We1F-5

A Full Duplex RF Front End Employing an Electrical Balanced Duplexer and a Chebyshev Load-Balancing Filter

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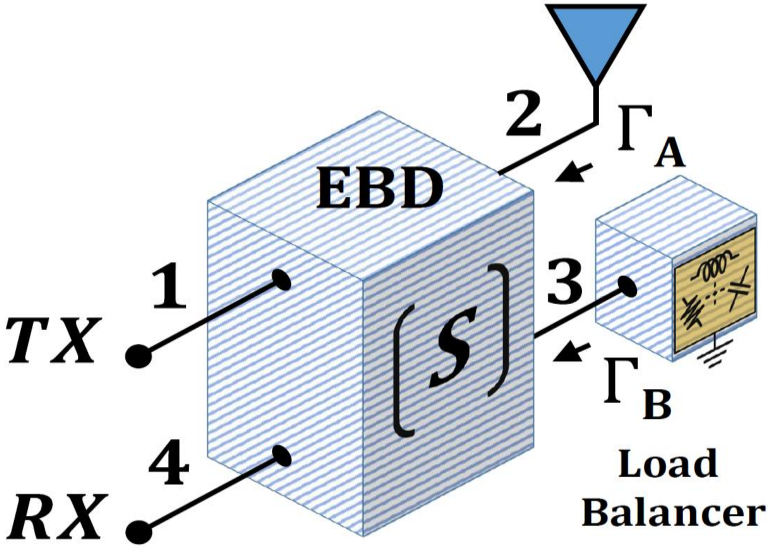
Outline of the Talk

- **Introduction –** Self-Interference Cancellation in electrical-balance duplexer (EBD) RF front-ends
- **Motivation -** Introduce **theoretical bounds** and methodical steps to achieve **optimal design** in practical self-interference cancellation (SIC) networks
- **The solution proposed in this work**
  - **Consider practical EBD RF front-end and antenna**
  - **SIC Load-Balancer (LB) design is equivalent to impedance matching**
  - **Fano-Bode limit - Impedance matching as SIC bandwidth integrals**
  - **Chebyshev BPF – an optimal extraction of the Fano-Bode bound**
  - **SIC - BW performance simulations vs. test results**
  - **Comparison with other reported works**
- **Conclusions**

Self-Interference Cancellation (SIC) in Electrical-Balance duplexer (EBD) RF front-ends.



TX Leakage — **Self-interference Cancellation**

$$S_{41_D} \approx S_{41} + \Gamma_A S_{21} S_{42} + \Gamma_B S_{31} S_{43}$$

$$\Gamma_{B\,ideal} \approx -\frac{S_{41_Q}}{S_{31_Q} S_{43_Q}} - \Gamma_A$$

Short delay — **Long delay**

a) Quadrature hybrid (or 0/180º). Passive/Compact. 3dB TX and RX Loss

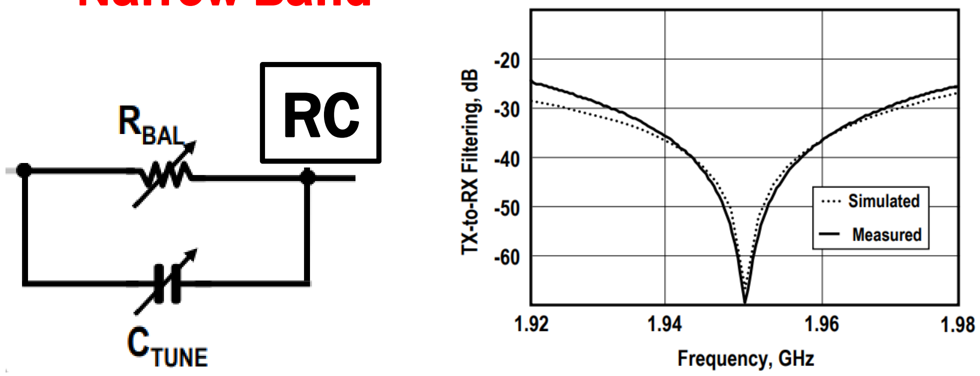
b) Load Balancer network. Lumped/Compact integrated SIC. Accuracy/Tunability and linearity are critical

Motivation – Introduce **Theoretical Bounds** and **Optimal Design** for the Self-Interference Cancellation

RC Load Balancer Network:

[Mikhemar, ISSCC '09]

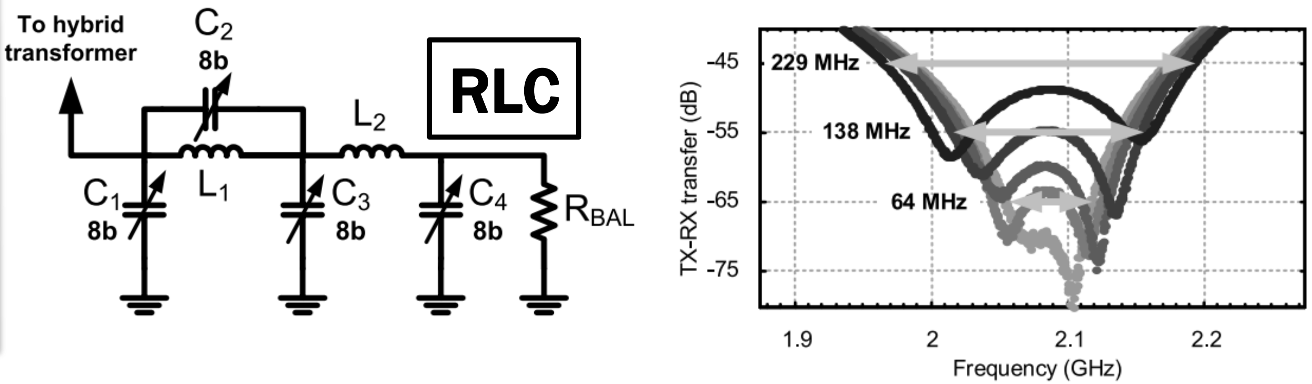
- ✓ Tunable
- – Non-compatible with real antenna SIC
- – Narrow Band



RLC Load Balancer Network:

[Van Liempd, TMTT '16]

- ✓ Tunable wide-band SIC performance
- ✓ Commercial antennas compatibility
- – Analysis of SIC LB design

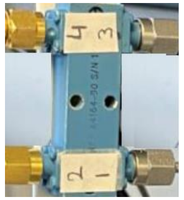


Objectives of this work:

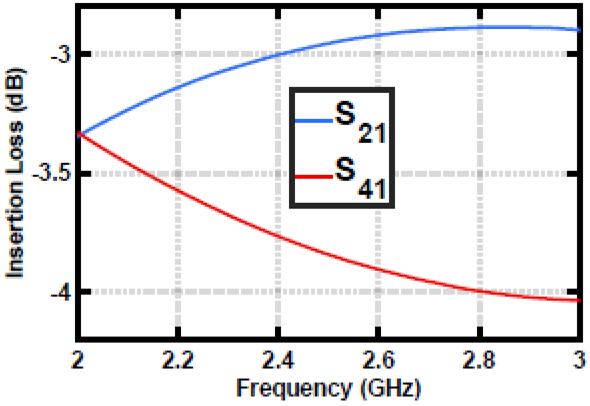
a) Analyze and define the **SIC-BW relationship** (SIC depth vs. Bandwidth)

b) Obtain an **optimal load-balancer network** to achieve maximum SIC-BW

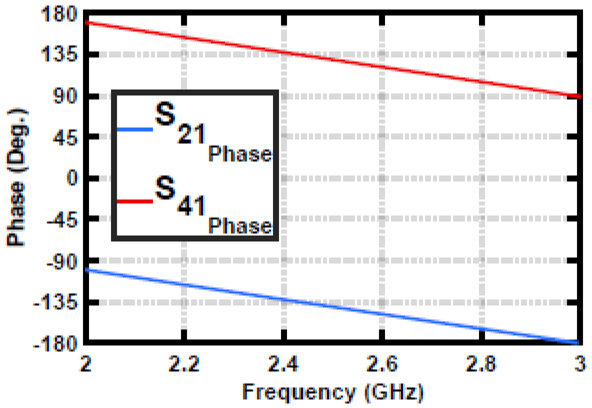
Practical EBD RF Front-End and Antenna



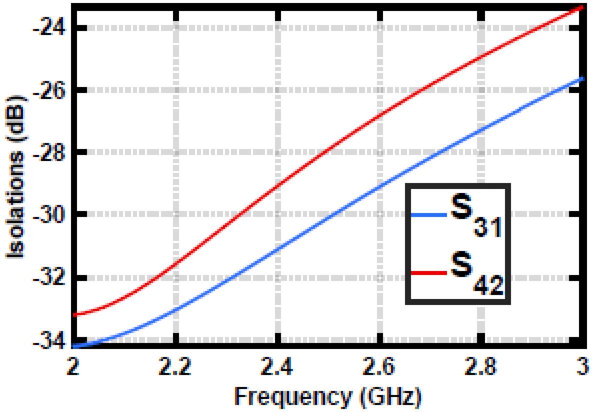
Quadrature Hybrid:
ARRA A4164-90

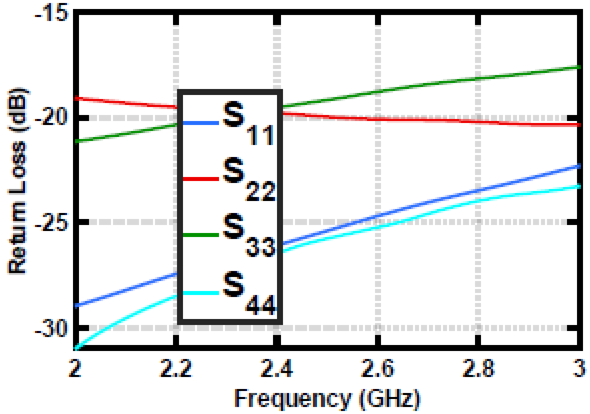


(a)



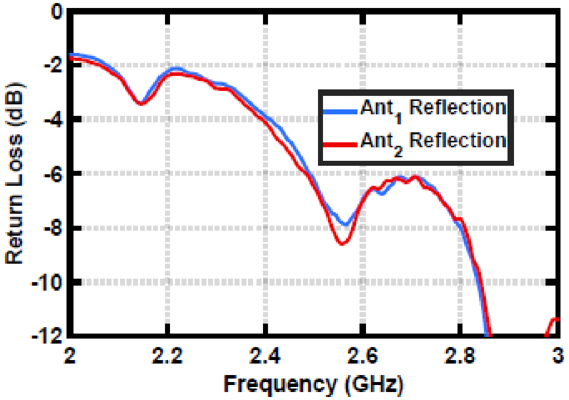
(b)

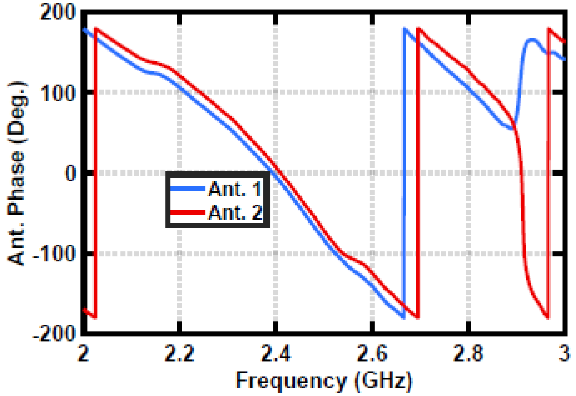




Antenna:
TAOGLAS FXP830.07.0100C

Free-space reflection coefficient test results for two commercial antenna samples





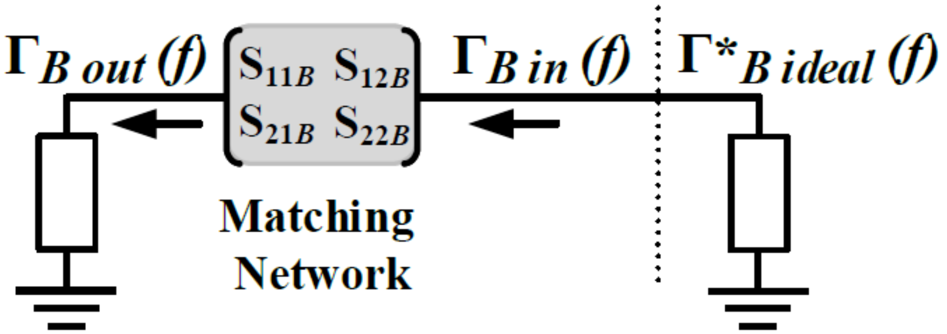
Load-Balancer design and Impedance matching

Γ_B- Load-Balancer reflection coefficient

$$\Gamma_B = S_{11_B} + \frac{S_{21_B} S_{12_B} \Gamma_{B_{OUT}}}{1 - S_{22_B} \Gamma_{B_{OUT}}} \quad (5)$$

where $\Gamma_{B_{OUT}}$ is the reflection coefficient of the LB load. For simplicity of implementation (and calculation), we assume an open circuit as the output of the balancer, hence full reflection ($\Gamma_{B_{OUT}} = 1$). Moreover, passive LB designs reduce (5) to

$$\Gamma_B = S_{11_B} + \frac{(S_{21_B})^2}{1 - S_{11_B}} \quad (6)$$



Short delay

Long delay

Load Balancer (LB) network design:

- **Similar terms** for the **ideal SIC** ($\Gamma_{B\ ideal}$) and **LB** (Γ_B) reflection coefficients

$$\Gamma_{B\ ideal}(f) \approx -\frac{S_{41_Q}(f)}{S_{31_Q}(f) S_{43_Q}(f)} - \Gamma_A(f) \approx S_{11_B}(f) + \frac{(S_{21_B}(f))^2}{1 - S_{11_B}(f)}$$

TX Leakage

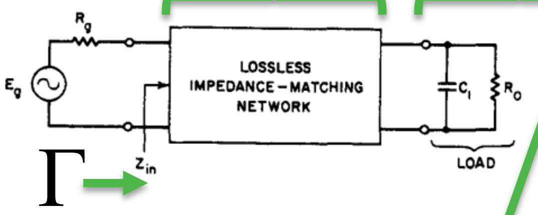
SIC Signal

- **LB design is equivalent to impedance matching**
- Dictate **conjugate matching with** $\Gamma^*_{B\ ideal}$

Fano-Bode limit - Impedance Matching Bandwidth

Bode

Matching Network | RC Load



$$\int_0^\infty \ln\left|\frac{1}{\Gamma}\right| d\omega = \frac{\pi}{R_0 C_1}$$

Constant
ln|$1/\Gamma$| integral

H. W. Bode,
"Network Analysis and Feedback Amplifier Design", Bell Labs, 1945.

- **Bode** related the **maximum magnitude of the reflection coefficient Γ(ω),** as seen by a real source with an **RC load.**

Fano

Matching Network | Arbitrary Reactive Load

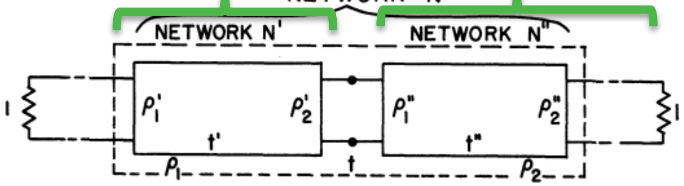


Figure 3. Two reactive networks in cascade.

$$\int_0^\infty g(\omega) \ln \frac{1}{|\Gamma(\omega)|} d\omega \leq A$$

where $g(\omega)$ is a weighting function that depends on the transmission zeros of the reactive network of the load when cascaded with the matching network. A is related to the reactive load and may also depend on the matching network.

R. Fano,
"Theoretical limitations on the broadband matching of arbitrary impedances," Journal of the Franklin Institute, 1950.

- **Fano generalized** the impedance matching problem for **any rational reactive load.**

Fano-Bode Limit and the SIC-BW Relationship

Matthaei, Young, and Jones, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures," , Artech House, 1980.

Mismatch error = SIC error

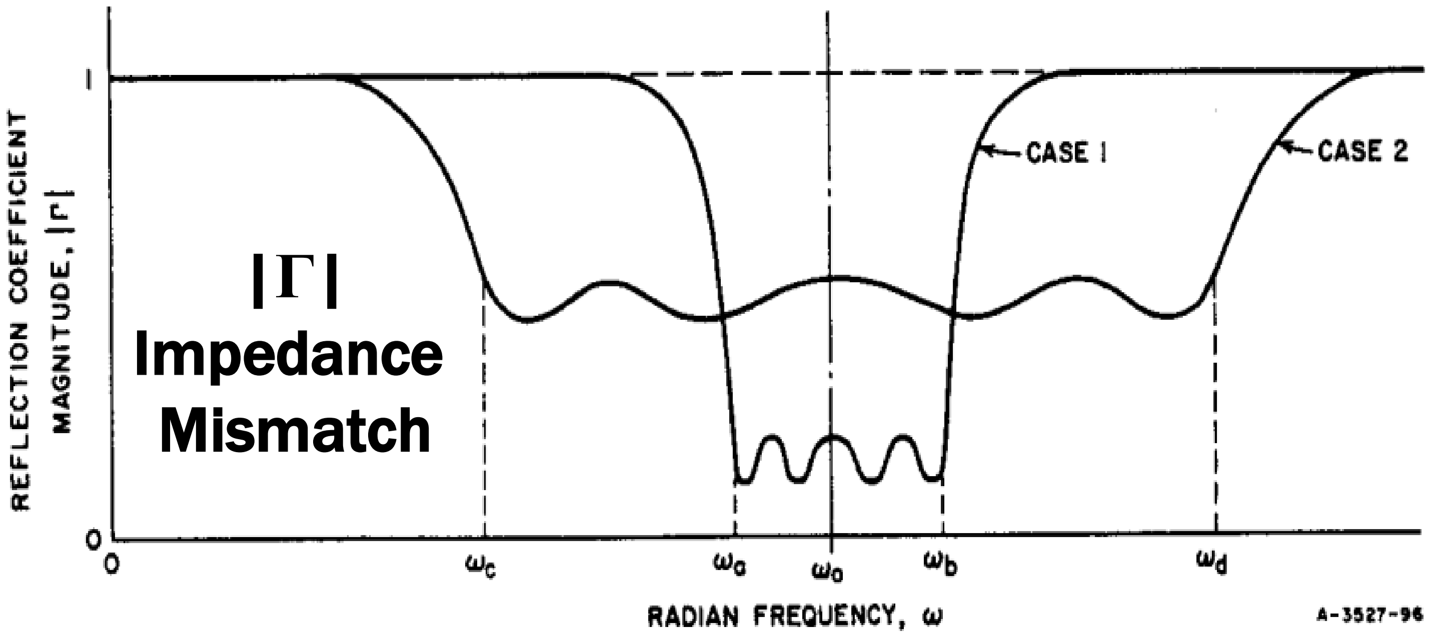
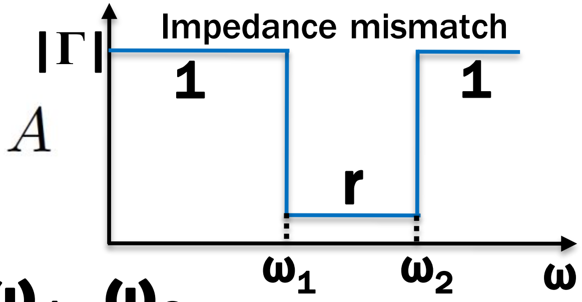


FIG. 1.03-2 CURVES ILLUSTRATING RELATION BETWEEN BANDWIDTH AND DEGREE OF IMPEDANCE MATCH POSSIBLE FOR A GIVEN LOAD HAVING A REACTIVE COMPONENT

- **Impedance-matching relationship, illustrates the SIC-BW trade-off**

Optimal Extraction of the Bound - Chebyshev BPF

$$\ln\frac{1}{r}\int_{\omega_1}^{\omega_2} T(\omega)d\omega \simeq A$$



Target impedance mismatch

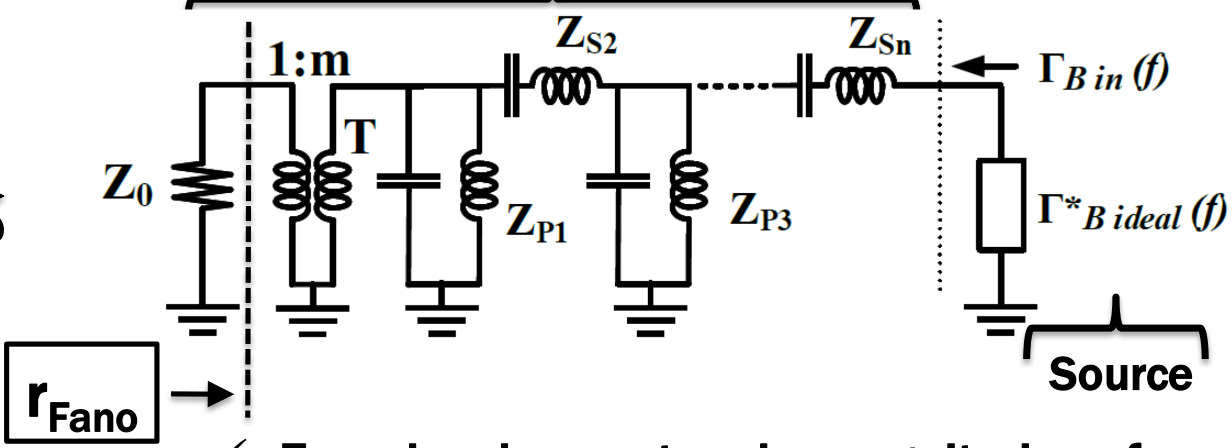
ω_1, ω_2

BPF corner frequencies

SIC - BW Integral

Mismatch error = SIC error = r

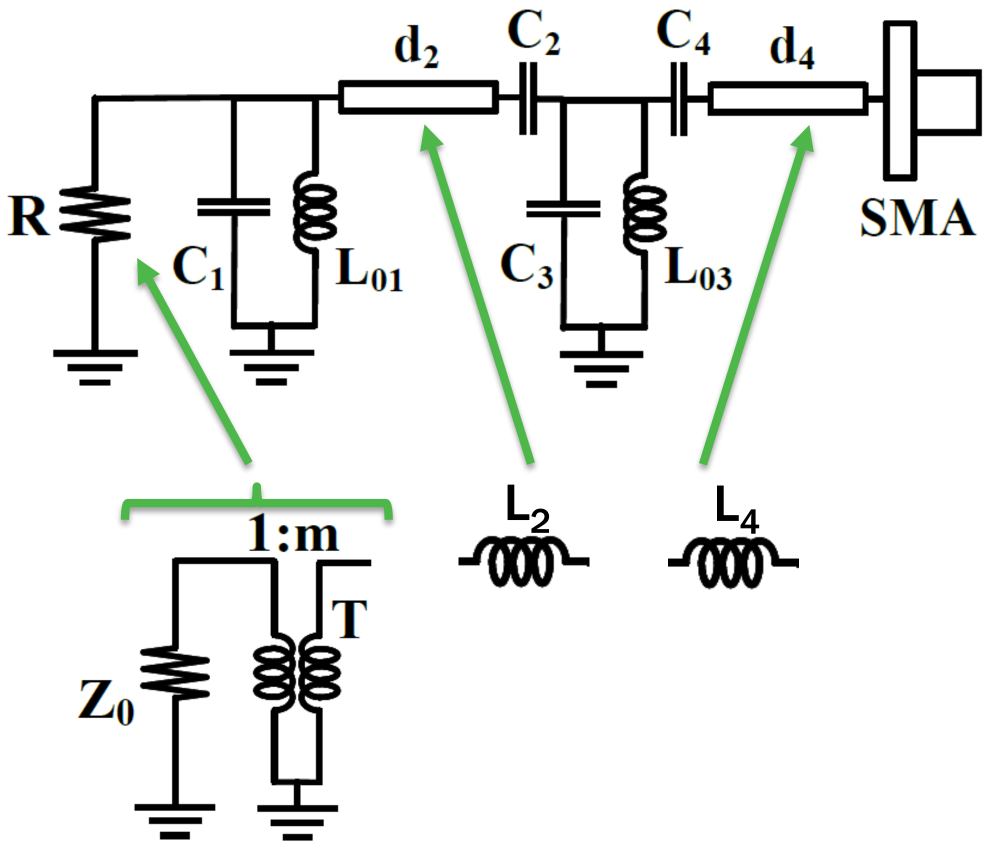
Chebyshev Matching Network

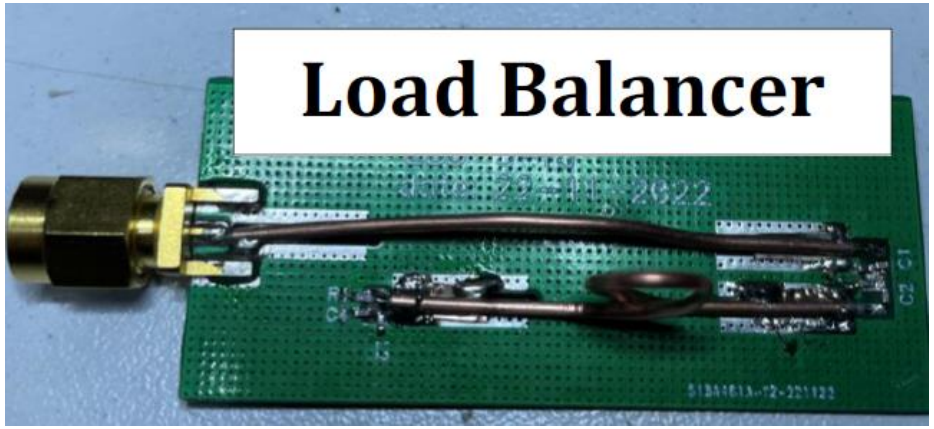


- ✓ **For a lossless network, magnitudes of input and output mismatches are equal!**
- ✓ **BPF** is a **displaced LC LPF @ $\omega_0=\sqrt{\omega_1\omega_2}$**

- A **BPF matching network** enables an **optimal extraction of the bound**
- **Ideal** extraction requires **square shaped BPF,** hence **infinitely high-order filter**
- **High order** filter enables an **approximation of a square shaped BPF**

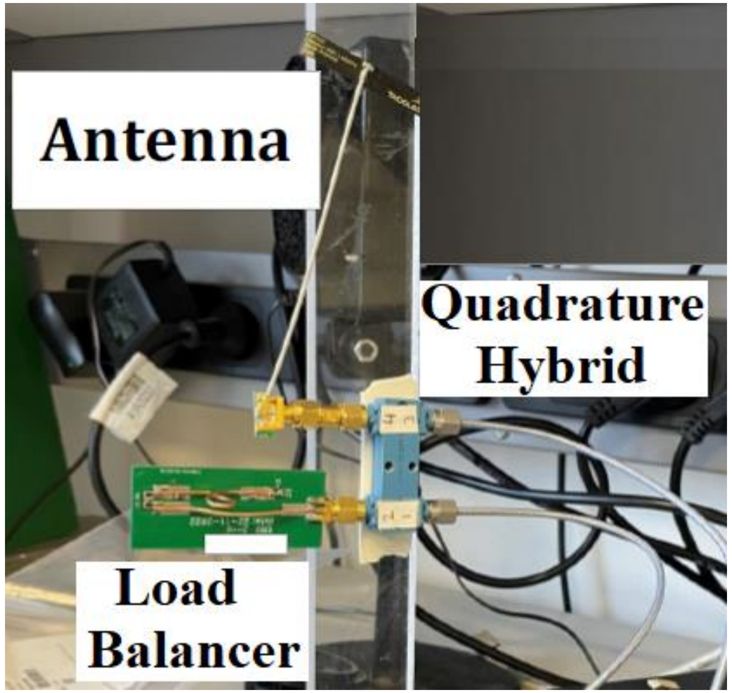
Chebyshev 4th Order Load Balancer

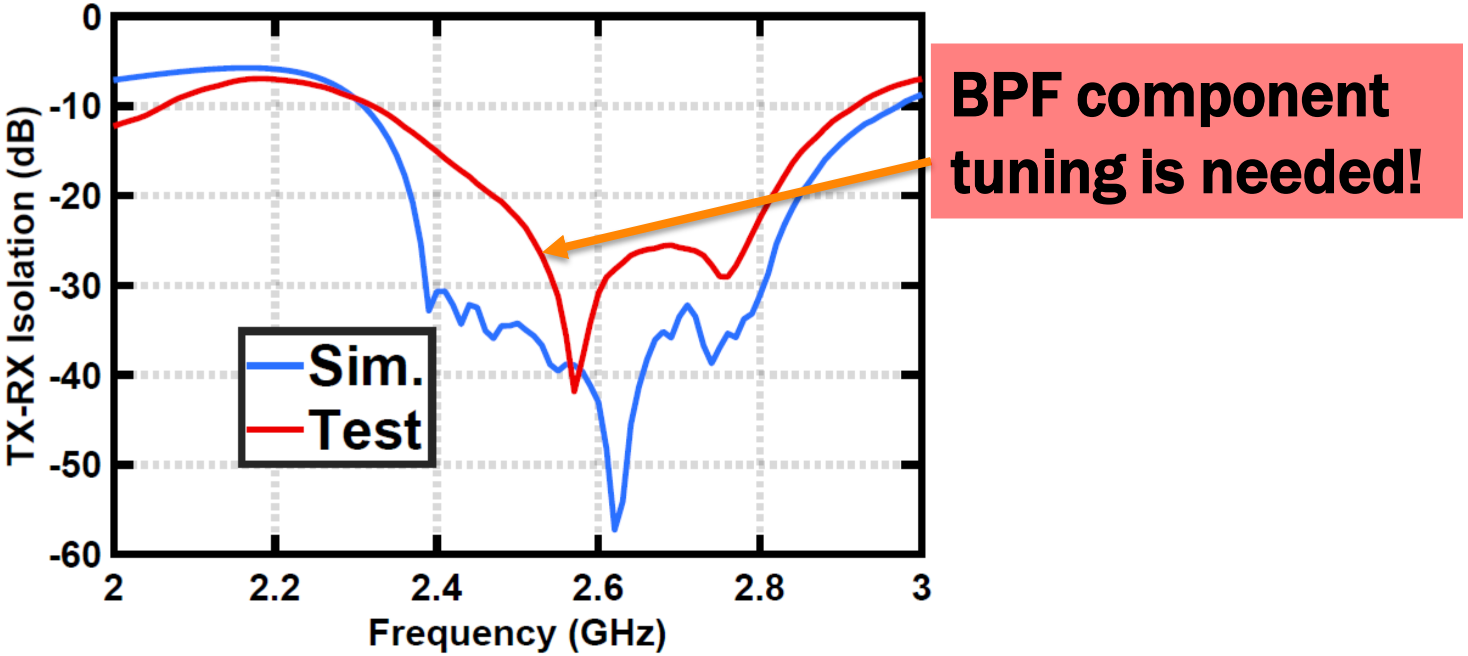




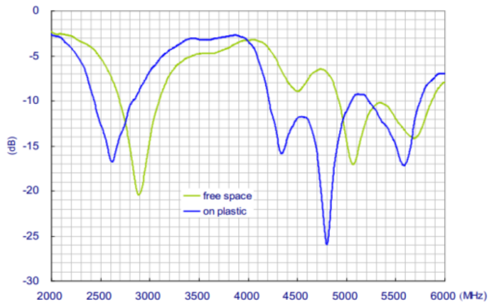
- Series inductors with high inductance were replaced with transmission lines
- A resistor replaced the transformed Z_0 load

Practical EBD Measured Results





- **Antenna and quadrature hybrid were connected by SMA and reinforced together to a mechanical Perspex sheet**
- **Antenna on Perspex deviated from free-space performance**
- The **BPF components were adjusted accordingly**



Comparison with Prior Art EBD

	f_0	Antenna	Balancer	SIC BW
[2]	1.95 GHz	50 Ω	40 nm CMOS RC Tunable	50 dB 6 MHz
[4]	2.08 GHz	50 Ω	0.18-μm SOI CMOS RLC 8 bit Tunable	45 dB 230 MHz
[8]	1.89 GHz	Yes 10 dBr	Electromechanical Tuner	40 dB 20 MHz
This work	2.65 GHz	Yes 7 dBr	Chebyshev on PCB Un-Tuned	25 dB 300 MHz

- **TX leakage** is highly **dependent** on the **antenna reflection magnitude** and the respective equivalent **reactive order**
- **SIC performance for a 50 Ω load is much better than for a real Wi-Fi antenna**
- **Tuning capability and network tolerances are critical for SIC performance**

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Conclusions

SAN DIEGO 2023

- Introduced the **Fano-Bode integral** as a **SIC - BW theoretical bound**

- Presented methodical steps and **Chebyshev filters load balancers** for achieving optimal design for the Self-Interference cancellation (SIC)

- **Cancelation** and tuning of any TX leakage becomes **more challenging when the equivalent order of the leakage increases.** Load balancer filter tuning is required

Thank you for your attention!