Th02A-2

Micro-machined Tunable Magnetostatic Forward Volume Wave Bandstop Filter

Y. Feng[1], S. Tiwari[1], S. A. Bhave[1], and R. Wang[2]

[1]OxideMEMS Lab, Purdue University, West Lafayette, USA

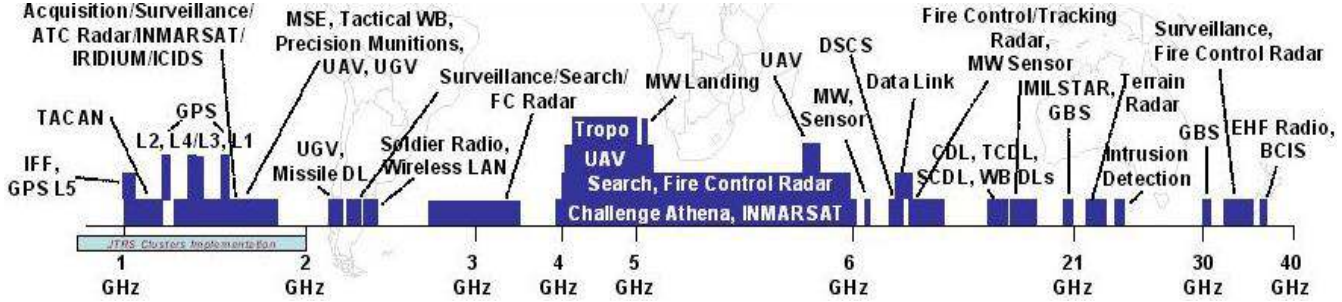
[2]FAST Labs™, BAE Systems, Inc., Nashua, USA

Outline

- Motivation
- Micro-machined YIG Thin Film MSW Filter Design
- Device Fabrication
- Measurements
- Summary

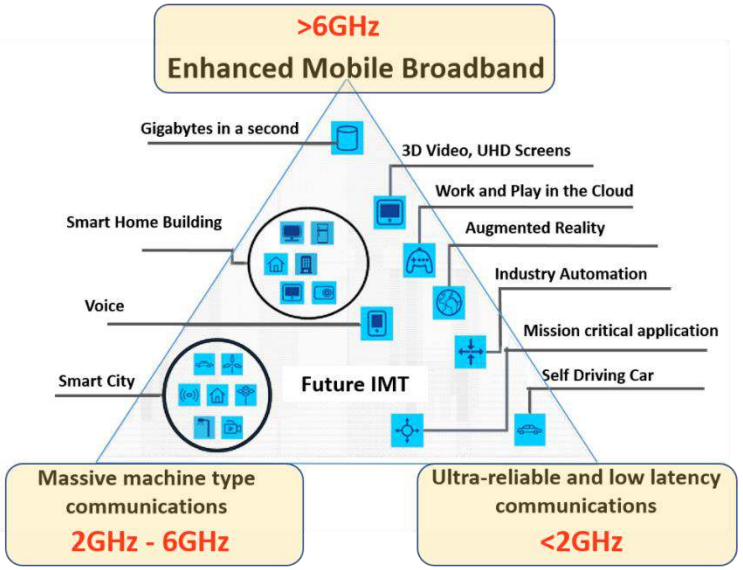
Motivation

Defense



	λ/2@2GHz	λ/2@20GHz	λ/2@40GHz
EM	75mm	7.5mm	3.5mm
Acoustic	2.5μm	0.25μm	0.125μm

Commercial Mobile



Defense Application

- Broad spectrum
- Conventionally EM wave based components: CPW, microstrip, cavity; moderate performance and large size
- Demands for higher performance and smaller footprint
- EM wavelength too long, acoustic wavelength too short

Commercial Mobile

- Conventionally focused on S band and below
- Acoustic wave components: BAW, SAW, high performance and small sizes
- Demands for scaling to much beyond S band
- Acoustic wavelength too short, EM wavelength too long

Is there another wave phenomenon with wavelength between EM and acoustic?

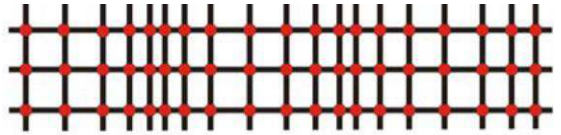
Motivation

Magnetostatic Wave (MSW)

Lattice of Magnetic Dipoles

Lattice Wave

Acoustic Wave



Lattice of Atoms

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} - \lambda \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}})$$

Landau-Lifshitz equation
+ Maxwell equations
+ quasi-magnetostatic approximation

Elastic wave equations (Piezo)
+ Maxwell equations
+ quasi-electrostatic approximation

Features of MSW

- Exists in ferro/ferrimagnetic materials, dipole moments originate from unpaired outer shell electrons spins
- Single crystal yttrium iron garnet exhibits the lowest damping for MSW
- Material limited Q > 10,000 from UHF to K_a band, and is frequency independent
- Group velocity on the order of 1000 km/s, and multi-octave tunable based on applied DC magnetic bias
- A promising technology with wavelength between acoustic wave and EM wave, and high Q

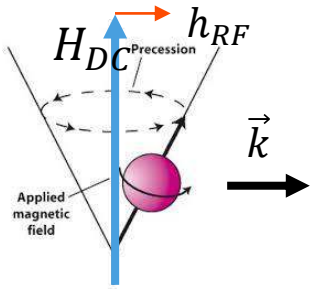
Micro-machined YIG Thin Film MSW Filter Design

Magnetostatic Wave (MSW) Supported in A Thin Film

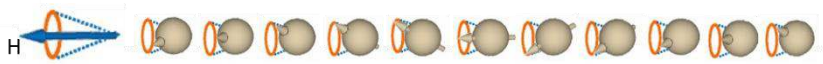
$$\omega^2 = \omega_0 \left[\omega_0 + \omega_M \left(\frac{1 - e^{-kd}}{kd} \right) \right]$$

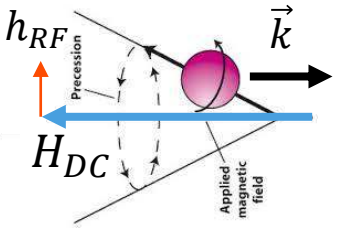
$$\omega_M = -\gamma \mu_0 M_S$$
$$\omega_0 = -\gamma \mu_0 H_{DC}$$
$$\gamma \mu_0 = 2.8 MHz/Oe$$

Magnetostatic Forward Volume Wave

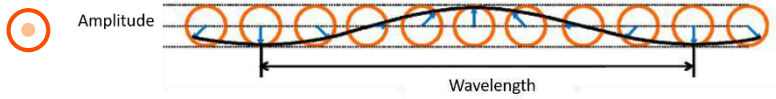


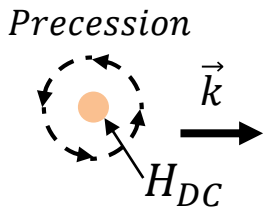
Magnetostatic Backward Volume Wave

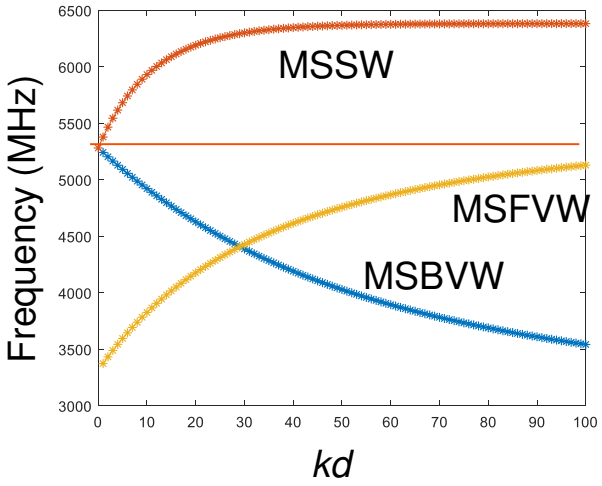




Magnetostatic Surface Wave

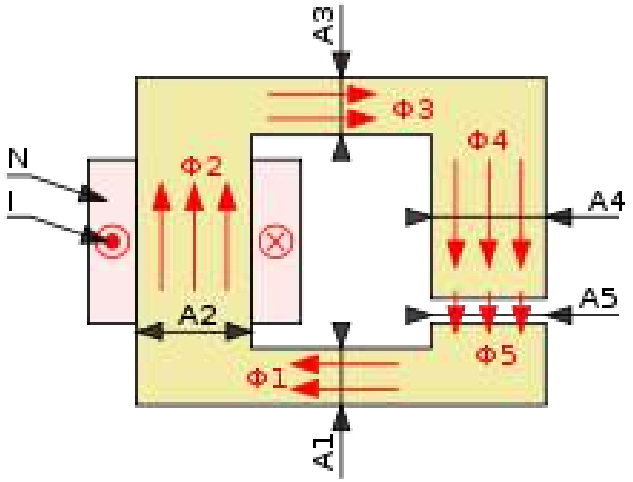






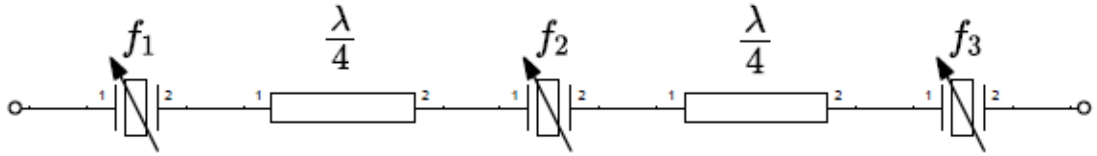
Micro-machined YIG Thin Film MSW Filter Design

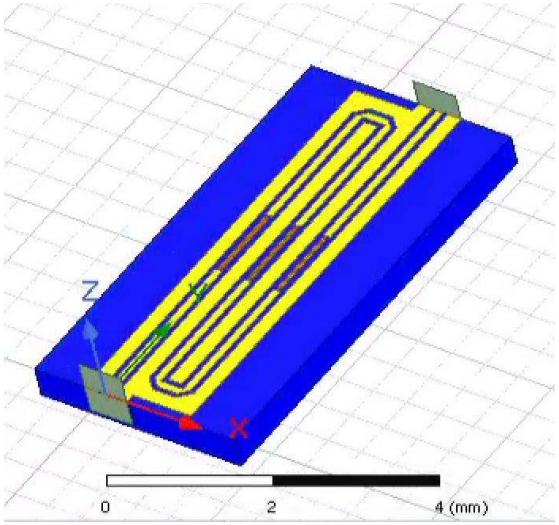
Magnetic			Electric		
Name	Symbol	Units	Name	Symbol	Units
Magnetomotive force (MMF)	$\mathcal{F} = \int \mathbf{H} \cdot \mathrm{dl}$	ampere-turn	Electromotive force (EMF)	$\mathcal{E} = \int \mathbf{E} \cdot \mathrm{dl}$	volt
Magnetic field	H	ampere/meter	Electric field	E	volt/meter = newton/coulomb
Magnetic flux	Φ	weber	Electric current	I	ampere
Hopkinson's law or Rowland's law	$\mathcal{F} = \Phi \mathcal{R}_m$	ampere-turn	Ohm's law	$\mathcal{E} = IR$	
Reluctance	$\mathcal{R}_\mathrm{m}$	1/henry	Electrical resistance	R	ohm
Permeance	$\mathcal{P} = \frac{1}{\mathcal{R}_\mathrm{m}}$	henry	Electric conductance	$G = 1/R$	1/ohm = mho = siemens
Relation between B and H	$\mathbf{B} = \mu \mathbf{H}$		Microscopic Ohm's law	$\mathbf{J} = \sigma \mathbf{E}$	
Magnetic flux density B	B	tesla	Current density	J	ampere/square meter
Permeability	μ	henry/meter	Electrical conductivity	σ	siemens/meter

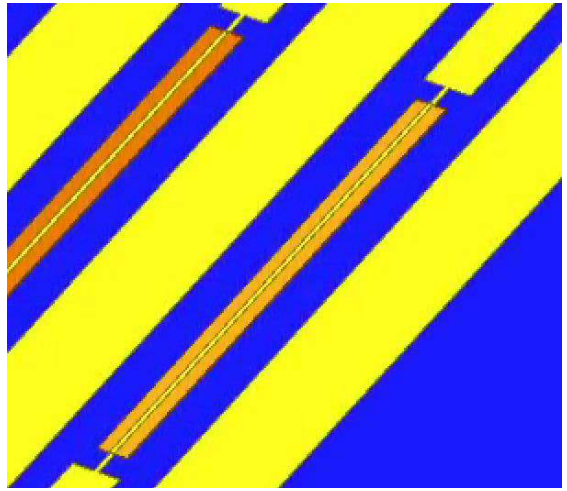


- This work focus on MSFVW for easier biasing and future integration
  - Device placed in the air gap of a yoke for biasing
  - Larger gap leads to higher magnetic reluctance, bigger magnets (electro or permanent) are needed to generate the same amount of bias
  - Biasing perpendicular to film thickness requires smaller air gap, easier for future integration and miniaturization

Micro-machined YIG Thin Film MSW Filter Design

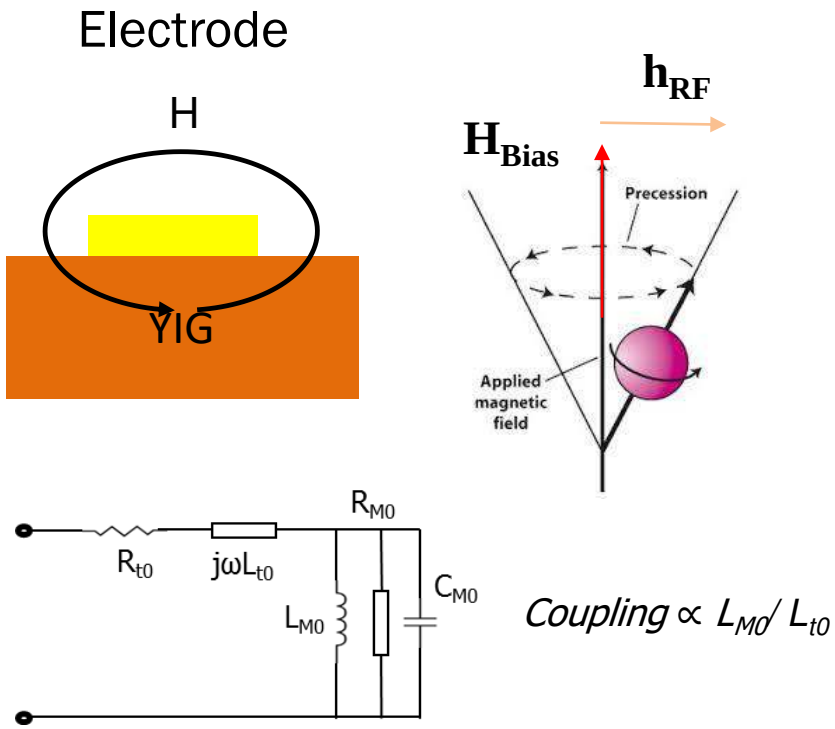




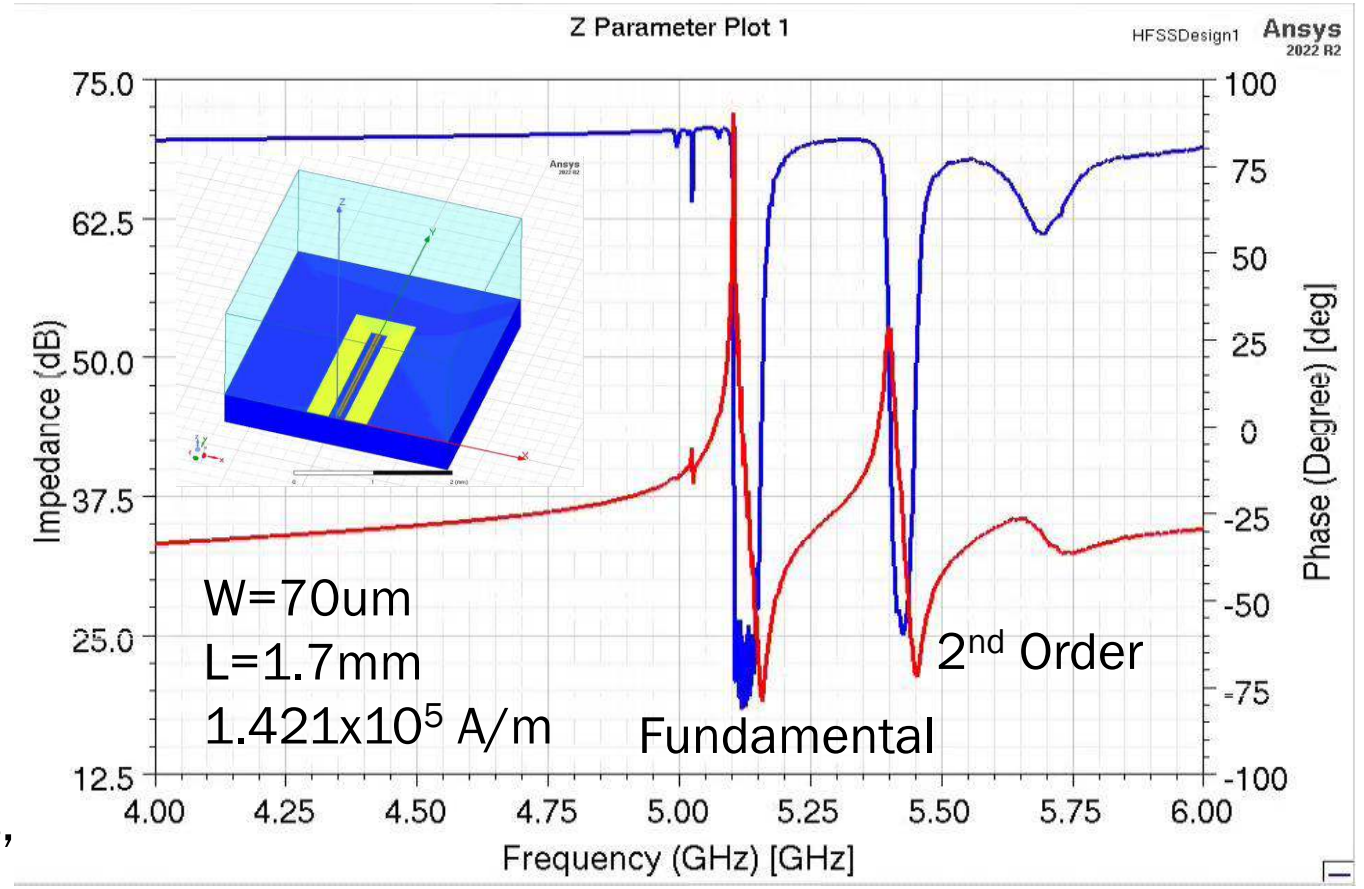


- Three tunable MSFVW resonator coupled by impedance inverters
- To achieve low passband insertion loss and high stopband rejection, requires resonator behaves as open at resonance and short off-resonance
  - High resonator quality factor
  - High energy coupling

Micro-machined YIG Thin Film MSW Filter Design



Coupling $\propto L_{M0}/L_{t0}$



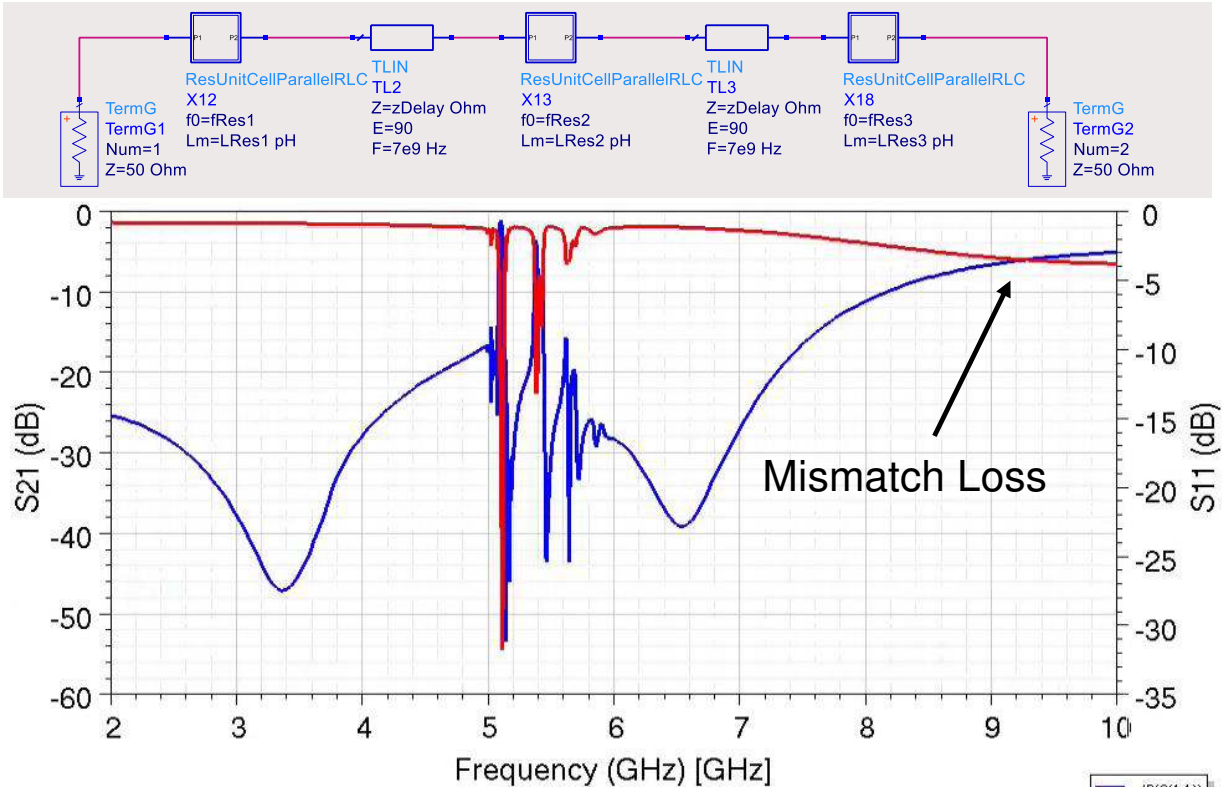
- RF current generates RF H-field, which applies torque to magnetic dipole moments, which excites MSW
- Directly placing electrode on YIG enable tight coupling between RF excitation and MSW

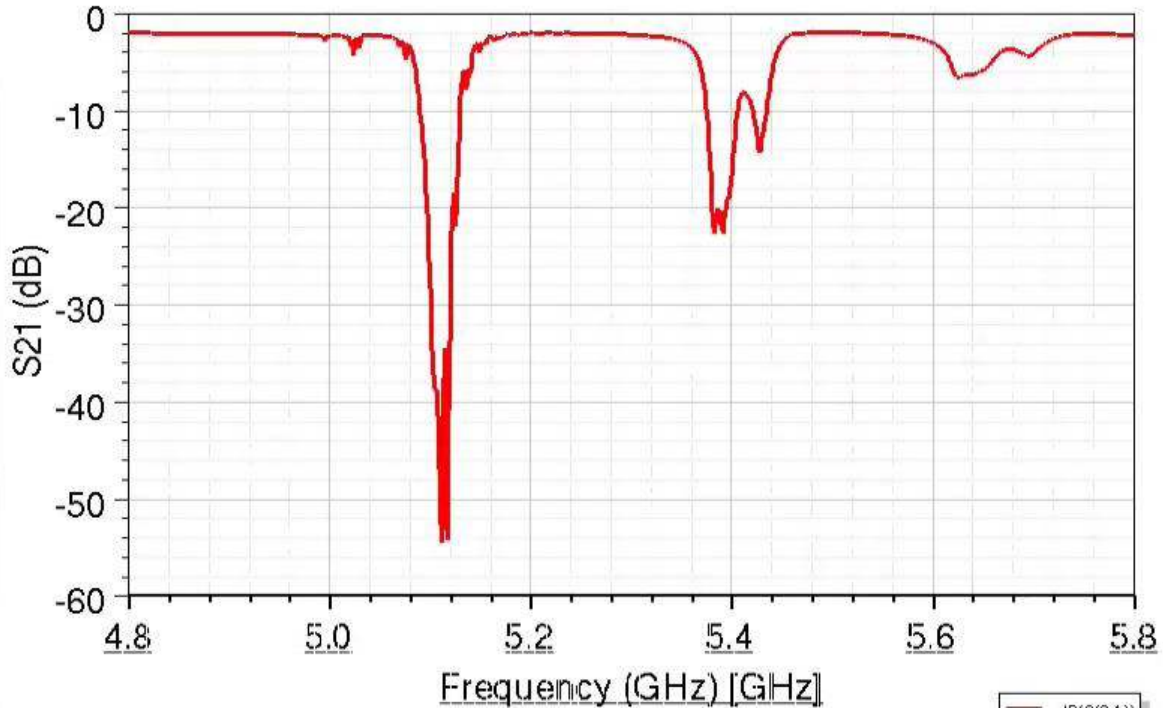
Normal Dispersion
Indicative of MSFVW

Micro-machined YIG Thin Film MSW Filter Design

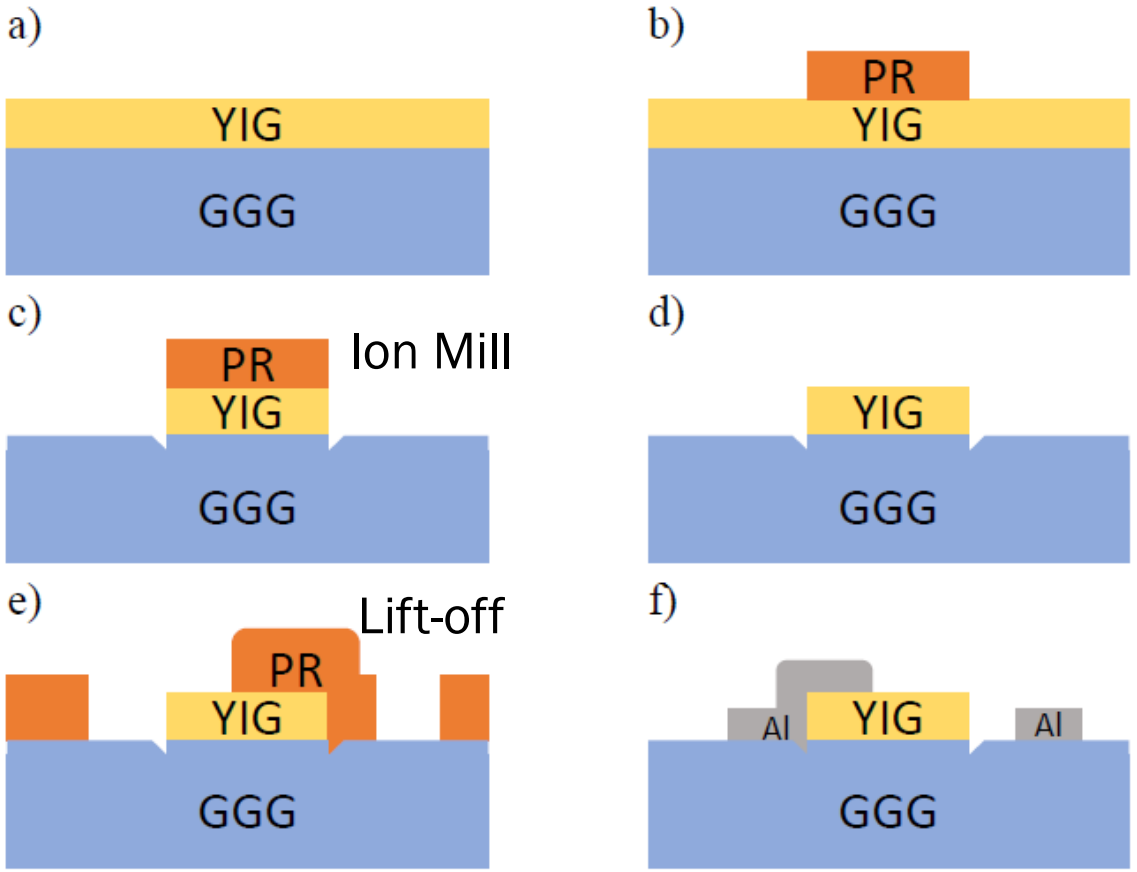
- Each resonator has slightly different width (73um, 70um, and 67um) to shift their resonant frequencies to synthesize 3rd order response
- Resonators are coupled by quarter wavelength lines (@7GHz)

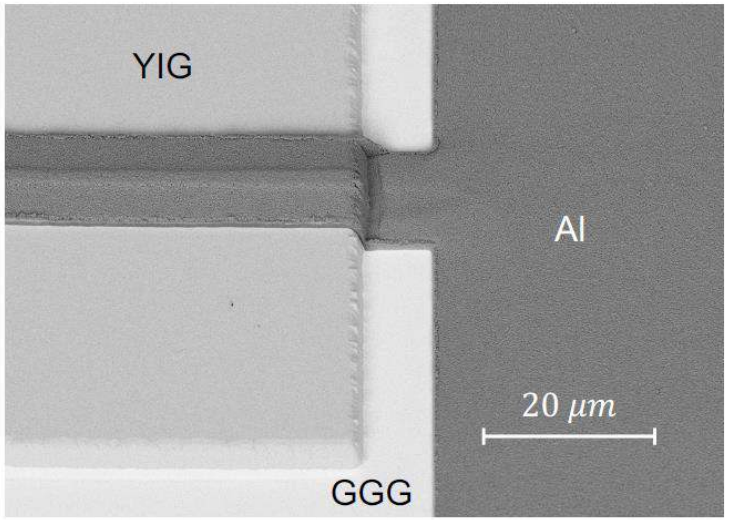
Simulated Response
~2dB Passband Insertion Loss
~40dB Stopband Rejection

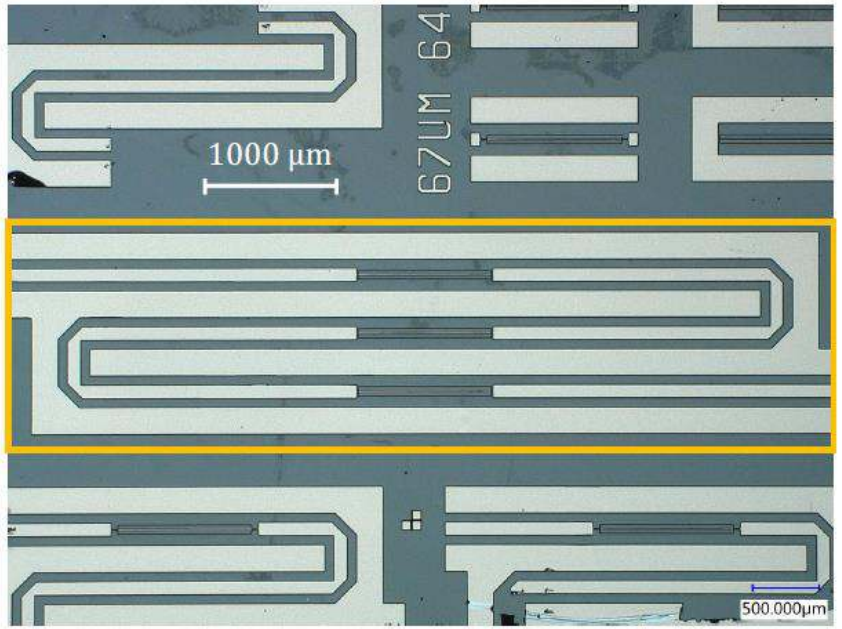




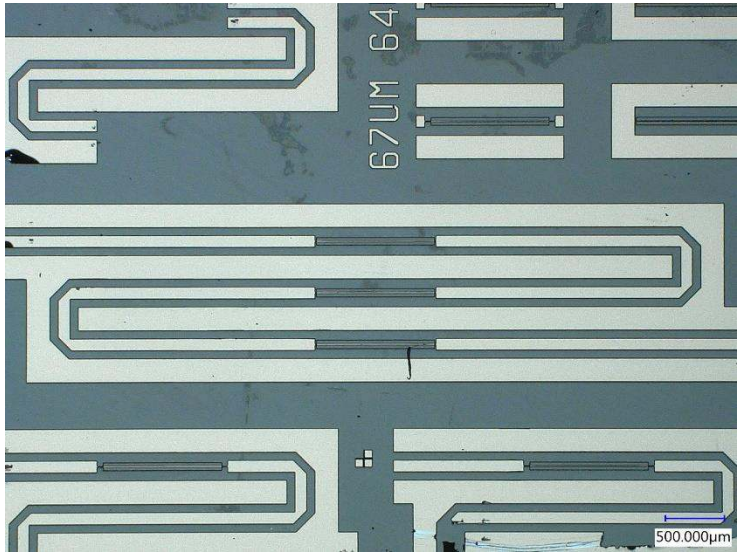
Device Fabrication





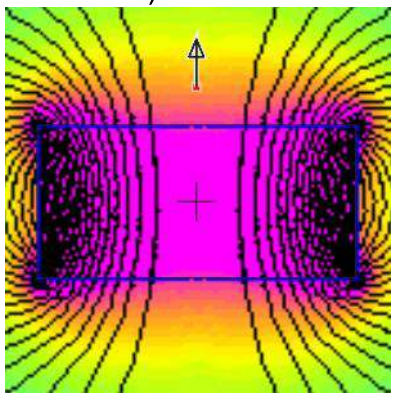


Measurement

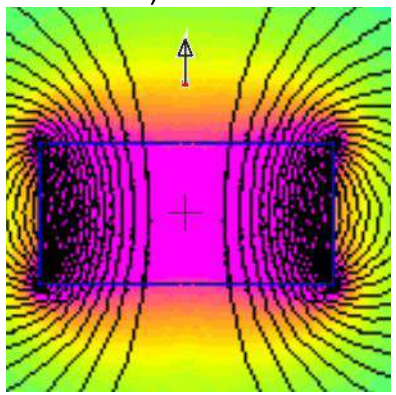


- Devices biased using permanent magnet
- Position of magnet controlled by a high precision positioner
- Control z field by positioning the chip at different vertical positions
- Field from different vertical position is calibrated by a Hall sensor

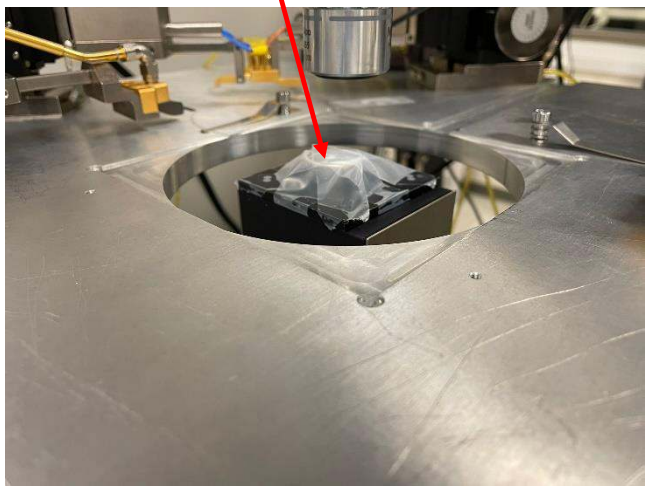
3mm, 3936 Oe

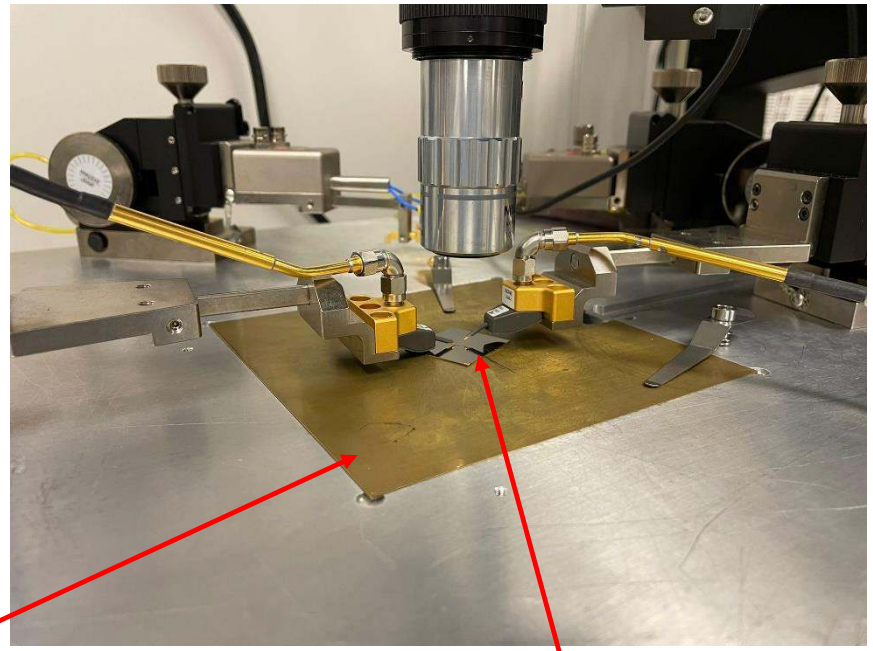


5mm, 3216 Oe



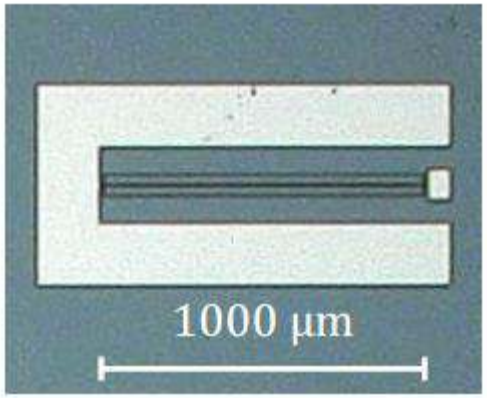
N52 Permanent Magnet
On Z Stage

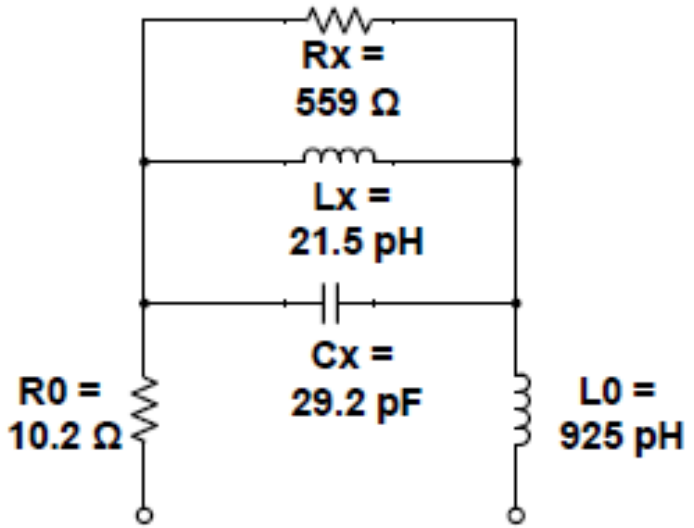


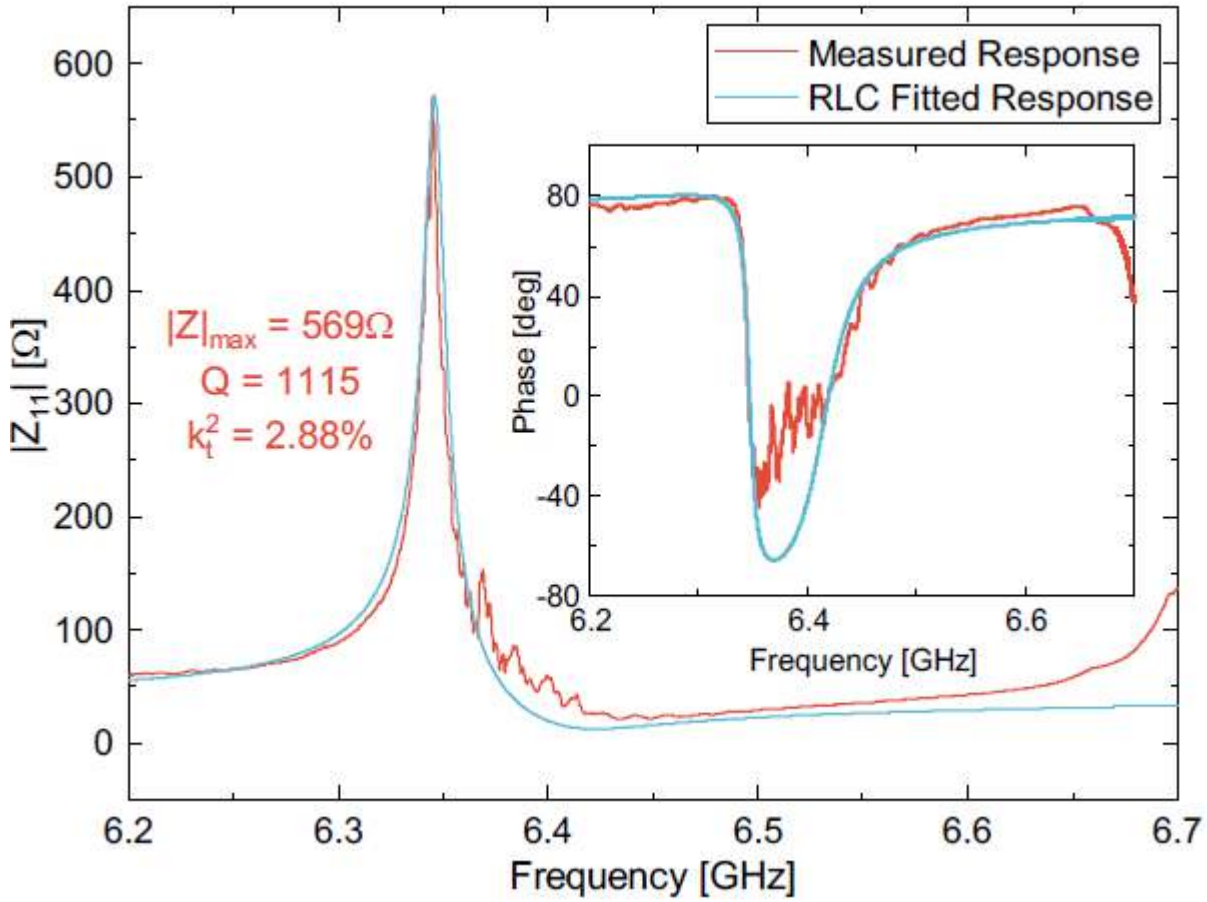


Measurement

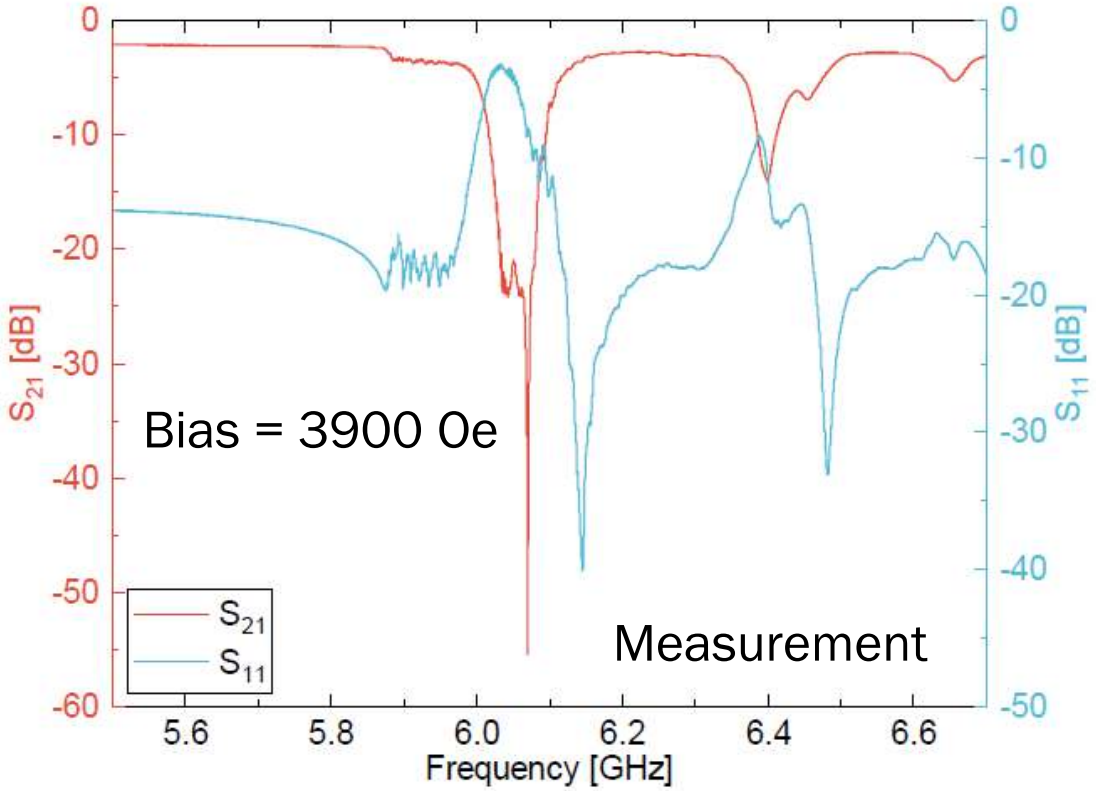
W=73um
L=1000um

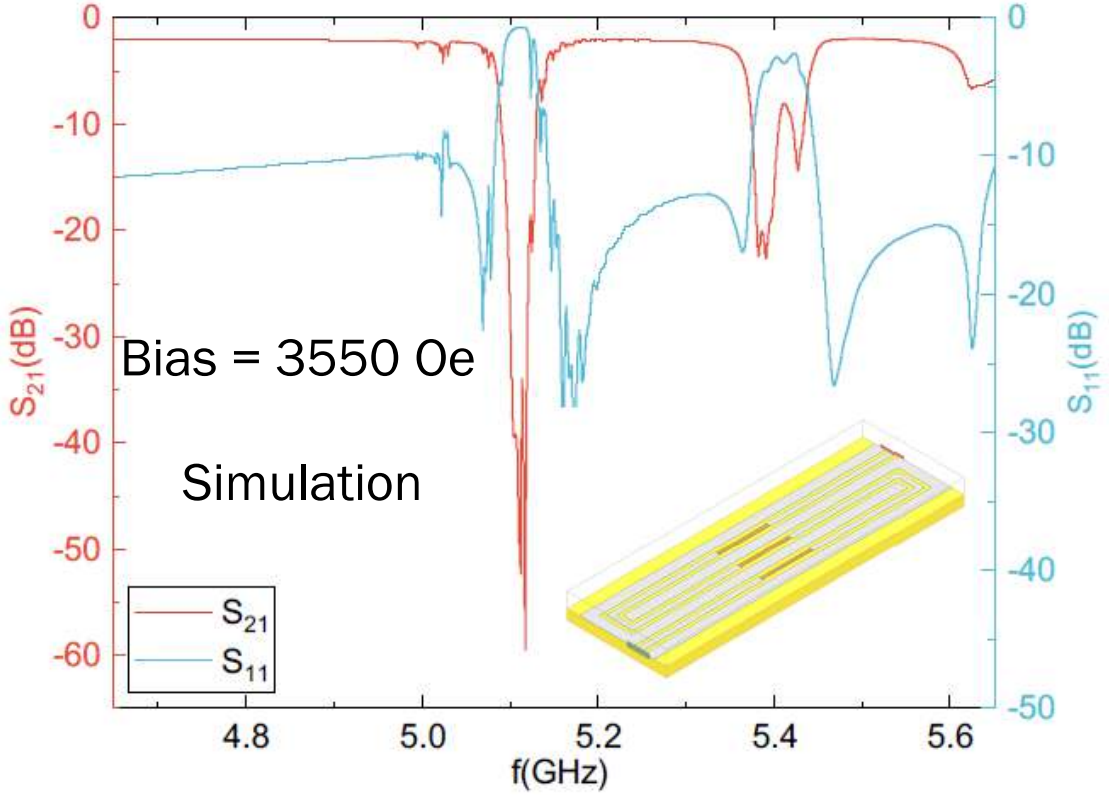






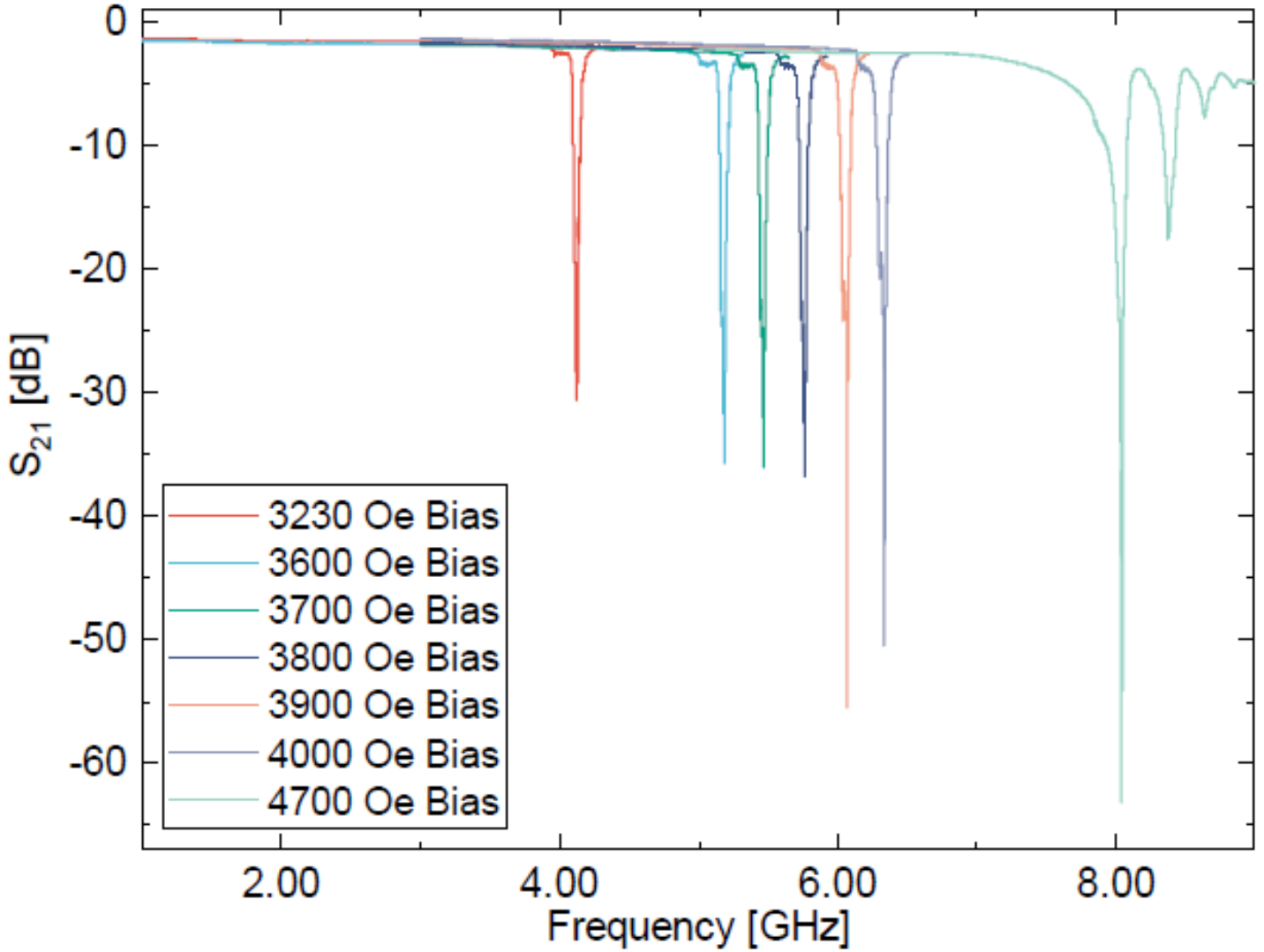
Measurement





- Center frequency 6.07GHz
- 10dB rejection BW ~1.1%, 20dB rejection BW ~0.7%

Measurement

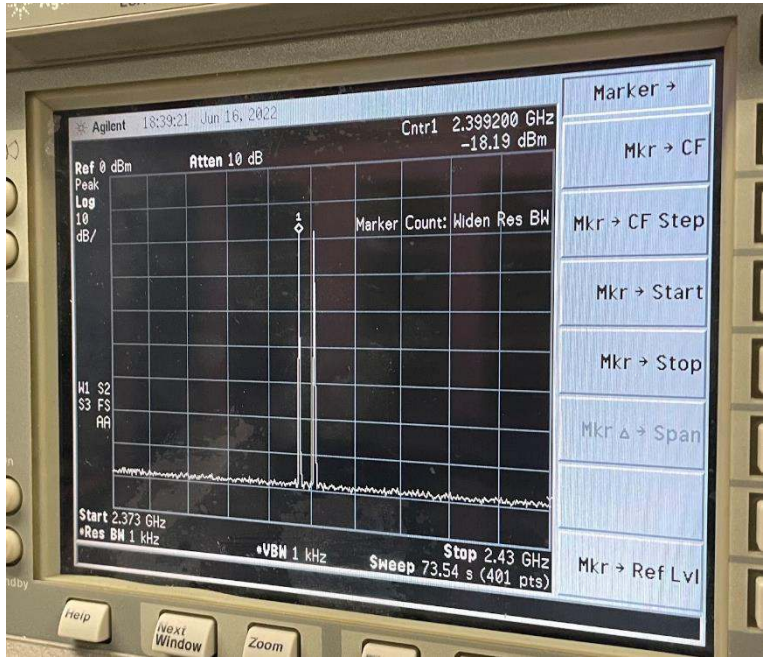


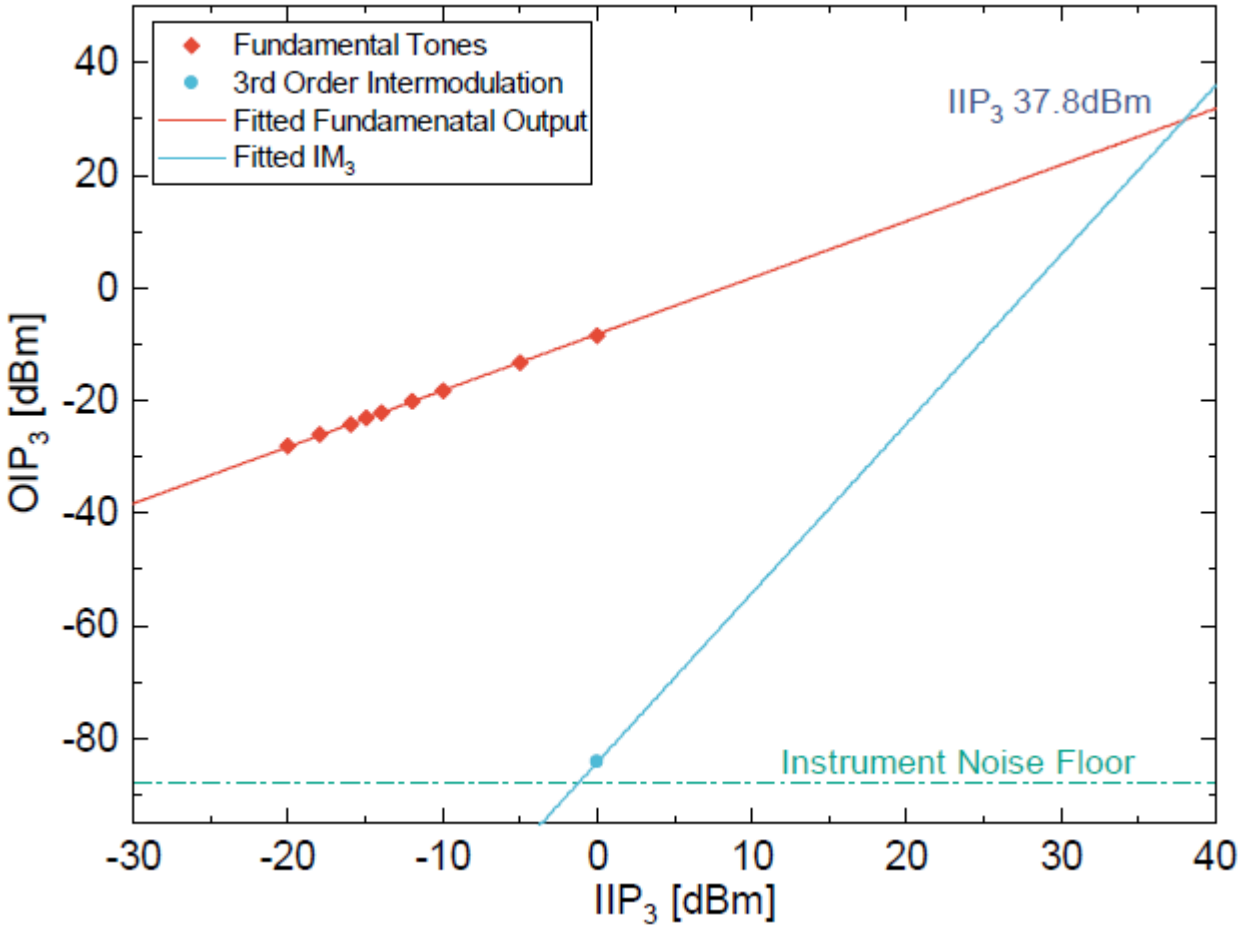
- Measured Frequency Tuning by Applying Different Magnetic Bias
- One octave of tuning
- Tuning efficiency 2.8MHz/Oe
- Passband IL ~1.5dB toward 2GHz, ~3dB toward 7GHz
- Increase passband IL is due to mismatch loss

Measurement

Passband Linearity:

- At -16dBm input power in passband (~2.3GHz), 3rd order tone below noise floor (89dBm)
- Highly linear, as filter equivalent to a small inductor in passband
- Stopband center frequency tuned to 5.85GHz





Summary

- We have successfully designed, fabricated and characterized a planar monolithic YIG MSFVW Chebyshev bandstop filter
- Stopband center frequency is tuned from 4 GHz to 8 GHz
- The filter exhibits about 2dB of passband IL at the center of the tuning range, with a 55 dB maximum stopband rejection, and a 37.8 dBm passband IIP3
- Incorporated with proper design of tunable compact electromagnet, this new filter design can enable compact tunable notch for blocker rejection