Adaptive Interference Rejection with Synthetic Channel Diversity (AIR SynCD)

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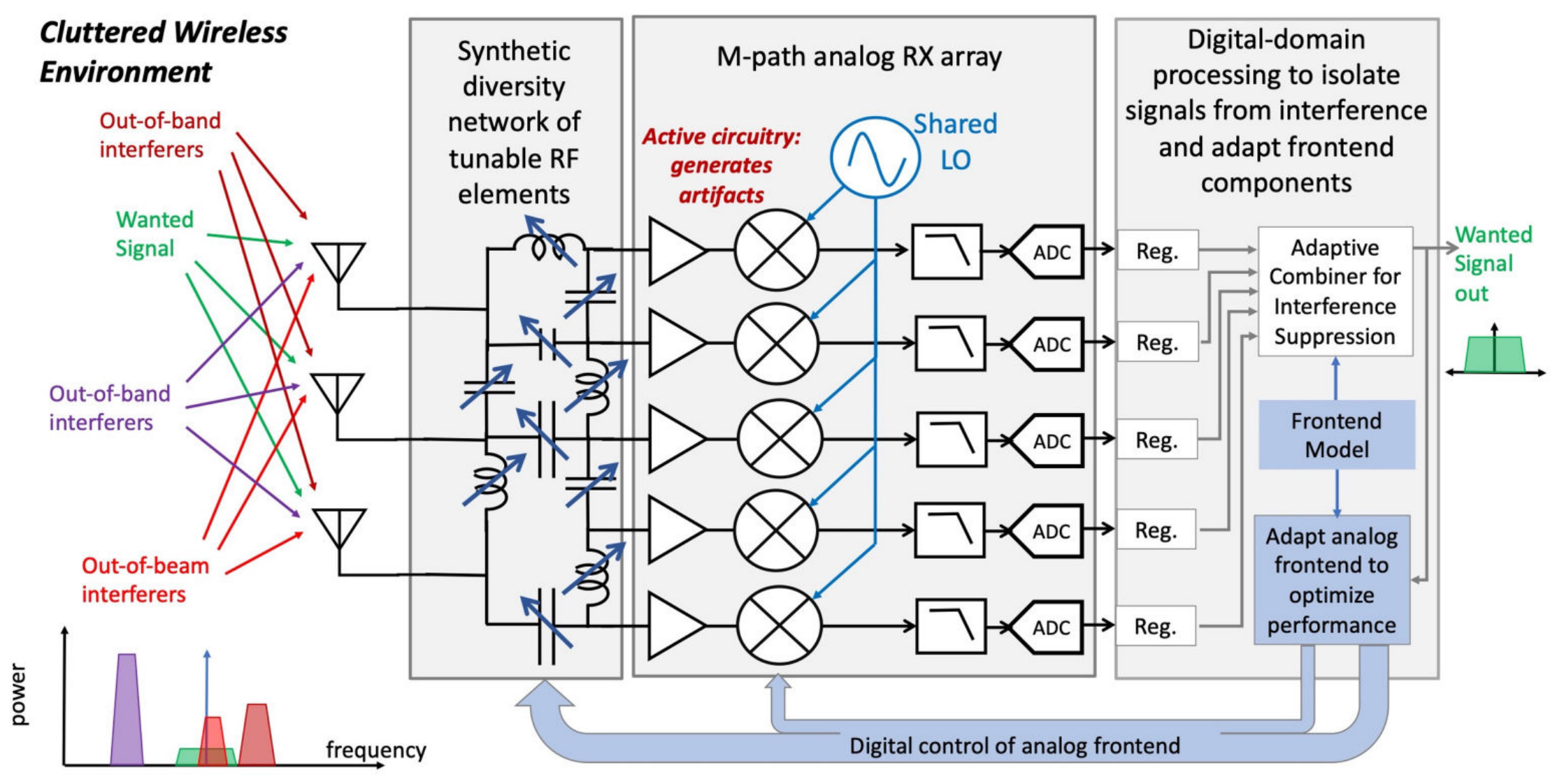
Project Summary

Problem to be Addressed Communications must move to higher frequencies and will benefit from the widely tunable properties of magnetic materials for applications in the tunable microwave and millimeter-wave systems.



Intellectual Merit Objectives

1. Design receiver front-ends that use passive networks (of inductors, capacitors, and other electromagnetic elements) to diversify the inputs from one or more antennas.
2. Development of digital-domain algorithms to optimally use the receiver front-end to identify and suppress interference artifacts relative to the signal, and to provide control feedback to the adaptive components.
3. Development of novel adaptive RF magnetic devices to provide real-time tunability to the receiver front-end.

Broader Impacts Objectives

1. Highly-adaptive and highly-interference tolerant radio receivers.
2. Seminar teaching first-year URM doctoral students the academic and research “survival skills” needed to succeed in their Ph.D. degrees and future career pursuits.
3. Graduate and undergraduate student training in understanding wireless systems holistically.

Receiver Front-Ends with Synthetic Diversity Networks

Problem:

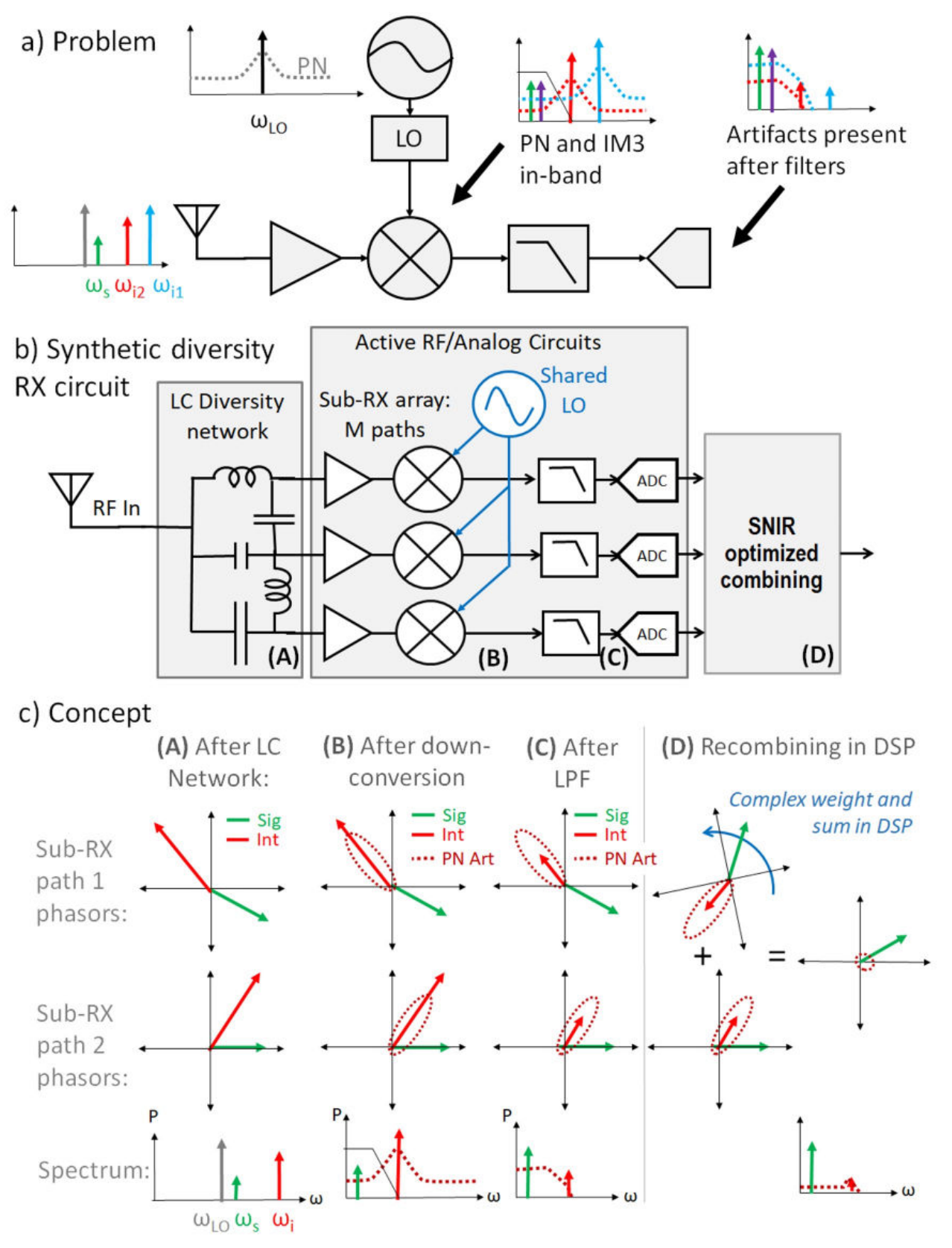
- Widely-tunable RF receivers (RX) cannot rely on high-selectivity filters at the frontend to deal with strong interference.
- RX sensitivity is degraded by strong interference due to circuit non-idealities e.g., LO phase noise and LNA nonlinearity.
- Significant improvements have been made in linearity, but phase noise remains a limiter.

Proposed Solution: Synthetic Diversity

- Split the signal from antenna to N sub-RXs.
- Create channel diversity akin to MIMO systems using passive LC network.
- Use strong frequency dependency of the LC network response to differentiate signal from interference by optimally combining outputs at the DSP

Concept:

- LC network interacts with the signal (v_s) and the interference (v_i) by applying complex gain vectors $\overrightarrow{H(j\omega_s)}$ and $\overrightarrow{H(j\omega_i)}$
- Signal and interferer are down-converted along with the in-band artifact from reciprocal mixing of PN, $PN(\omega_i - \omega_{LO})v_i\overrightarrow{H(j\omega_i)}$
- Although the down-converted interferer gets filtered at the BB, PN artifact remains
- Optimal complex weights ($\overrightarrow{W_{opt}}$) are applied to suppress the interferer and recover the signal



(A) $v_s\overrightarrow{H(j\omega_s)} + v_i\overrightarrow{H(j\omega_i)}$

(B) $v_s\overrightarrow{H(j\omega_s)} + v_i\overrightarrow{H(j\omega_i)} + PN(\omega_i - \omega_{LO})v_i\overrightarrow{H(j\omega_i)}$

(C) $v_s\overrightarrow{H(j\omega_s)} + PN(\omega_i - \omega_{LO})v_i\overrightarrow{H(j\omega_i)}$

(D) $\left\langle \overrightarrow{W_{opt}}, v_s\overrightarrow{H(j\omega_s)} + PN(\omega_i - \omega_{LO})v_i\overrightarrow{H(j\omega_i)} \right\rangle$

$$\overrightarrow{W_{opt}} = \overrightarrow{H(j\omega_s)}^* - \frac{\overrightarrow{H(j\omega_i)}^*\,\overrightarrow{H(j\omega_s)}}{\overrightarrow{H(j\omega_i)}^*\,\overrightarrow{H(j\omega_i)}}\overrightarrow{H(j\omega_i)}^*$$

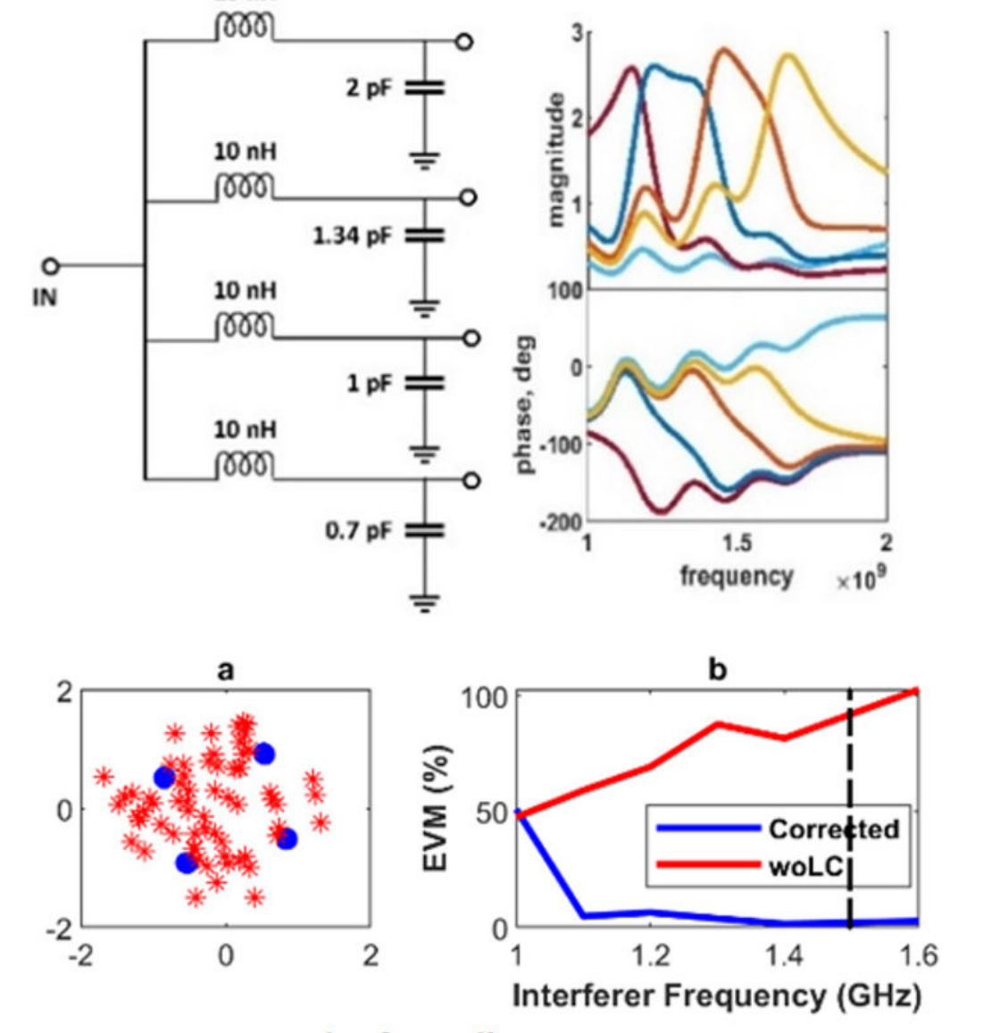
LC Diversity Network Design

What constitutes a good LC diversity network?

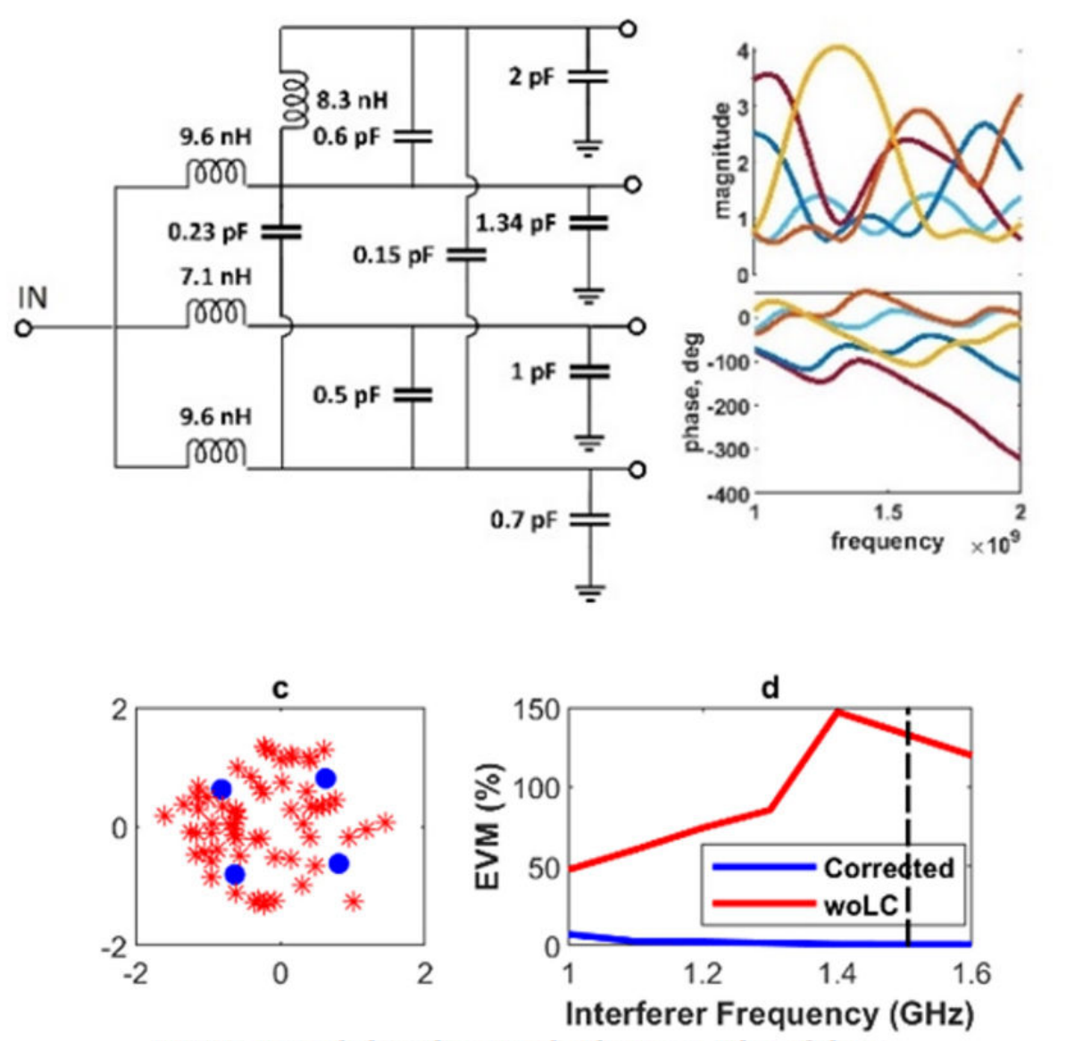
- Minimizes $\overrightarrow{H(j\omega_s)} \cdot \overrightarrow{H_i(j\omega_i)}^*$ for any choice of ω_s and ω_i in the RX’s tuning range
- Maintains good NF over frequency

A bank of LC bandpass filters partially works, but fails to recover the signal over the whole tuning range

LC network generated by an evolutionary algorithm, recovers the signal over the whole tuning range with better performance, while using a lower overall inductor value, thus saving area



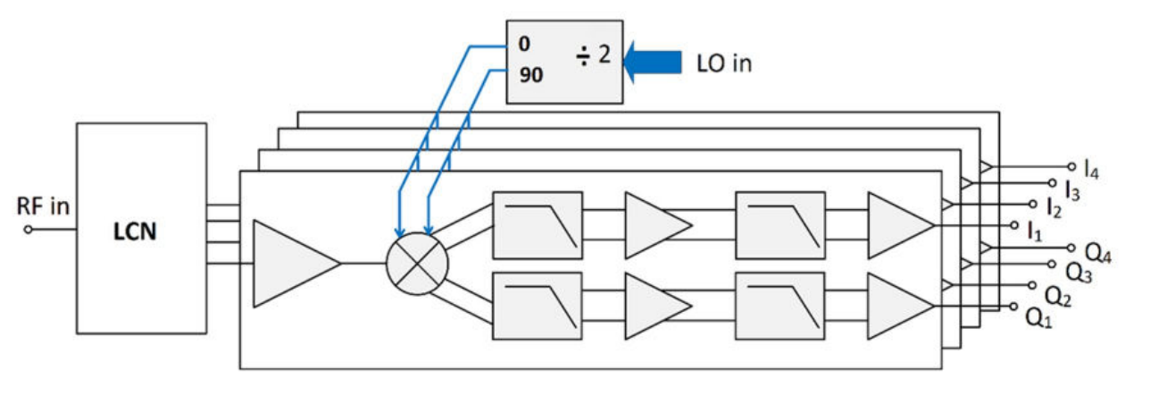
Bank of BP Filters

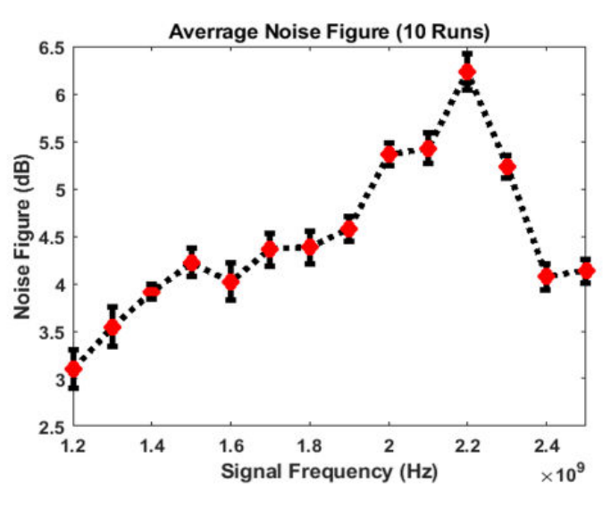


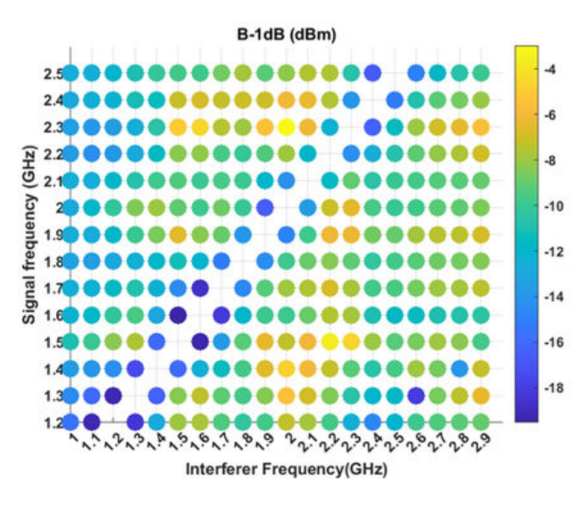
LC Network by the Evolutionary Algorithm

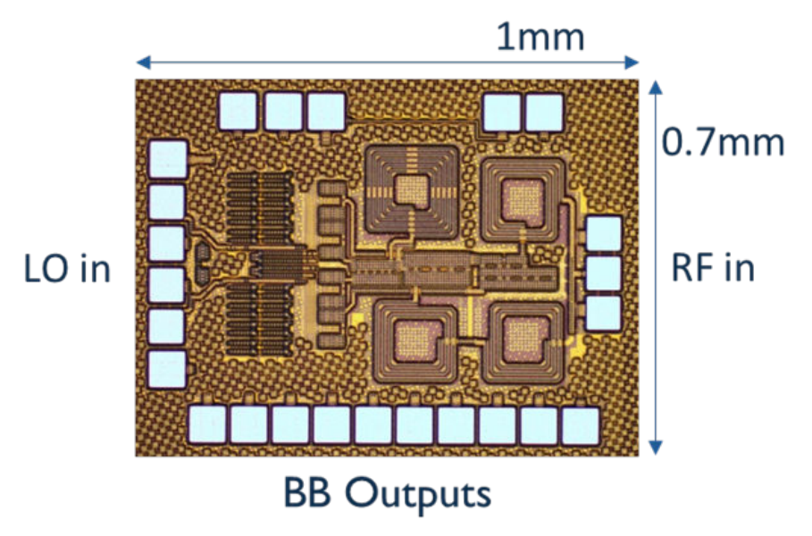
Experimental Validation

- Taped-out in 45nm RFSOI
- 1.2-2.4 GHz RF frequency range
- 4 sub-RXs, sharing the same LO
- On-chip LO CMR → Low I/Q imbalance





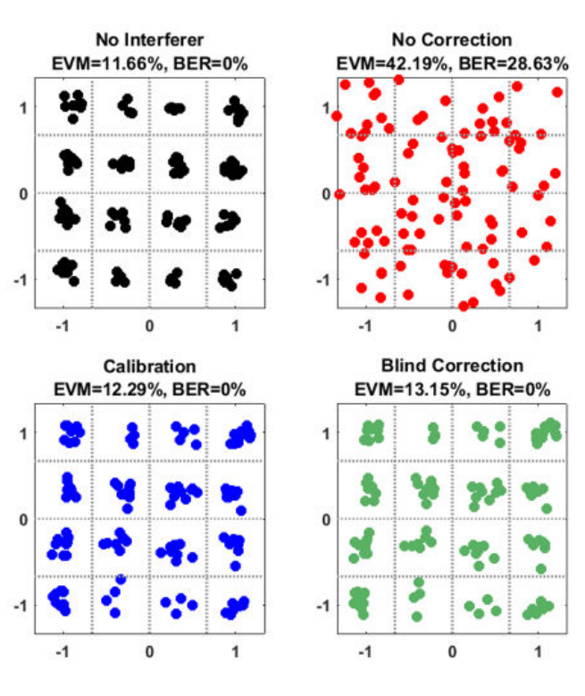




Artifact Suppression, Representative Measurement Results

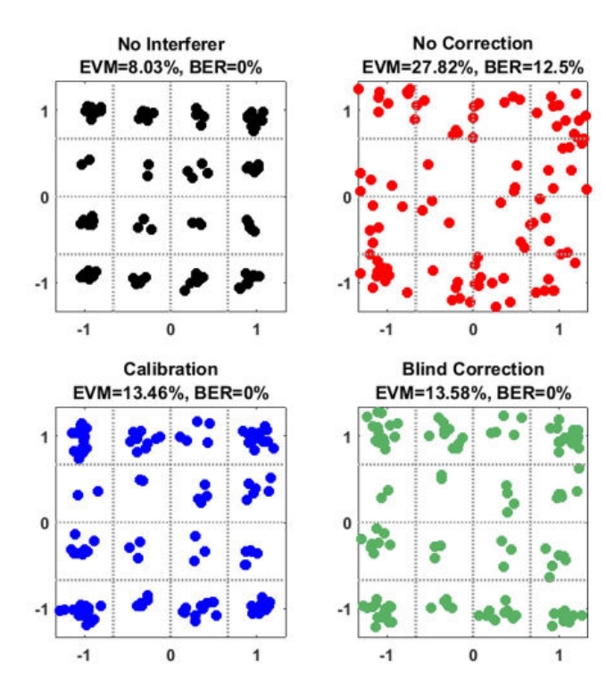
- Signal is 16QAM with 128 symbols at 1.28 MSPS.
- PN is introduced by frequency modulating a tone by uniformly distributed noise

IM3 Artifacts



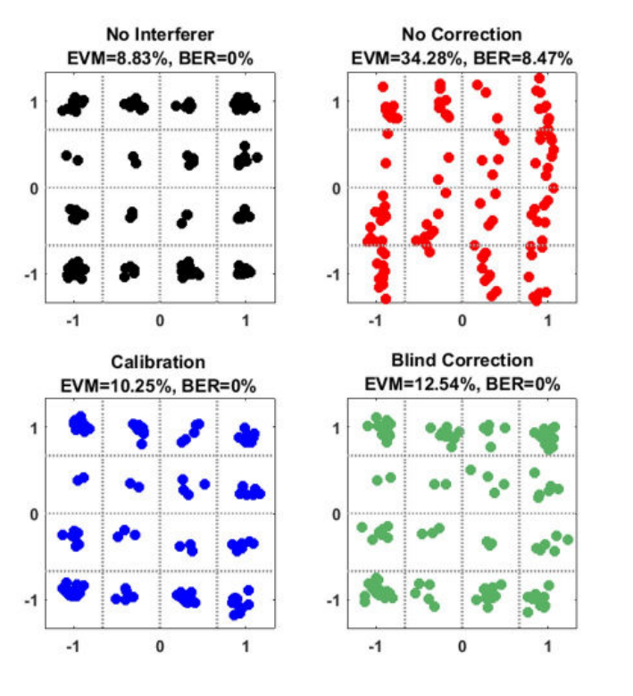
-83dBm signal at 1.7GHz
Interferers -20dBm at 2.1GHz(tone) and 2.5GHz(16QAM)

PN Artifacts



-83dBm signal at 1.7GHz
Interferers -28dBm at 1.5GHz(QPSK)

Harmonic Downconversion



-83dBm signal at 1.5GHz
Interferers -36dBm at 3GHz(16QAM)

Molnar et al , "Synthetic Diversity To Mitigate Out-of-Band Interference in Widely Tunable Wireless Receivers," *2019 53rd Asilomar Conference on Signals, Systems, and Computers*
Sadeghi et al, "Widely-Tunable RF Receiver Employing Synthetic Diversity for Interference Mitigation," *2022 IEEE International Symposium on Circuits and Systems (ISCAS)*, Austin, USA.

Optimized Digital-Domain Algorithms

Indices and subscripts:
k – interferer (or signal of interest)
m – channel number
n – sample number

Baseband Signal Model

Frequency Domain (complex baseband):

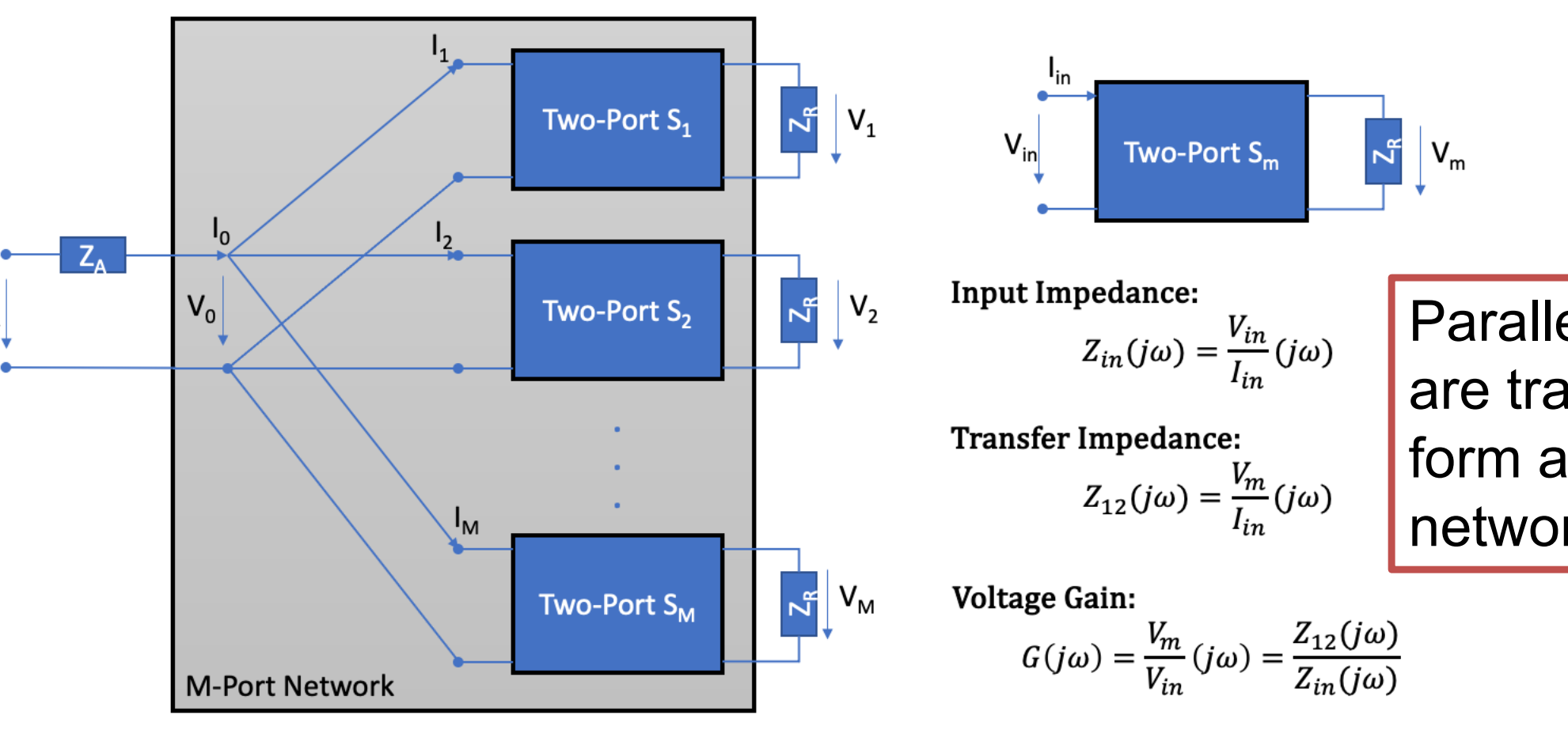
$$\vec{R}(j\omega) = S(j\omega)\cdot\vec{H}(j\omega_0) + \sum_k \tilde{S}_k(j\omega)\cdot\vec{H}(j\omega_k) + \vec{W}(j\omega)$$

Each vector component corresponds to a channel m in the M-Port network

If signals are narrow-band, then transformation to time-domain is simply:

$$\vec{r}[n] = s[n]\cdot\vec{H}(j\omega_0) + \sum_k \tilde{s}_k[n]\cdot\vec{H}(j\omega_k) + \vec{w}[n]$$

Narrow-band means $H_m(j\omega) \approx H_m(j\omega_k)$ over the bandwidth of k-th signal



Input Impedance:
$$Z_{in}(j\omega) = \frac{V_{in}}{I_{in}}(j\omega)$$

Transfer Impedance:
$$Z_{12}(j\omega) = \frac{V_m}{I_{in}}(j\omega)$$

Voltage Gain:
$$G(j\omega) = \frac{V_m}{V_{in}}(j\omega) = \frac{Z_{12}(j\omega)}{Z_{in}(j\omega)}$$

Parallel two-ports are tractable and form a rich class of networks.

Performance Characterization

Linear combiner:

$$v_{\text{comb}} = \sum_{m=1}^{M} w_m^*\, v_{\text{out},m} = \langle \vec{v}_{\text{out}}, \vec{w}\rangle.$$

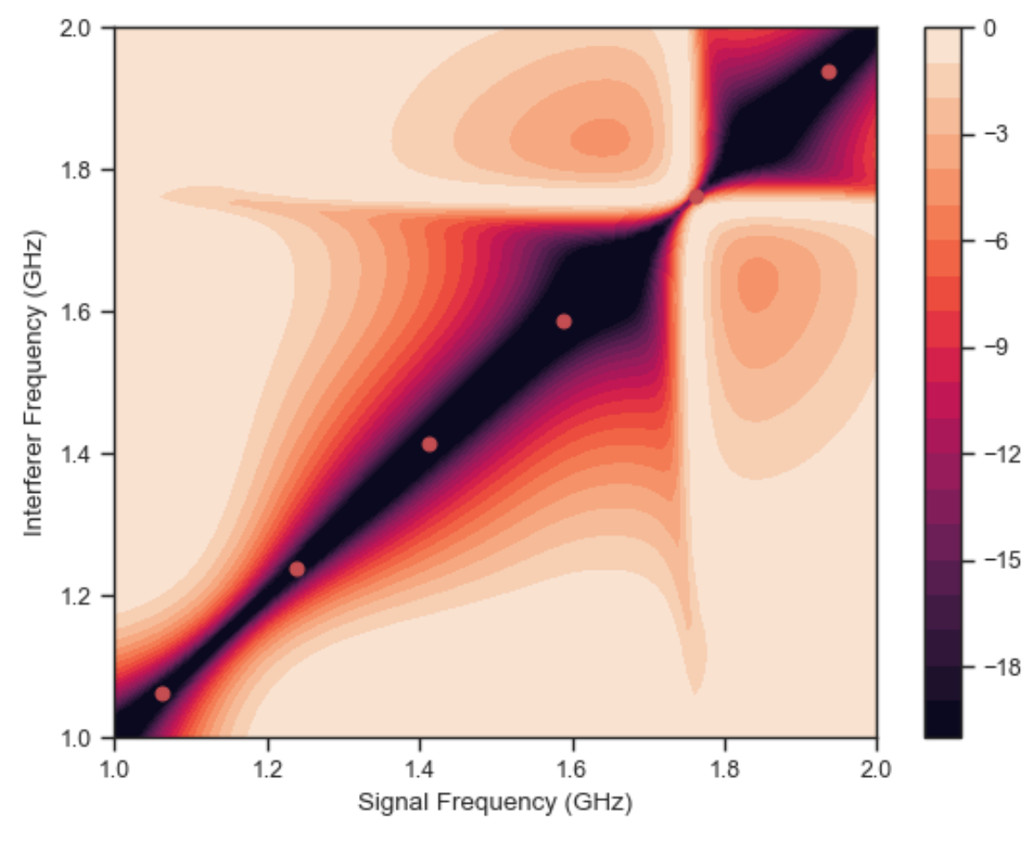
MMSE weights:

best trade-off between interference rejection and noise amplification: $\vec{w} \sim \mathbf{R}_n^{-1}\vec{\tilde{G}}(jf_o)$, where $\mathbf{R}_n$ is the noise plus interference correlation matrix.

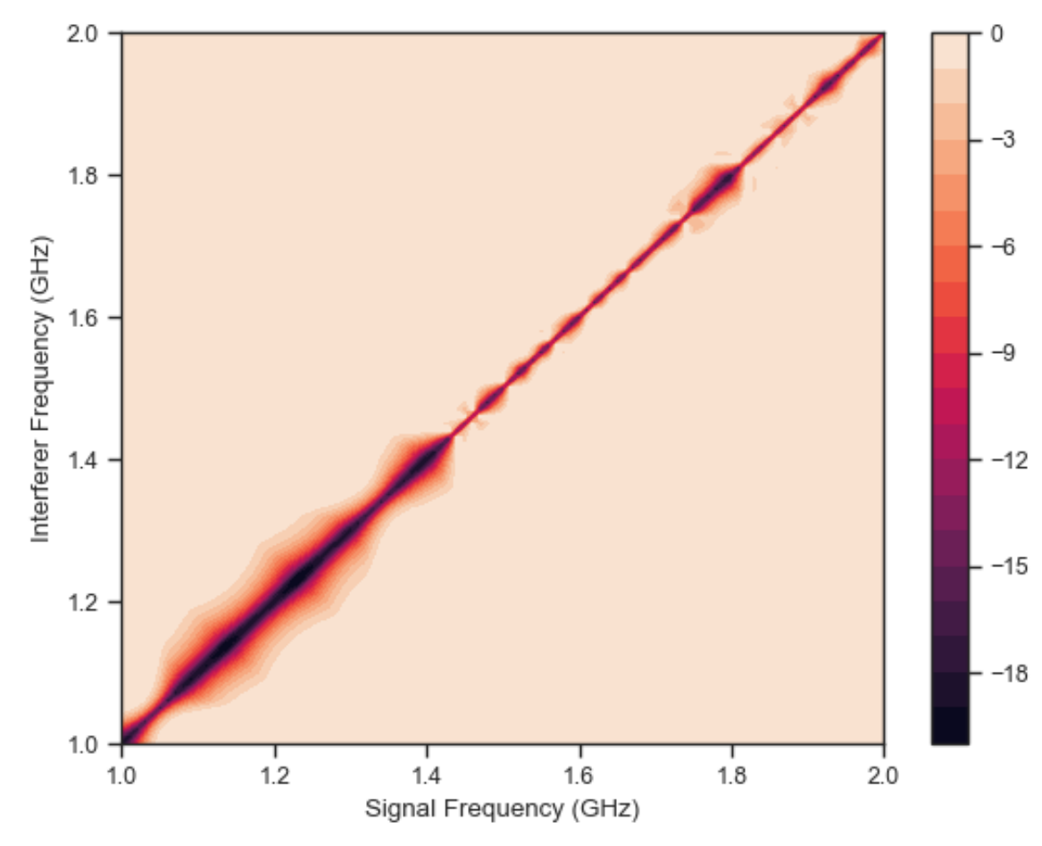
Performance metric:
Ratio of SINR at output of MMSE combiner to SNR without interference and with perfect matching:

$$L = \underbrace{S(f_0)}_{\substack{\text{Insertion}\\ \text{Loss}}}\cdot\left(1 - \underbrace{|\langle\vec{\tilde{G}}(j2\pi f_0), \vec{\tilde{G}}(j2\pi f_I)\rangle|^2}_{\substack{\text{Correlation between}\\ \text{frequency responses at } f_0 \text{ and } f_I.}}\cdot\underbrace{\frac{\alpha P_I S(f_I)}{\sigma^2 + \alpha P_I S(f_I)}}_{\substack{\text{Trade-off between}\\ \text{noise and interference}}}\right).$$

Insight: Even with optimal digital combining, performance can be improved by tuning the frequency responses $\vec{\tilde{G}}(j2\pi f_0)$ and $\vec{\tilde{G}}(j2\pi f_I)$.



Static Diversity Network: for some combinations of frequencies f_0 and f_I large losses are observed. This occurs mainly when the two frequencies are close.



Tunable Diversity Network: By allowing the network components to be tuned (within 20% of nominal values), excellent interference mitigation is possible even when frequencies are similar

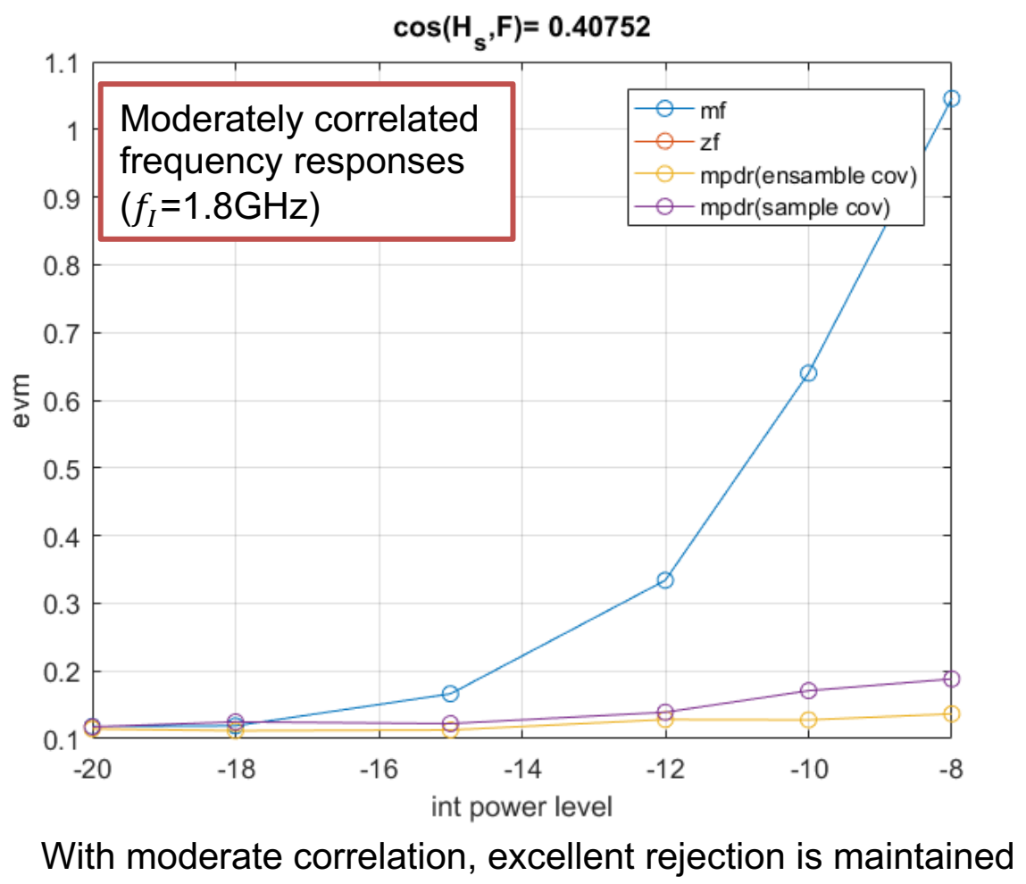
Performance with Experimental Data:

Experimental data were collected at Cornell. For this example:

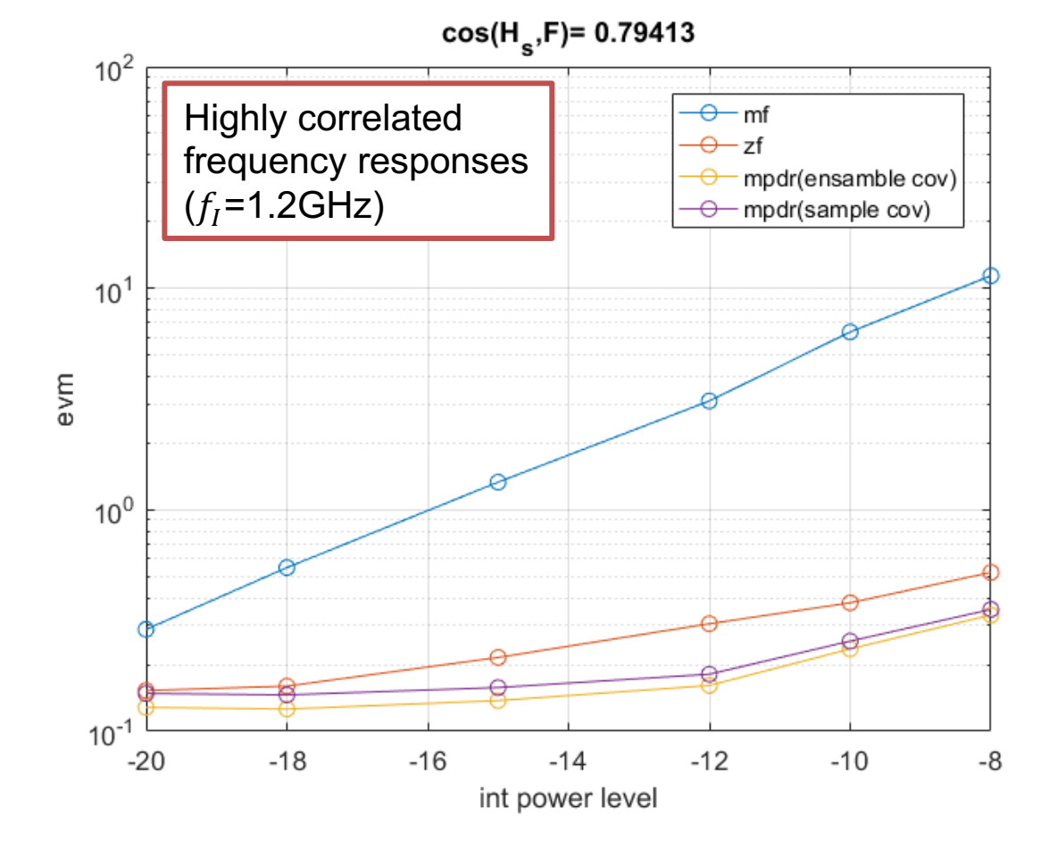
- Signal of interest: 16QAM, symbol rate 1.28 MHz, f_0 is 1.5GHz
- Interferer: strong CW signal at f_I 1.2GHz or 1.8GHz
- Interference mechanism: Intermodulation due to non-linear distortion (IM3)

Measured signal quality (EVM) after digital combining for three different linear combiners:

1. Matched filter – coherent combination of signal of interest; ignore interferer
2. Zero-forcing decorrelator – reject interferer regardless of noise gain; requires knowledge of frequency response at f_I.
3. MVDR – adaptive MMSE



With moderate correlation, excellent rejection is maintained even with very strong interference.

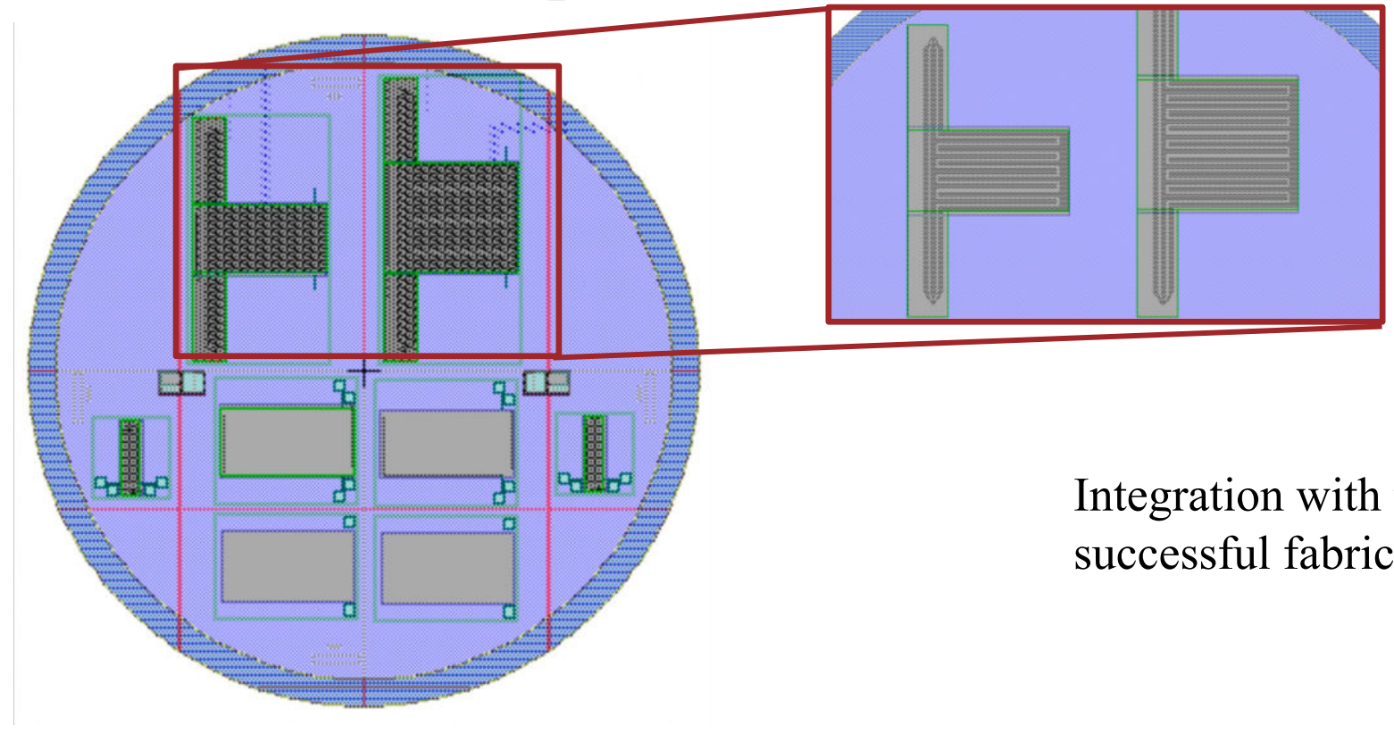


With strong correlation, good rejection is maintained even with very strong interference while MF fails completely.

Paris and Zhang, "Synthetic Diversity for Interference Mitigation in Widely Tunable receivers," *2024 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*

Remaining Tasks and Future Directions

Adaptive Device Fabrication and Integration



Silicon-integrated fabrication is currently underway for tunable phase shifters and quarter-wave resonant waveguides.

Integration with the receiver front end will follow successful fabrication and characterization.

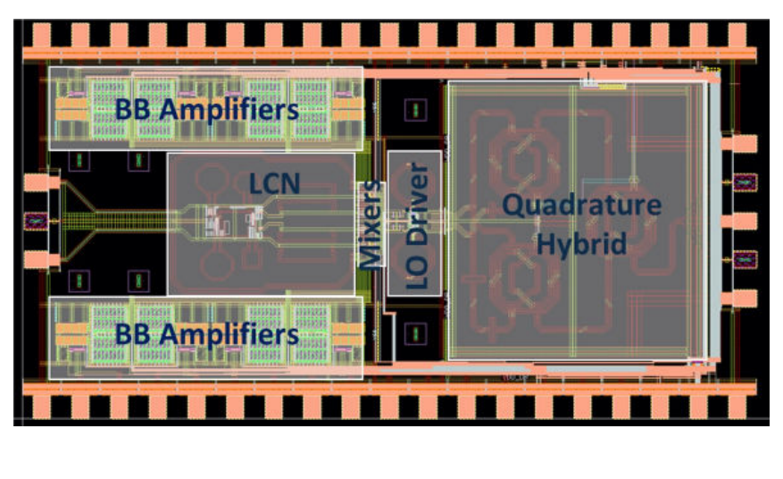
System Optimization

- Improve optimization of network elements via rational function optimization to reduce computational complexity.
- Fully develop feedback control system to adjust element values of network.
- Support for multiple receiving antennas.

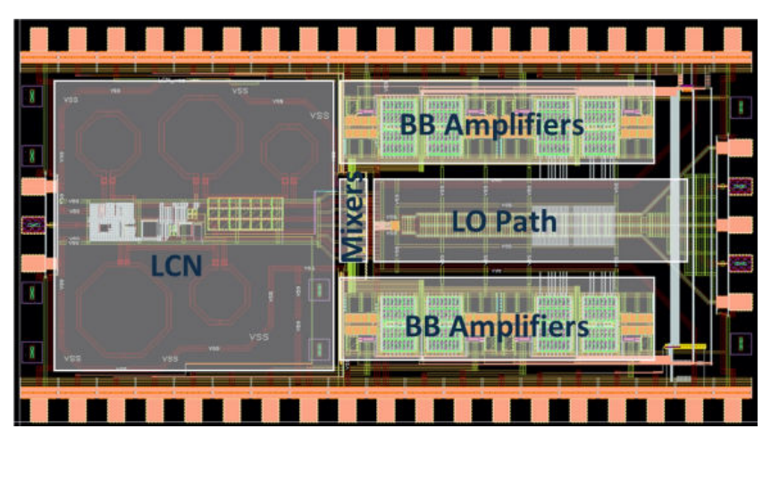
Receiver Chain Optimization and Frequency Scaling

- Intel 16nm FinFET
- Passive mixer-first
  - Higher OOB linearity
- Higher Frequencies
  - PN gets worse → Artifact mitigation is more necessary

12-24 GHz

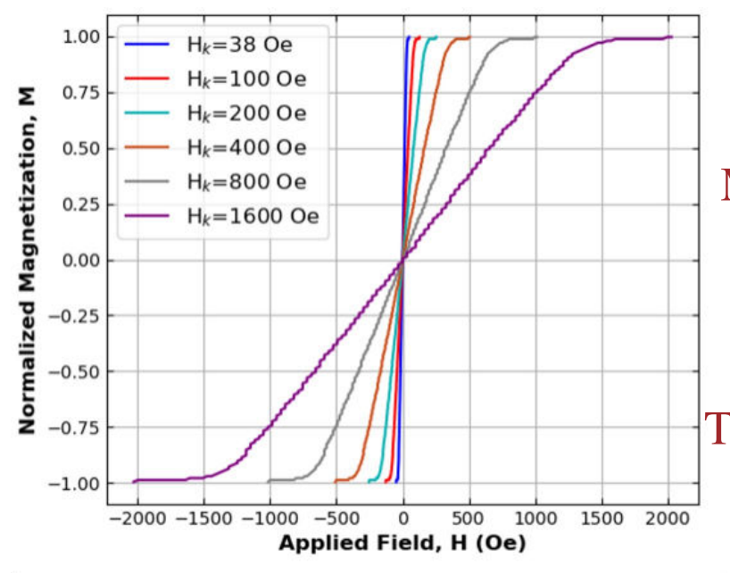


3-6 GHz

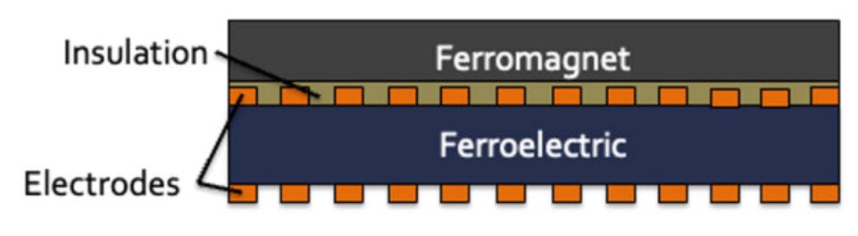


Development of Adaptive RF Magnetic Devices

Tuning in Adaptive Magnetic Components – permeability and resonance frequency are controlled by magnetic anisotropy. In-situ tuning increases the magnetoelastic anisotropy through strain. The strain is generated by voltage control to a piezoelectric layer coupled to the magnet.



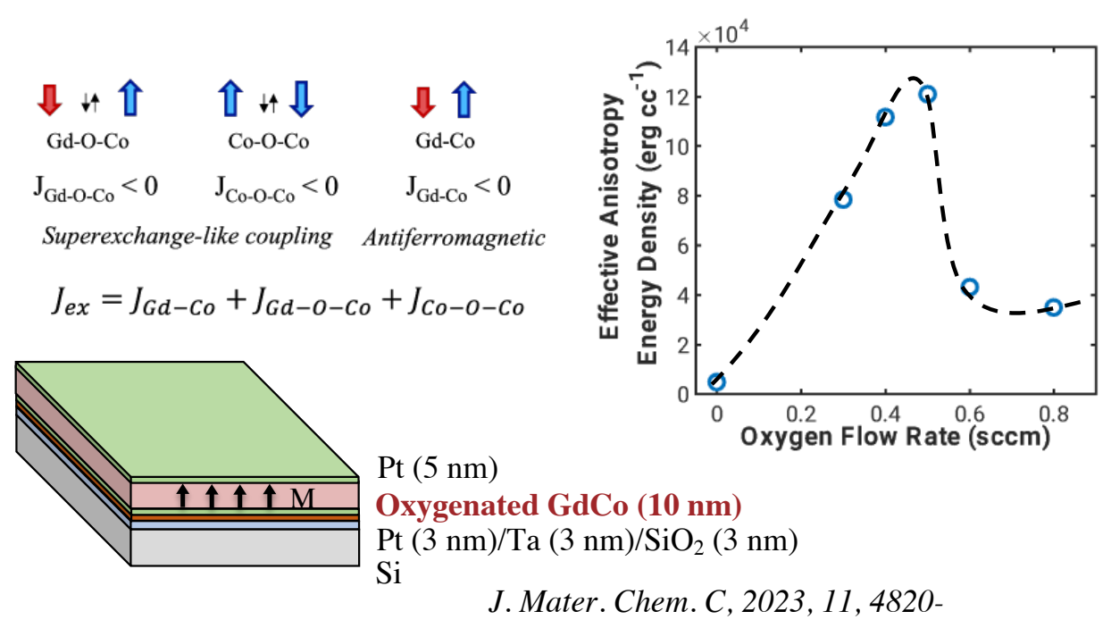
Large Anisotropy Field (H_K) for Microwave Bandwidth



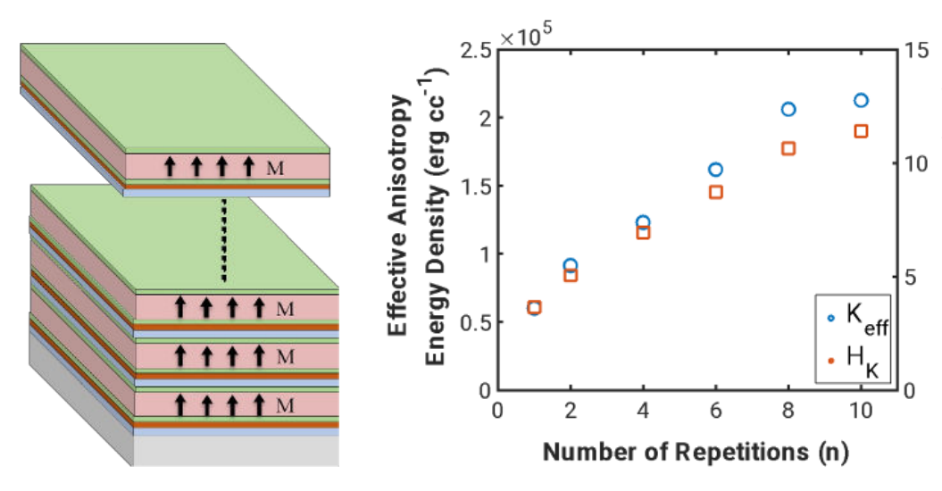
Tunable Magnetic Anisotropy for Adaptive Permeability

Perpendicular Magnetic Materials and Tunable Circulators

Perpendicular Magnetic Materials – In-plane magnetized radio frequency thin-film materials have long been available. Here, Bias-free perpendicularly-magnetized materials have been developed as a step towards enabling compact circulators and other non-reciprocal components for integrated transceivers.

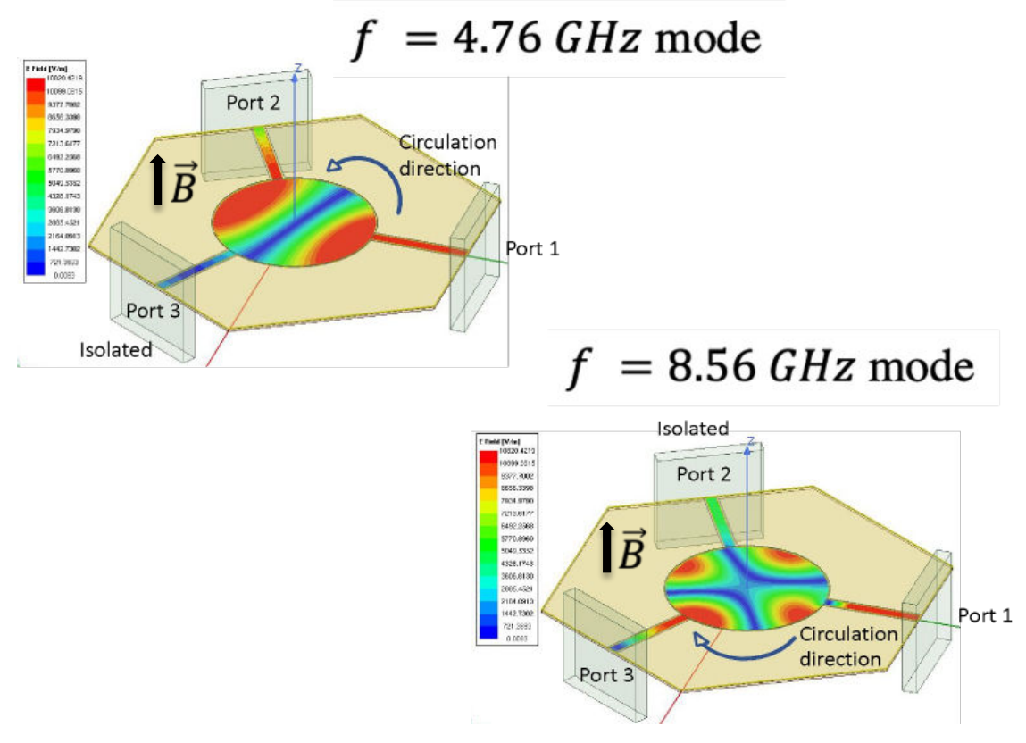


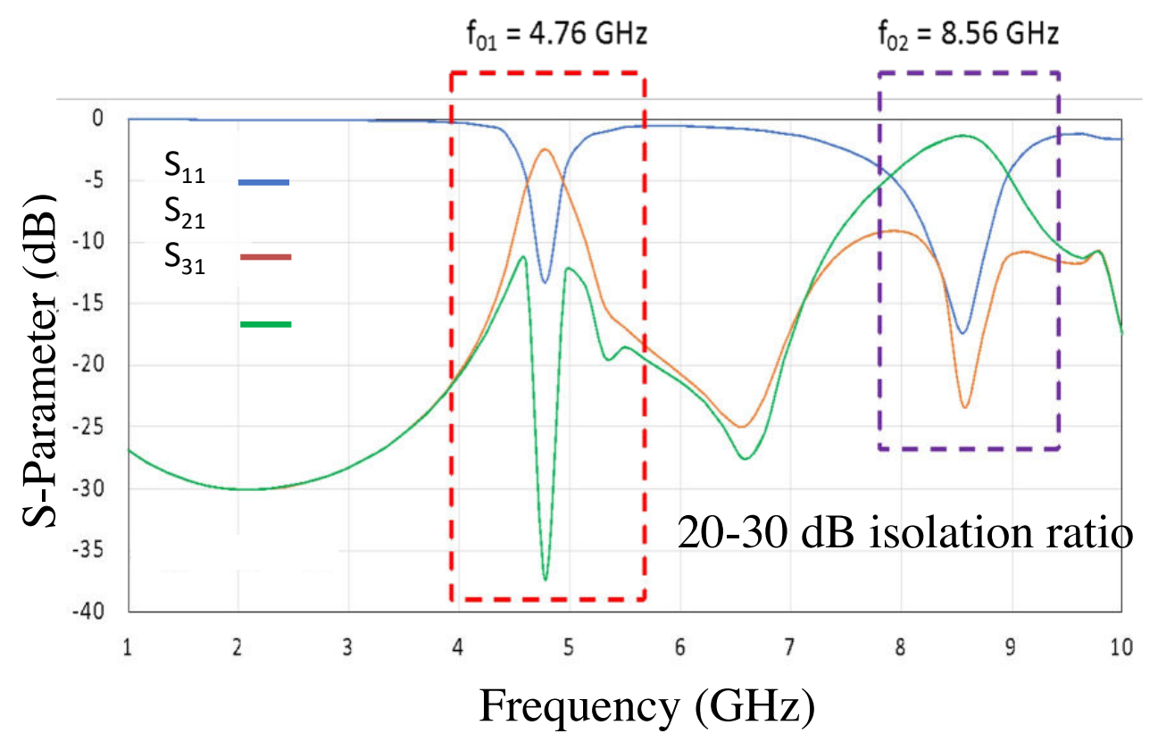
J. Mater. Chem. C, 2023, 11, 4820-4829



For n = 10, H_k = 11 kOe ----> f ~ 30 GHz

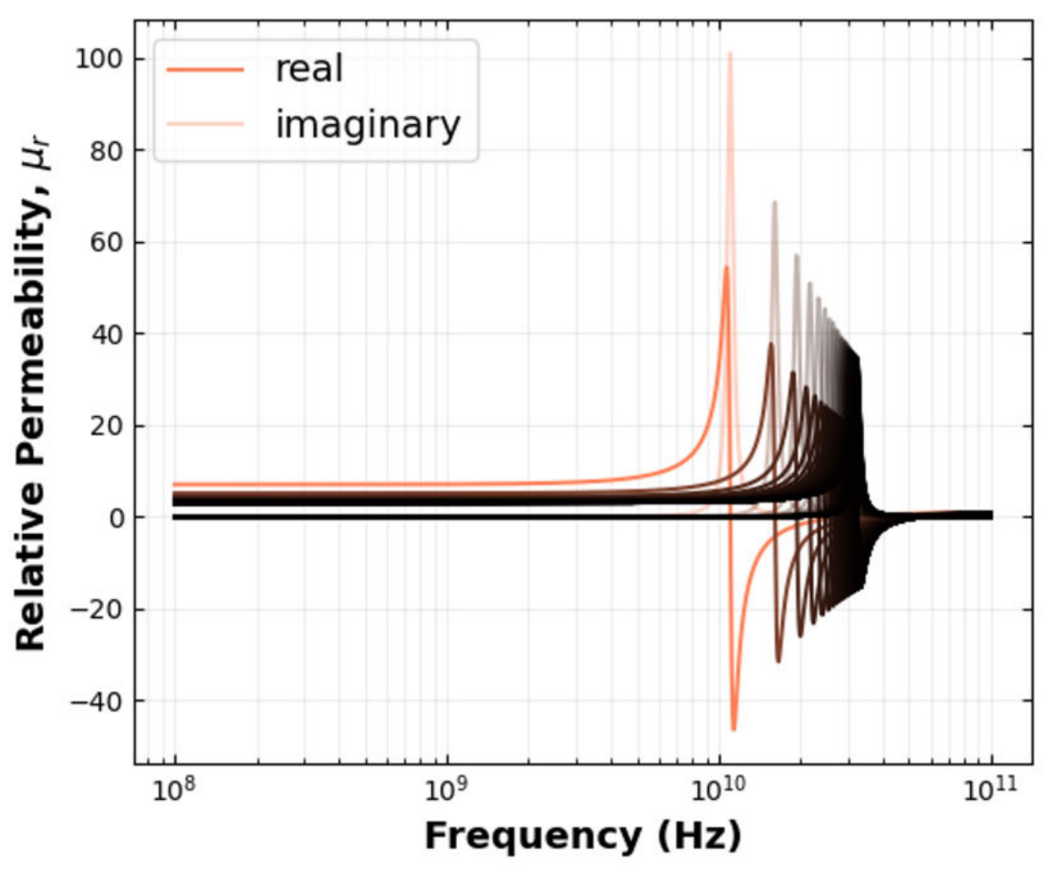
Tunable Circulators – Circulators are 3-port ferrite-based non-reciprocal devices that allow signal propagation in either clockwise or counter-clockwise direction. Tunable operation is possible with higher order modes.

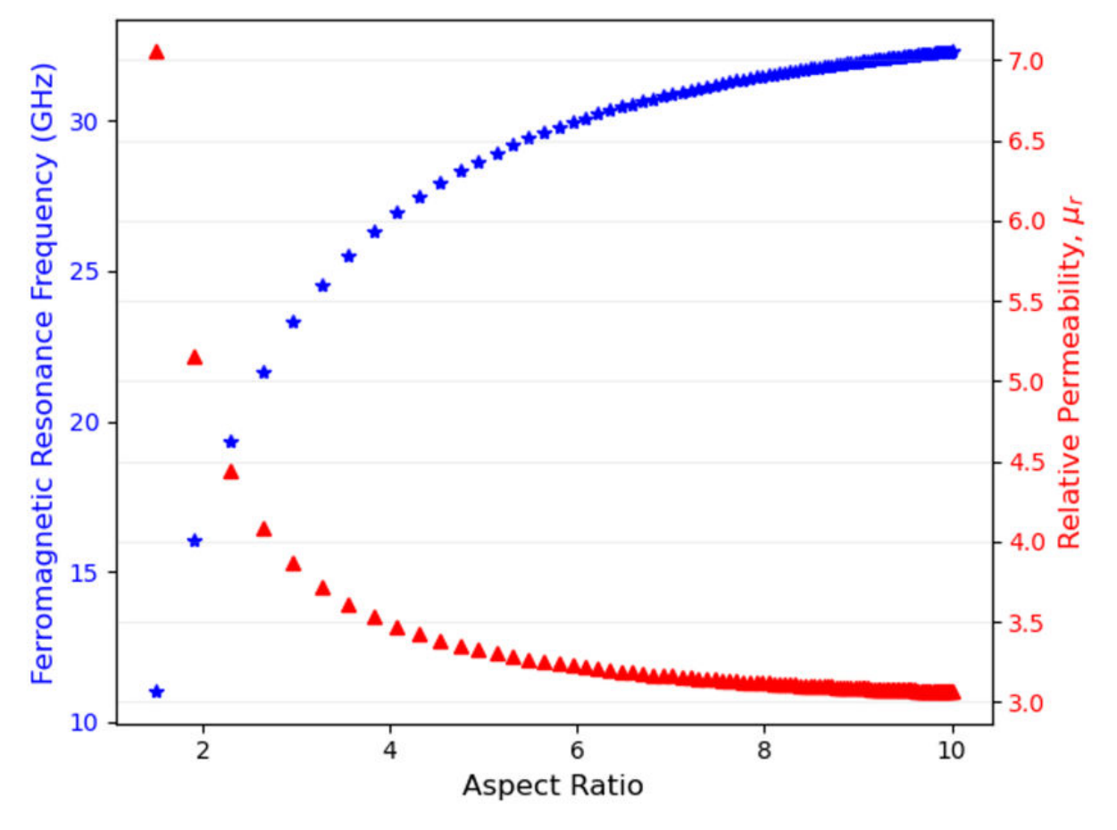




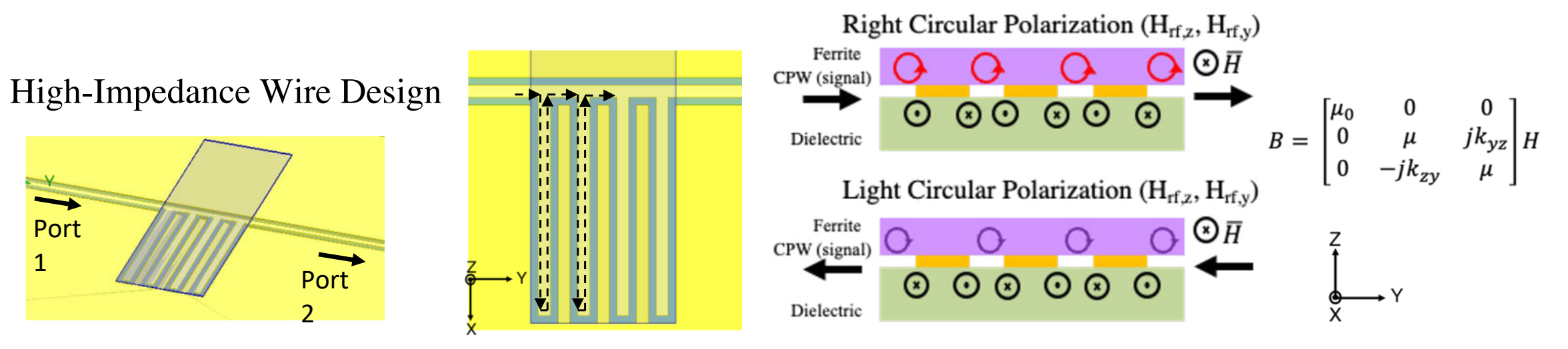
In-Plane Magnetic Materials and Tunable Phase Shifters

In-Plane Magnetic Materials – Thin-film magnetic materials like CoFeB, FeCo and GdCo will be biased during deposition to achieve constant tunability up to high frequencies and subsequent voltage tuning of the permeability and bandwidth through coupling to a piezoelectric film.





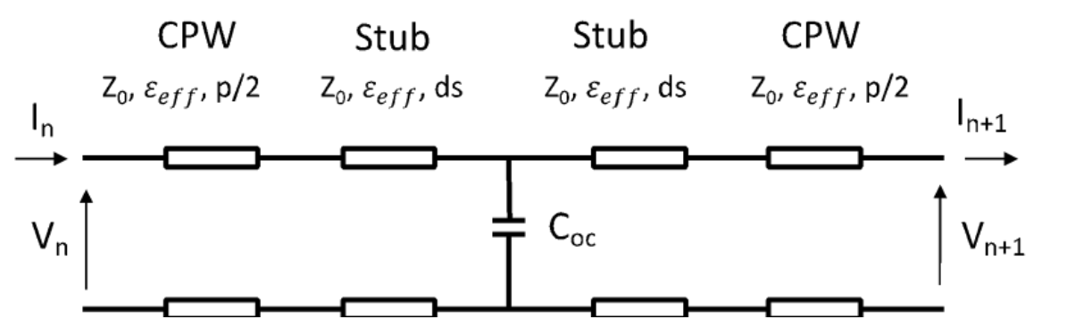
Tunable Phase Shifters – Non-reciprocal phase shifters based on high-impedance wire design offer tunable phase difference between the input and output selectively for a transmission direction.



$$B = \begin{bmatrix}\mu_0 & 0 & 0\\ 0 & \mu & jk_{yz}\\ 0 & -jk_{zy} & \mu\end{bmatrix}H$$

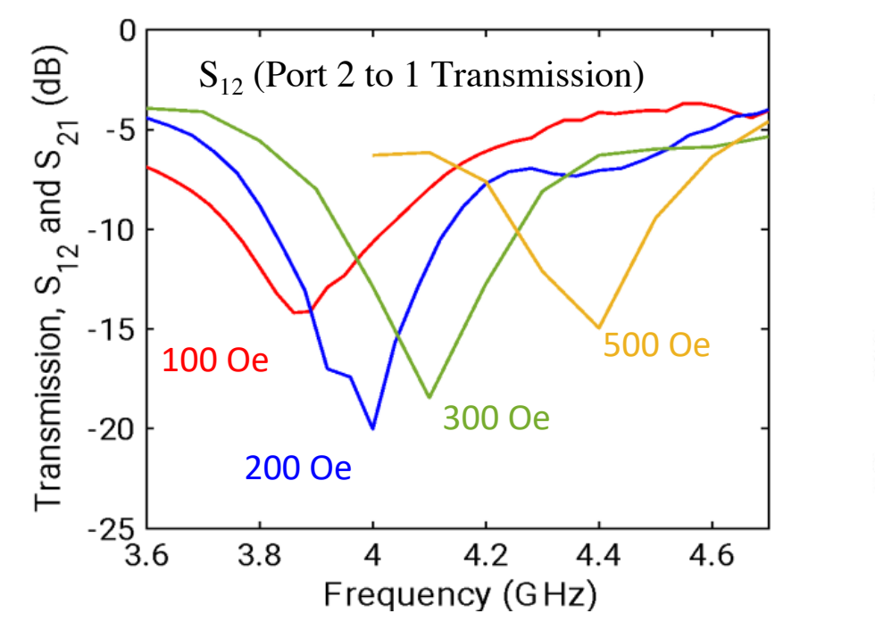
Strong ferromagnetic resonance and phase shift for LCP waves or reverse transmission.

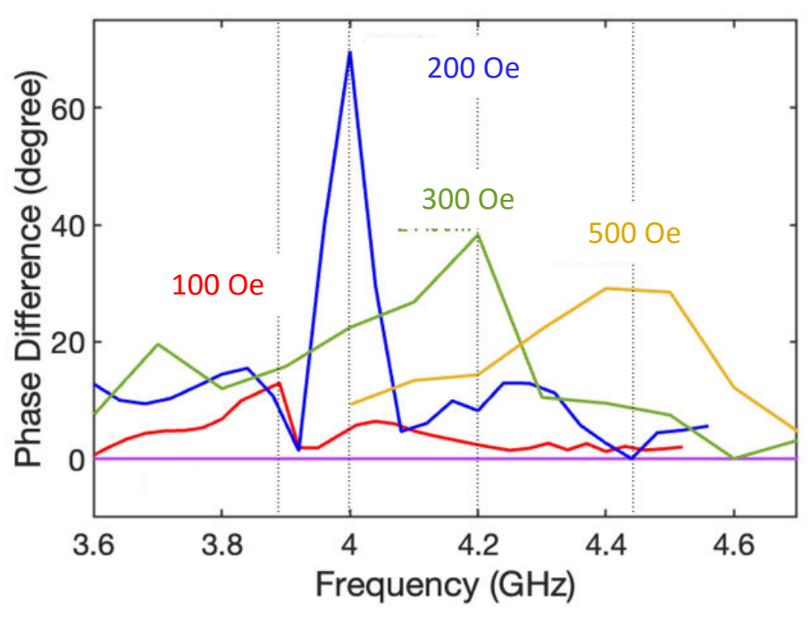
Circuit Model



$$\begin{bmatrix}S11 & S12\\ S21 & S22\end{bmatrix} = \frac{e^{-j\beta\theta}}{(4+Zs^2)}\begin{bmatrix}-Zs*(Zs+2j) & 2(2-jZs)\\ 2(2-jZs)*e^{-j\beta_{NR}d_s} & -Zs*(Zs+2j)\end{bmatrix}$$

HFSS Model





2023 International Microwave and Antenna Symposium (IMAS), 2023, pp. 62-65

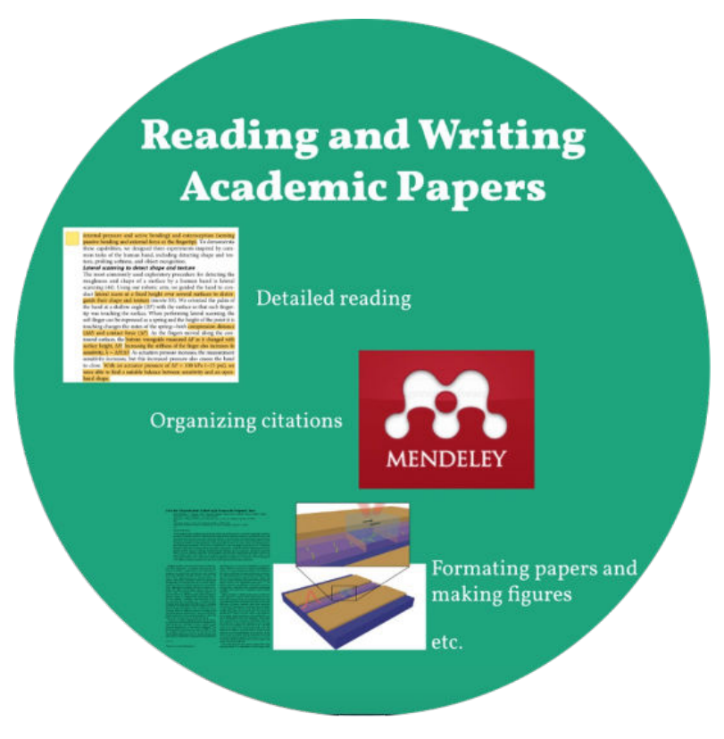
Tunable phase difference over a bandwidth of 600 MHz is possible with just 400 Oe of tuning field!

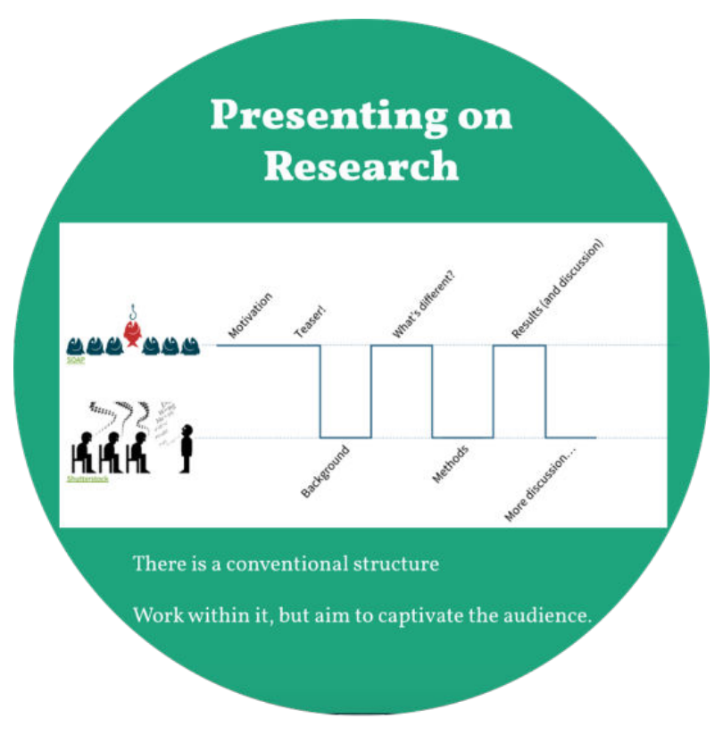
Broader Impacts

Seminar Course – URM first-year doctoral students are taught the essentials “soft skills” needed to be successful in their doctoral degrees. The goal: increase retention of URM doctoral students in engineering.

“Survival Skills”

(Just to name a few…)

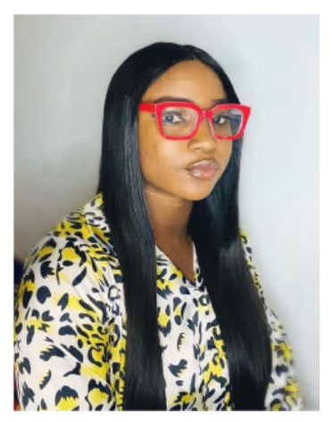




This research would not have been possible without the *students and postdoc* in training!

Karthik Srinivasan
Postdoc, Cornell

Sanaz Sadeghi
Ph.D. Student, Cornell



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