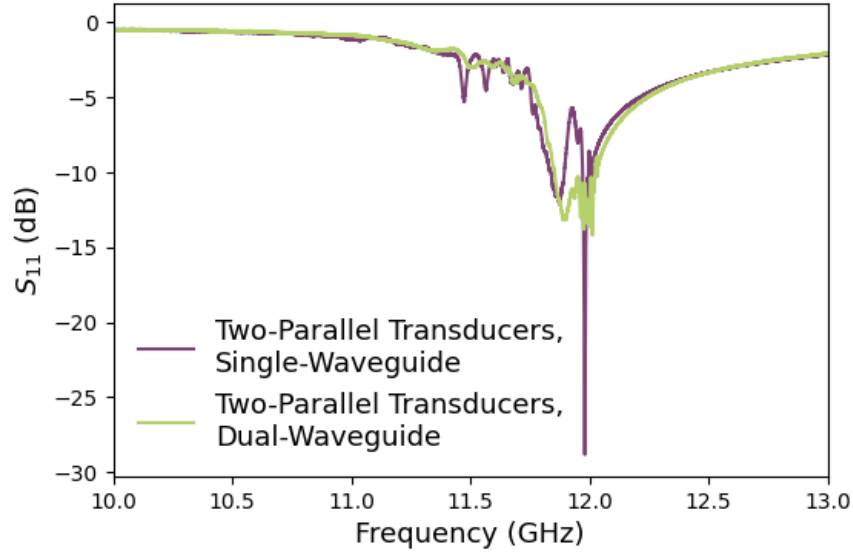


(b)



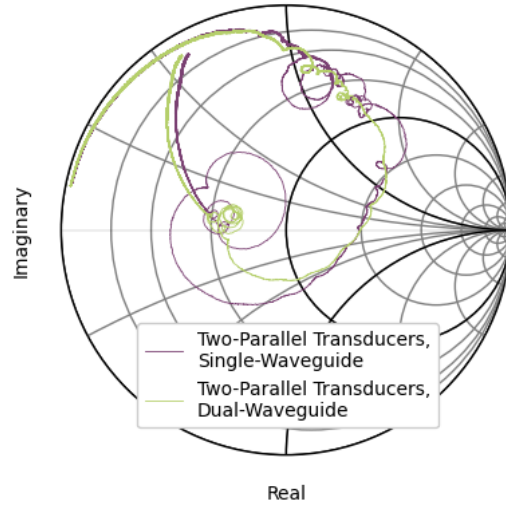
Supplementary Figure 18. Comparison of measured (a) S_{12} , (b) S_{11} , and (c) S_{11} in Smith graph between two parallel meander-line transducer dual and single waveguide YIG filters under applied magnetic flux densities of approximately 2500 Gauss.





(b)

Complex Plane



(c)

Supplementary Figure 19. 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.

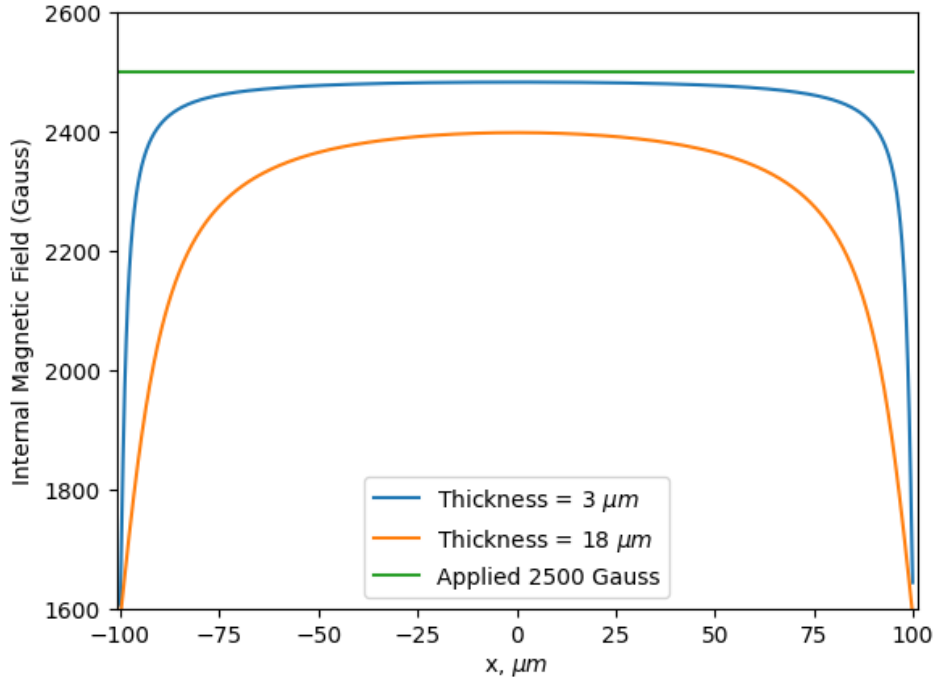
Although the dual-waveguide YIG filter suppresses several strong spurious responses near the resonance frequency, it exhibits more, albeit smaller, spurious peaks at frequencies significantly lower than the main passband. For instance, additional spurious resonances are observed in the ranges of 4–5 GHz (1500 Gauss), 6.5–7.5 GHz (2500 Gauss), and 9.5–10.5 GHz (3500 Gauss). This behavior is attributed to enhanced demagnetization effects in the dual-waveguide configuration. Previous studies have shown that the internal magnetic field can be calculated as[2]:

$$H(x) = H - \frac{M_s}{\pi} \left[\arctan\left(\frac{S}{2x+w}\right) - \arctan\left(\frac{S}{2x-w}\right) \right] \quad (\text{S6})$$

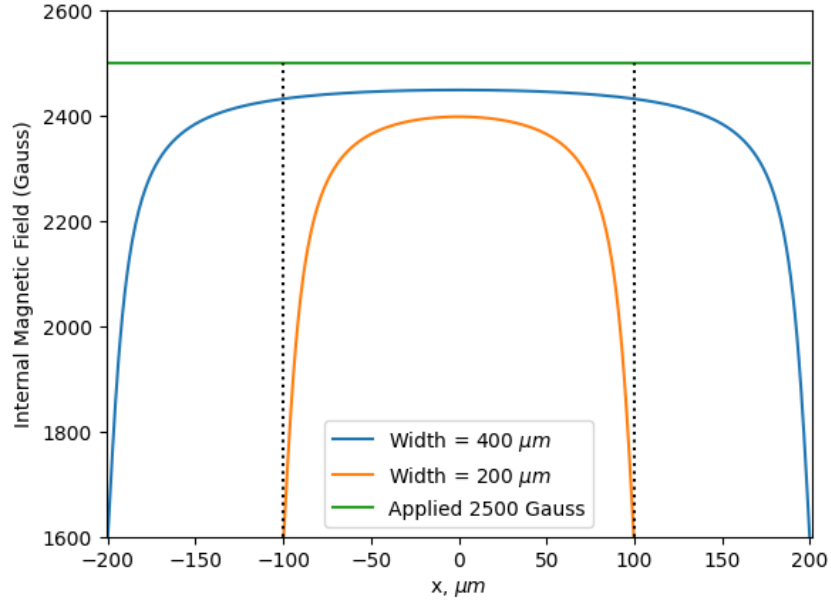
Here, $H(x)$ is the internal magnetic field, H is the applied magnetic field, M_s is the saturation magnetization, S is the thickness of the YIG, w is the width of the YIG,

As illustrated in **Supplementary Figure 20**, the demagnetizing effect significantly reduces the internal magnetic field near the edges of the YIG waveguide. This could lead to the formation of field-induced channels where spin waves can become localized. These localized spin wave modes are typically concentrated near the edges and appear at much lower frequencies than those supported in the center region of the waveguide.

This demagnetization effect is more pronounced in the 18 μm thick YIG waveguide used in this study, compared to previously reported 3 μm thick waveguides. Both the edge-induced channel width and the reduction in the central internal field are more severe in thicker waveguides. Furthermore, **Supplementary Figure 20 (b)** suggests that increasing the width of the YIG waveguide can mitigate this effect—explaining why the single-waveguide design, which has a wider YIG region, shows fewer and weaker low-frequency spurious modes.



(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 μm and 18 μm , both with a fixed width of 200 μm . **(b)** Comparison between waveguide widths of 200 μm and 400 μm , with a fixed thickness of 18 μm . The green line indicates the value of the applied external magnetic field.

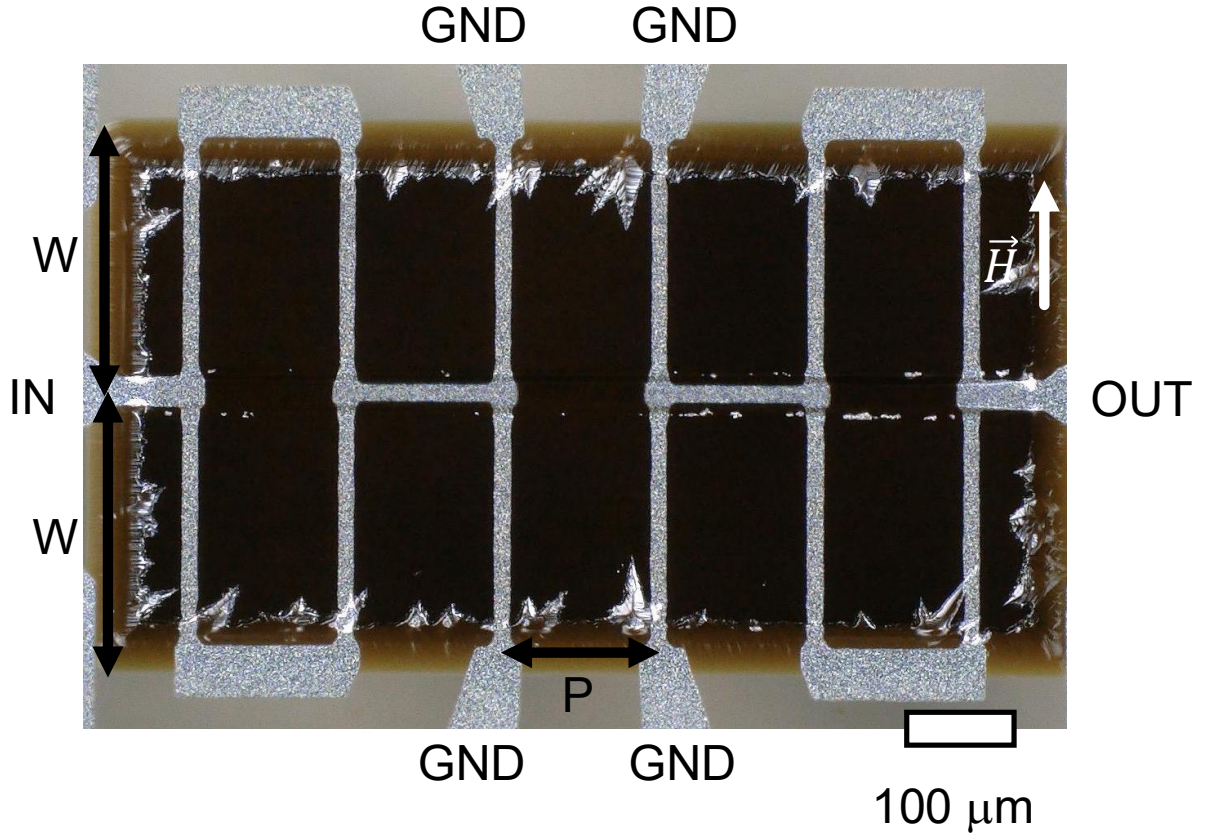
Supplementary Note #7: Effect of Pitch on YIG Filters with Meander Line Transducers

Supplementary Figure 21 presents a two-parallel meander-line filter incorporating a single 18 μm thick YIG waveguide with a transducer pitch of 130 μm . All other design parameters remain identical to the YIG filter previously discussed.

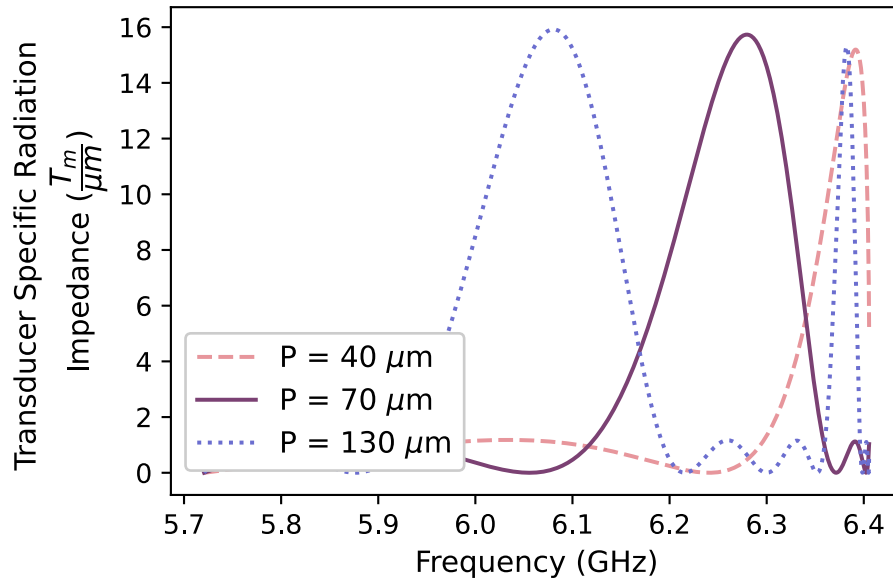
The impact of transducer pitch can be understood through the transducer-specific radiation impedance per unit length, as described by Equation (1). A theoretical comparison of different pitch values is provided in **Supplementary Figure 22**, considering only the first-order width mode ($n = 1$). Although higher-order width modes also exist at lower frequencies, they share similar profiles with the first-order mode and are thus not individually analyzed.

For a small pitch of 40 μm , the filter exhibits only a single fundamental mode near the ω_{max} frequency. As the pitch increases, the radiation impedance slightly rises and begins to saturate around 70 μm , beyond which the difference between 70 μm and 130 μm becomes negligible. However, the number and magnitude of the higher-order length modes increases significantly with increasing pitch.

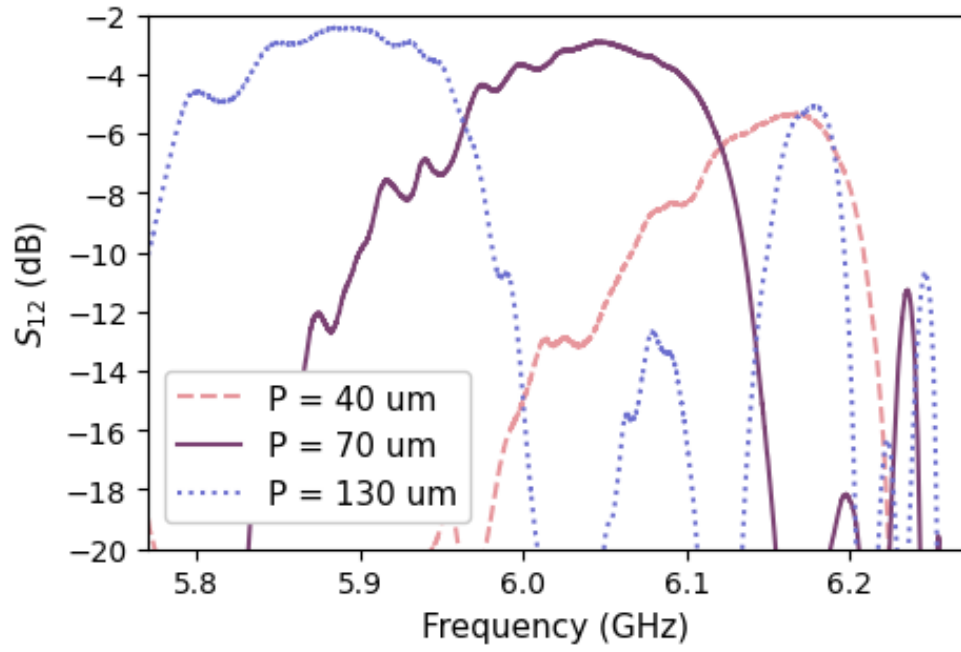
Supplementary Figure 23 shows the measured S_{12} result, which validates the theoretical predictions. All filters in this comparison share identical transducer dimensions except for pitch. The filter with a 70 μm pitch also has been featured in **Fig. 3e** and discussed in **Supplementary Notes #4 and 5**. This comparison shows that the pitch of 70 μm is the best design as it has both low insertion loss and high spurious mode attenuation. Moreover, the out-of-band rejection also increases with respect to the pitch of the meander line transducer.



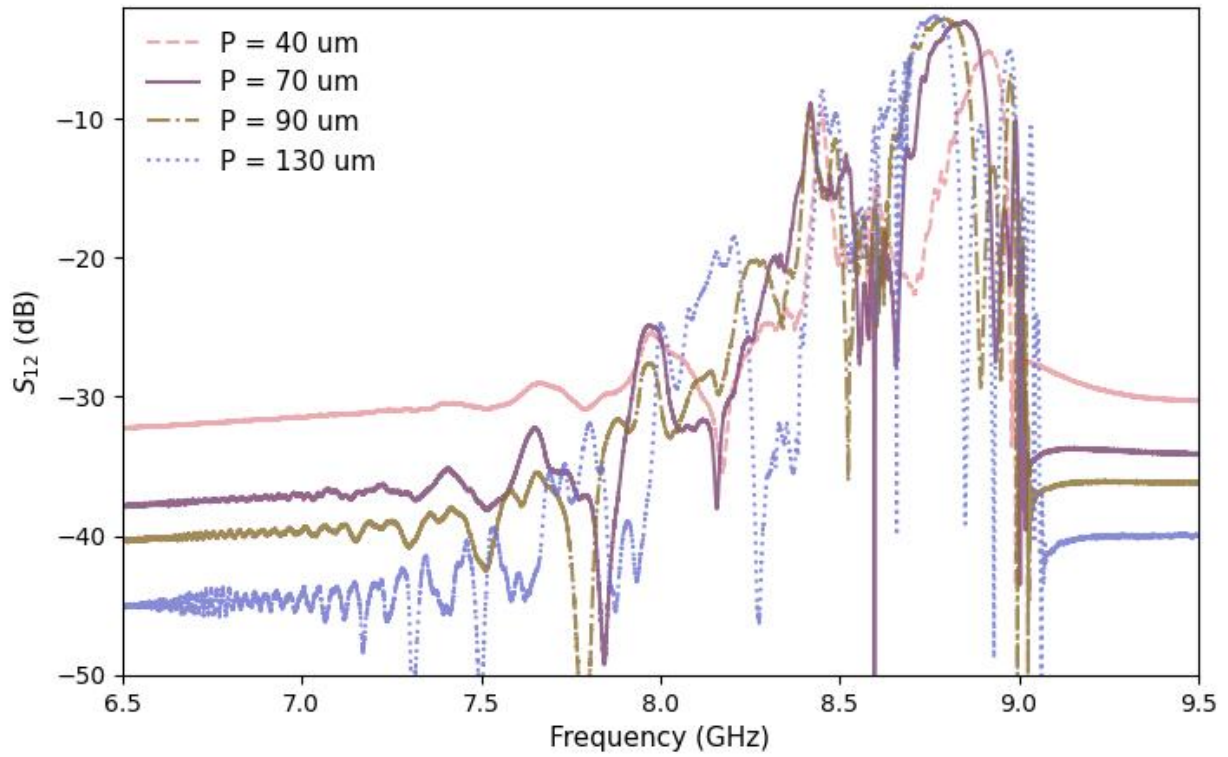
Supplementary Figure 21. Optical image of a YIG filter with two parallel meander-line transducers with a larger pitch of 130 μm and width of 200 μm



Supplementary Figure 22. Comparison of the calculated transducer specific radiation impedance for different meander-line transducer pitches.



(a)



(b)

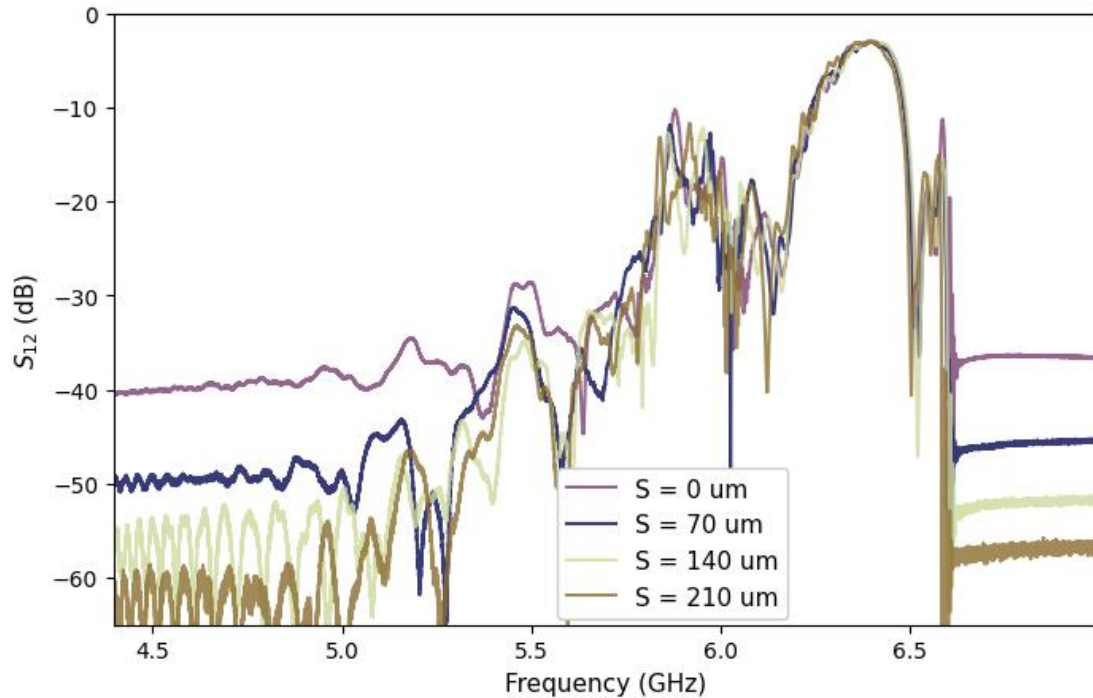
Supplementary Figure 23. Measured S_{12} frequency responses for different meander-line transducer pitches with magnetic flux density of approximately 2500 Gauss. **(a)**

Zoomed-in view showing the passband and higher-order spurious length modes. **(b)** Full frequency response across the entire measurement range.

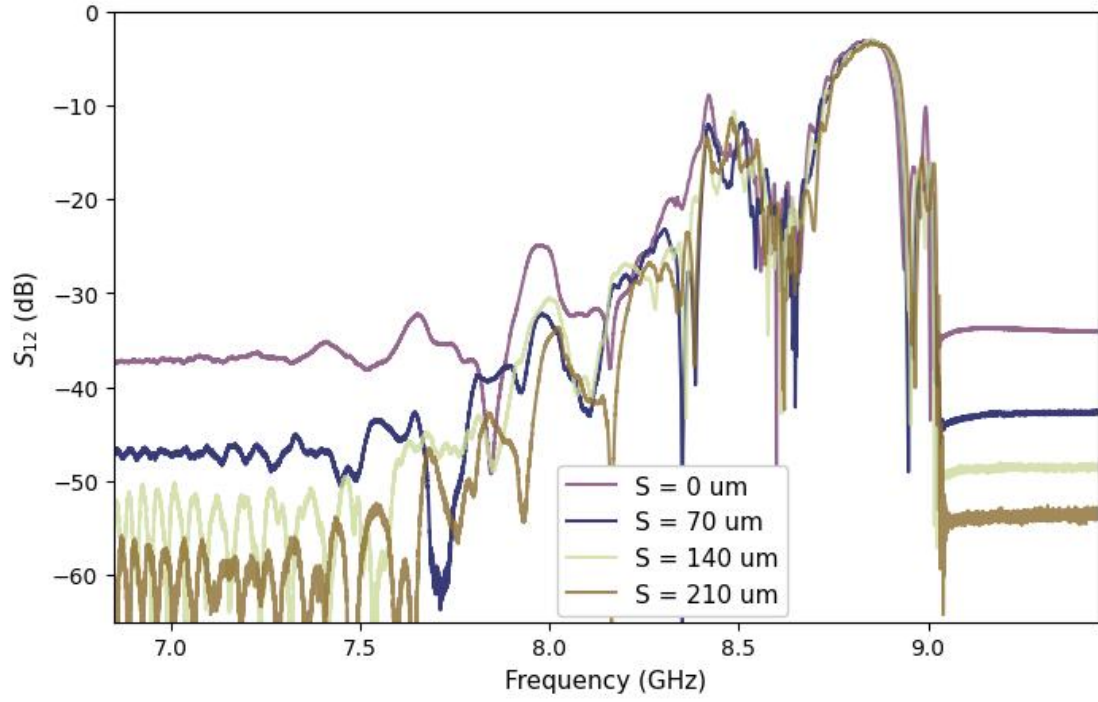
Supplementary Note #8: Effect of Spacing on YIG Filters with Meander Line Transducers

Supplementary Figure 24 presents a comparative analysis of the frequency responses of 18 μm thick, two-parallel meander-line single-waveguide YIG filters with varying transducer spacings under applied magnetic flux densities of 1500, 2500, and 3500 Gauss, respectively. All filters share the same waveguide width (200 μm), transducer pitch (70 μm), and transducer width (10 μm). The filter without additional transducer spacing, also featured in **Fig. 3e** and discussed in **Supplementary Note #4**, serves as a baseline for comparison.

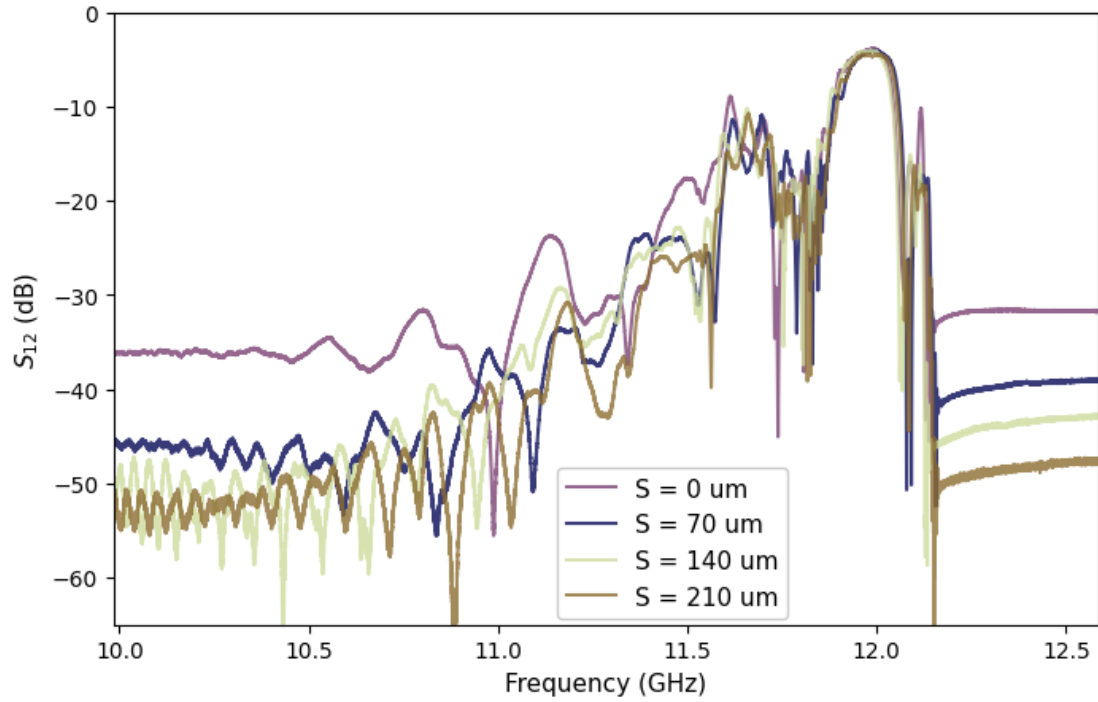
These results reveal that increasing the spacing between transducers significantly improves the out-of-band rejection, while maintaining a nearly constant insertion loss across the measured frequency range.



(a)



(b)

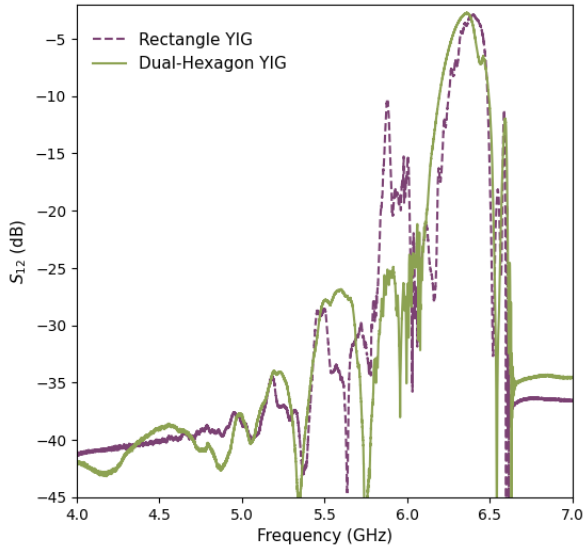


(c)

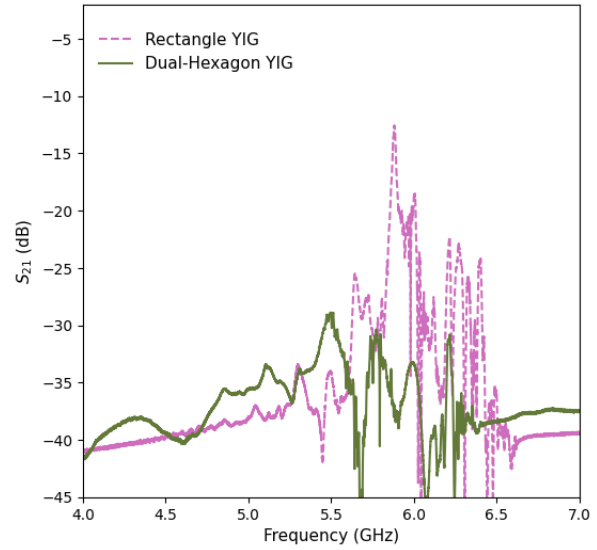
Supplementary Figure 24. Comparison of the measured S_{12} frequency responses for YIG filters with different spacings under three different applied magnetic flux densities of (a) ~ 1500 , (b) ~ 2500 , and (c) ~ 3500 Gauss, respectively.

Supplementary Note #9: Dual-Hexagon-Shape YIG Filters

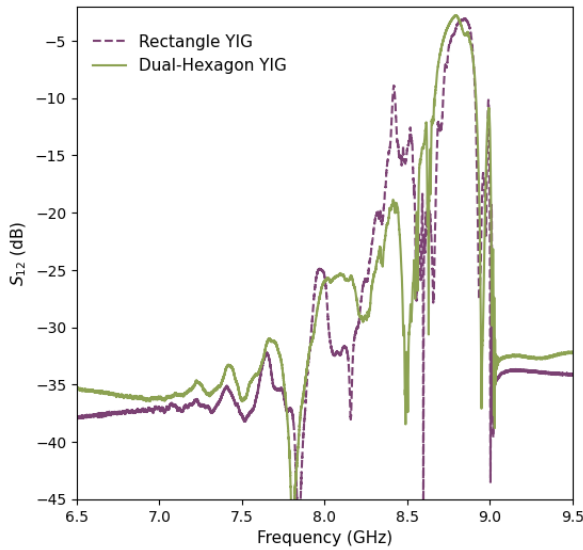
Supplementary Figure 25 presents a comparative analysis of the frequency responses of 18 μm thick, two-parallel meander-line single-waveguide YIG filters with a dual-hexagon shaped YIG and a rectangular shaped YIG under applied magnetic flux densities of 1500, 2500, and 3500 Gauss, respectively. Both filters share the same waveguide width (200 μm), transducer pitch (70 μm), and transducer width (10 μm). The filter with a rectangular shape, also featured in **Fig. 3e**, serves as a baseline for comparison. The dual-hexagon shaped YIG filter is highlighted in **Fig. 4e**.



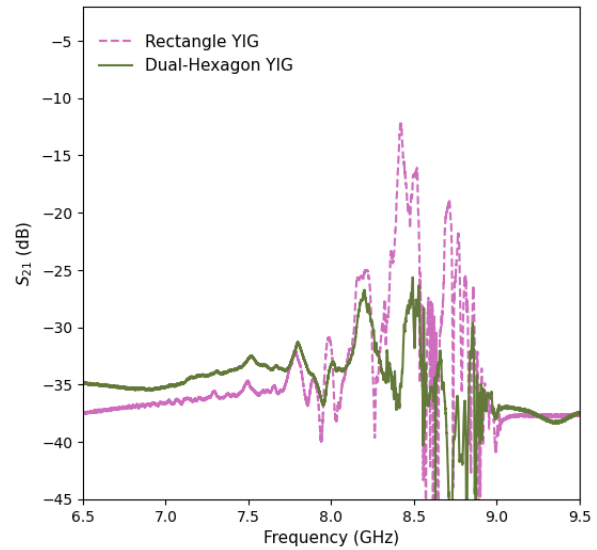
(a)



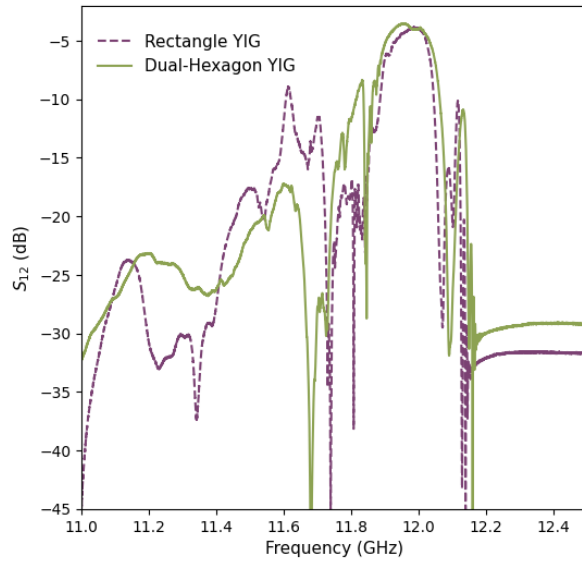
(b)



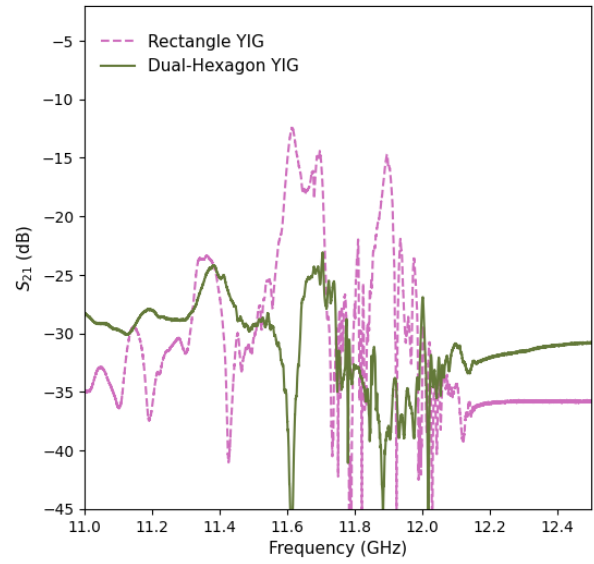
(c)



(d)



(e)



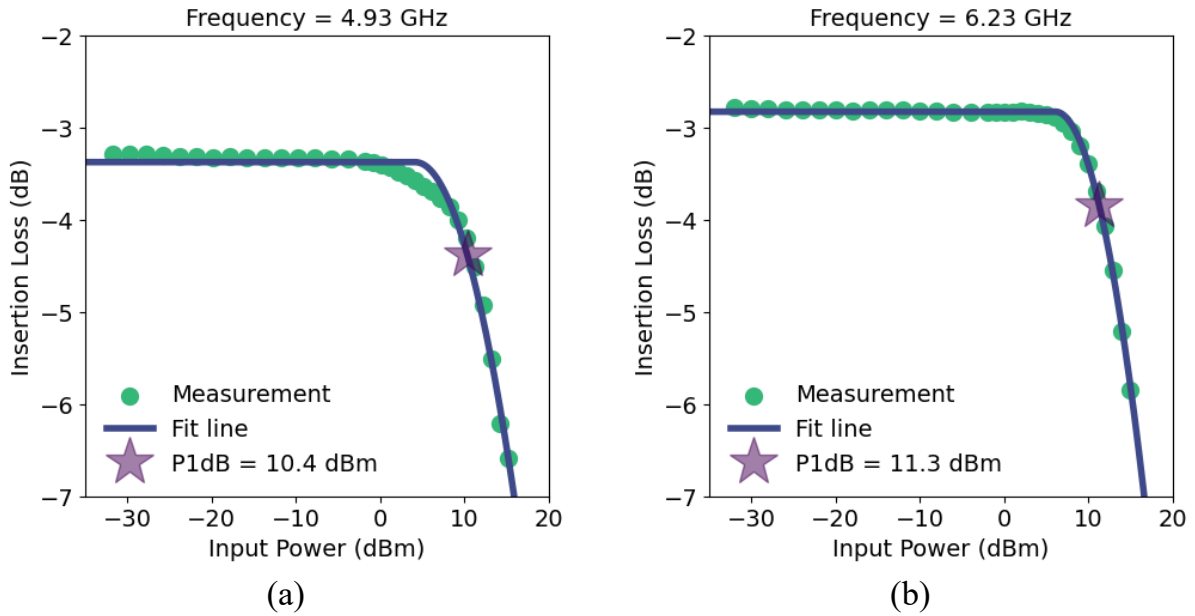
(f)

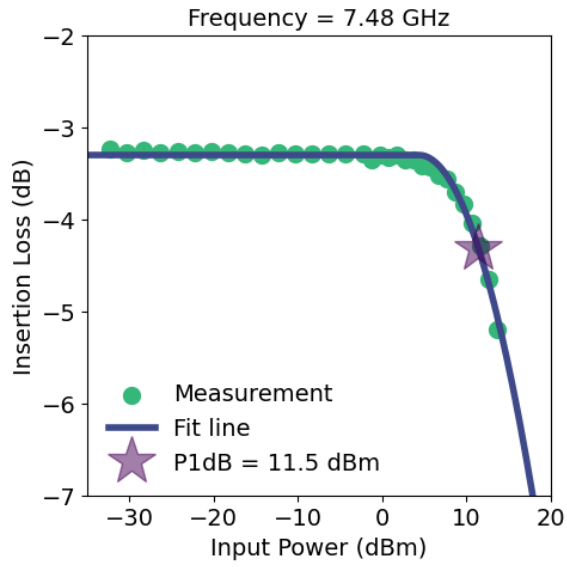
Supplementary Figure 25. Comparison of the measured S_{12} and S_{21} frequency responses for YIG filters with dual-hexagon shaped YIG and rectangle shaped YIG under three different applied magnetic flux densities of (a) ~ 1500 , (b) ~ 2500 , and (c) ~ 3500 Gauss, respectively.

Supplementary Note #10: Power Handling Characteristics

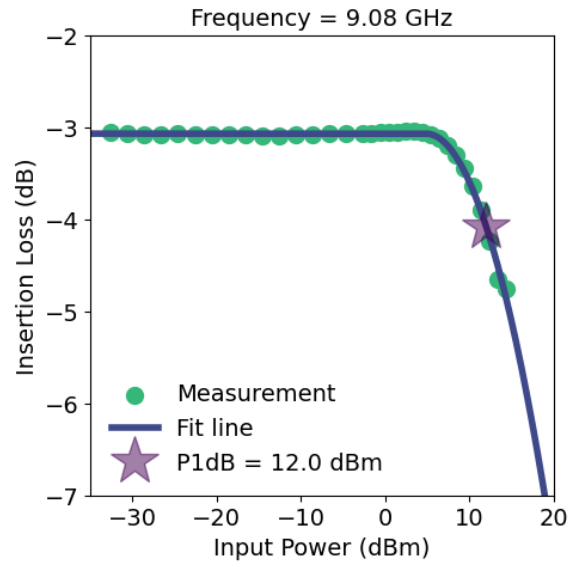
Supplementary Figures 26, 27, and 28 present a comparative analysis of the frequency responses of the filter with different input power levels, ranging from -30 dBm to 16 dBm. The filter under test is an 18 μm thick dual-hexagon-shaped YIG filter with two-parallel meander-line transducers. It features 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 29** reports the power handling of a meander-line transducer filter realized in a 3 μm thick YIG film with a 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.

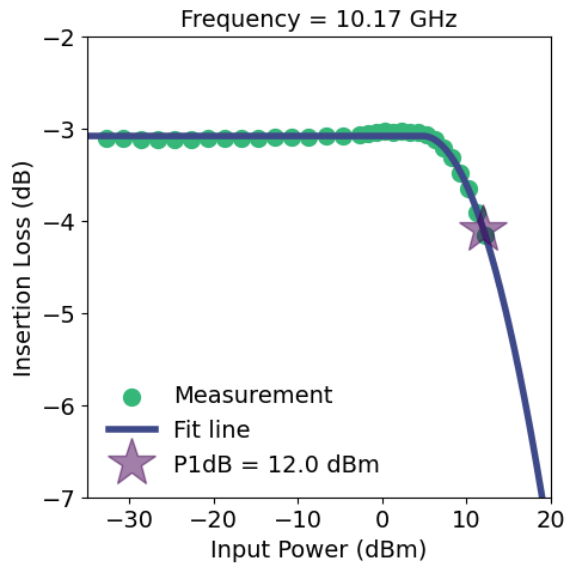




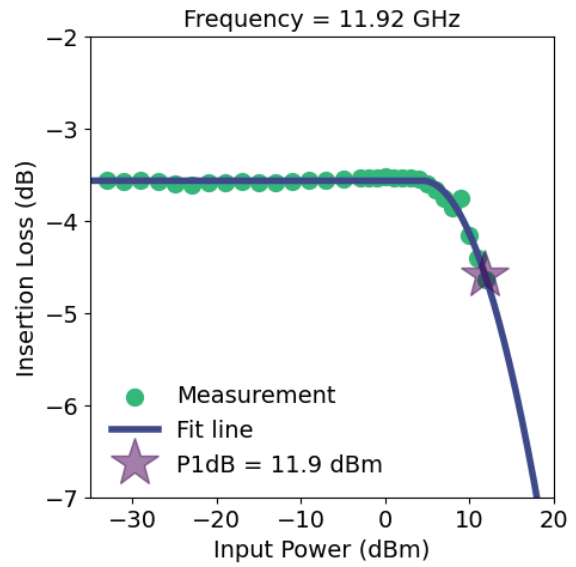
(c)



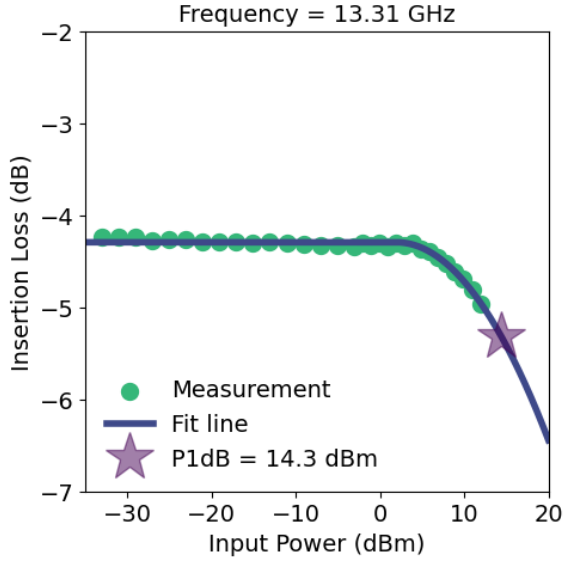
(d)



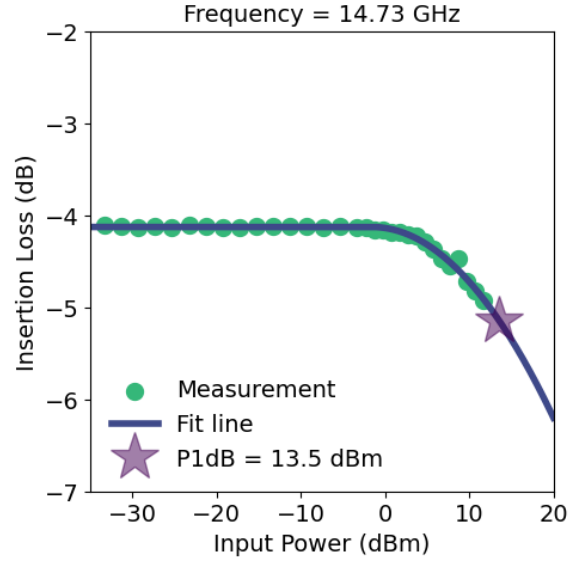
(e)



(f)

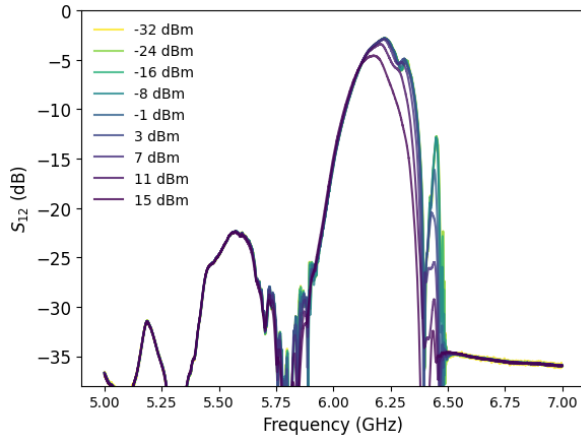


(g)

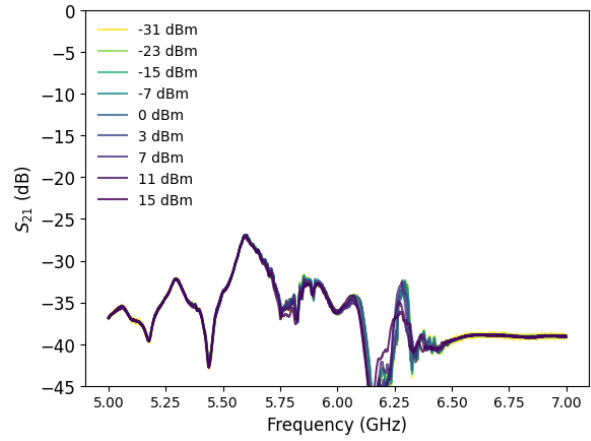


(h)

Supplementary Figure 26. 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.

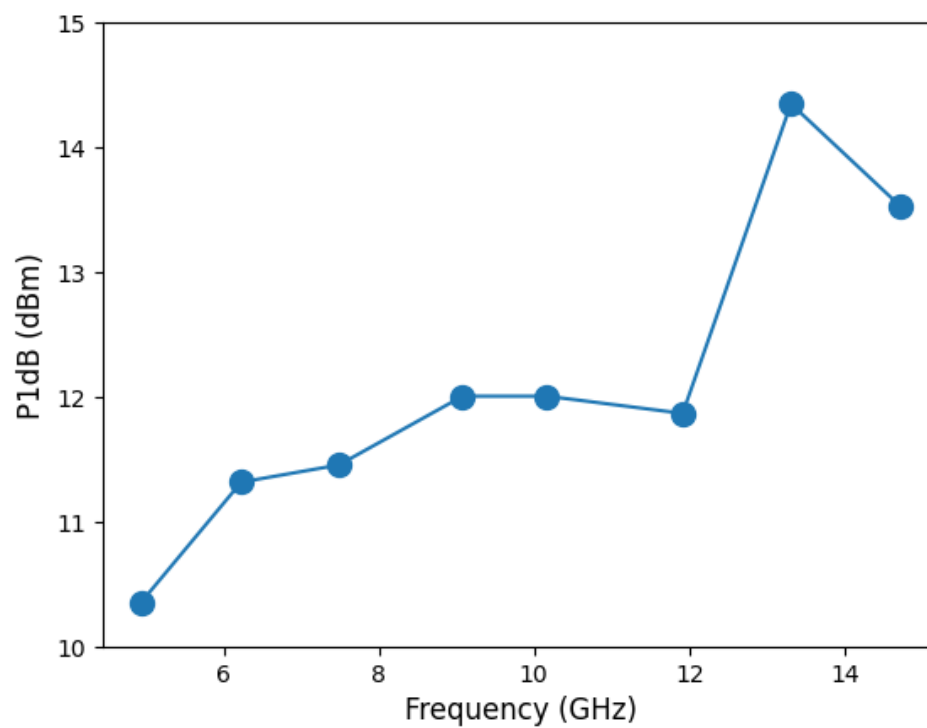


(a)

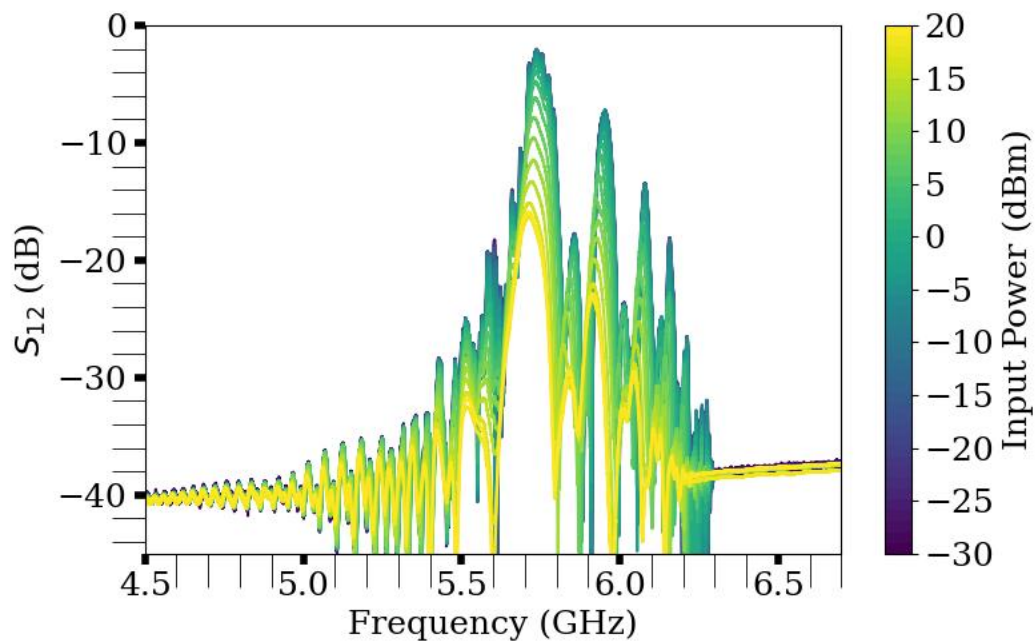


(b)

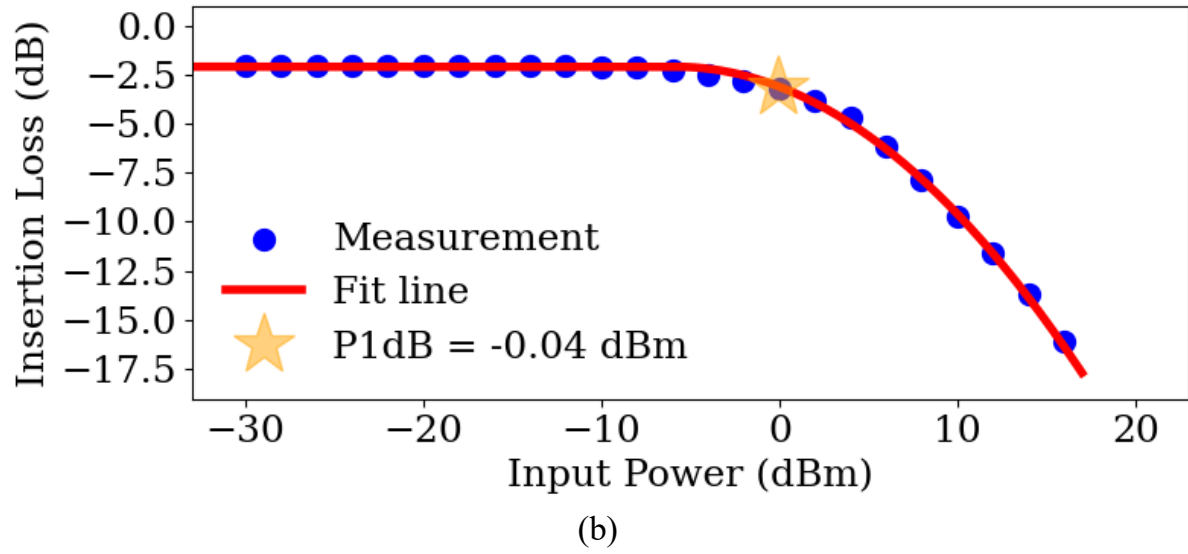
Supplementary Figure 27. Comparison of the measured (a) S_{12} and (b) S_{21} frequency responses with different input power with a bias field of ~1500 Gauss.



Supplementary Figure 28. Summary of the P1dB results as a function of frequency.



(a)

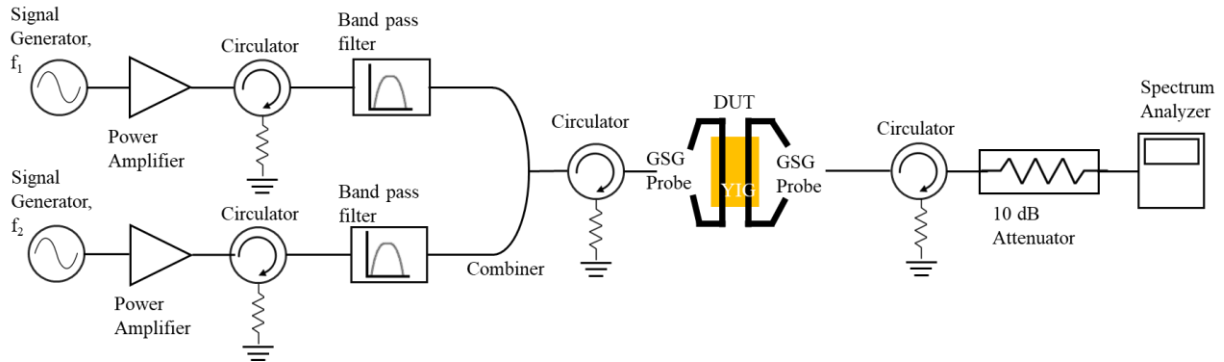


Supplementary Figure 29. Comparison of the measured (a) S_{12} frequency responses and (b) insertion loss with different input power at 5.8 GHz. This 3 μm thick YIG meander-line filter was previously reported in [16].

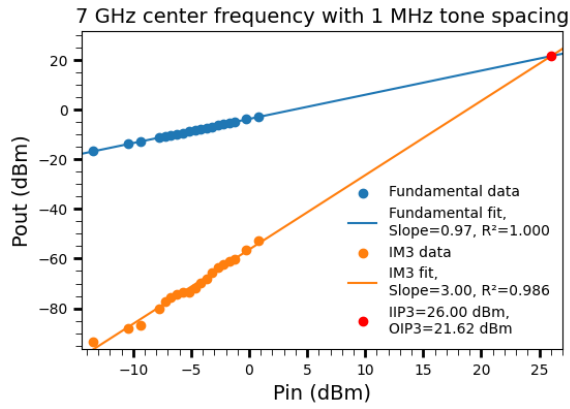
Supplementary Note #11: In-Band Linearity

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 30**. Two-tone signals (f_1 and f_2) were generated using two signal generators (Keysight P5024B). The combined signal was amplified by a Minicircuits ZX60-24-S+ amplifier. To suppress unwanted harmonics and spurious tones, two bandpass filters (Minicircuits 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).

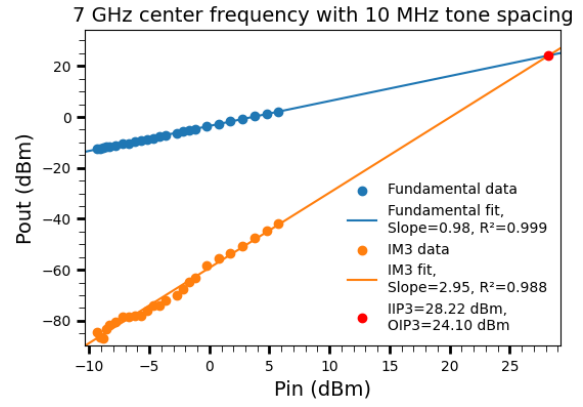
Supplementary Figure 31 presents the resulting in-band IIP3 data measured at 7 GHz and 11 GHz for tone spacings of 1 MHz, 10 MHz, and 100 MHz. For 1 MHz and 10 MHz tone spacings the third order intermodulation (IM3) products fall fully within the filter passband. Over all conditions the IIP3 remains 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.



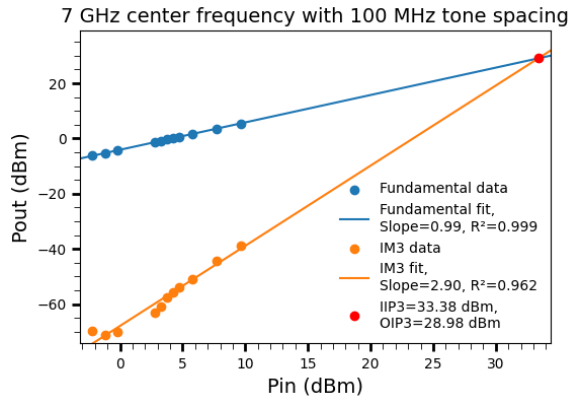
Supplementary Figure 30. In-band third order intermodulation intercept point (IIP3) measurement setup schematic.



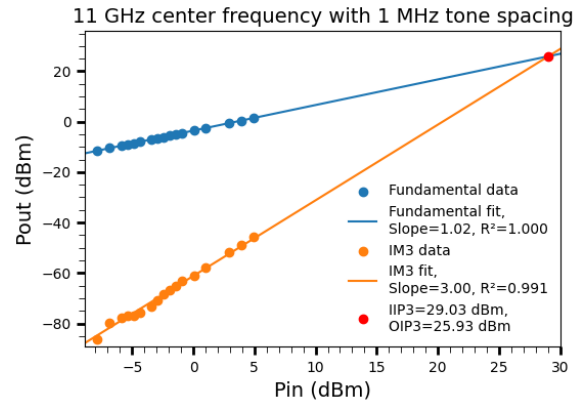
(a)



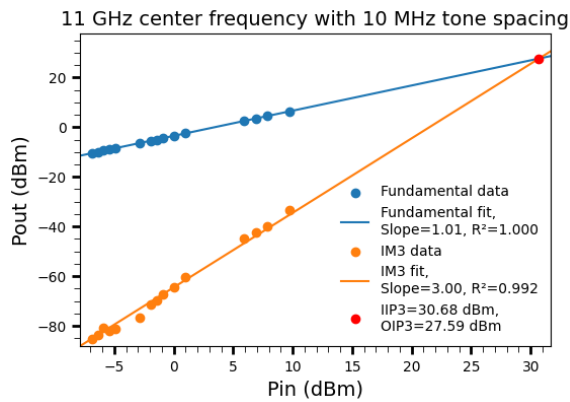
(b)



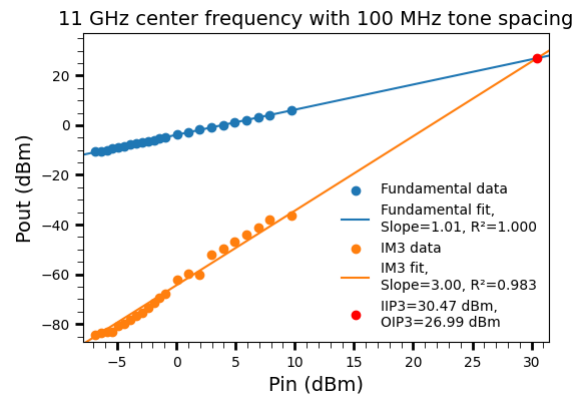
(c)



(d)



(e)

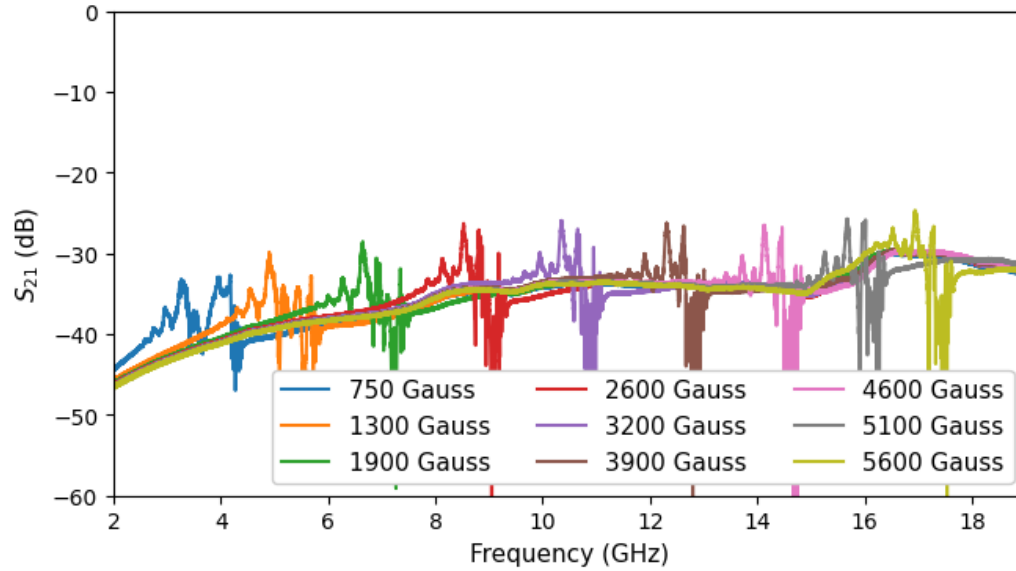


(f)

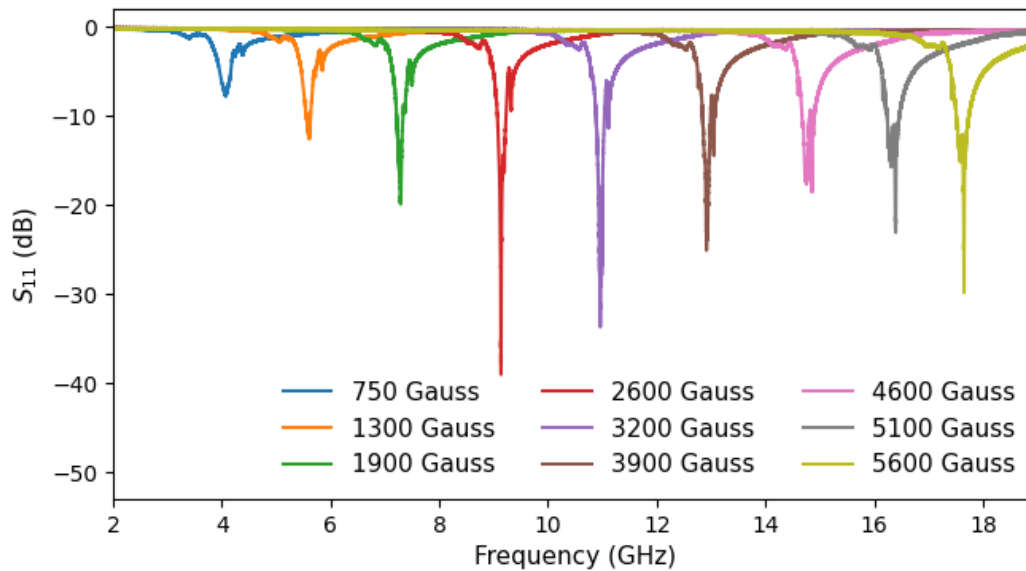
Supplementary Figure 31. In-band input third order intercept point (IIP3). The device is measured at **(a, b, and c)** 7 GHz and **(d, e, and f)** 11 GHz with tone spacings of **(a and d)** 1 MHz, **(b and e)** 10 MHz, and **(c and f)** 100 MHz

Supplementary Note #12: Integrated Filter

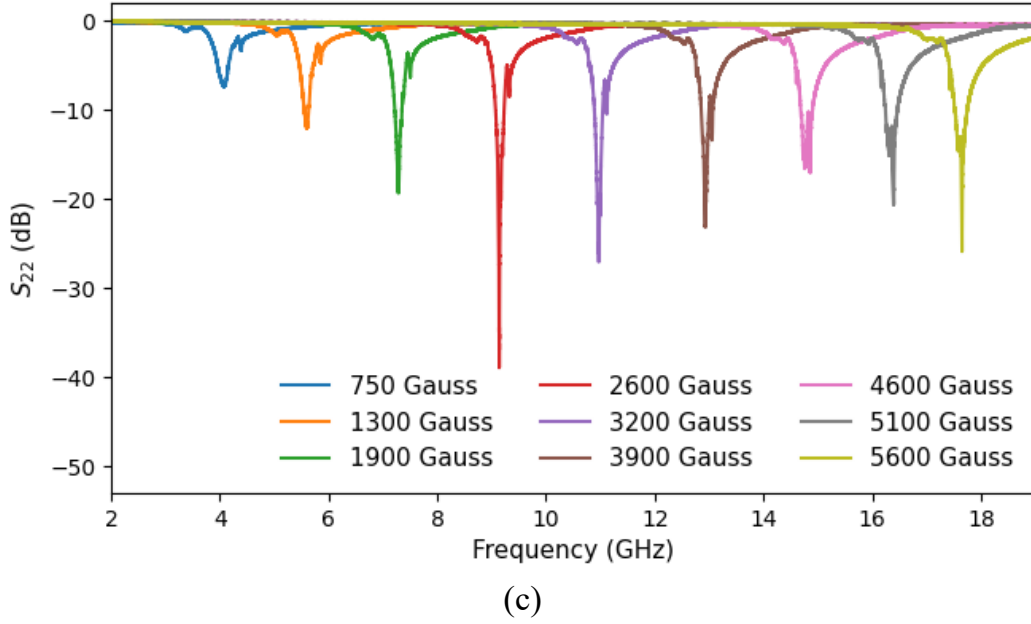
Supplementary Figure 32 shows the measured S_{21} , S_{22} and S_{11} frequency response across 4-18 GHz.



(a)

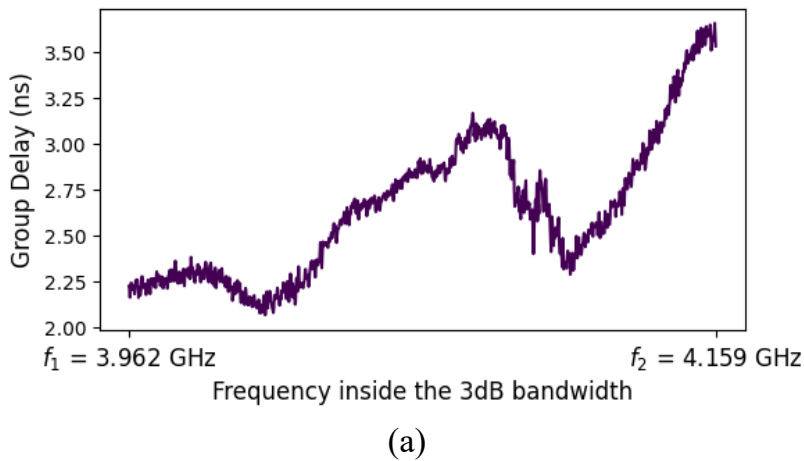


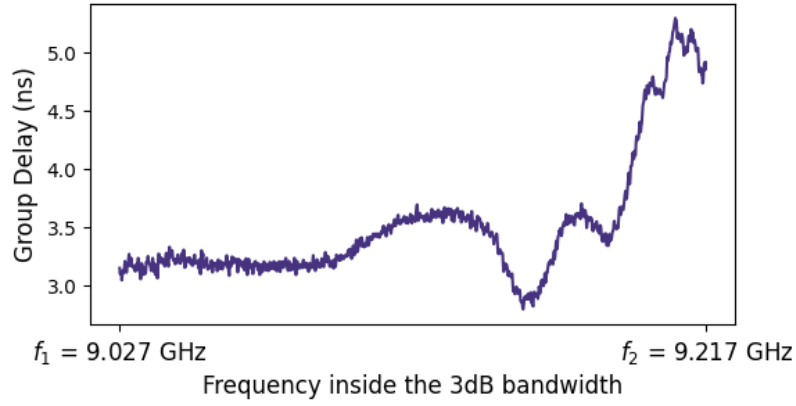
(b)



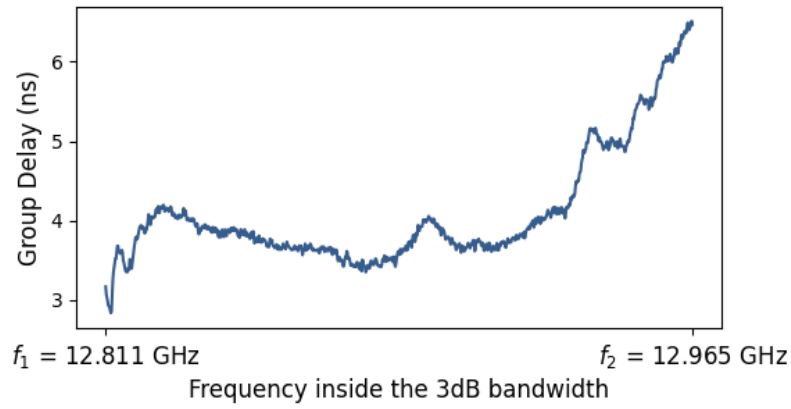
Supplementary Figure 32. Measured (a) S_{21} , (b) S_{11} , and (c) S_{22} frequency responses with the magnetic field supplied by the zero static power consumption magnetic bias circuit.

Supplementary Figure 33 highlights the small passband group delay variation of the filter. At 7.2 GHz, a minimum group delay variation of 1.0 ns is observed, with the group delay ranging from 2.7 ns to 3.7 ns. The largest group delay variation occurs at 16.3 GHz, where the delay ranges from 1.3 ns to 7.4 ns, resulting in a maximum variation of 6.0 ns. These results demonstrate the filter's ability to maintain relatively flat group delay performance across a wide tuning range.

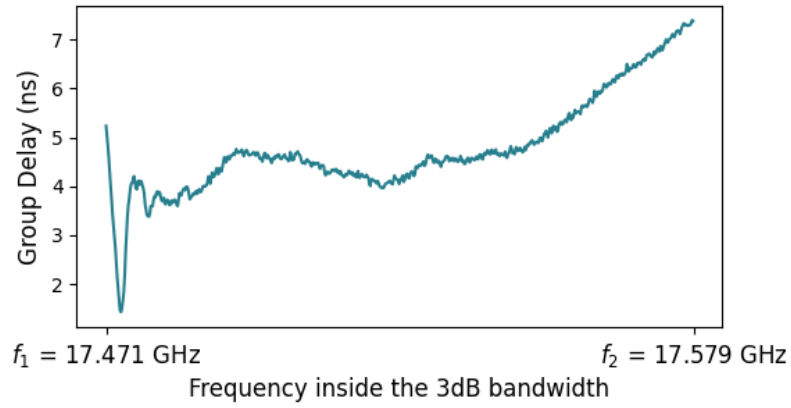




(b)



(c)

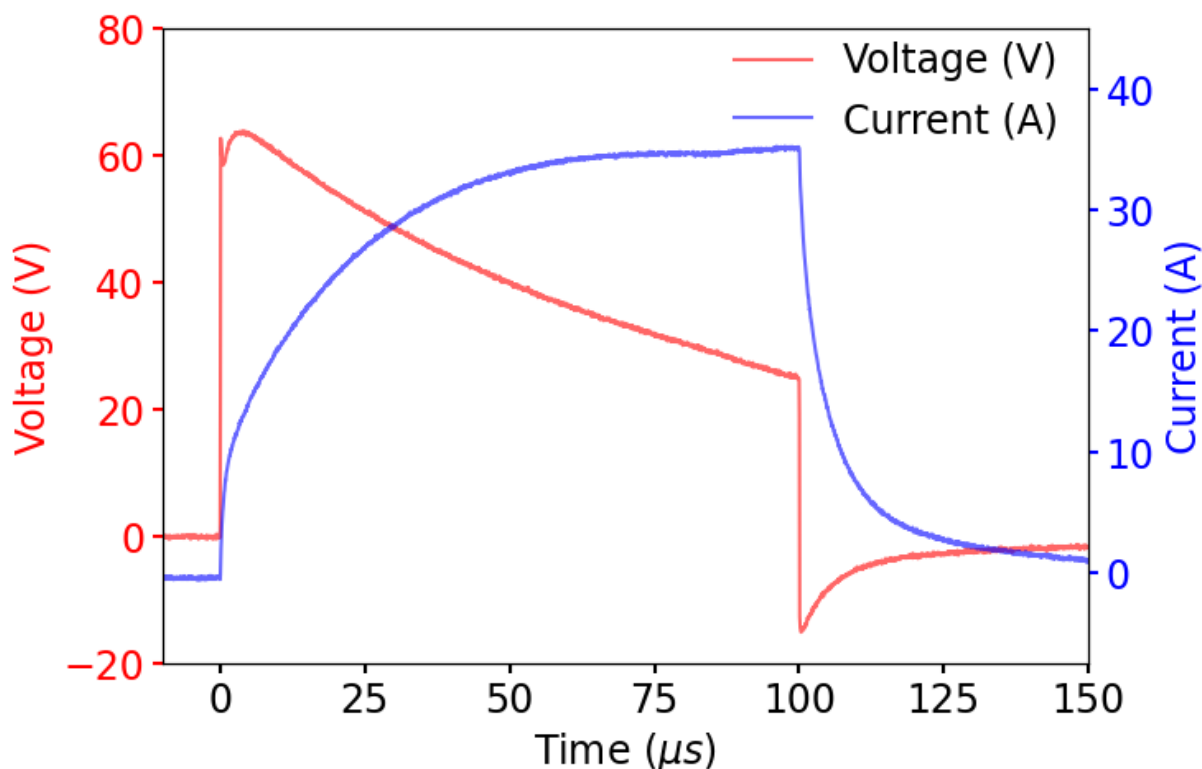


(d)

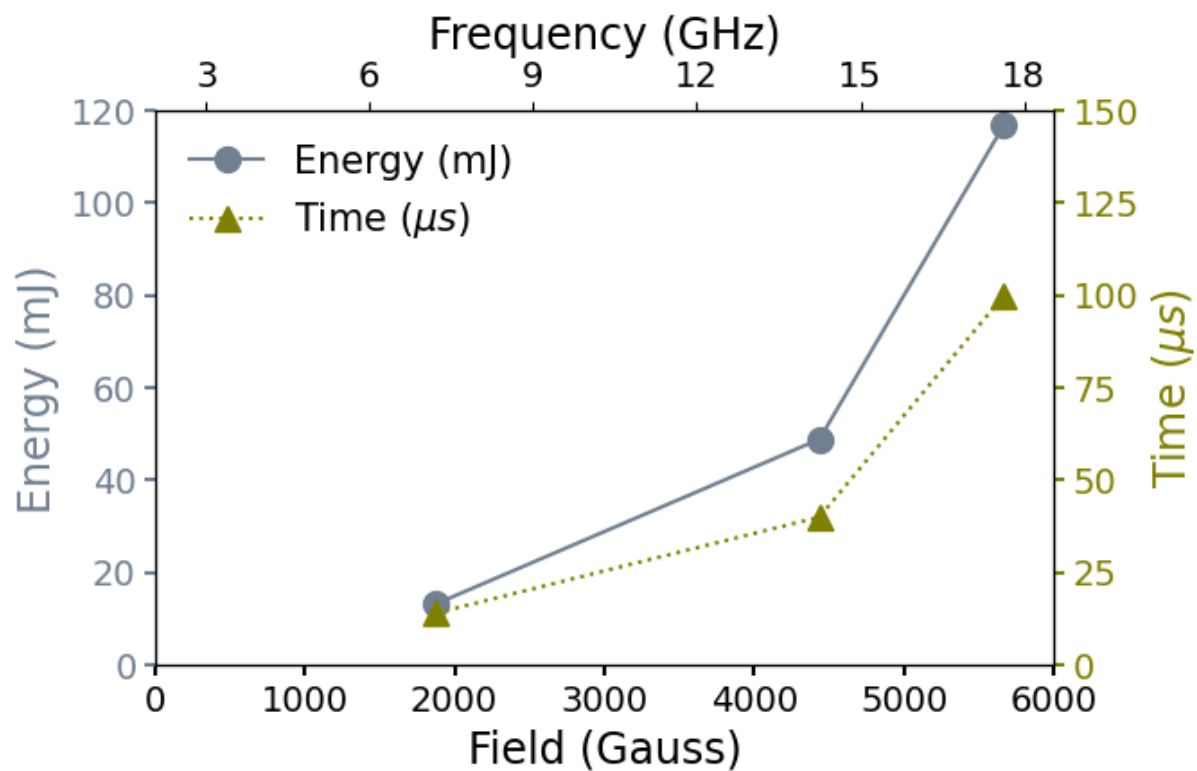
Supplementary Figure 33. Measured passband group delay with different bias circuit current pulse programming amplitudes of **(a)** 12 A, **(b)** 17 A, **(c)** 21 A, and **(d)** 33 A.

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

Supplementary Figure 34 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 35** summarizes the energy and time requirements for tunable filters from the minimum frequency to different frequencies.



Supplementary Figure 34. 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 35. 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.

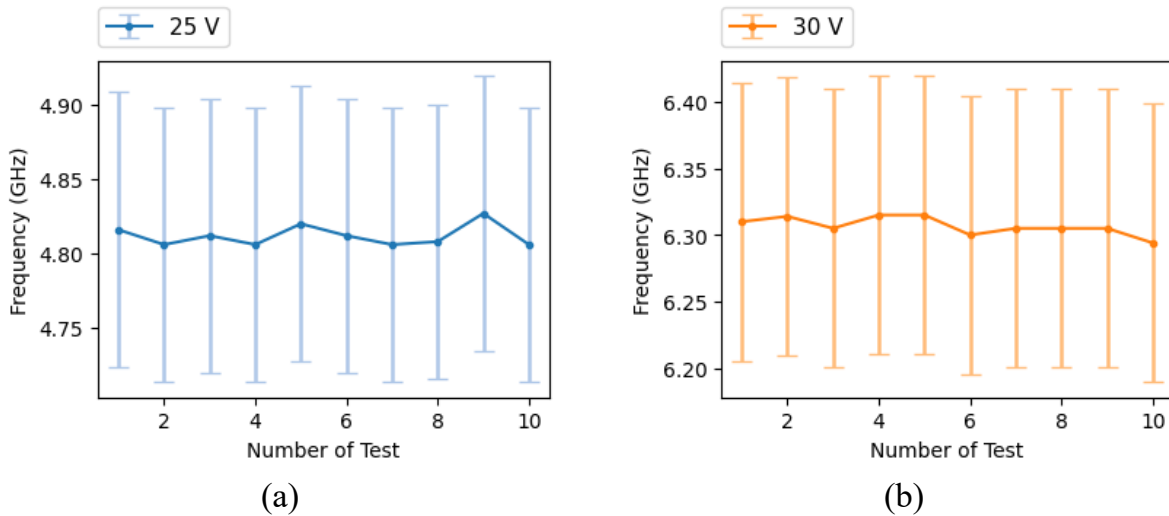
Supplementary Note #14: Repeatability of Frequency Tuning

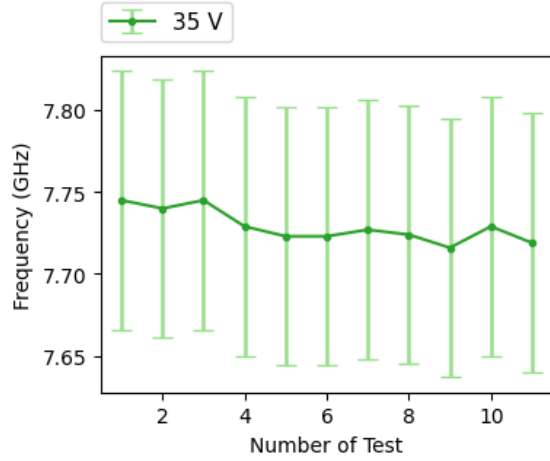
The tunable filter's non-volatile magnetic bias circuit is based on a programmable AlNiCo magnet, which exhibits magnetic hysteresis. This hysteresis introduces uncertainty in frequency tuning. To minimize this effect and improve tuning consistency, the AlNiCo magnet is fully demagnetized before each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

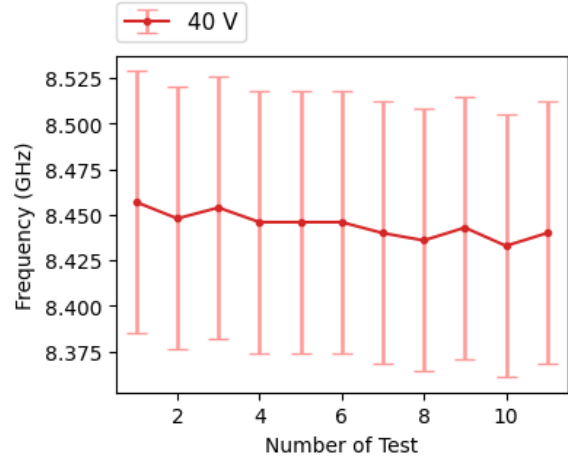
Supplementary Figure 36 shows the measurement results detailing the repeatability of the programming. The filter was first demagnetized by discharging a capacitor charged to -60 V through the coil for $100\text{ }\mu\text{s}$, followed by magnetization using $100\text{ }\mu\text{s}$ voltage pulses of 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.

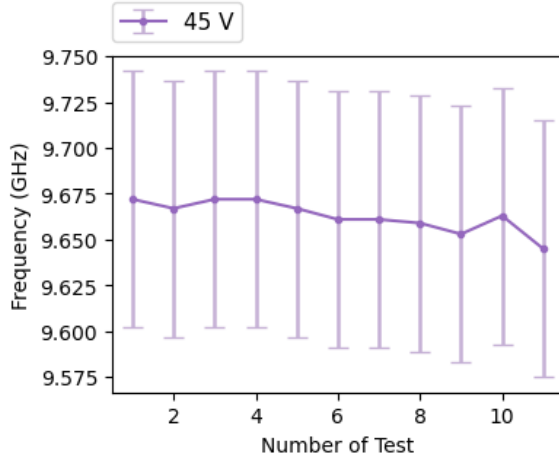




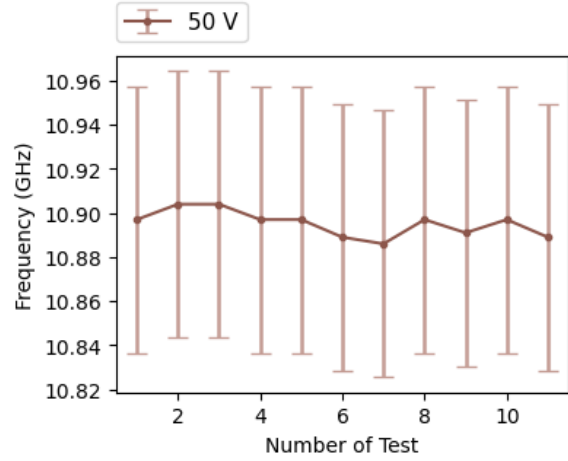
(c)



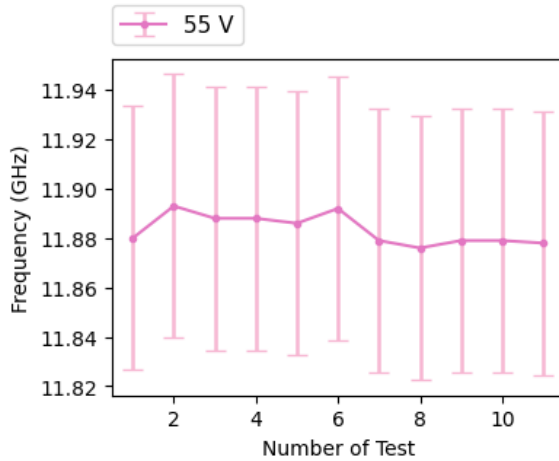
(d)



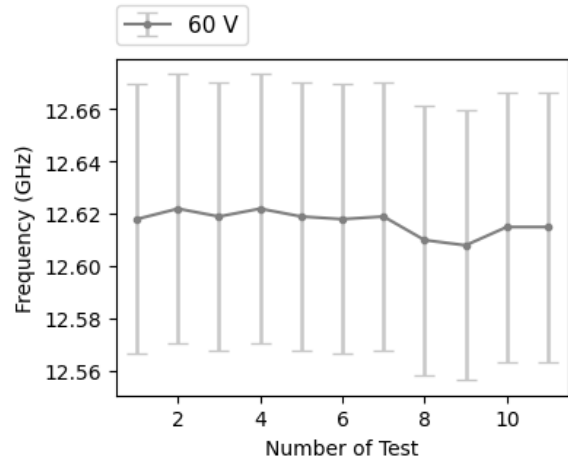
(e)



(f)



(g)



(h)

Supplementary Figure 36. 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.

Supplementary Note #15: Performance Comparison with Nonreciprocal Bandpass Filters

Supplementary Table S1. Performance metrics comparison for nonreciprocal filters spanning from 1-18 GHz.

Type	Reference	Frequency (GHz)	Insertion Loss (dB)	Bandwidth (MHz)	Isolation (dB)	Rejection (dB)	Size (mm)	PDC (mW)	P1dB (dBm)
YIG (tunable)	[18]	5.3	3	220	22	15	1.2*3.6 (YIG Area)	-	-
	[18]	6.7	1.8	220	22	15	1.2*3.6 (YIG Area)		-
	[18]	7.5	1.7	220	22	15	1.2*3.6 (YIG Area)		-
YIG (tunable)	[19]	7.26	2.79	240	45	10	3.73*1.92 (YIG Area)	-	-
	[19]	8.38	3	270	30	10	3.73*1.92 (YIG Area)		-
YIG	[20]	3.75	~4		~20	30	0.5*7 (YIG Area)	-	-

Type	Reference	Frequency (GHz)	Insertion Loss (dB)	Bandwidth (MHz)	Isolation (dB)	Rejection (dB)	Size (mm)	PDC (mw)	P1dB (dBm)
YIG (tunable)	[21]	5.5	-	-	-	-	81.4*19.0 5*63.5	57600	-
	[21]	7	-	-	-	-			-
Ferrite	[22]	3.19	1.31	850	15.43	15	58.02*97.58	0	-
Ferrite	[23]	2.2	2.5	150	27.1	30	45.26*45.26*1.55	0	-
	[23]	2.5	2.5	160	29.4	10	101.64*101.64*1.55	0	-
Spatiotemporal Modulation (STM) (tunable)	[24]	1.97	3.96	85	18.06	~30	-	-	-
	[24]	1.65	4.98	88	17.29	~38	-	-	-
STM	[25]	1.1	4.5	20	23.5	~22	-	-	-
PIN diode switch	[26]	1.3	5.9	56	20	~40	48*20	15	-

Type	Reference	Frequency (GHz)	Insertion Loss (dB)	Bandwidth (MHz)	Isolation (dB)	Rejection (dB)	Size (mm)	PDC (mw)	P1dB (dBm)
Transistor	[27]	8.8	0.2	3186	14.9	~8	0.93*1.1	114.3	15.5
	[27]	8.6	1.9	1342	30.6	~40	1.2*8.0	228.6	8
Transistor	[28]	9	-4.2	675	31.3	~10	1.87*1.84	-	-
	[28]	9	-2.8	729	28.8	~25	2.4*1.84	-	-
Transistor	[29]	7.8	-	1000	60	~22	-	141	-5.8
Transistor (tunable)	[29]	6.1	0.36	900	60	~25	-	135	-7.5
	[29]	10	0.36	1500	60	~25	-	135	-7.5
Transistor (tunable)	[30]	1.4	0.2		46	~30	107*56	11.6	
	[30]	1.9	0.2		46	~30	107*56	11.6	

Type	Reference	Frequency (GHz)	Insertion Loss (dB)	BW (MHz)	Isolation (dB)	Rejection (dB)	Size (mm)	PDC (mw)	P1dB
This Study		4.06	4.93	198	30.2	47@2GHz	24.0 mm × 15.6 mm × 3.2 mm	0	10.4@ 4.9 GHz
		5.6	3.5	187	38.7	43@3GHz			11.3@ 6.2 GHz
		7.28	3.15	179	38.6	41@4GHz			11.5@ 7.5 GHz
		9.12	2.93	190	40.4	39@5GHz			12@9. 1 GHz
		9.62	3.23	187	39.1	38@6GHz			12@10 .2 GHz
		10.93	3.53	177	38.8	38@7GHz			11.9@ 11.9 GHz
		12.87	3.81	154	43.7	36@8GHz			14.3@ 13.3 GHz
		14.7	4.16	133	29.6	35@9GHz			13.5@ 14.7 GHz
		16.25	4.74	119	26.1	34@10GHz			-
		17.51	4.8	107	28.3	34@11GHz			-
		-	-	-	-	34@12GHz			-
		-	-	-	-	34@13GHz			-

	-	-	-	-	34@14GHz			-
	-	-	-	-	35@15GHz			-
	-	-	-	-	32@16GHz			-
	-	-	-	-	30@17GHz			-
	-	-	-	-	31@18GHz			-

For the YIG filter in [21], the DC power consumption is determined by a current of 1.2 A flowing through a $20\ \Omega$ resistor in each of the two electromagnets. This configuration results in a total static power consumption of 57.6 W.

PDC stands for DC power consumption. Rejection is referred to as the out-of-band rejection.

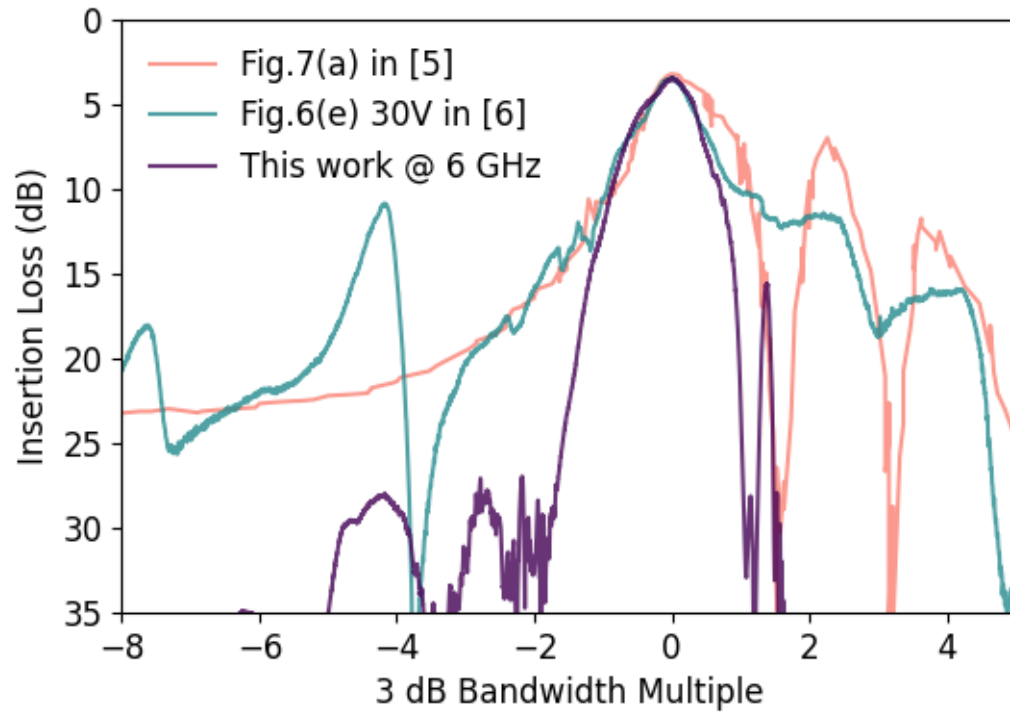
Supplementary Note #16: Comparison of Filter Skirt Performance

Supplementary Table S1 compares the key performance metrics with previous microfabricated YIG based filters. **Supplementary Figure 37** compares the filter skirt of this work with previous state-of-the-art YIG tunable filters [5, 6, 16]

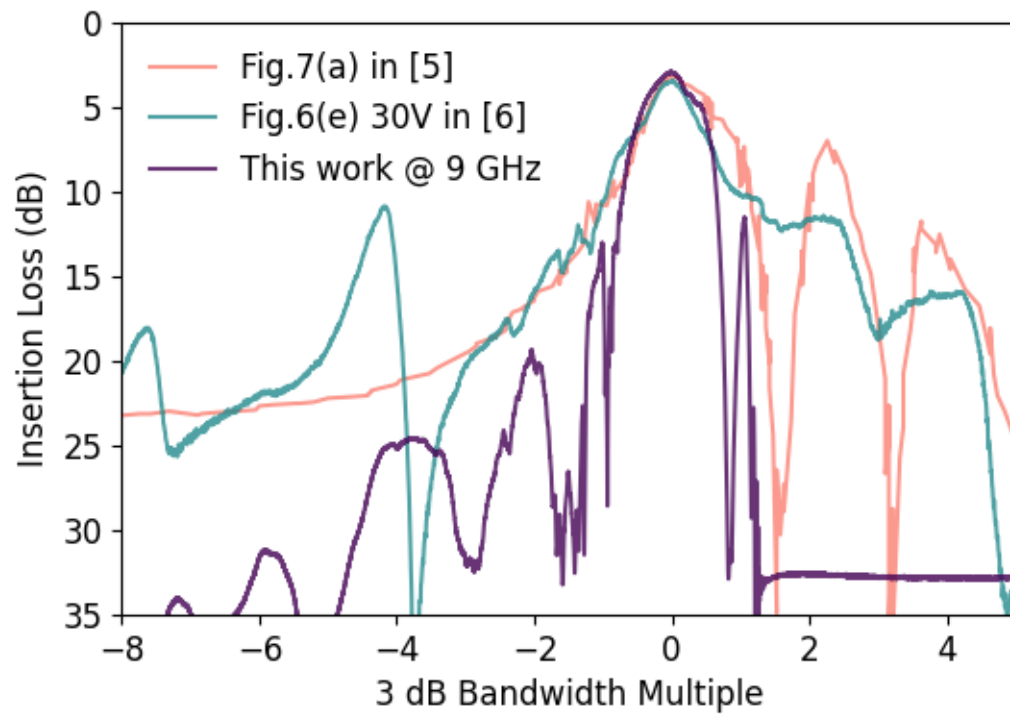
All previous studies [5, 6, 16] using 3 μm -thick YIG films exhibit prominent spurious modes appearing at approximately 1.8 times the 3 dB bandwidth above the center frequency. In contrast, the filter demonstrated in this work, realized using an 18 μm -thick YIG film, achieves nearly 30 dB of out-of-band rejection at the same relative offset. Moreover, higher-frequency spurious modes are eliminated due to the dispersion profile of the thicker YIG. The filter skirt performance on the lower-frequency side of the passband also shows significant improvement compared to previous studies.

Supplementary Table S2. Performance metrics comparison for microfabricated YIG based filters.

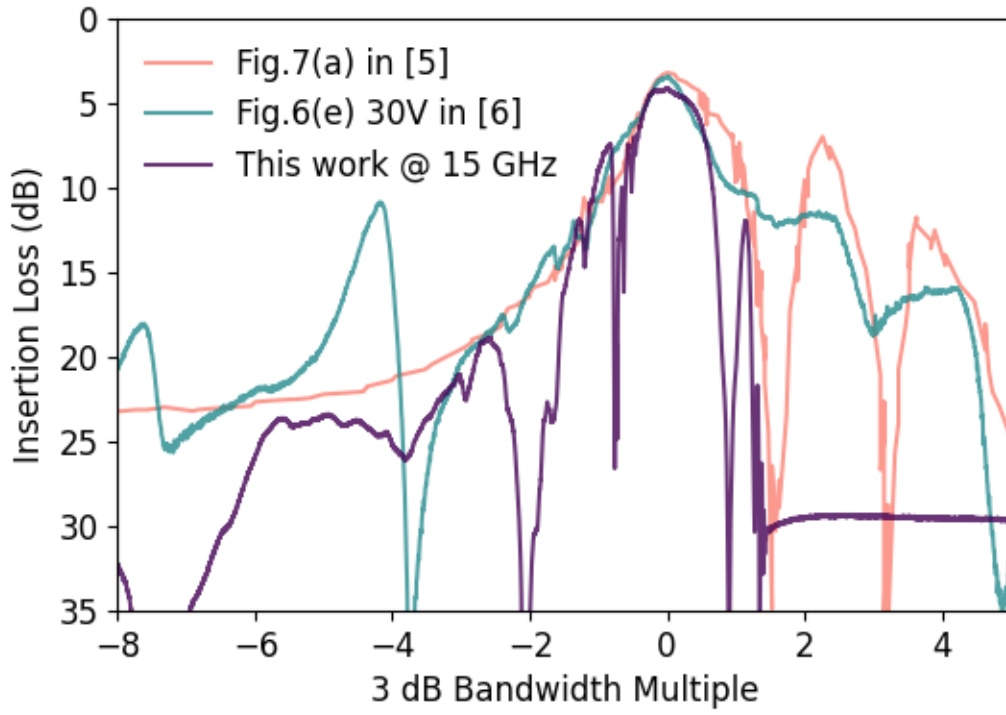
	Freq (GHz)	Insertion Loss (dB)	Out-of- band rejection	Bandwidth (MHz)	Electrically Tunability	P1dB (dbm)	IIP3 (dBm)
[6]	3.4 - 11.1	3.2 - 5.1	>25	18 - 25	Yes	>-17	>-10
[16]	3.3 - 9.7	2.1 - 3	>35	24 - 65	Yes	0	0
[5]	4.5 - 10.1	<6	>25	29 - 39	No	-	-
[5]	4.5 - 10.1	<11	>35	11 - 17	No	-	-4.9
[17]	7.1 - 21.6	2.5 – 5.8	3.6 - 13.8	281 – 663	No	>5	>11
[17]	7.4 - 20.4	6.8 – 11.7	14.6 – 24.8	255 - 539	No	-	-
This Study	4.0 - 17.5	2.9 - 4.9	>30	107 - 198	Yes	>10.4	26-31



(a)



(b)



(c)

Supplementary Figure 37. Comparison of the filter skirt performance of this work with previous state-of-the-art tunable filters based on magnetostatic wave realized in microfabricated YIG. The filter of this work operates at (a) 6 GHz, (b) 9 GHz, and (c) 15 GHz.

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