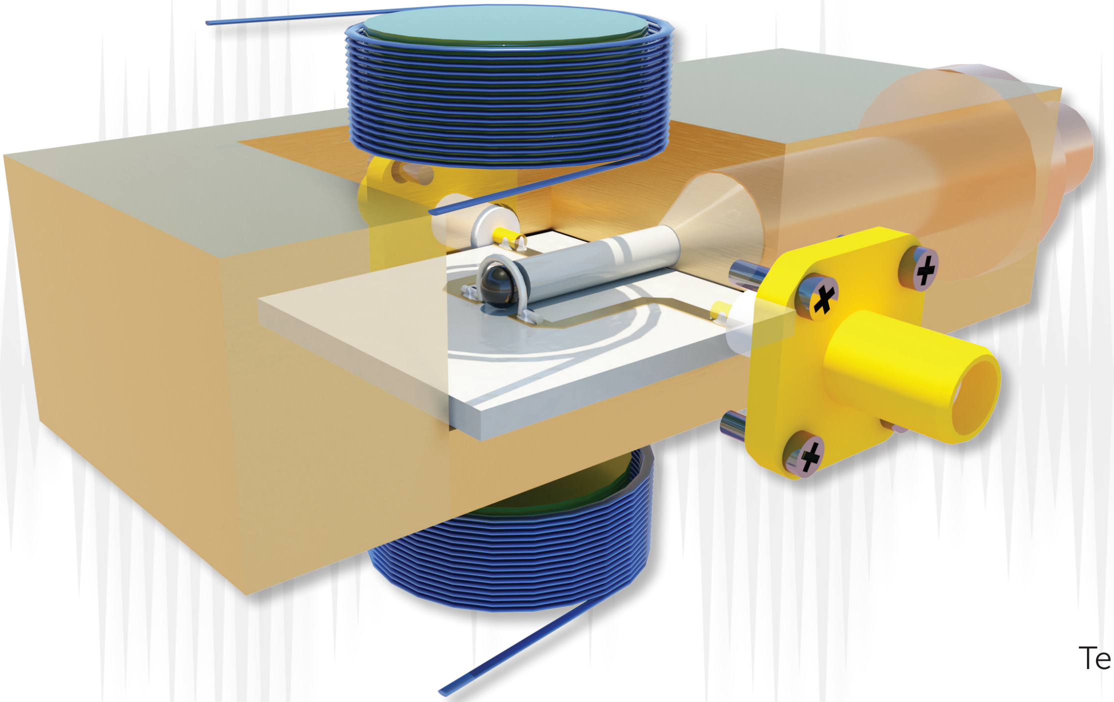
A New Approach to YIG-Based Band-Reject Filters – An Introduction



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Introduction

Staples of many microwave block diagrams, oscillators and filters rely on resonant behavior to function. At higher frequencies, it is often the physical size of the item being leveraged that dictates the frequency of resonance – the size of the crystal, the size of the cavity, as examples. Yttrium iron garnet (YIG) has an unusual property, in that its resonant properties do not depend directly on size, but instead on the strength of magnetic field passing through it. This has some downsides, but also some major benefits, as we'll see.

YIGs have been around for many decades and are rarely the first choice in applications requiring small size or low power. Like traveling wave tubes (TWTs), their demise has been forecast almost since they were invented, and yet they healthily persist in certain applications simply because they provide benefits unavailable from any other technology. They are commonly found in test equipment such as spectrum analyzers and clock recovery units, and military applications on land, sea and airborne. A table showing relative advantages and disadvantages of YIG technology is shown in Table 1, below.

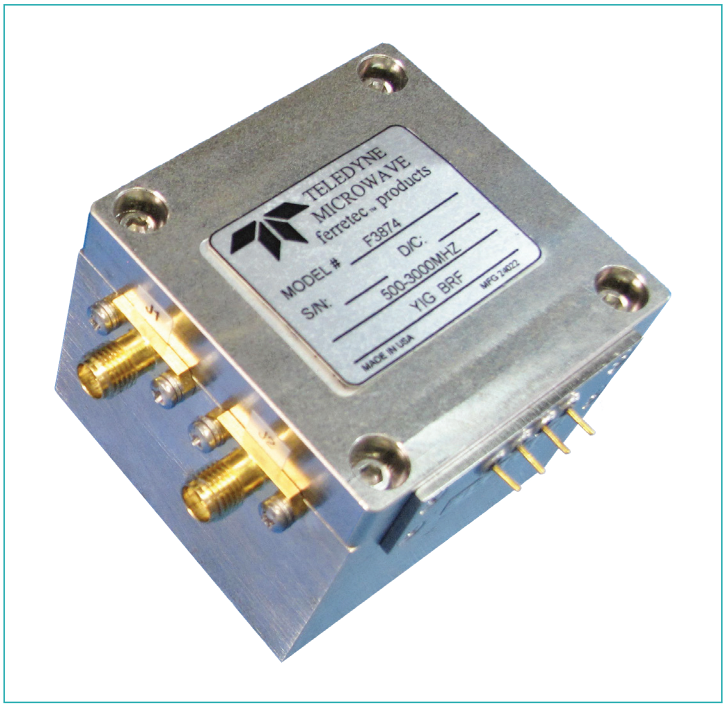

Figure 1: A band-reject YIG filter

Advantages	Disadvantages
Multi-octave tunability at microwave frequencies (e.g. Teledyne F4002 tunes 2-20 GHz)	Not the fastest tuning speed (ms)
Very high Q	Physically larger than many competing technologies
High tuning linearity	Require current to energize magnetic coils, and for some extended temperature range models, power heating element
Extremely low phase noise (oscillators)	Expensive
Low out-of-band insertion loss	Vibration sensitive
High in-band rejection (e.g. >60 dB over entire tuning range)	
Excellent shape factor	

Table 1: Pros and cons of YIG-based resonators

Common functions provided by YIG resonators include oscillators, band pass filters, and band reject filters. This paper focuses on the latter, but many of the principles discussed apply to all.

Why Use Band Reject Filters?

A common issue in test and some military applications is the need to have very sensitive receiver equipment located next to extremely high-power transmitters, and how to stop them becoming blinded to incoming signals of interest. An example might be on a ship where on-board surveillance equipment sits near very high-power radar (see Figure 2, (a)), but the same is true for other domains and applications. For interference that is either predictable in frequency, or dwells long enough to be measured and responded to, it is possible to notch out the unwanted signal.

One approach is to have a switched filter bank (b), another is to use a tunable filter (c). A filter bank has switch insertion losses that mount up as the number of filters increase, and lacks flexibility. A tunable filter is more flexible, and YIGs shine in this application if the receiver has to operate over a very wide band. As an example, a single production bandpass YIG filter will tune from 3.5-50 GHz, far wider than other common approaches.

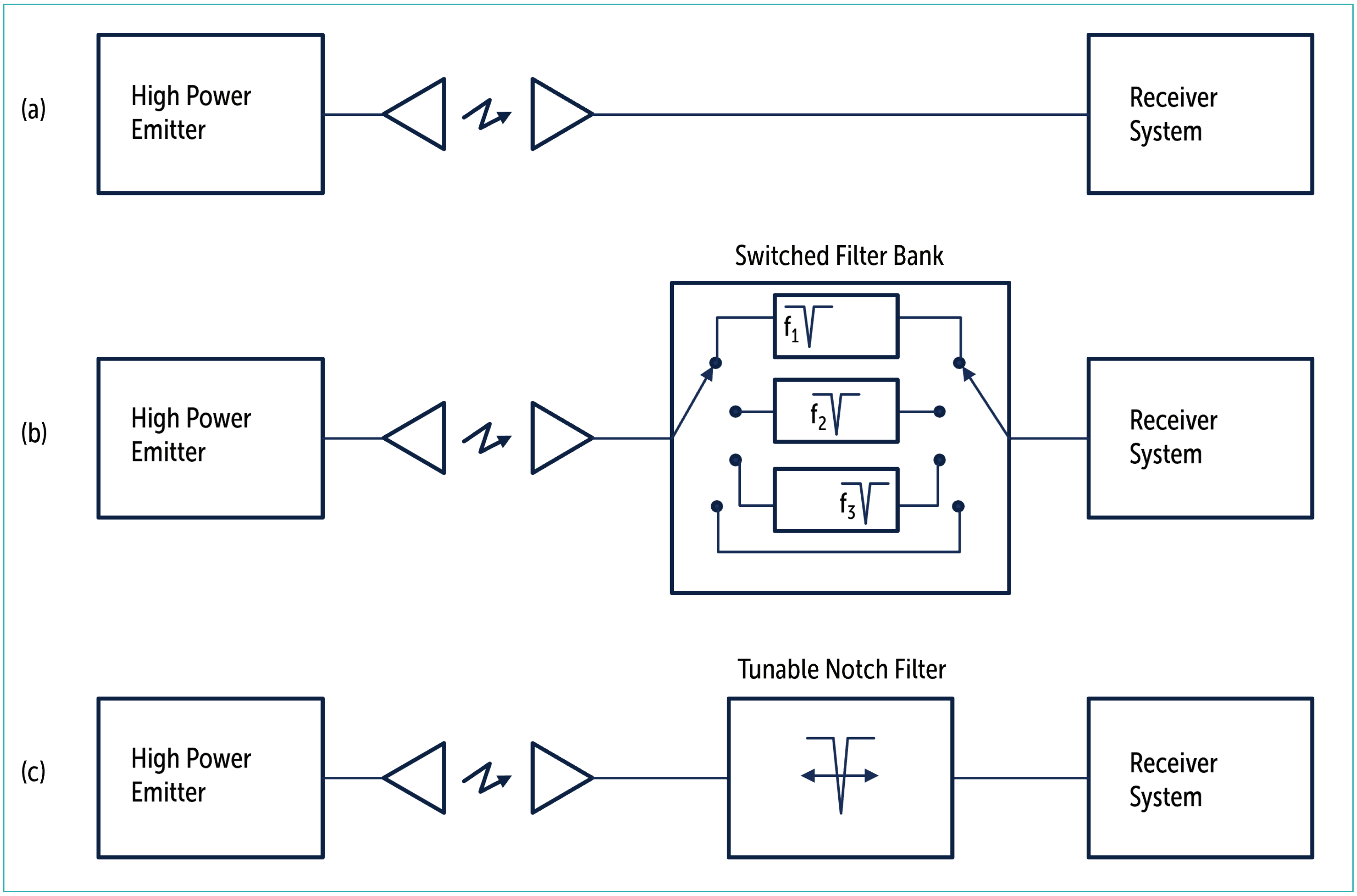

Figure 2: A wideband receiver experiencing high power interference can use a notch filter to reduce its impact

How Do They Work?

A key property of a YIG sphere is the behavior of the magnetic dipoles inside it. As shown in Figure 3, with no applied field (a), the diploes are randomly arranged. As an external magnetic field is applied, they start to align in the same direction (b), and as the applied field increases, a point is reached where all are aligned in the direction of the field, and the sphere is said to be saturated (c). Beyond the point of saturation, the sphere can couple with a nearby RF field and influence it, but only if the field is at exactly the right frequency - to frequencies outside a narrow range, the sphere is invisible. More details are given in the Appendix.

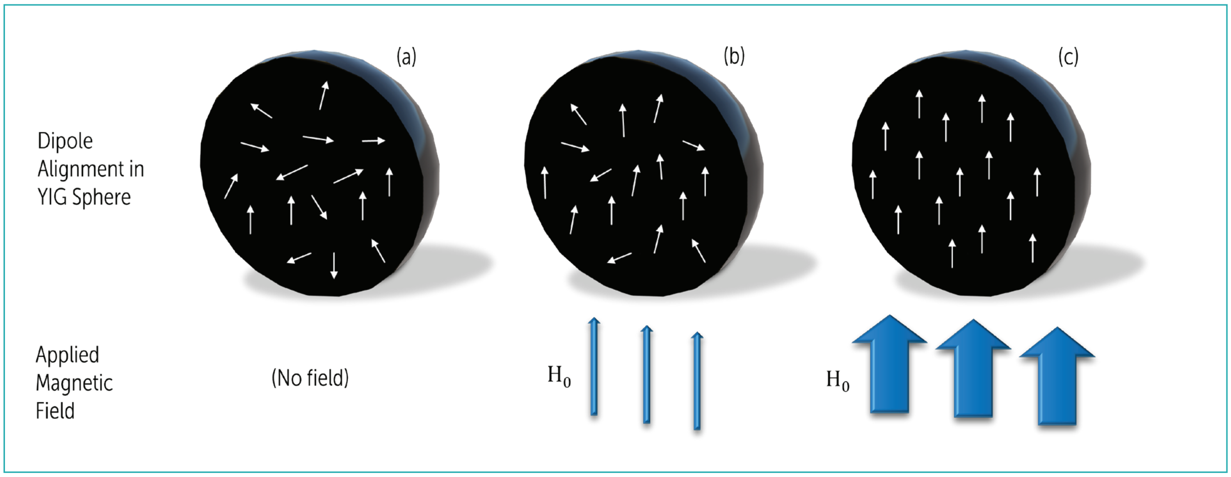

Figure 3: Behavior of diploes in a YIG spehere under the influence of a constant magnetic field

The properties of YIG spheres are such that resonant behavior is independent of the amount of material, and the resonant frequency is linearly dependent upon magnetic field. This allows YIG spheres to be very small, typically 0.5mm (see Figure 4) and allows tuning over a very wide band. It also gives rise to many of the downsides listed in Table 1, as typical YIG devices require the size, weight and current needed by electromagnets for them to work. However, in performance the benefits can be considerable, with >60 dB rejection, steep sides and good shape factor.

To understand the basic functioning of a YIG band-reject filter, consider the situation shown in Figure 5. A YIG sphere is suspended between the pole pieces of an electromagnet. Tuning of the resonant frequency is achieved by varying the current in the electromagnet. Here the sphere is next to a microwave transmission line, and the impact it has on the signal passing between the connectors along the transmission line is dependent on how much coupling occurs by the coupling loop. Such loops can be made of several turns, or as simple as a straight transmission line passing nearby. The amount of coupling is a critical factor in the design of the filter and is frequency dependent.

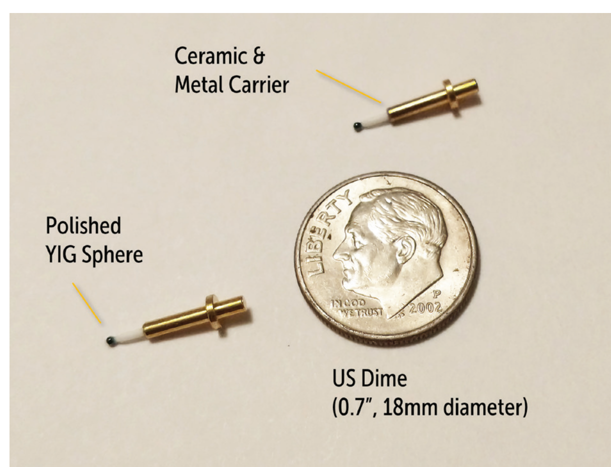

Figure 4: Shiny black YIG spheres mounted on carriers, pictured next to a coin for scale

The tuning is dependent upon the electromagnet current, which for the example product shown at the beginning of this paper, is around 300 mA on an 8 Ω coil; it is very linear, making control straight forward – again for this example it's in the range of 10 MHz/mA depending upon model. However, tuning is not instantaneous, as there is inherent inductance in the coil, as well as eddy currents causing an opposing magnetic field in the pole piece, which must settle before the notch can reach it's final frequency. Typical tuning speeds might be a few milliseconds.

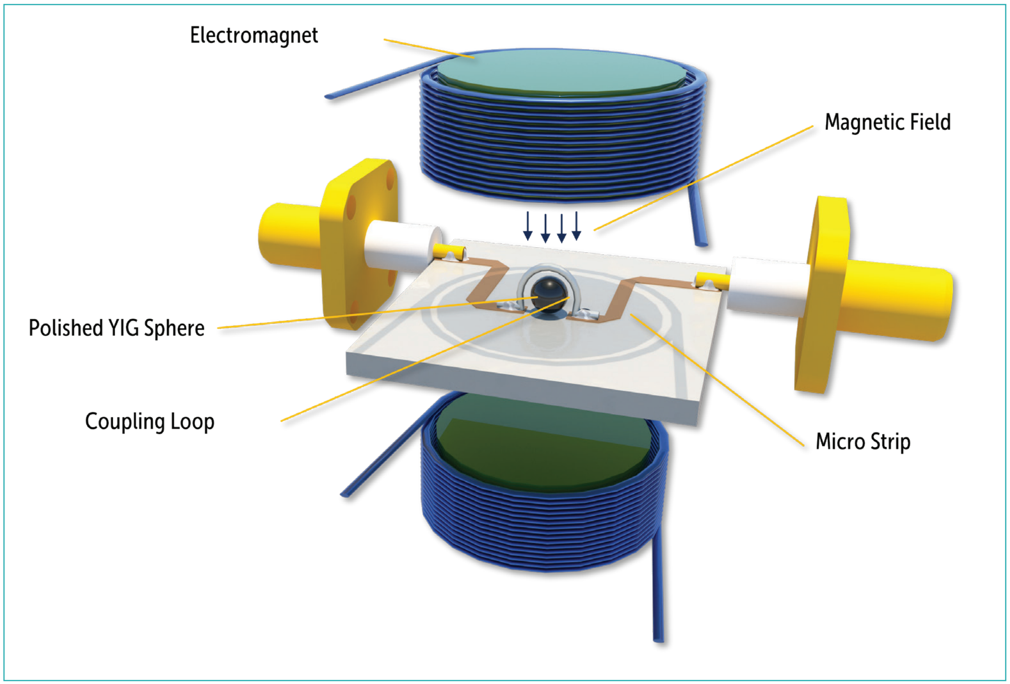

Figure 5: The basic elements of a single stage YIG band-reject filter

The microwave portion of the assembly can be thought of in electrical terms as shown in Figure 6. The inductance of the coupling loop is followed by a parallel RLC circuit which provides high impedance at resonance, low impedance out of the resonance band. The higher the value of R_0 we're able to achieve, the deeper the notch/higher the rejection.

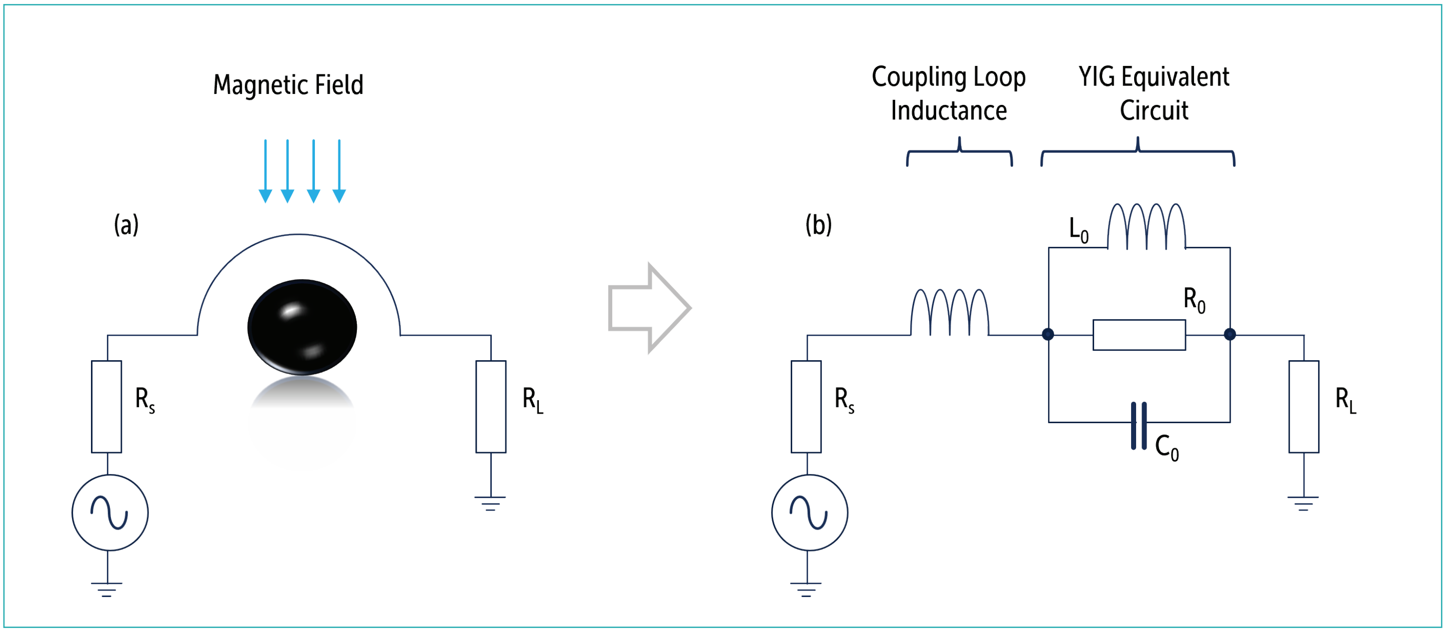

Figure 6: Equivalent circuit of the YIG and coupling loop

For the discussions that follow, we'll use 0.5 to 2.7 GHz filter as our example, although the same ideas apply across any frequency band that YIGs operate over. The graph of Figure 7 shows an overlay of measured plots of the insertion loss (s_{21}) of a single stage YIG band-reject filter of the type shown conceptually above as it is tuned by a changing magnetic field over its entire band.

Some features become immediately apparent. The notches are extremely narrow, with steep sides – a very good attribute for a notch filter. The notches are also encouragingly deep – over 15 dB at higher frequencies, and the out-of-band insertion loss is very low. It's a promising start, but at the low end of the range, the notch is only providing 5 dB of rejection, so we need to see what approaches are open to us to improve matters. The obvious first step towards increasing in-band rejection is to stack multiple filters in series. 8 stages is a common approach, although it can be as many as 16. A representation of an 8-stage filter like the one used in these measurements is shown in Figure 8. Such filters can be laid out linearly as the one shown or like the spokes of a wheel in a circle.

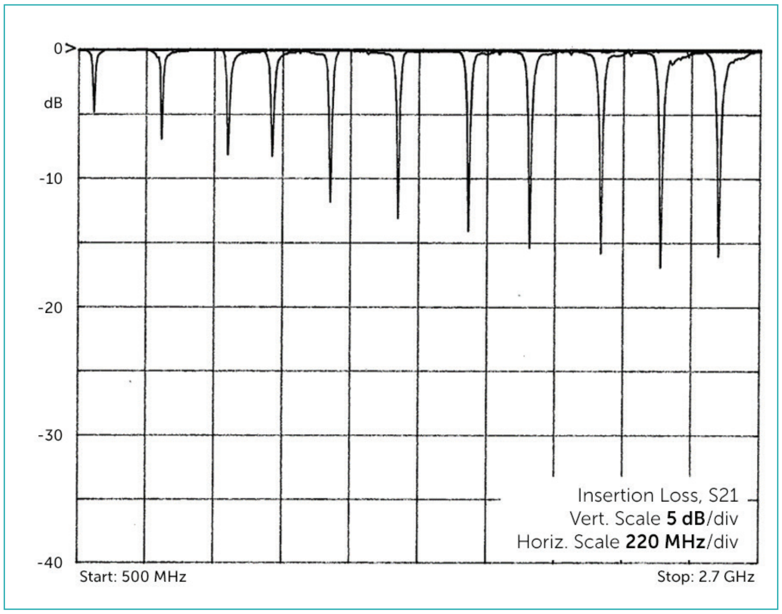

Figure 7: An overlay of notches from a single YIG resonator placed at different center frequencies between 0.5 and 2.7 GHz

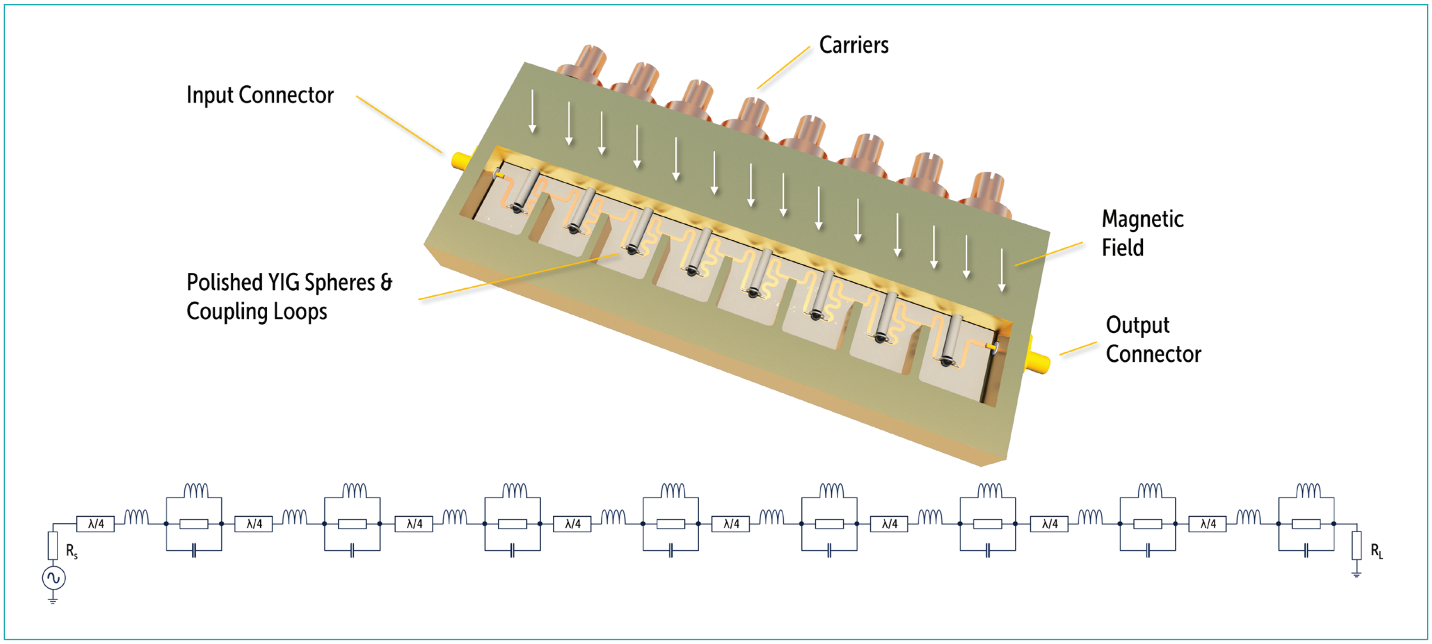

Figure 8 (Upper) 8-stage band reject filter showing YIG spheres on carriers with half-loop coupling. Magnets removed for clarity. (Lower) Equivalent circuit.

Placing 8 stages similar to the one above in series yield the four plots in Figure 9. All use the same scale – a magnified 200 MHz span on the horizontal axis, 10 dB/ division on the vertical, but with different center frequencies. Again, we see that the Q is higher and the notch deeper at higher frequencies, but we've improved the depth of the notch at lower frequency from -5 dB to somewhere in the range -30 to -40 dB, which is better but not enough for many applications and the shape at the bottom of the deep is not helpful. The notch is also getting wider at higher frequencies, which is less desirable.

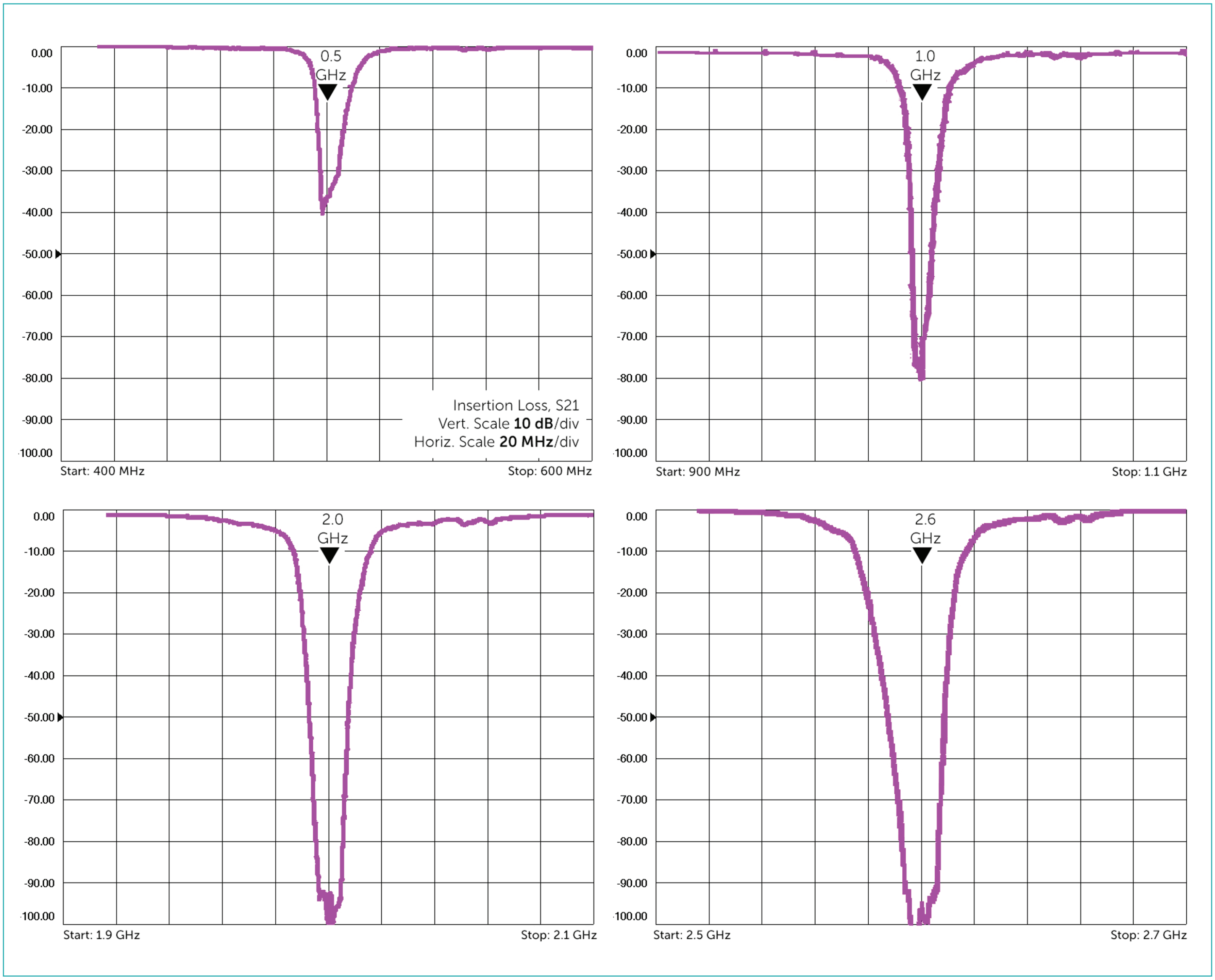

Figure 9: S_{21} plots of our 8-stage band-reject filter

Another lever we have available to improve notch-depth is to strengthen the influence of the YIG by increasing the degree of coupling. This is typically achieved by either increasing the size of the sphere or decreasing the size of the loop. For this example, the loops were kept constant, and the spheres increased in size, with results shown in Figure 10.

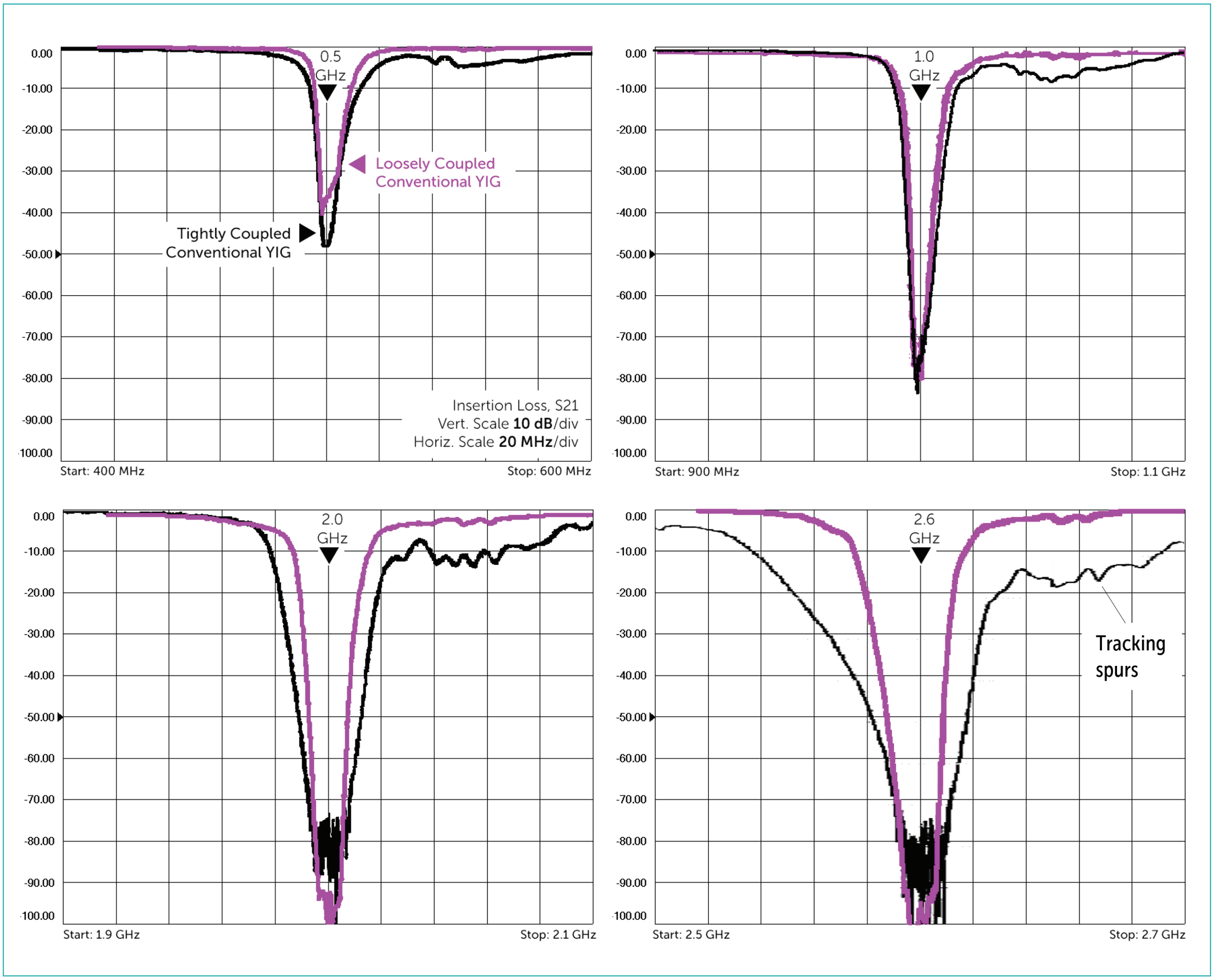

Figure 10: 8-stage filter as previously described (purple traces) compared to the same with tighter coupling to the sphere (black)

Figure 10 shows that tighter coupling has had a noticeable impact, the low frequency notch is much improved. However, several other factors are creeping in that are undesirable. Firstly, the higher frequency notches are getting much wider. Secondly, outside the main notch the insertion loss is increasing and tracking spurs are also becoming troubling. Tracking spurs are inherent troubles with YIGs particularly at lower frequencies, but their magnitude relative to the main notch can be influenced. The dominant ones are usually slightly above the main notch in frequency and are most harmful to system design when they are in close proximity to it, effectively expanding the width of the main notch. The purity of the YIG material, and quality of the surface finish play roles in the quality of the notch and position of the spurs.

Traditionally, this is about as far as an 8-stage design like this can be taken, with tighter or looser coupling being used to vary the depth of the notch until the tracking spurs go beyond acceptable limits for the system design.

A New Way Forward

Going back to our single stage filter example, there is another way of achieving band rejection, using a coupled loop to ground to form a shunt resonator. Notches can be created in just the same way as before, but there is one unique feature that we can take advantage of. Whereas the performance of the series resonators degrade as the frequency gets lower, the shunt resonators exhibit the opposite behavior. The ideas are captured in Figure 11, with our original single stage filter shown in the top section, our alternative topology in the bottom section.

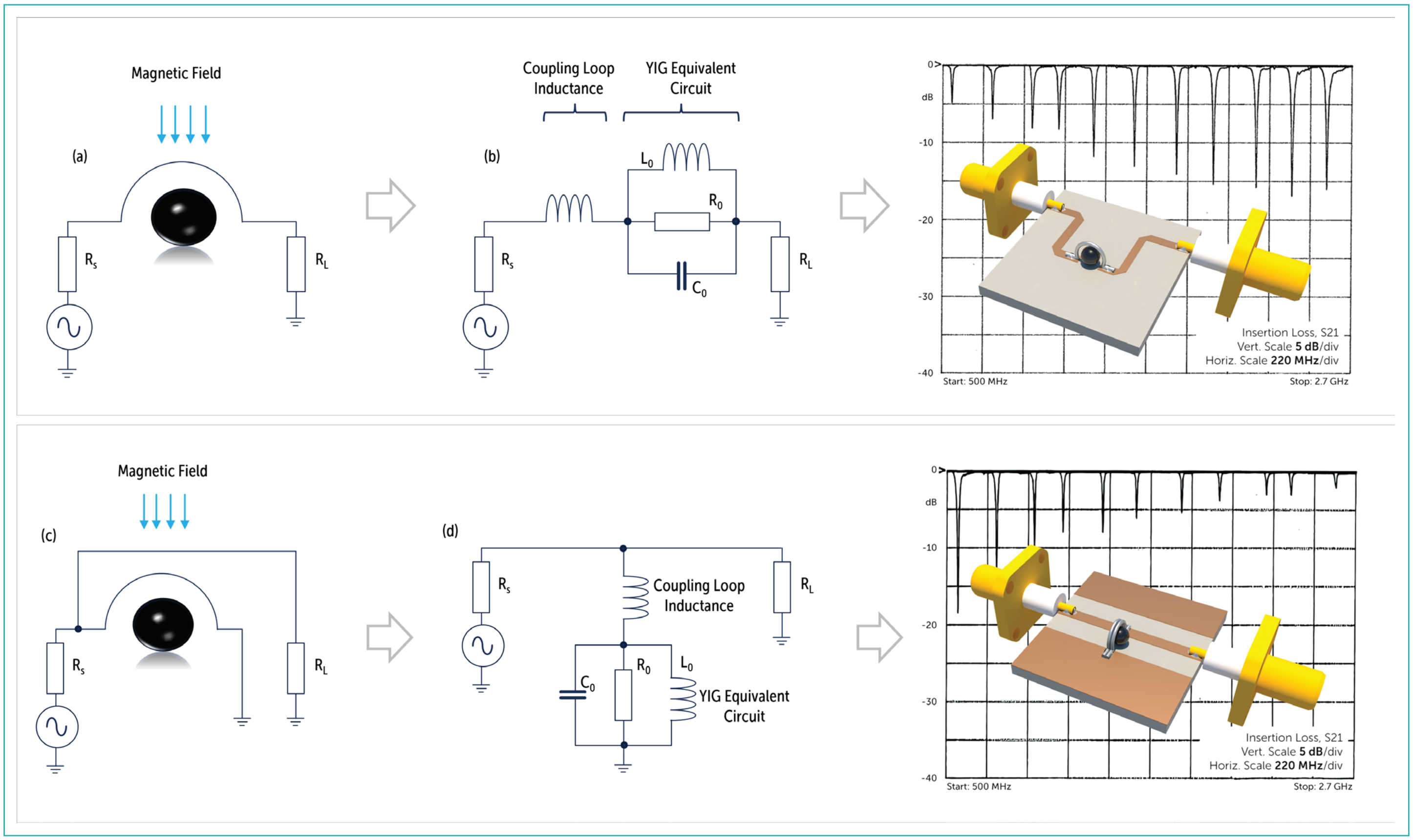

Figure 11: Our original single stage series resonator (above), compared to our alternative approach, the shunt resonator (below).

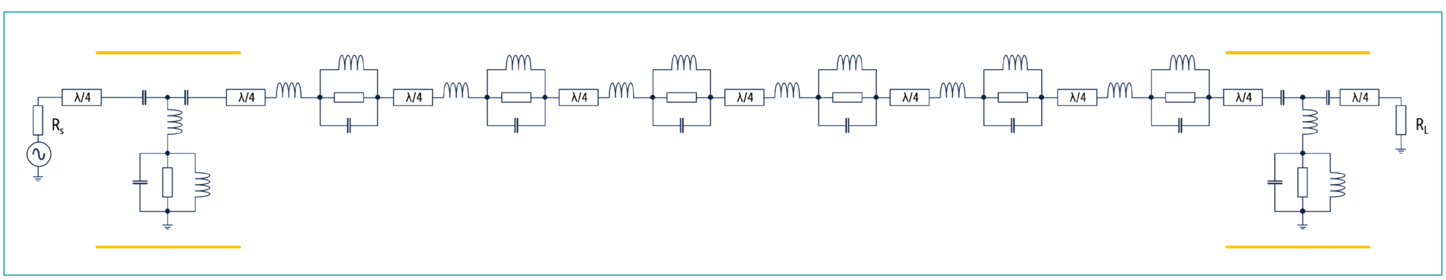

Figure 12: Equivalent circuit of the improved 8-stage tunable notch filter

The shunt resonator gives us another lever for improving performance. Removing two series stages in our 8-stage filter, we get less notch depth, but crucially, lower levels of spurs. Replacing the missing stages with shunt resonators (shown in Figure 12) gives us the performance shown in Figure 13.

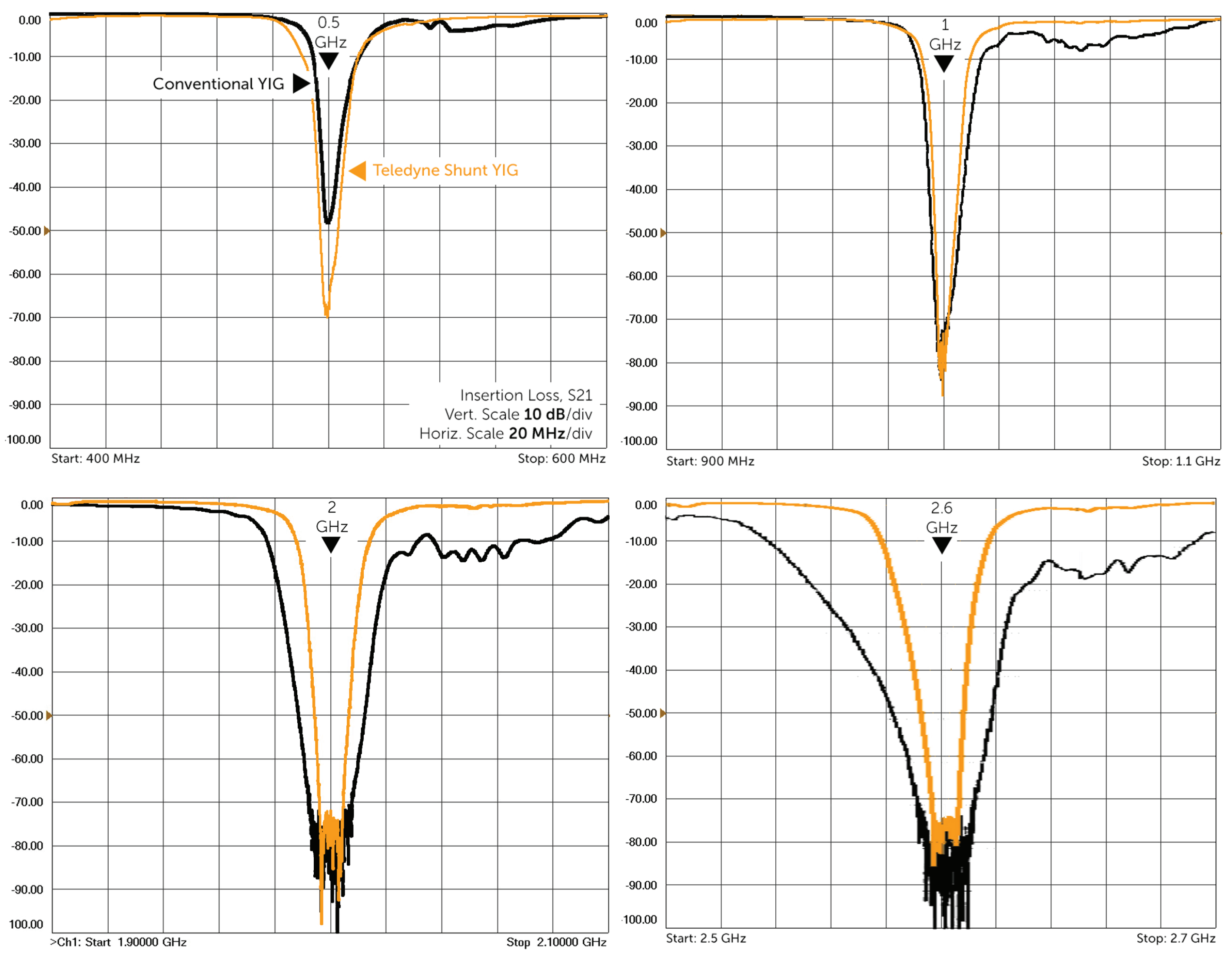

Figure 13: 8-stage filter with tight coupling to the sphere (black) as before, compared to our improved design (gold)

We've combined the benefits of both approaches, and deep notches with steep sides and suppressed tracking spurs, making a much higher performance component as a result. This is the basis of Teledyne's latest YIG-based notch filters. Note that the number of shunt stages can be varied depending upon the required performance trade-offs.

Most applications would like narrow and consistent notches that do not vary in bandwidth as they are tuned in frequency. While this ideal is not achievable, the new design is significantly closer than previous ones. Common metrics used to gauge this are bandwidth 3 dB down, and the same at 40 dB down. A comparison is shown in Figure 14.

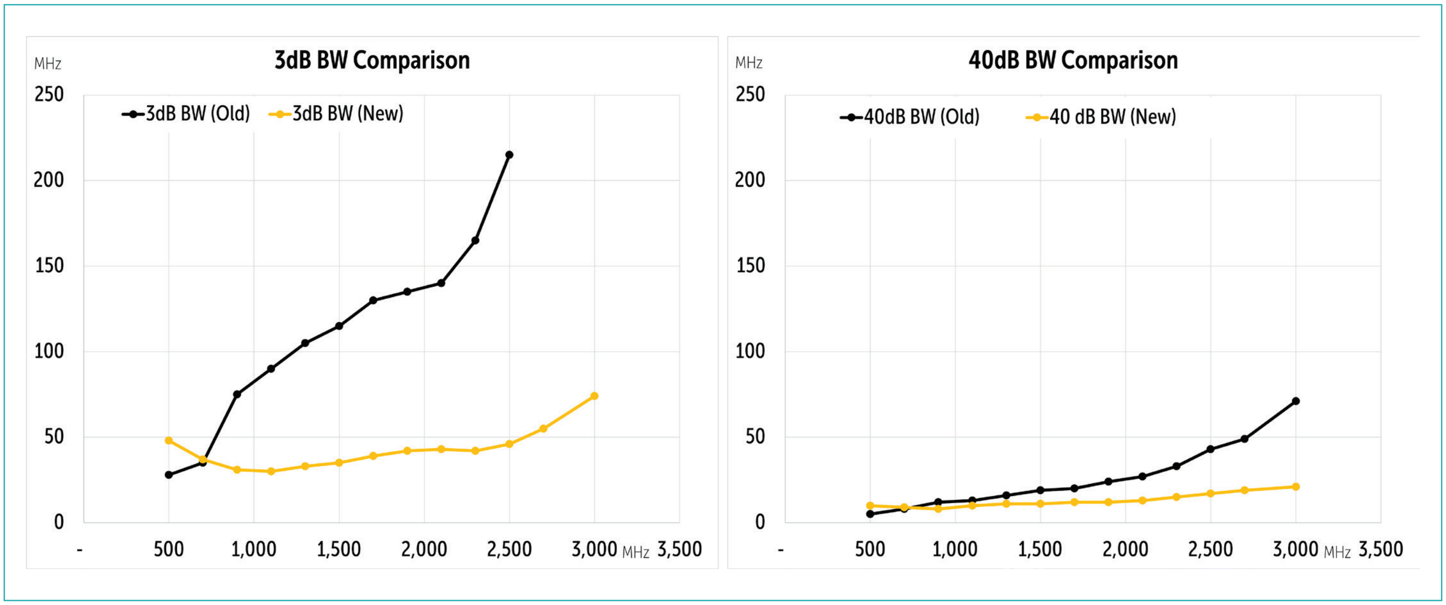

Figure 14: Comparing the consistency of notch bandwidths as our example 8-stage devices are tuned across the frequency range of 500 MHz to 3 GHz.

Summary

We've seen that although YIG filters are not the answer for every application, for those needing the utmost notch performance over a very wide tuning range, they are hard to beat. This applies most often to applications in test equipment and the military. We've looked at some of their strengths and weaknesses and taken a deeper dive into some of the design trade-offs that are required to get good performance, including how the degree of coupling to the YIG sphere improves notch depth but at the cost of intrusive spurs. Finally, we've looked at a new patented topology that mitigates most of the downsides of traditional designs and provides performance closer to the ideal tunable notch than has been achieved before. The new approach is available in standard products from Teledyne up to 20 GHz; please contact us for more information.

Further Reading

1. For an in depth technical description of the shunt band reject filter, see Teledyne patent: US 9,203, 129B2.
2. P.S. Carter, Jr., "Magnetically-Tunable Microwave Filters Using Single-Crystal Yttrium-Iron-Garnet Resonators" IRE Transactions on Microwave Theory and Techniques, Volume: 9, Issue: 3, May 1961 - Classic YIG paper
3. G. L. Mattheal, L. Young, and E. M. T. Jones, "Microwave Filters, Impedance-Matching Networks and Coupling Structures", New York: McGraw-Hill, 1964, pp. 1027-1049 - Classic text with good section on YIG filters
4. Helszajn, Joseph, "YIG Resonators and Filters", Wiley & Sons, April, 1985
5. Carter, Philip S., "Equivalent Circuit of Orthogonal-Loop-Coupled Magnetic Resonance Filters and Bandwidth Narrowing Due to Coupling Inductance", IEEE Transactions on Microwave Theory and Techniques, Volume: 18, Issue: 2, February 1970, pp. 100-105

Marinus (Ron) Korber has worked at Teledyne for 19 years as a Senior RF-Design engineer. He has been in the Microwave industry, almost exclusively in YIG devices for 55 Years including 30 years at Watkins Johnson Co., starting as an entry level Technician,

Ron has multiple YIG device patents.

Appendix 1: YIG Relationships

Definition of terms:

- $\Delta H =$ Linewidth in oersteds (oe). The oersted is defined as a dyne per unit pole. The oersted is 1000/4π (≈79.5774715) amperes per meter, in terms of SI units. The linewidth is basically the width of the resonance in oersteds as the signal frequency is held constant and the applied dc field is varied.
- H_0 = biasing external magnetic field
- $4\pi M_s$ = Saturation magnetization, measured in Gauss.
- Q_u = unloaded Q

Four very important parameters described below are the following:

- The resonant frequency of the YIG sphere.
- Saturation Magnetization of the sphere.
- The linewidth of the sphere. Another way of saying the Unloaded Q, Qu
- The position (relative to the notch) of tracking spurs is determined only by the $4\pi M_s$

The resonant frequency in Hz of a YIG sphere is $F_0 = 2.8 \times 10^6 \times H_0$, where H_0 is the magnetic field in the air gap measured in Gauss. i.e. if H_0 is 1000 Gauss, then F_0 = 2.8GHz

When all the magnetic dipoles in a YIG sphere are aligned by an external magnetic field (H_0), the sphere is said to experience saturation magnetization, symbol $4\pi M_s$, our desired state for good rejection performance.

ΔH (oe)	$4\pi M_s$ (Gauss)
0.4	1,780
0.45	1,500
0.5	1,200
0.55	1,000
0.6	800
0.7	600
1.0	400
2.5	200
4.0	100

Table 2: LInewidths & saturation magnetism

All YIG spheres are characterized by two important properties, $4\pi M_s$ and LineWidth (ΔH). The relationship between ΔH and unloaded Q (Q_u) is:

$$Q_u = \frac{H_0 - \frac{1}{3}4\pi M_s}{\Delta H}$$

The highest $4\pi M_s$ achievable is that of a pure YIG sphere, 1780 Gauss. A $4\pi M_s$ as low as 100 Gauss can be achieved with the substitution of impurities into a pure YIG sphere (see Table 2). These impurities degrade the Linewidth and hence the Q_u of the sphere. These are called "doped spheres". Table 2 is also shown in the graph in Figure 15, right.

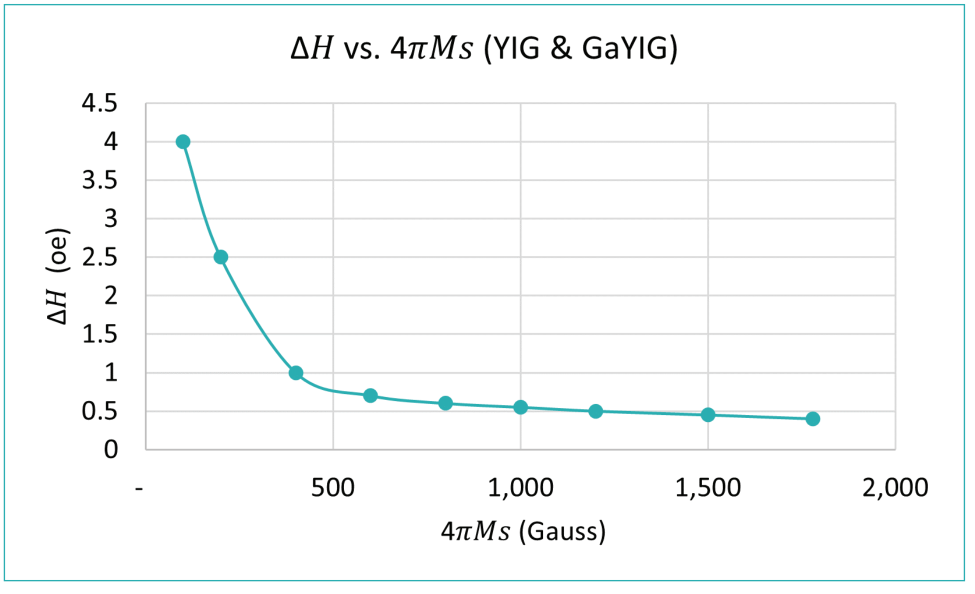

Figure 15: Relating linewidth (ΔH) to saturation magnetism ($4\pi M_s$)

$4\pi M_s$ has a huge influence on Q_u over frequency. The use of highest $4\pi M_s$ is always desirable for low loss in a bandpass filter, a deep notch in a band reject filter, or low phase noise in an oscillator. But the highest value of $4\pi M_s$ is determined by the minimum desired frequency over the operating band. The numerical value of $4\pi M_s$ determines the minimum operating frequency of this YIG sphere and plays a big roll in determining the linewidth.

The minimum external magnetic field (in Gauss) that will saturate a YIG sphere is equal to (0.666 x$4\pi M_s$). For pure YIG (which has the highest possible Q_u) this means that the minimum external magnetic field, H_0, needed to saturate the YIG sphere and make it a useful resonator is (0.666 x 1,780) = 1,185 Gauss. Therefor the minimum usable frequency, F_0, of pure YIG is (2.8 x 1185) = 3,400 MHz. For a 1,000 gauss sphere it would be 1860 MHz; for a 200 Gauss sphere the minimum operating frequency would be 372 MHz etc. The chosen Gauss level depends on the minimum desired tuning frequency of the YIG filter or oscillator.

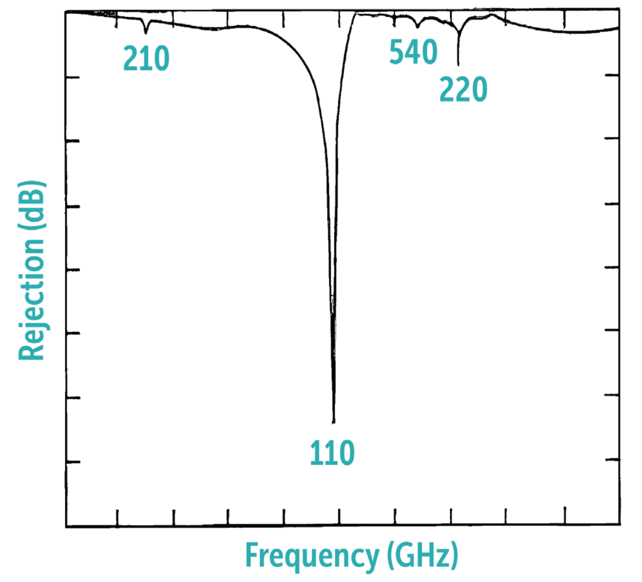

Figure 16: Modes in a YIG band reject filter

Finally, the distance of tracking spurs (known as magnetostatic modes) offset from the main resonance is strictly determined by the $4\pi M_s$ (see Figure 16). In our design the separation of the *540* and the *220* modes from the main resonance *110* is most important (we will ignore the small and further-out *210* mode.) The *110 – 540* separation is 0.084 x $4\pi M_s$, the *110 - 220* separation is 0.186 x $4\pi M_s$. For a band using pure YIG the *110-220* separation is 331 MHz, but in the band of interest in our particular 0.5-3 GHz filter, we are forced to use 250 Gauss spheres, for which the *110-540* separation is only 21 MHz and the *110-220* separation is only 47 MHz from the notch (*110*), cutting right into the upper side of the notch and expanding it's 3 dB bandwidth. Once the material is chosen, we can't impact the spur spacing, but as discussed earlier, our aim is to optimize the design to suppress their levels as much as possible.

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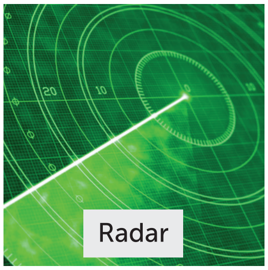

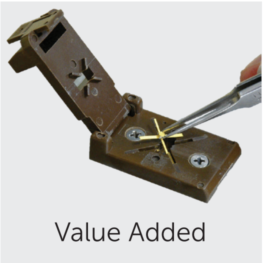

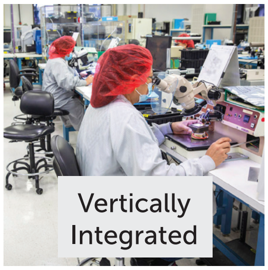

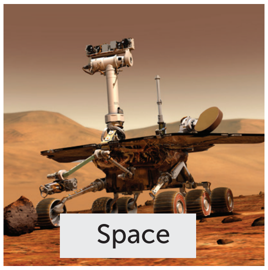

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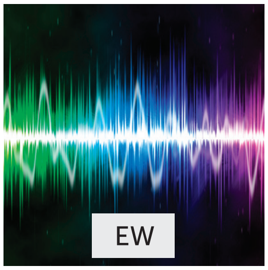

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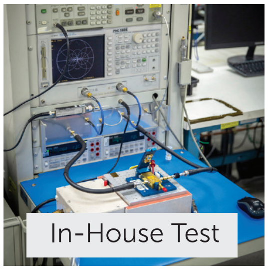

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Years of Heritage

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