Full Duplex Wireless: From Fundamental Physics and Integrated Circuits to Complex Systems and Networking

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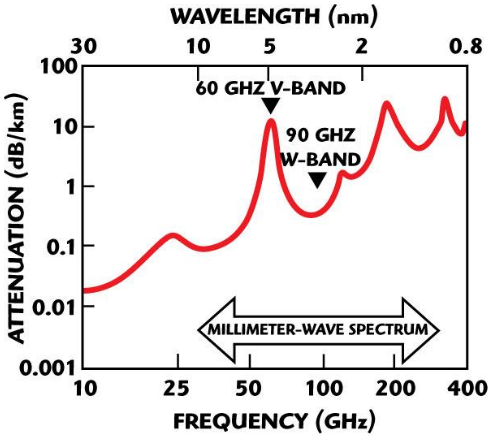
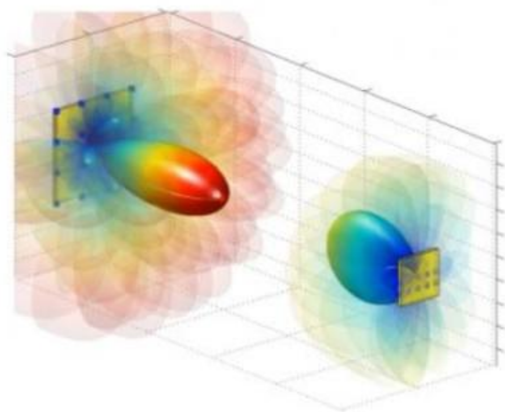
Overview

- **Introduction**
- Full Duplex Wireless
- FD at the Higher Layers
- Conclusion

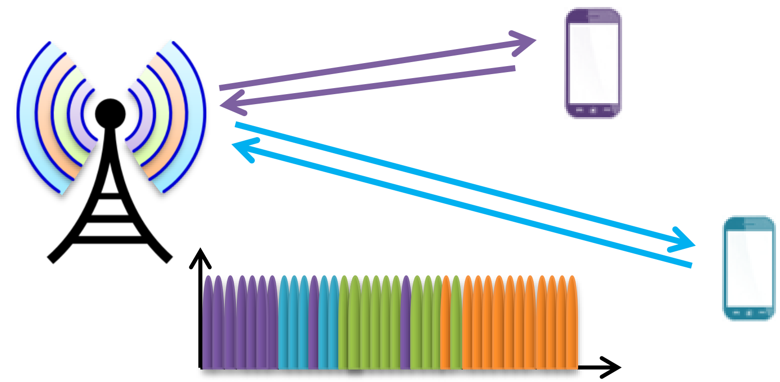
Emerging Wireless Paradigms

mmWave Mobile

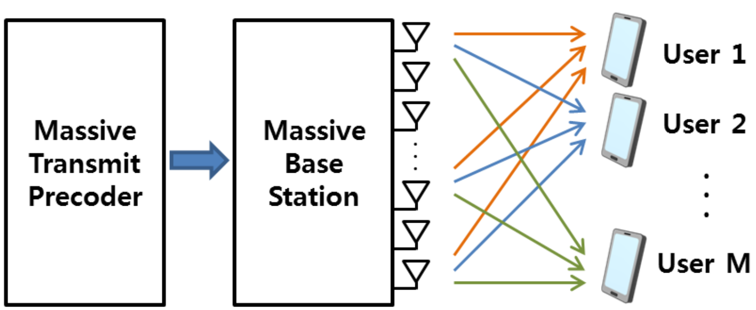




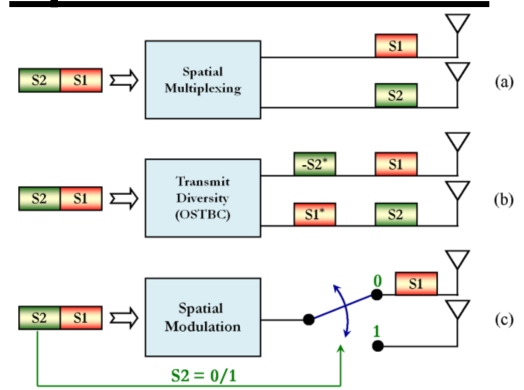
Full Duplex Wireless



Massive MIMO



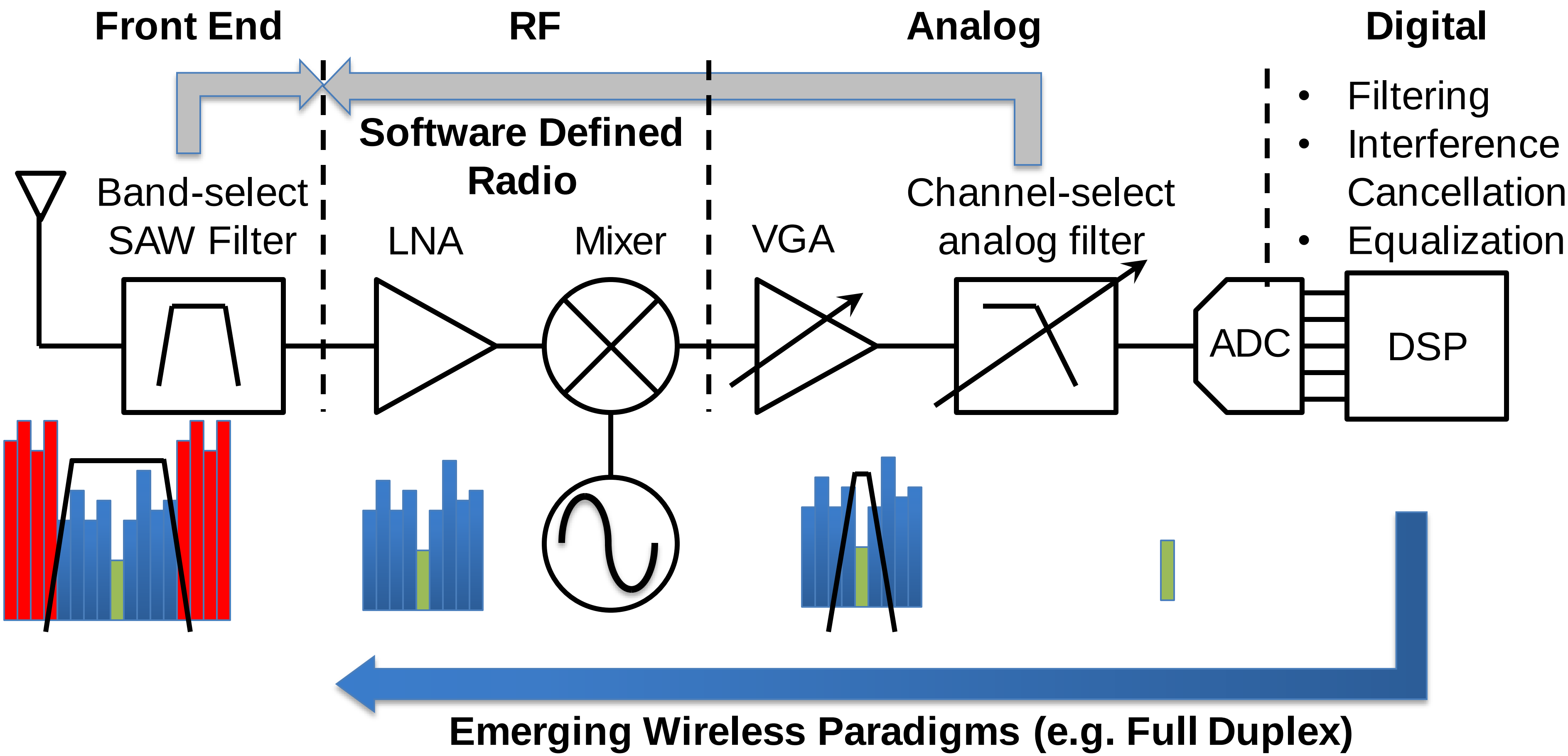
Spatial Modulation



Next generation (5G) communication systems are targeting 1000x increase in data capacity!

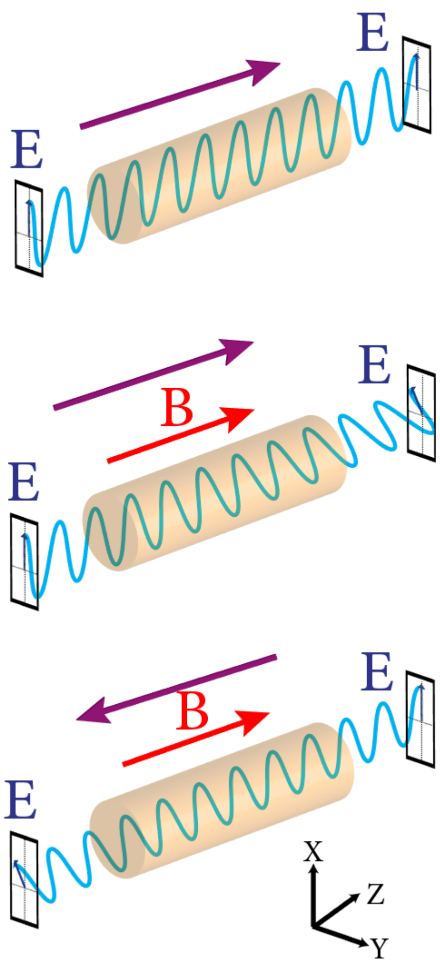
Images courtesy Microwave Journal, University of Bristol, Proc. IEEE

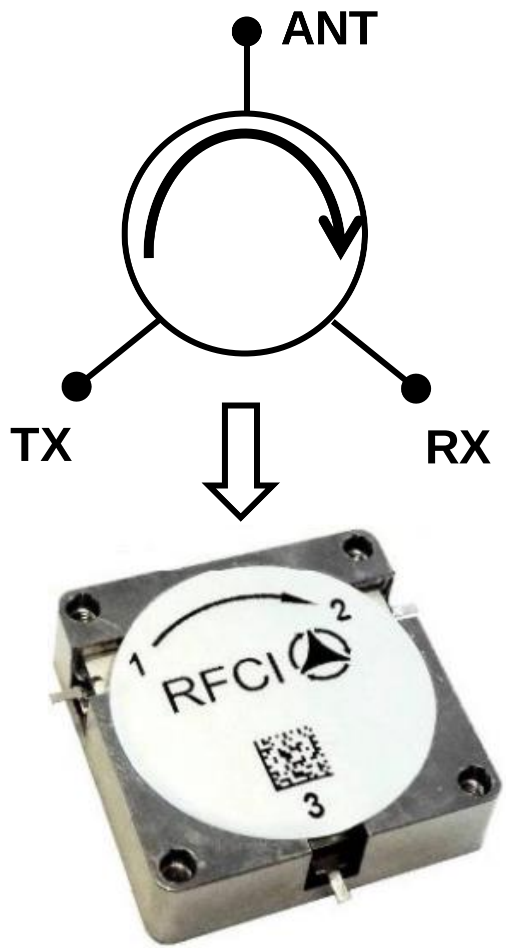
Signal Processing at the Antenna?



Can we move complex analog and digital signal processing to RF *at the antenna* to enable new functionalities?

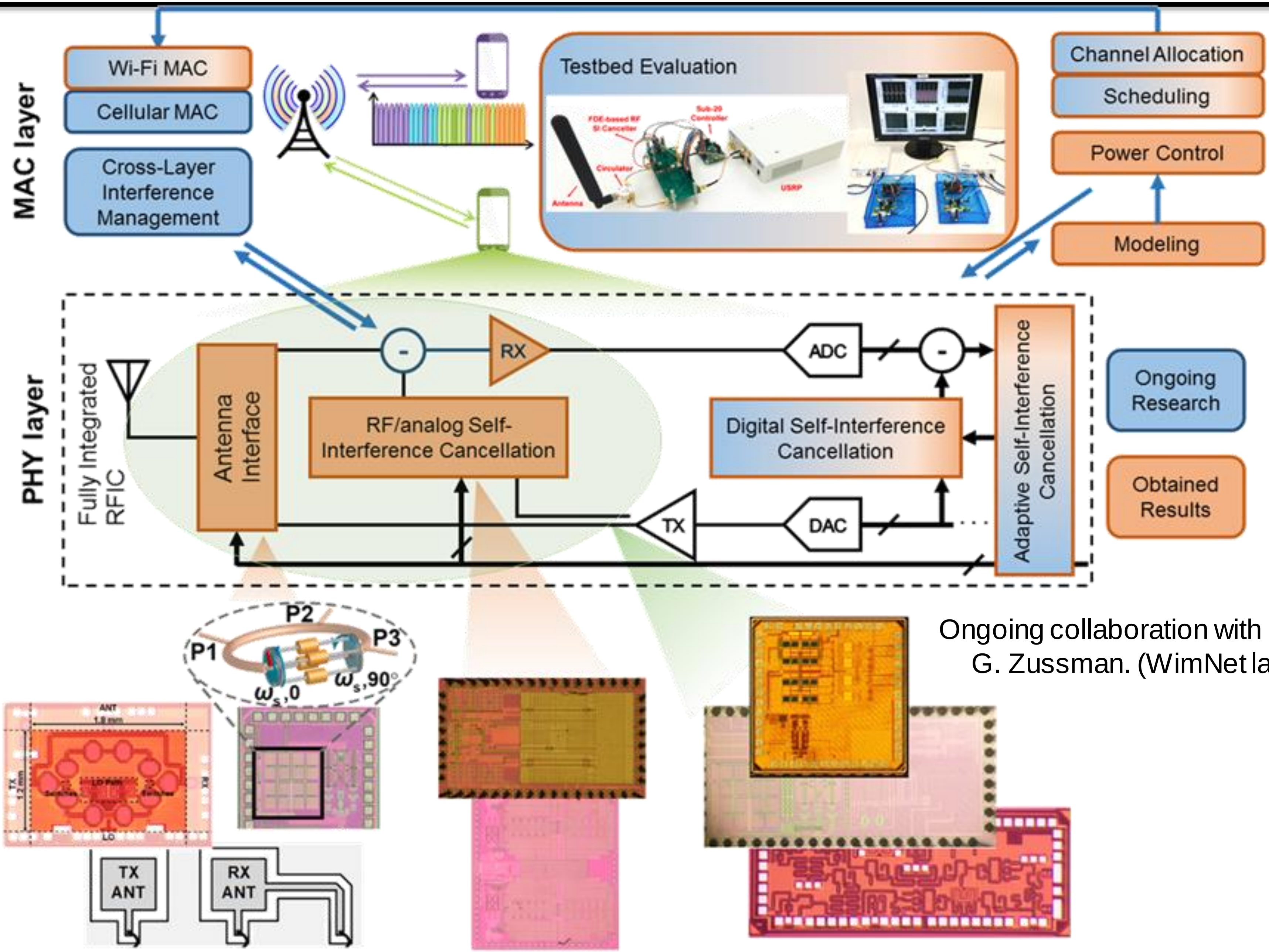
Fighting Fundamental Physics





Breaking Lorentz Reciprocity has traditionally required exploiting the magneto-optic Faraday Effect.

Columbia's FlexICoN Project



Ongoing collaboration with Prof. G. Zussman. (WimNet lab)

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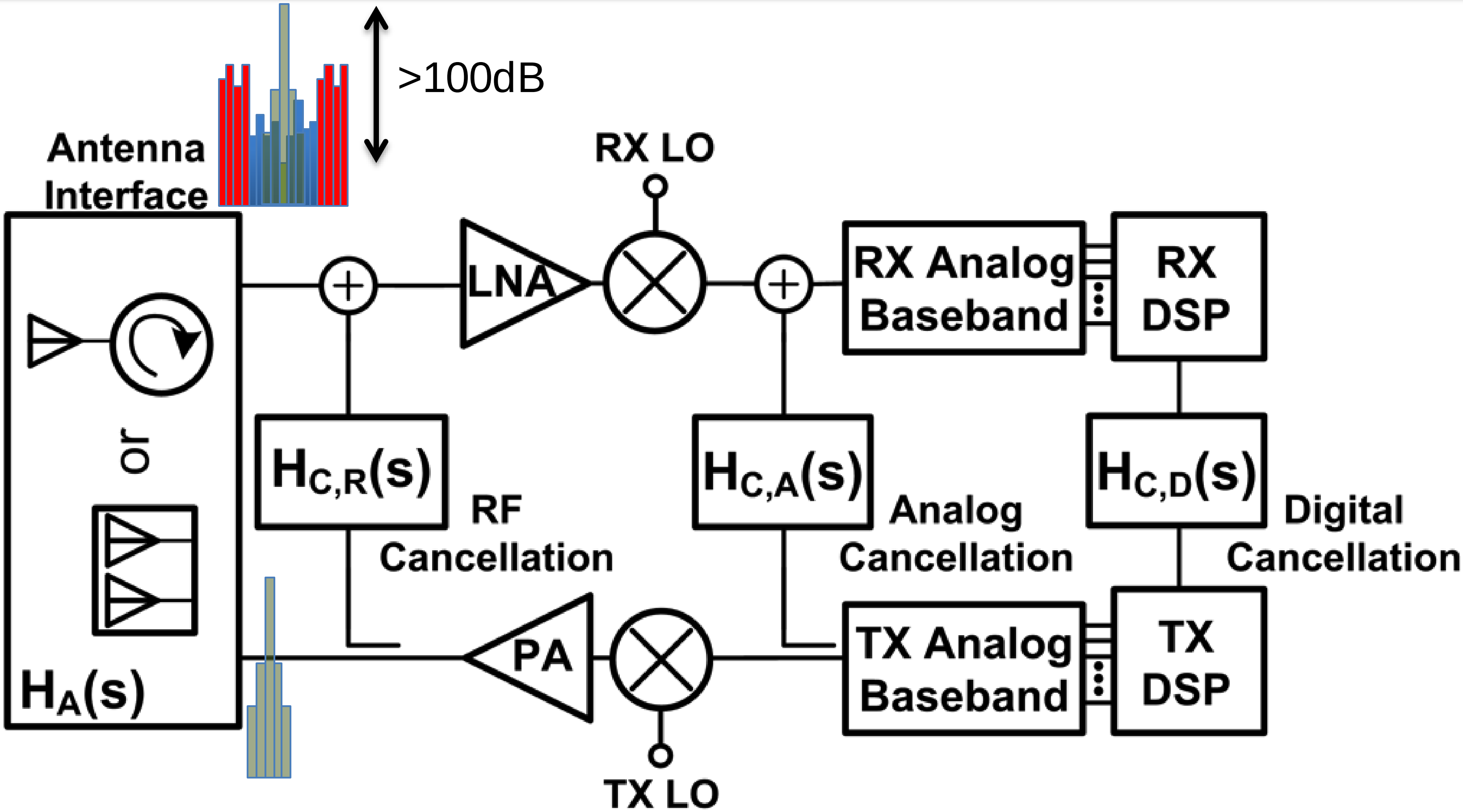
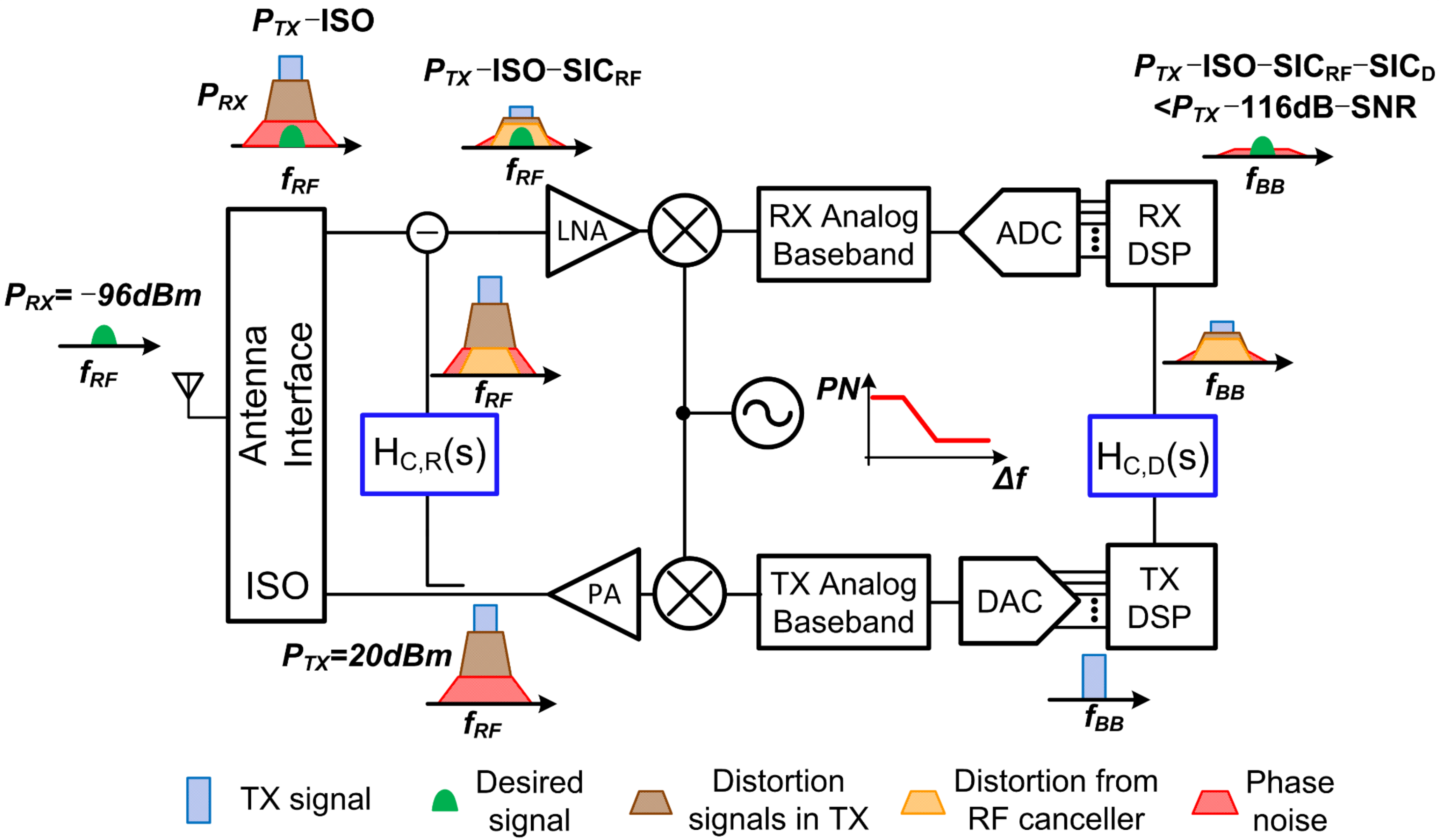
Self-Interference in Full Duplex



Full Duplex requires >100dB of self-interference cancellation, which must be obtained across all domains.

SI Management: A Closer Look



- SI management is complicated by ***noise, distortion, phase noise introduced in the TX, RX, cancellers*** and an ***uncertain wireless channel***.

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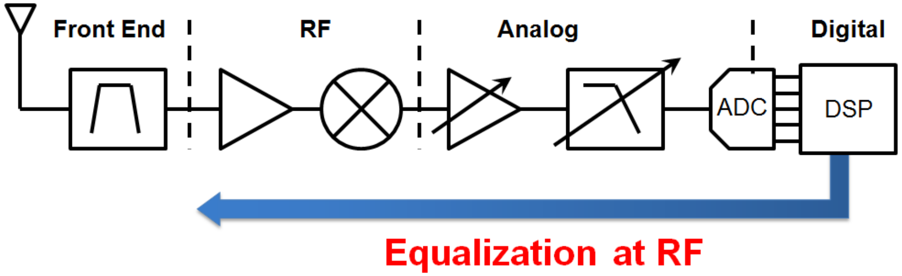
  - **SIC RX based on Frequency-Domain Equalization**



  - 60GHz TRX with Polarization-Based Antenna SIC
  - Full-Duplex Radio with Integrated Magnetic-free N-Path-Filter-Based Circulator and Analog Baseband SIC
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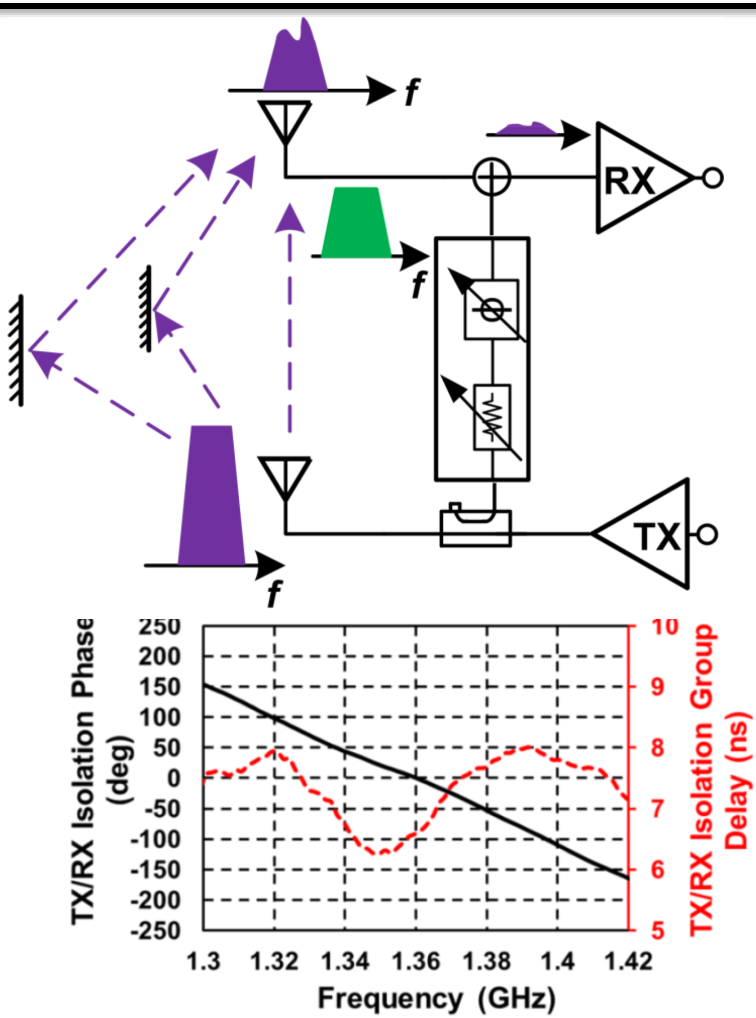
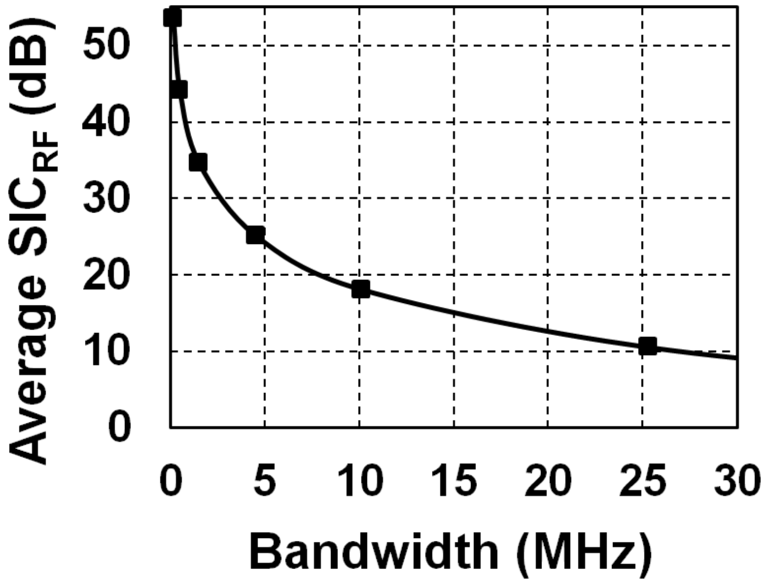
Wireless SI Channel

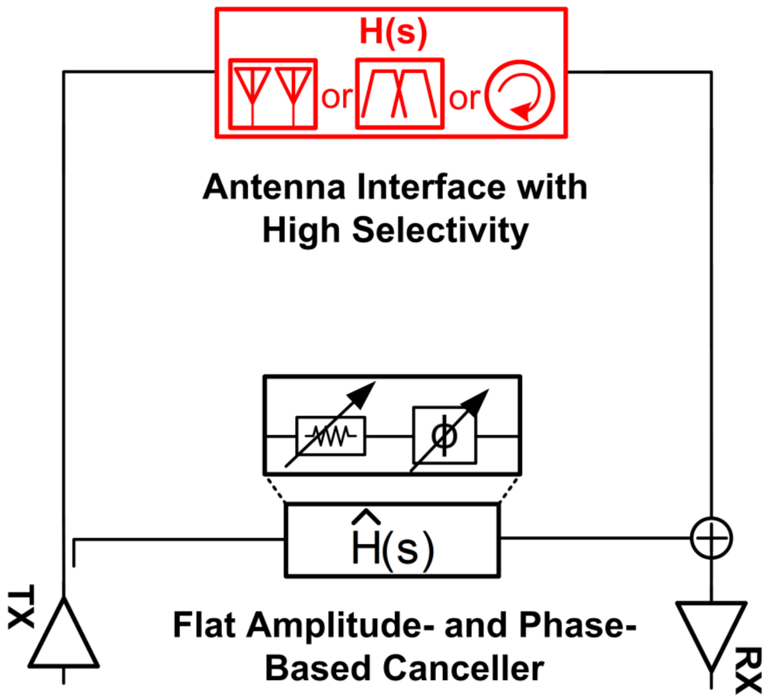


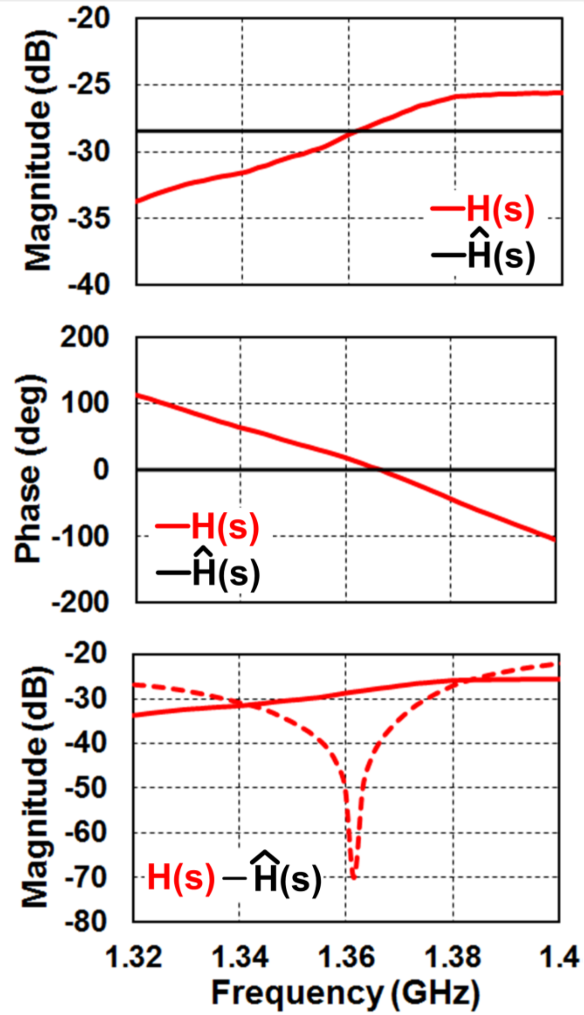


* OFDM signal with 50 sub-carriers and varying BW is applied in simulation.

For 25dB RF SIC with a frequency-flat canceller, the maximum supported signal BW is only ~3MHz.

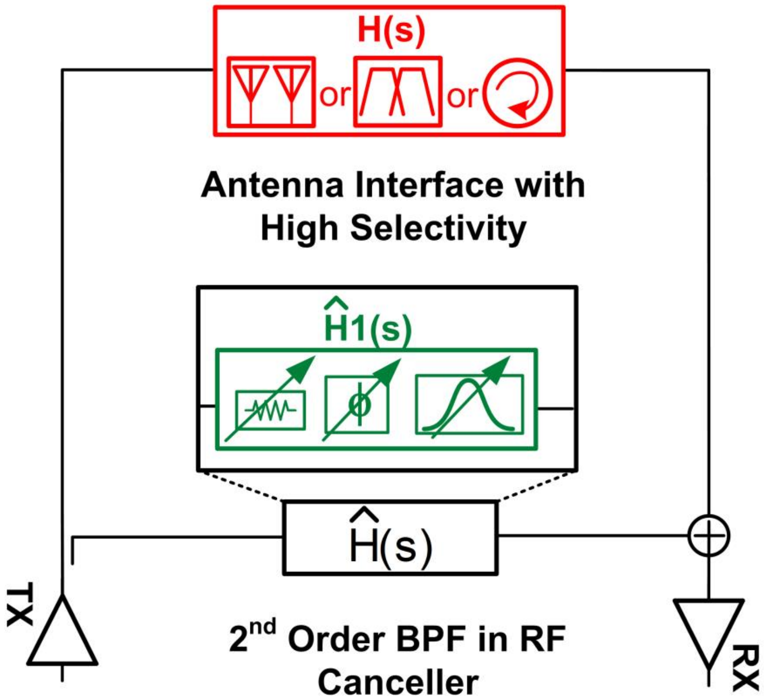
Conventional RF SI Canceller

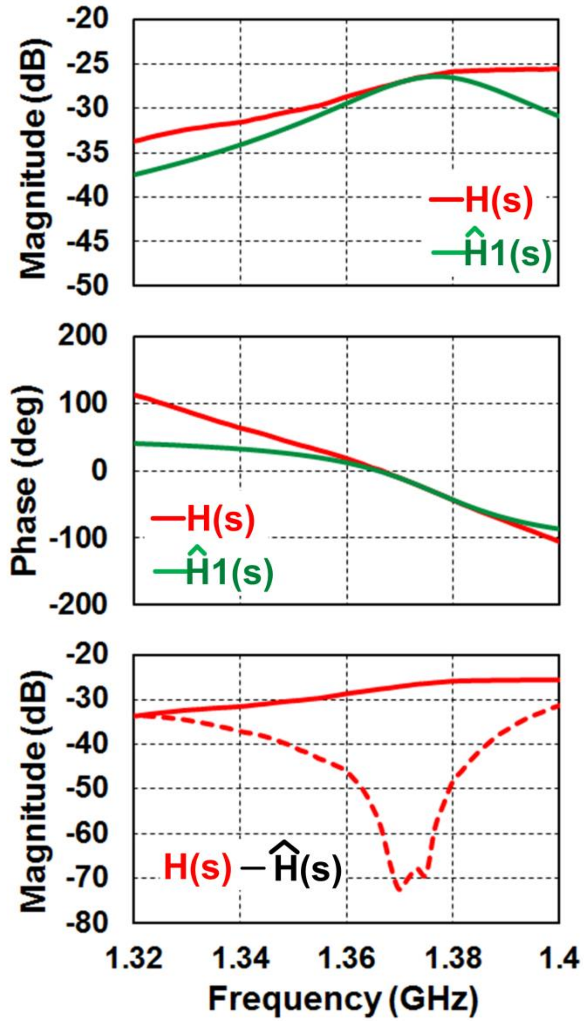




- Frequency-flat RF canceller can emulate a frequency-selective antenna interface *only at one frequency*.

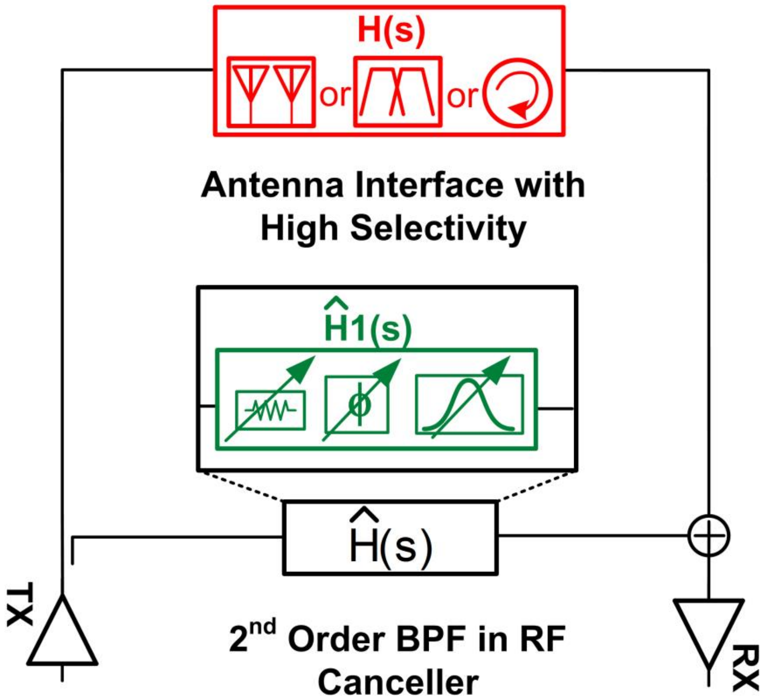
RF Canceller with 2nd Order BPF

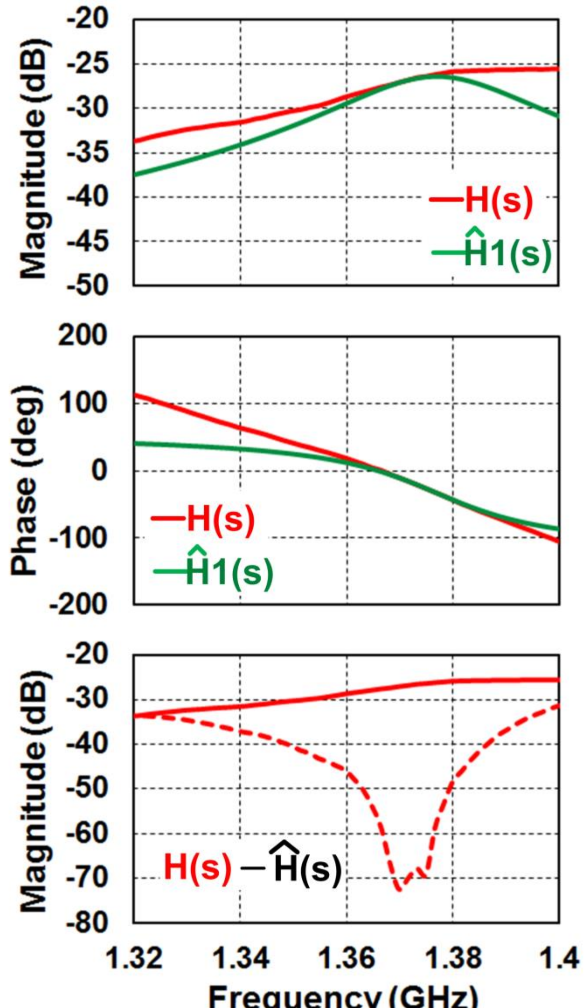




- Reconfigurable 2nd order RF BPF in canceller features 4 degrees of freedom: center frequency, Q, absolute amplitude and absolute phase.

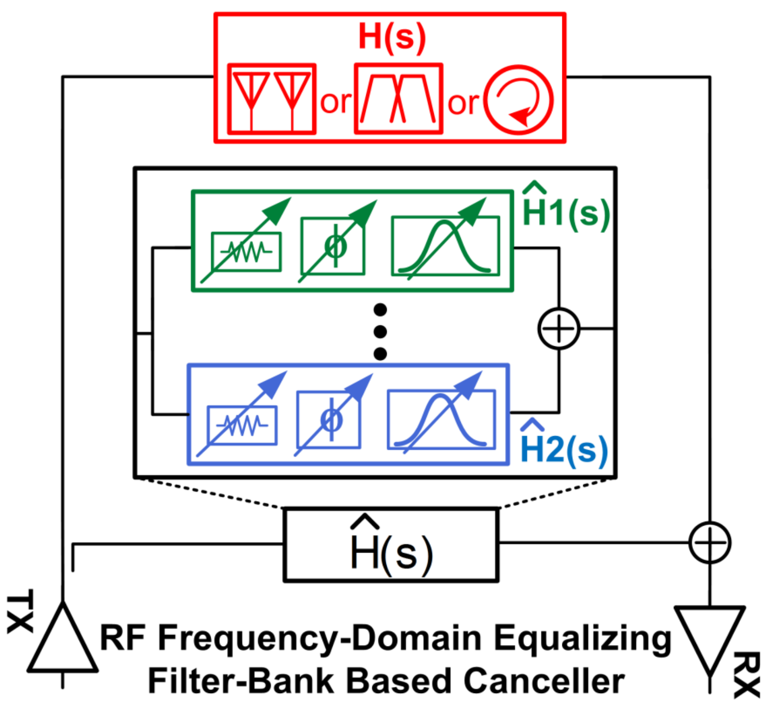
RF Canceller with 2nd Order BPF

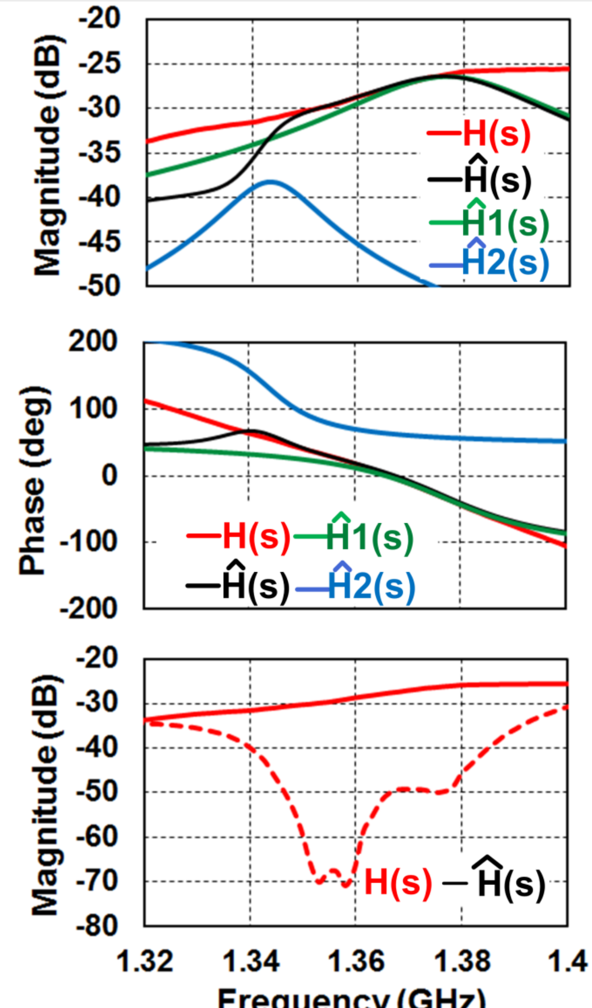




Replication of not only the amplitude/phase, but also the slope of the amplitude/phase(i.e. group delay).

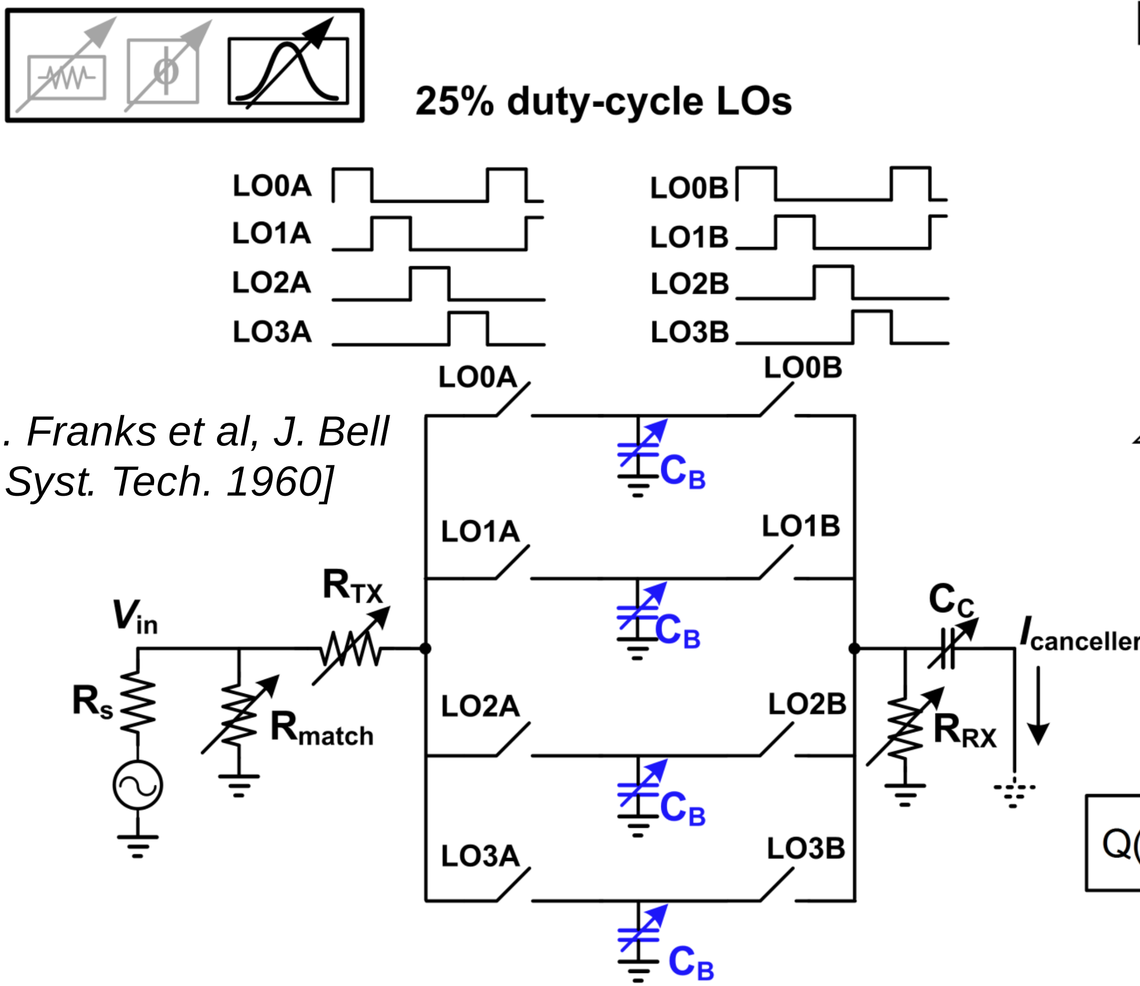
Frequency-Domain Equalization



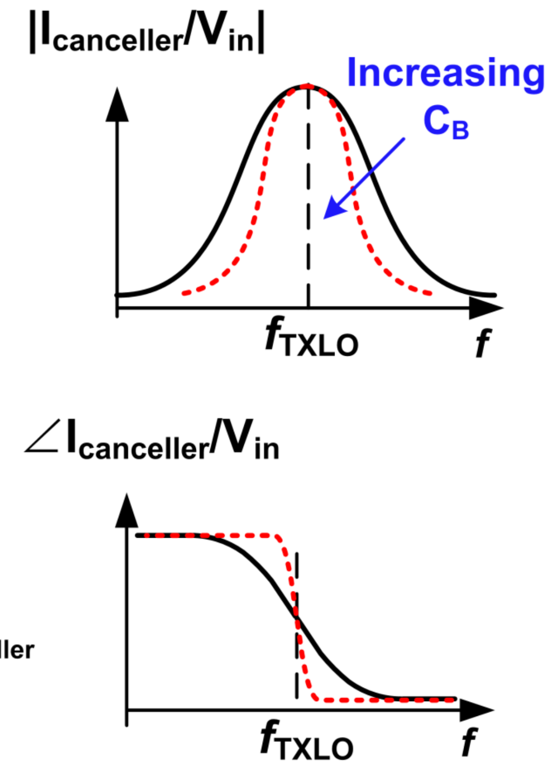


A filter bank enables replication at multiple points in different sub-bands – *Freq. Domain Equalization*.

High-Q Two-Port N-Path BPF



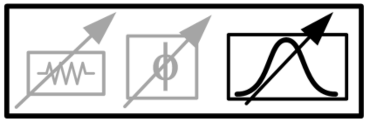
[*L. Franks et al, J. Bell Syst. Tech. 1960]



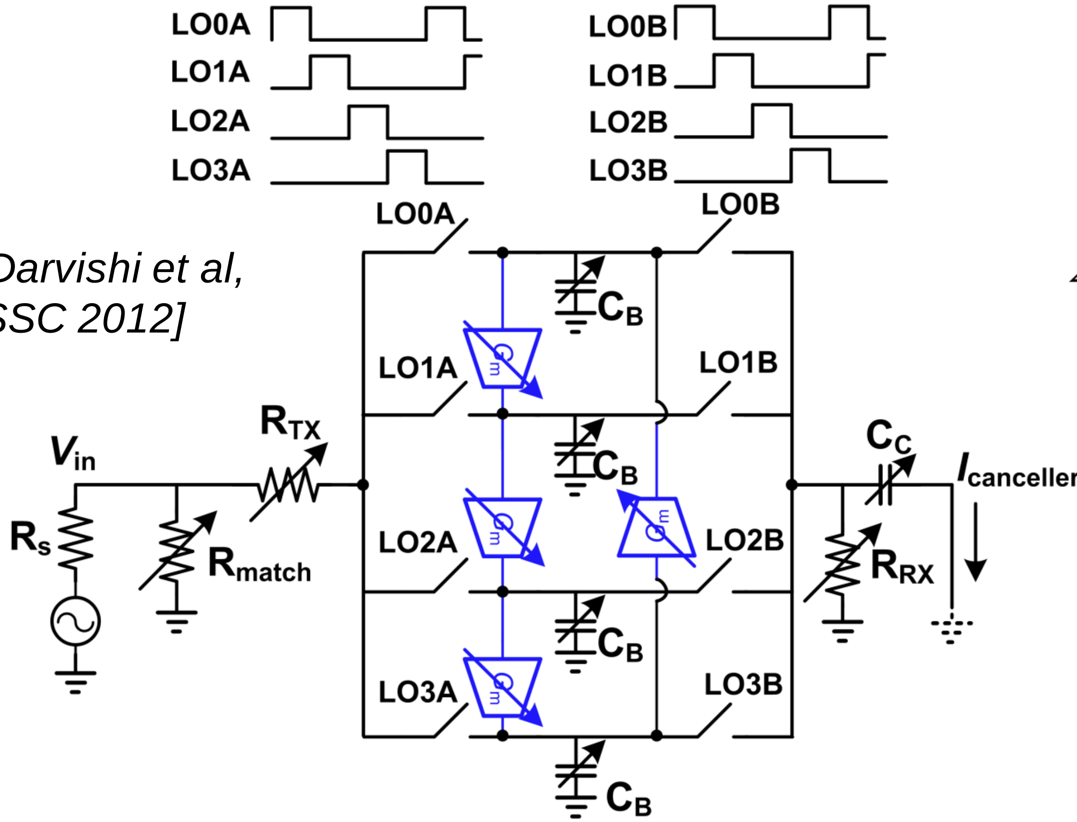
$$Q(f=f_{TXLO}) \approx 4\pi f_{TXLO}(R_{TX} \,||\, R_{RX})C_B$$

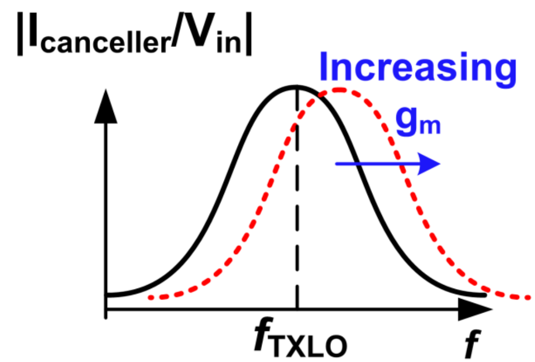
- Q of the N-path band-pass filter is reconfigured through the baseband capacitor C_B.

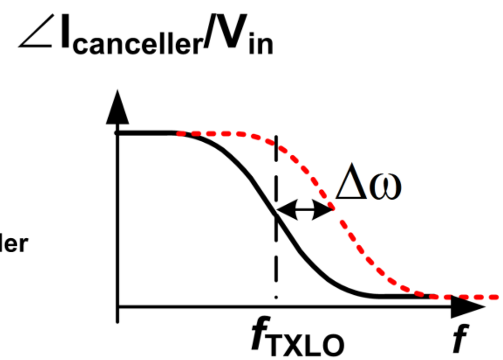
G_m-C Filter for Tunable Offset Freq.



[*M. Darvishi et al, JSSC 2012]



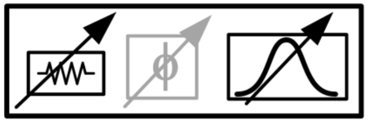


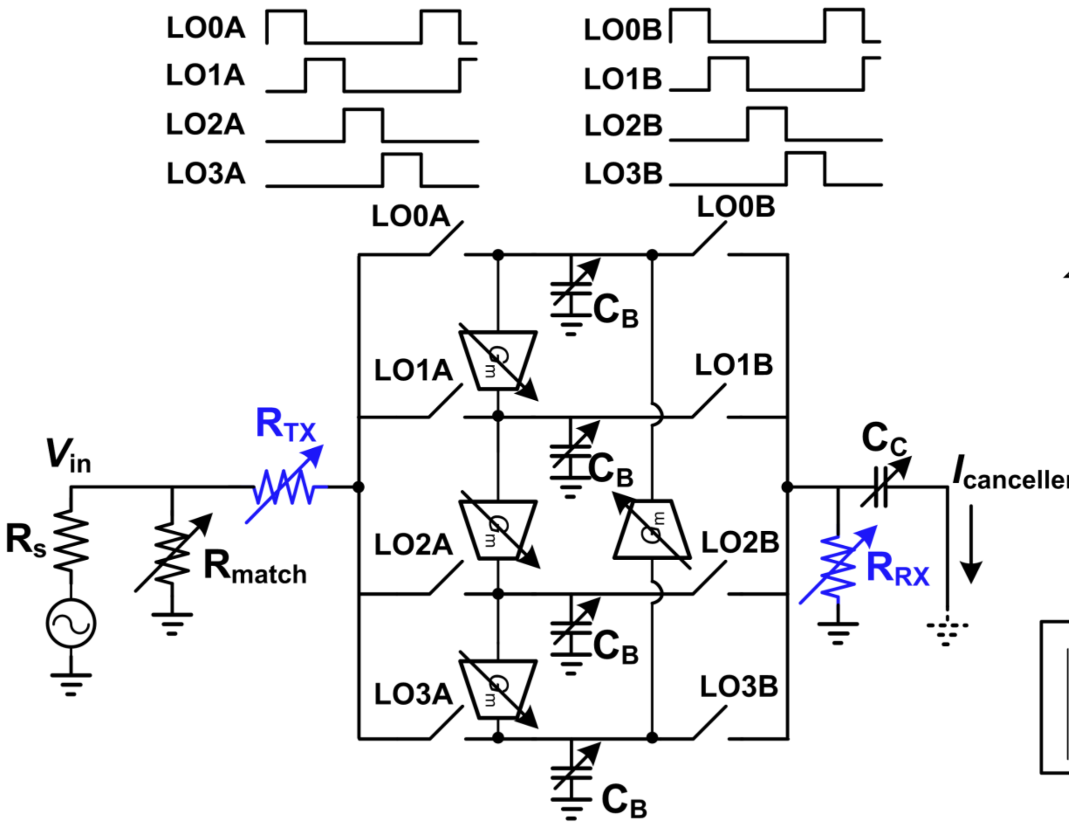


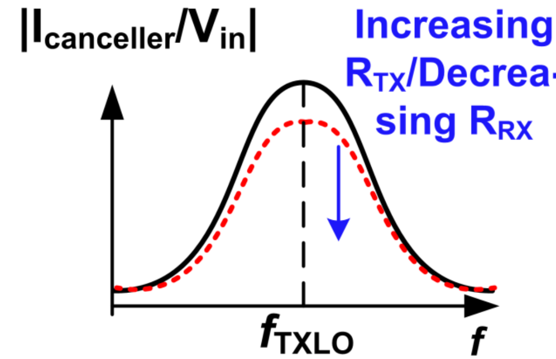
$$\Delta\omega = \frac{g_m}{C_B}$$

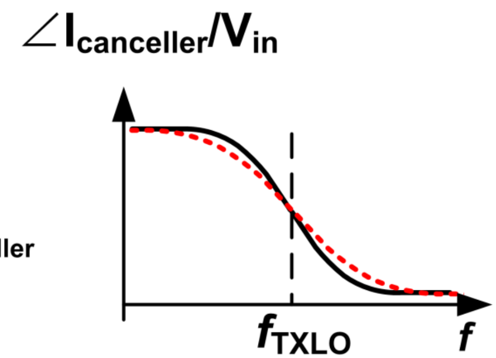
- Center frequency shifts can be achieved and reconfigured through the clockwise/counter-clockwise-connected Gm cells.

Embedded Variable Attenuation





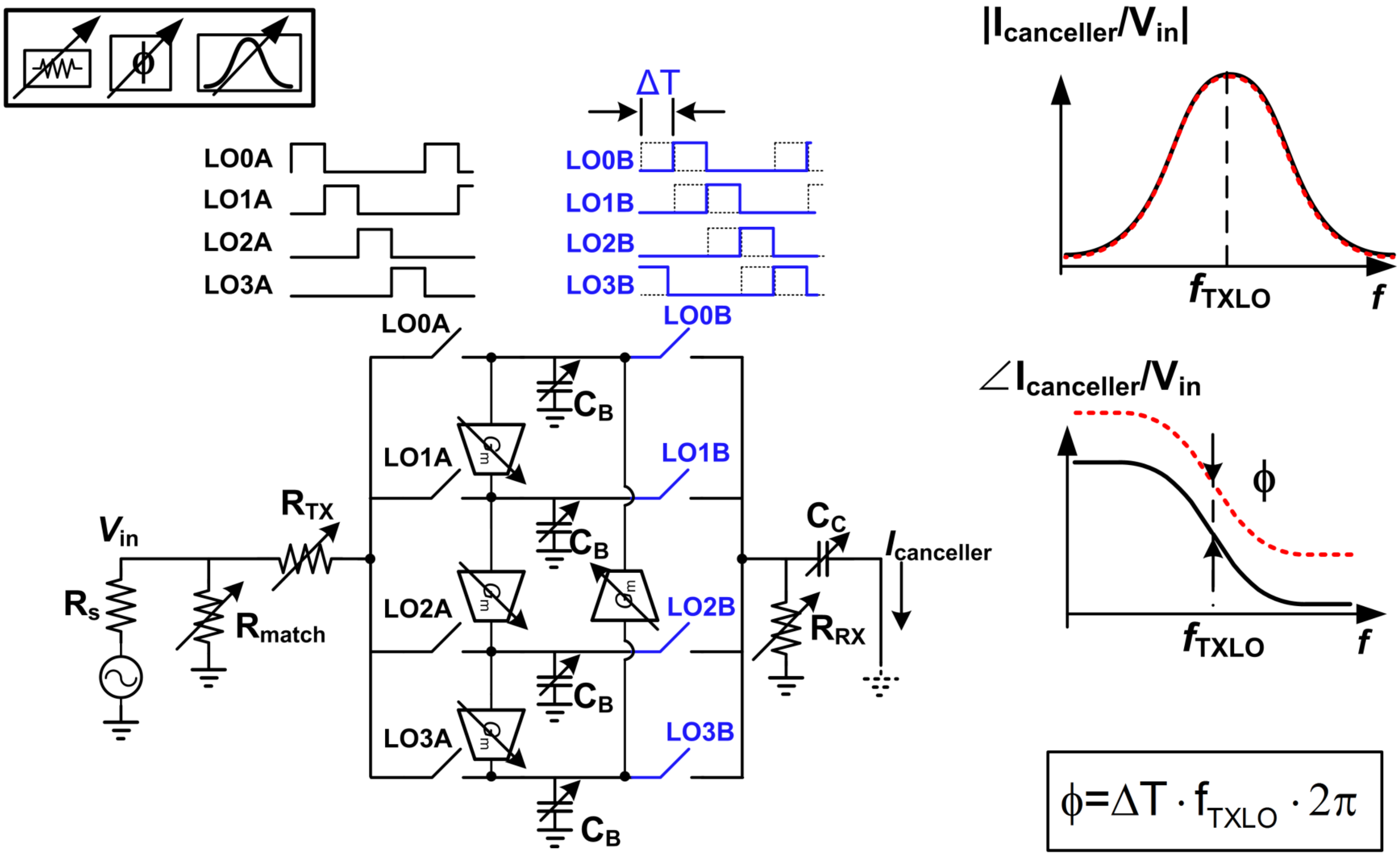




$$\left|\frac{I_{Canceller}}{V_{in}}\right|(f=f_{TXLO}) \approx \frac{8}{\pi^2}\frac{\omega R_{RX} C_C}{R_{TX}+R_{RX}}$$

- Variable attenuation (amplitude scaling) is introduced by reconfiguring R_{RX} and R_{TX} relative to each other.

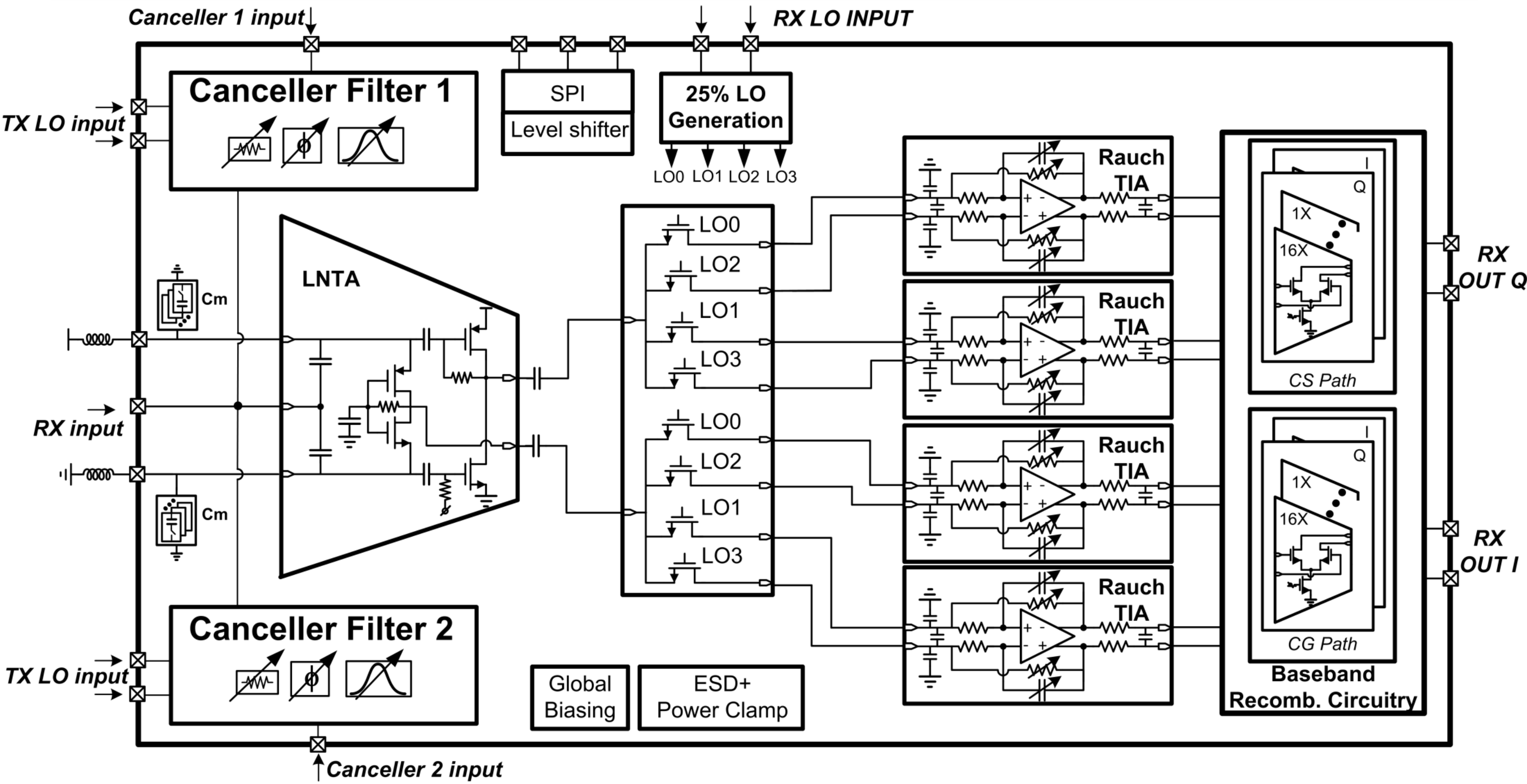
Embedded LO-Path Phase Shift



$$\phi = \Delta T \cdot f_{TXLO} \cdot 2\pi$$

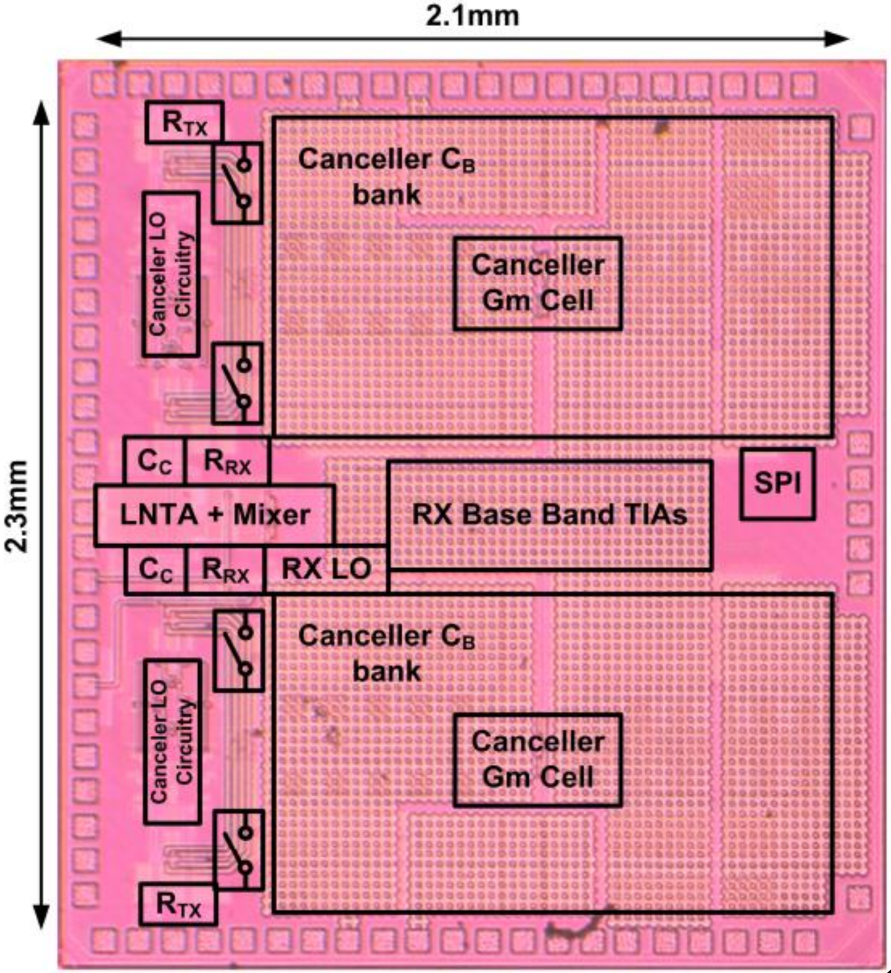
Phase shifts can be embedded in the LO path of a two-port N-path filter with no impact on close-in frequency response.

0.8-1.4GHz RX with FDE RF SIC

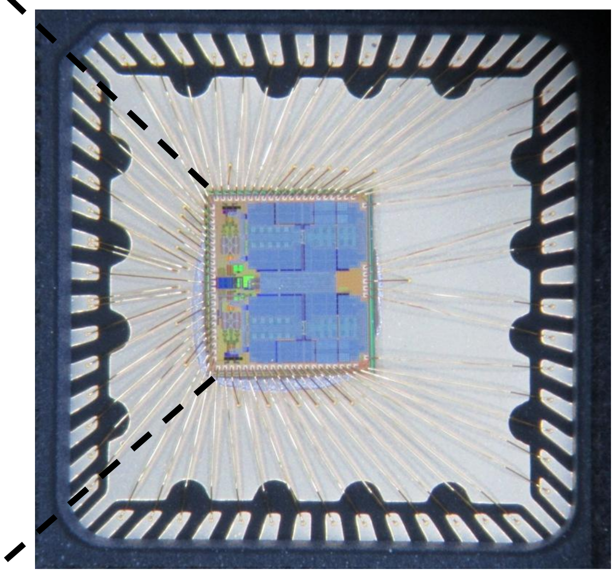


- Reconfigurable 0.8-1.4GHz 65nm CMOS current-mode receiver.
- FDE RF canceller operates at RX input and uses two filters.

0.8-1.4GHz RX with FDE RF SIC



- QFN packaged
- Mounted on a 4-layer FR-4 PCB

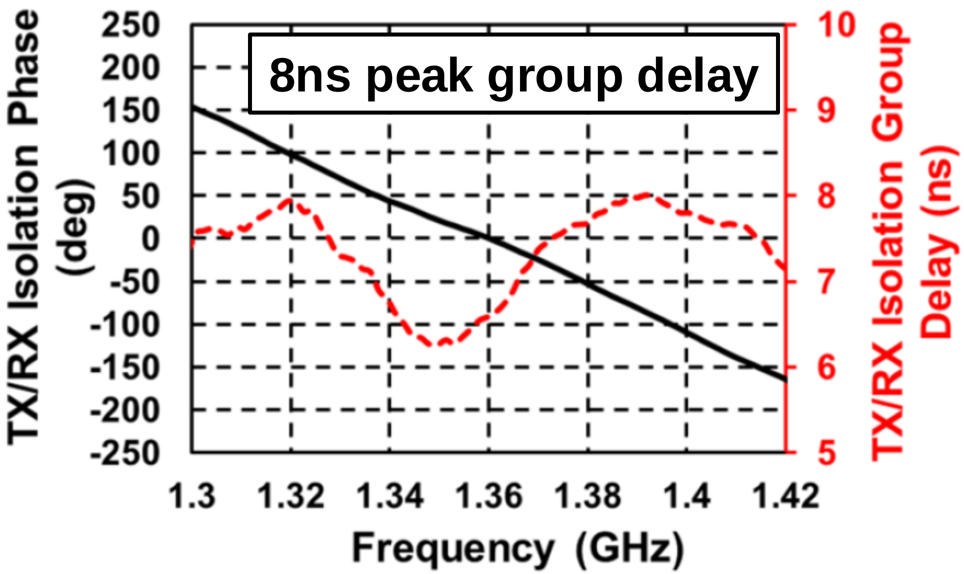


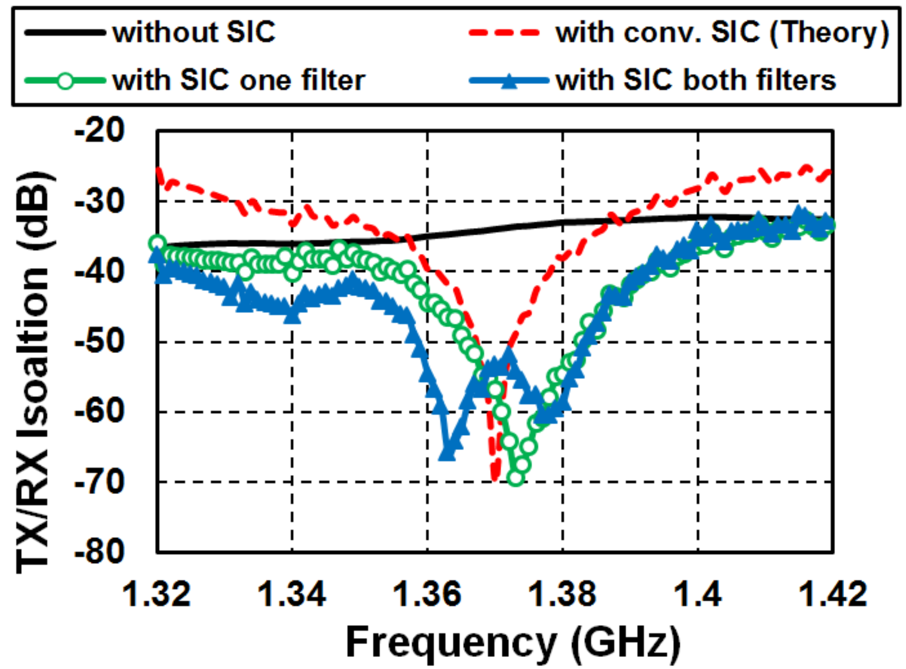
Jin Zhou, Tsung-Hao Chuang, Tolga Dinc and Harish Krishnaswamy, "Reconfigurable receiver with >20MHz bandwidth self-interference cancellation suitable for FDD, co-existence and full-duplex applications," in *2015 IEEE ISSCC*.
Jin Zhou, Tsung-Hao Chuang, Tolga Dinc and Harish Krishnaswamy, "Integrated Wideband Self-Interference Cancellation in the RF Domain for FDD and Full-Duplex Wireless," **(invited paper)** *IEEE JSSC*, vol. 50, no. 12, pp. 3015-3031, Dec. 2015.

Full Duplex Using Antenna Pair

AntennaFactor by Linx

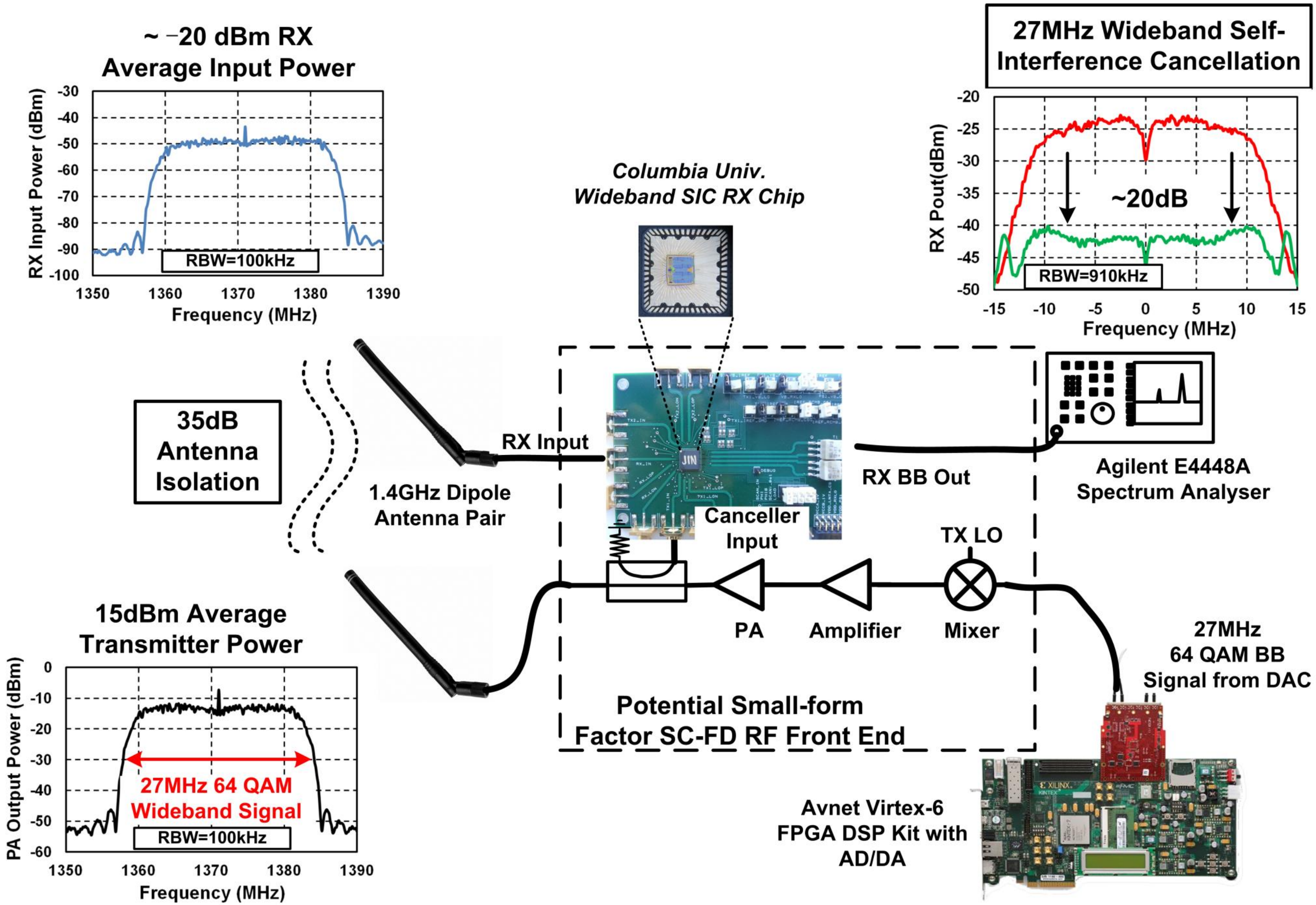
ANT-1.4-CW-HWR-RPS





Proposed canceller has a SIC BW of 15/25MHz using one/two filters, up to 8X over a conventional canceller.

27MHz 64-QAM RF SIC Demo



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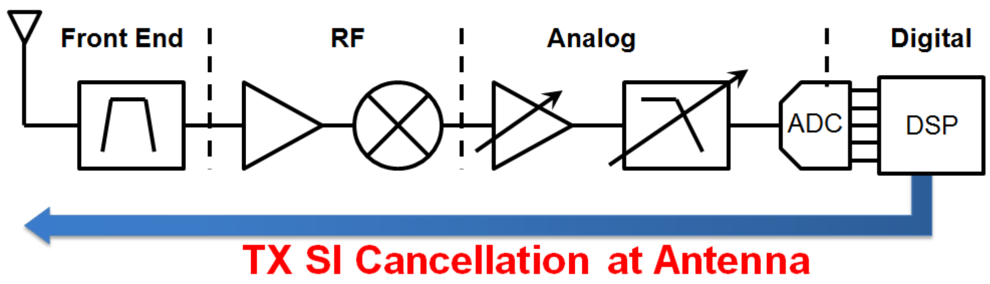

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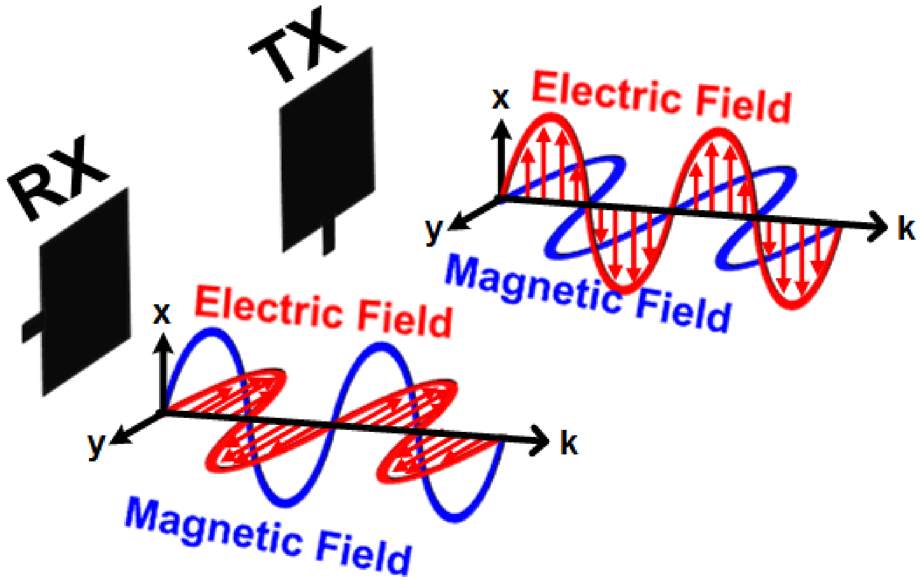
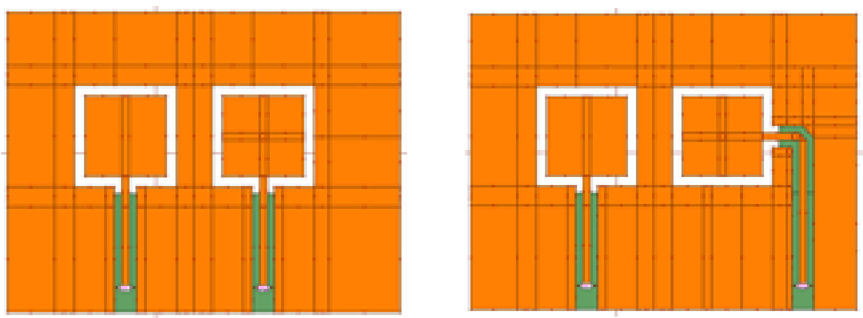
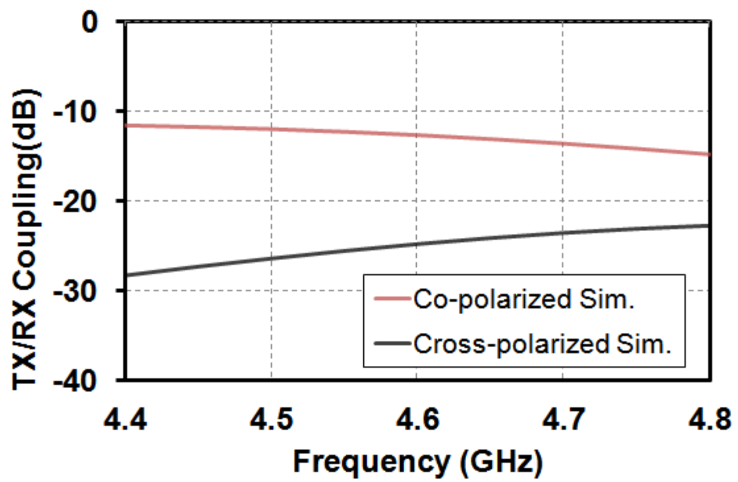
Polarization-Division Duplexing

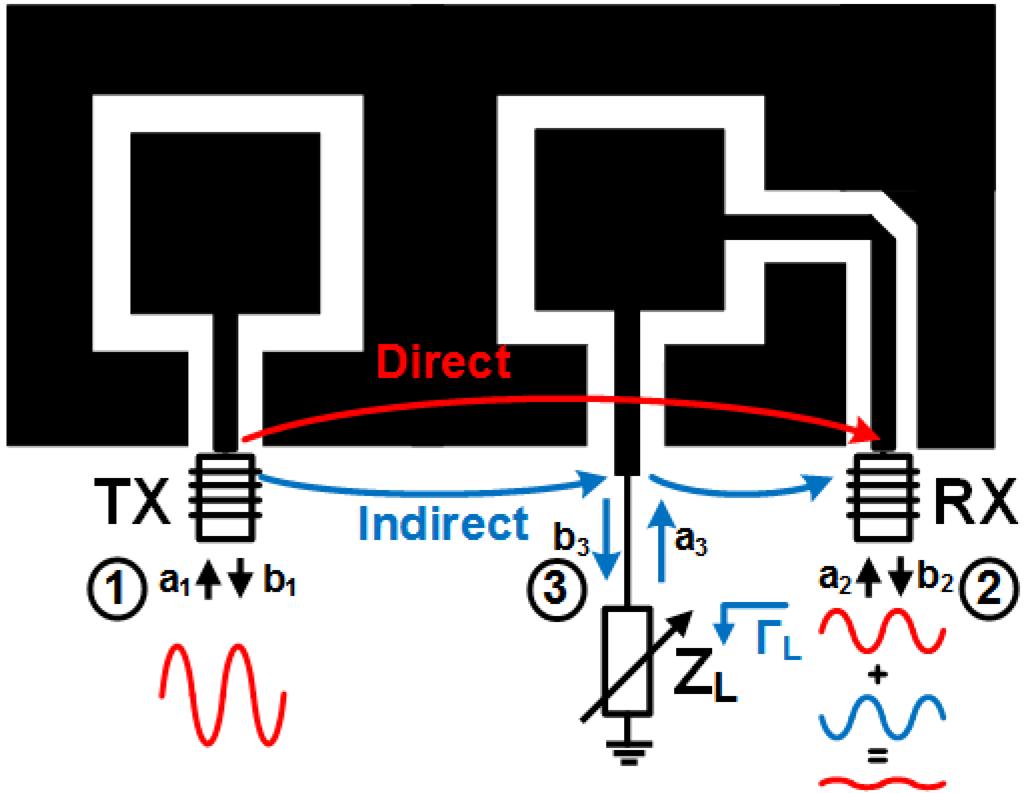






- Using different polarizations for T/R *improves the isolation by 8-16 dB.*

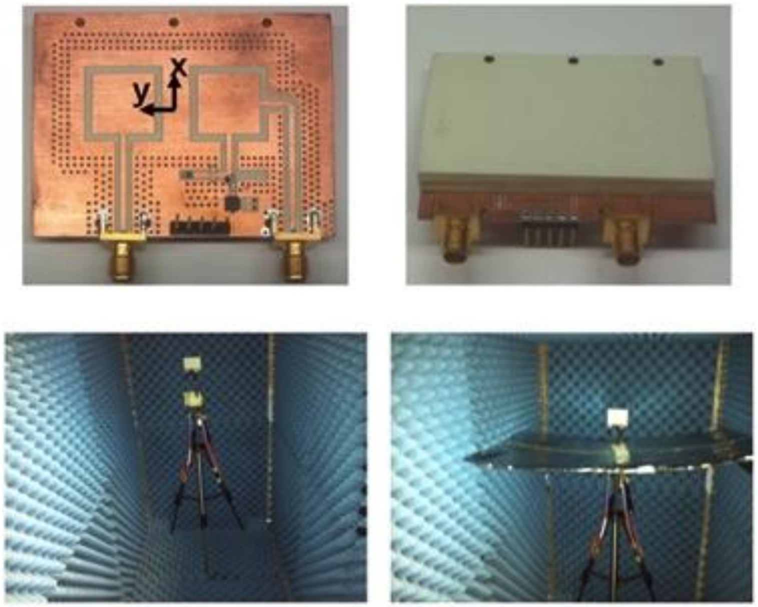
Polarization-Based Antenna SIC

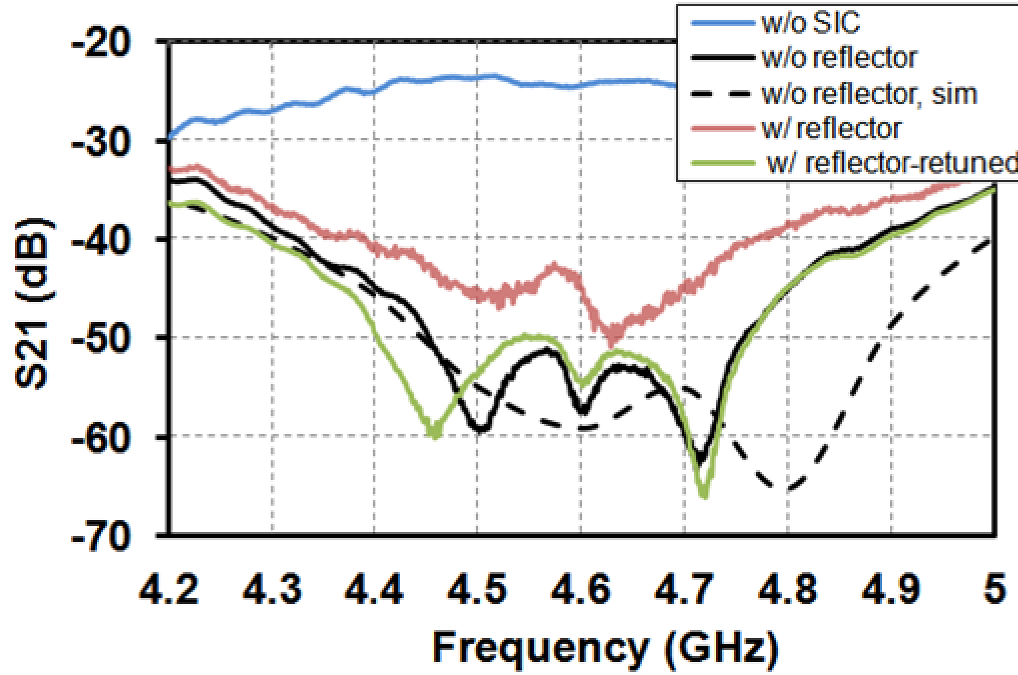


$$b_2 = \left(S_{21} + \frac{S_{23}S_{31}\Gamma_L}{1 - S_{33}\Gamma_L} \right) a_1$$

- An auxiliary port is introduced on the RX antenna that is co-polarized with TX and terminated with a reflective termination to achieve wideband SIC.

5GHz Antenna SIC Results

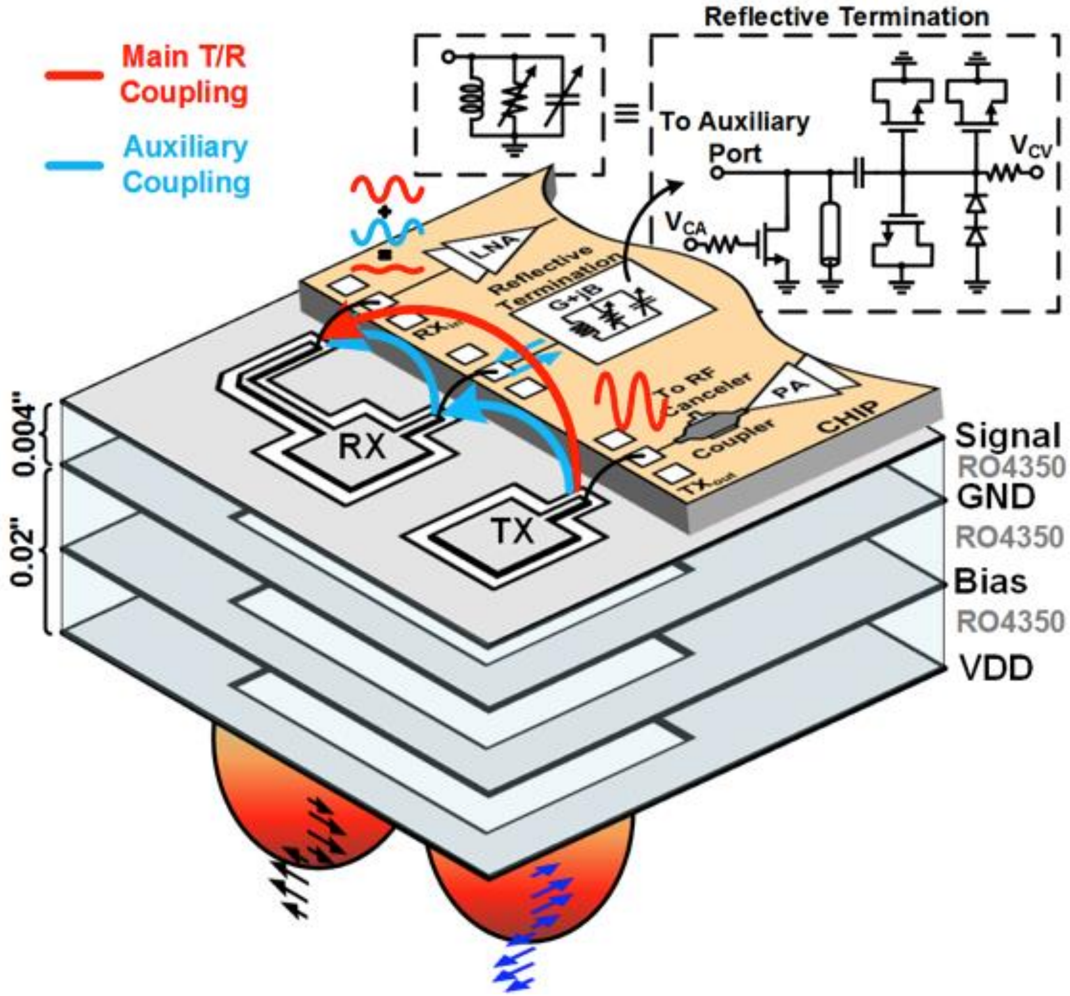


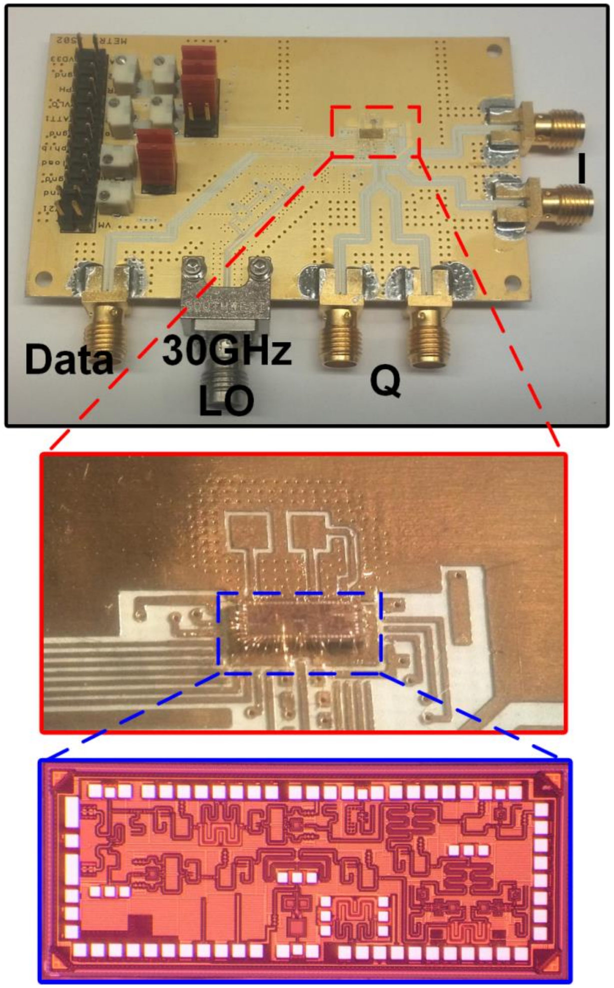


- **50 dB isolation over 300MHz at 4.6 GHz (14x SIC BW).**
- **Reflective termination can be reconfigured to combat the variable SI scattering from the environment.**

Tolga Dinc and Harish Krishnaswamy, "A T/R Antenna Pair with Polarization-Based Reconfigurable Wideband Self-Interference Cancellation for Simultaneous Transmit and Receive," in the *2015 IEEE International Microwave Symposium*.

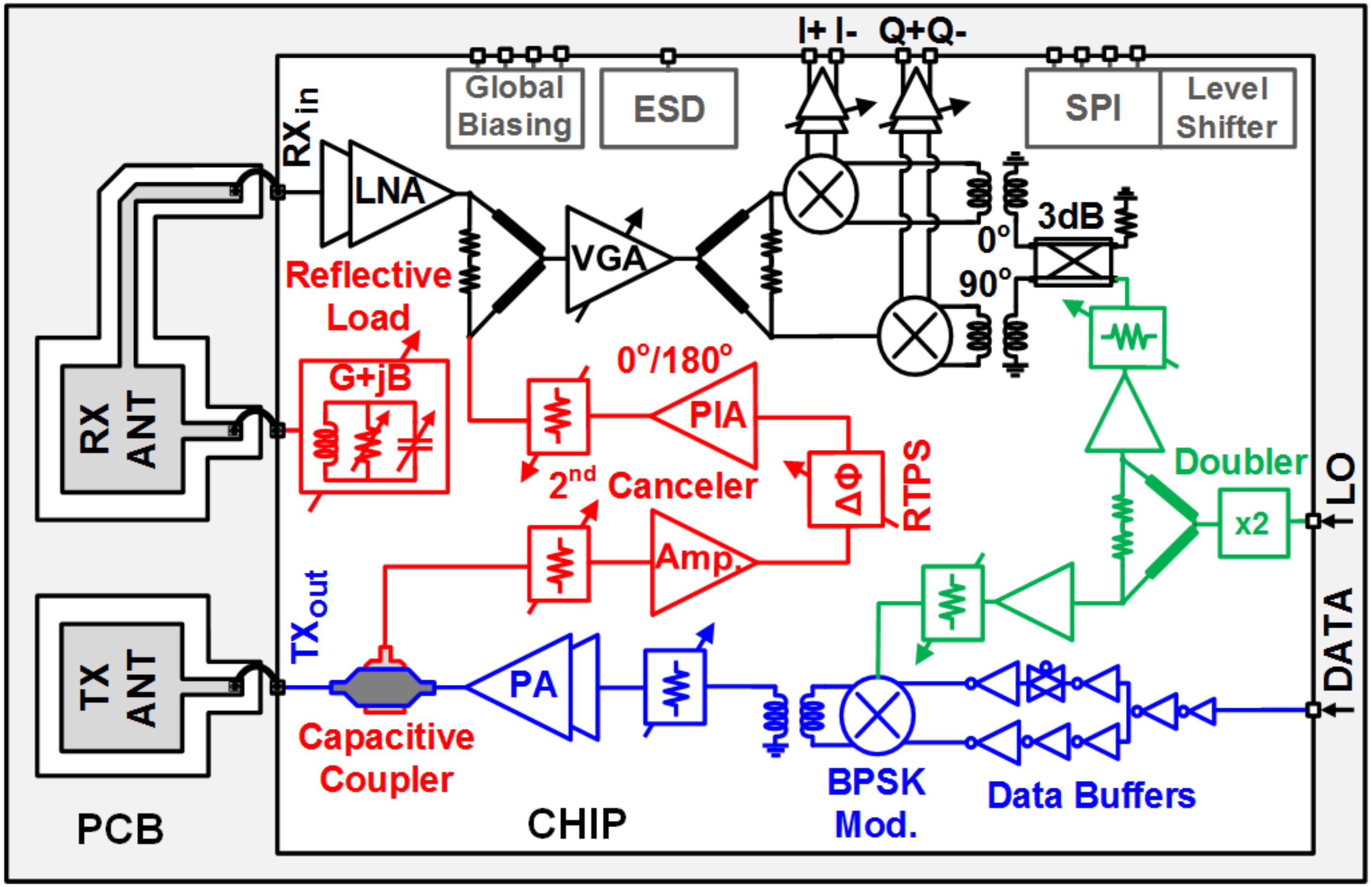
60GHz Full Duplex Transceiver





▪ The reconfigurable wideband polarization-based antenna cancellation is implemented at 60GHz and integrated with a 45nm SOI full-duplex TRX.

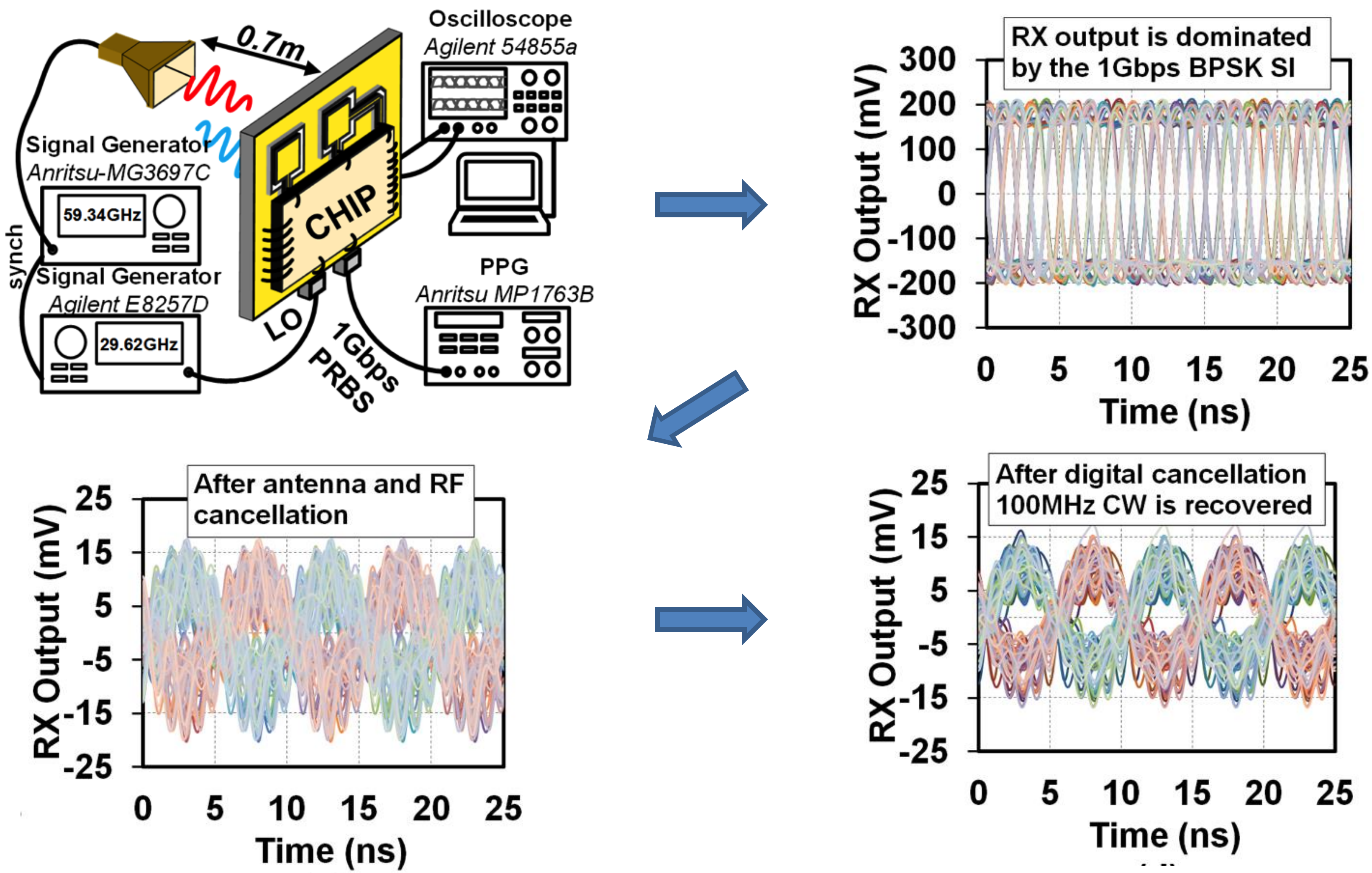
60GHz 45nm SOI CMOS TRX



World's first fully-integrated full-duplex TRX front-end.

Tolga Dinc, Anandaroop Chakrabarti and Harish Krishnaswamy, "A 60 GHz Same-Channel Full-Duplex CMOS Transceiver and Link Based on Reconfigurable Polarization-Based Antenna Cancellation," in the *2015 IEEE RFIC Symposium* **(Best Student Paper Award)**.

60GHz Full Duplex Wireless Link



Tolga Dinc, Anandaroop Chakrabarti and Harish Krishnaswamy, "A 60GHz CMOS Full-Duplex Transceiver and Link with Polarization-Based Antenna and RF Cancellation," **(invited paper)** *IEEE JSSC*, vol. 51, no. 5, pp. 1125-1140, May 2016.

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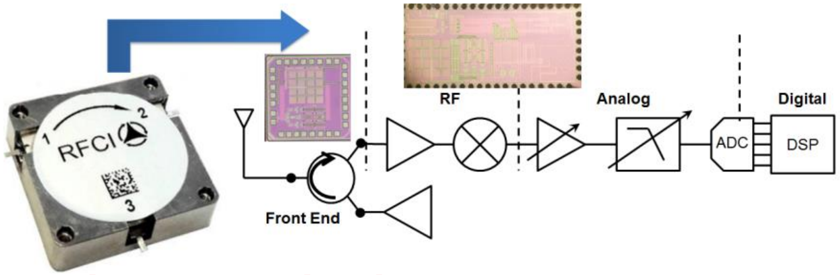

Fighting Fundamental Physics

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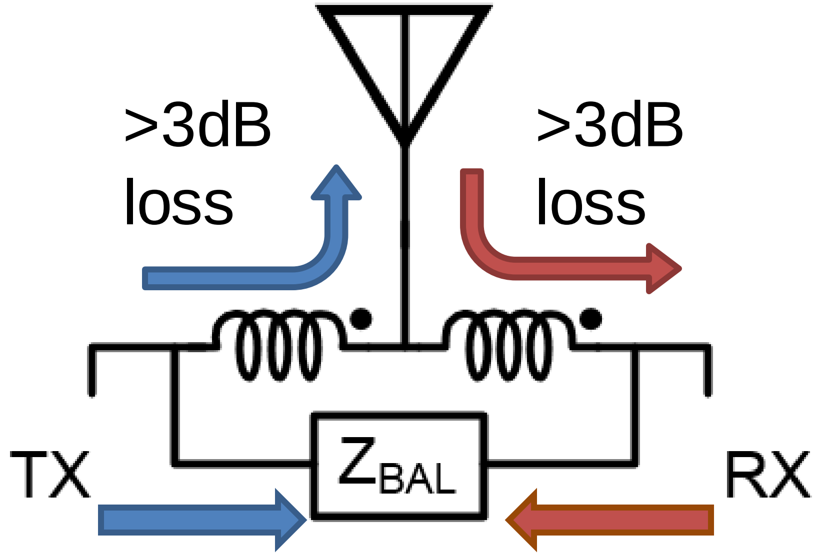
Reciprocal Circuits and Systems

Linear time-invariant (LTI) passive systems based on conventional materials are reciprocal.



[Ref: B. van Liempd, et al., ISSCC 2015.]

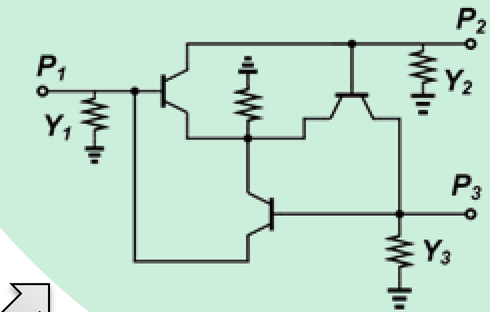
How can we avoid this fundamental 3dB loss?

Achieving Non-Reciprocity

Magnetic materials (ferrites)

[Ref: RF-CI, Inc..]

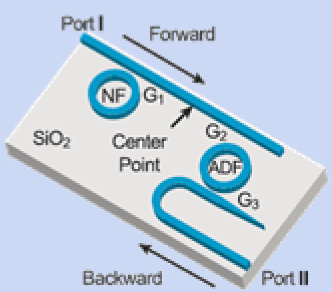
Active devices



[Ref: Tanaka, Proc. of IEEE, 1965.]

Any linear, time-invariant, passive system based on conventional materials is RECIPROCAL.

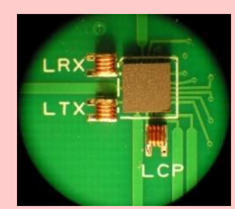
Non-linear systems



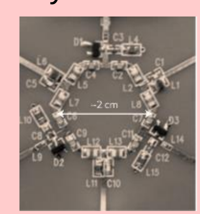
[Ref: Fan, Science 2012.]

Time-variant systems

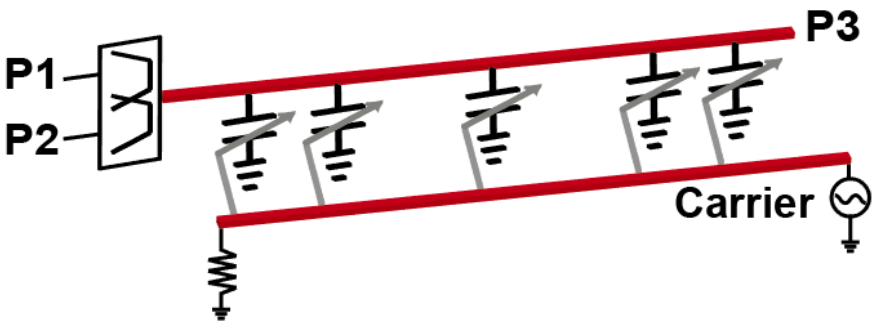
[Ref: Reiskarimian, Nat. Comm. 2016.]

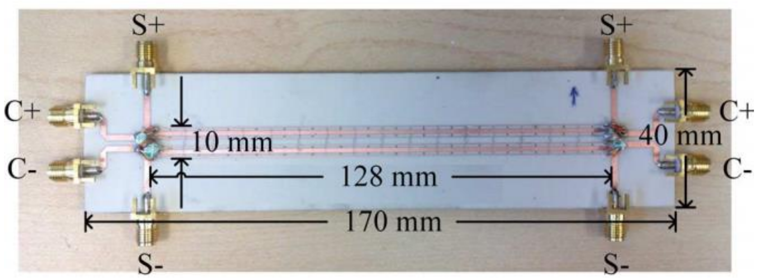


[Ref: Estep, Nat. Physics 2014.]

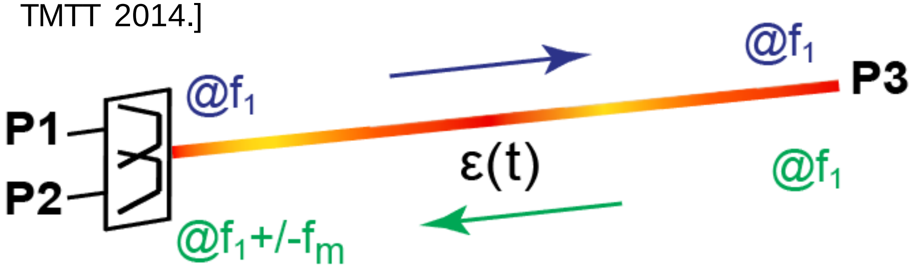


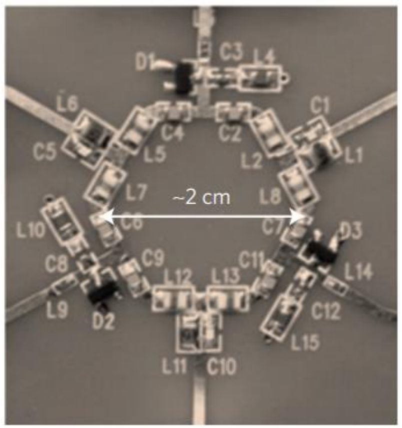
Non-Reciprocity Via Time-Variance

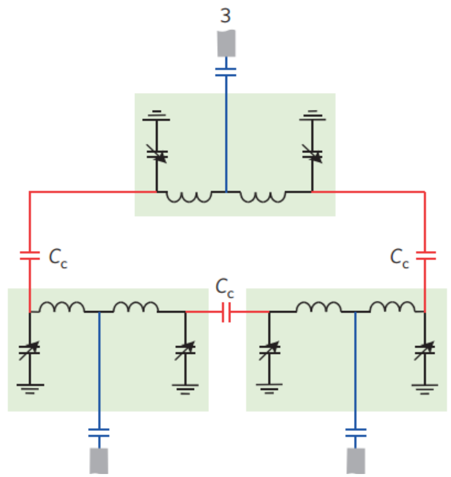




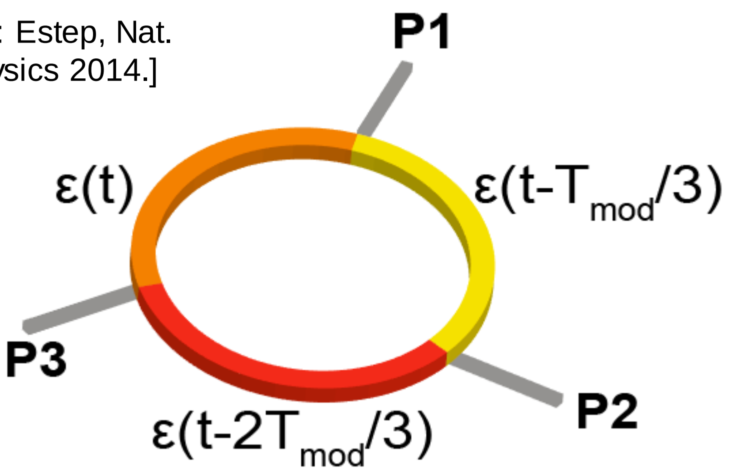
[Ref: Qin, IEEE TMTT 2014.]





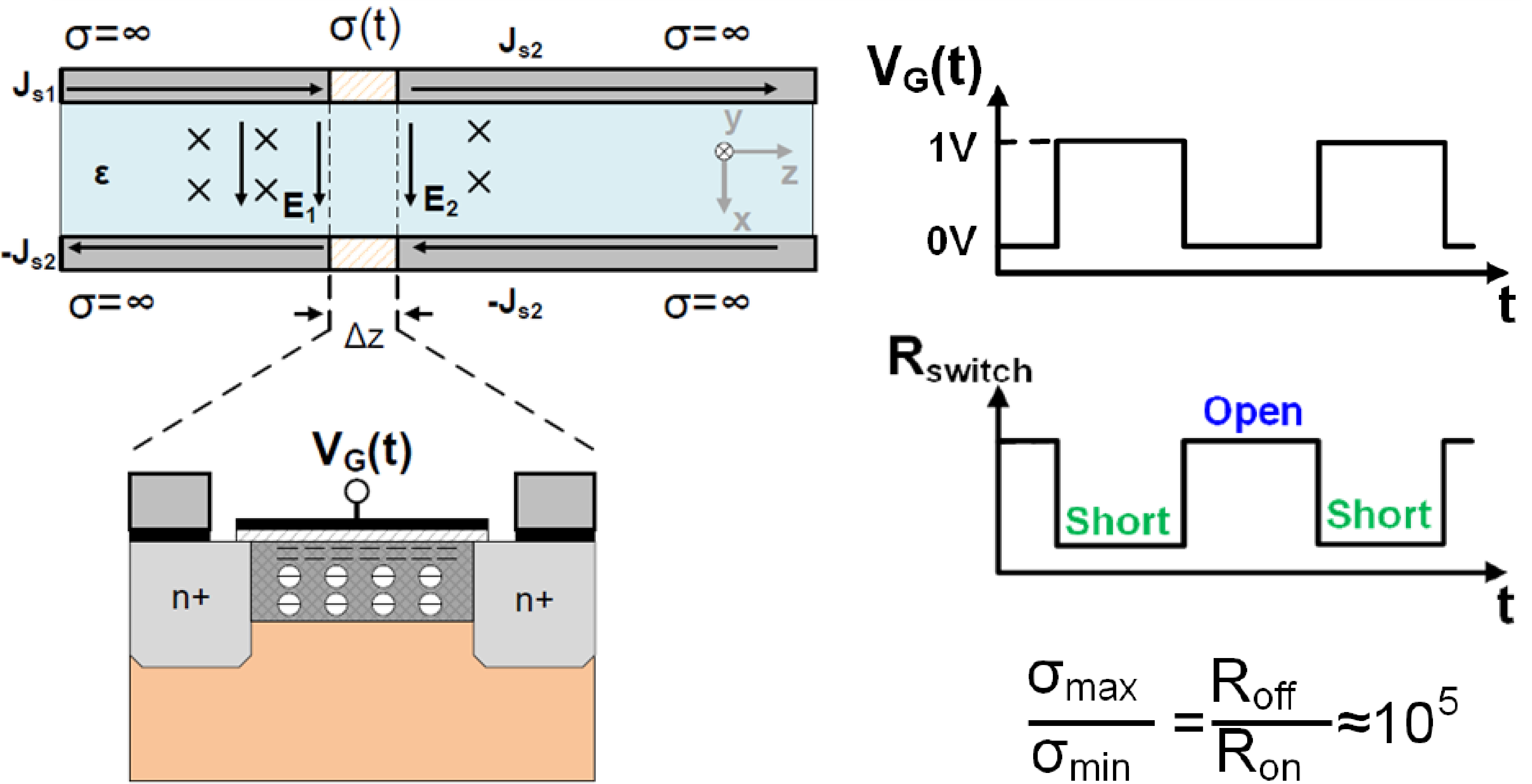


[Ref: Estep, Nat. Physics 2014.]



Permittivity modulation in silicon has limited modulation index (C_{max}/C_{min}~2-4).

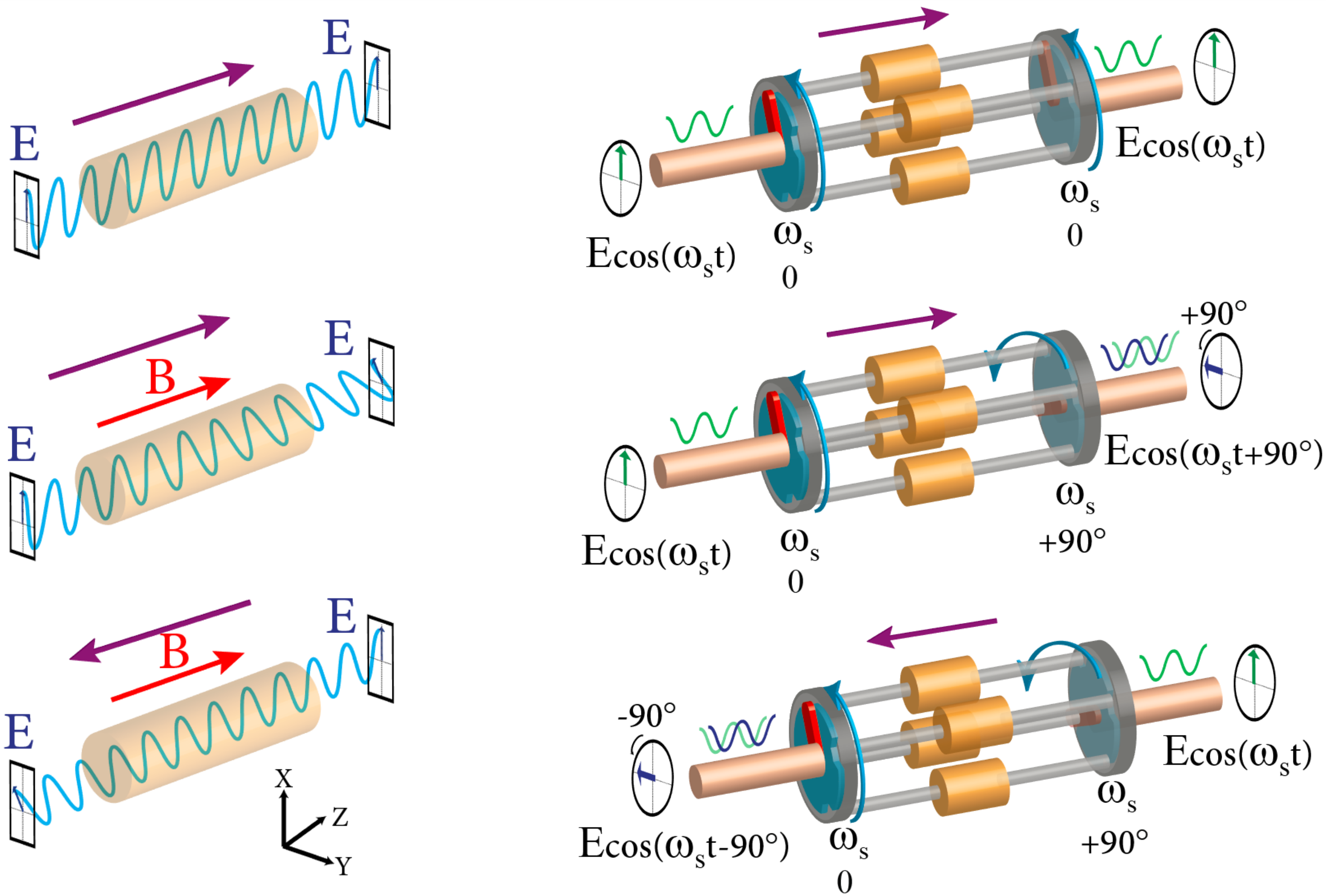
Conductivity Modulation



$$\frac{\sigma_{max}}{\sigma_{min}} = \frac{R_{off}}{R_{on}} \approx 10^5$$

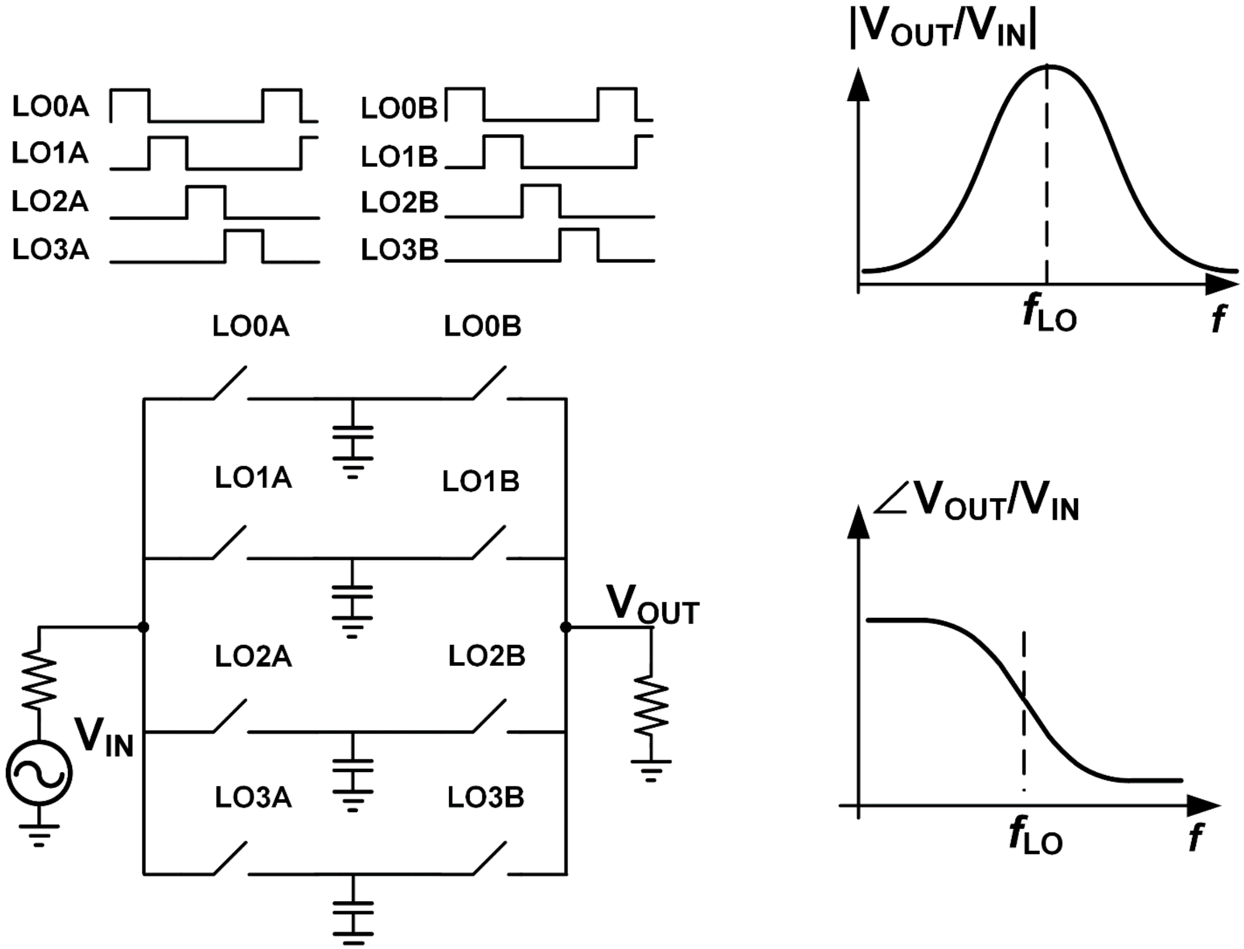
Conductivity can be modulated over a large index on a semiconductor substrate using passive transistor switches.

Staggered Commutation



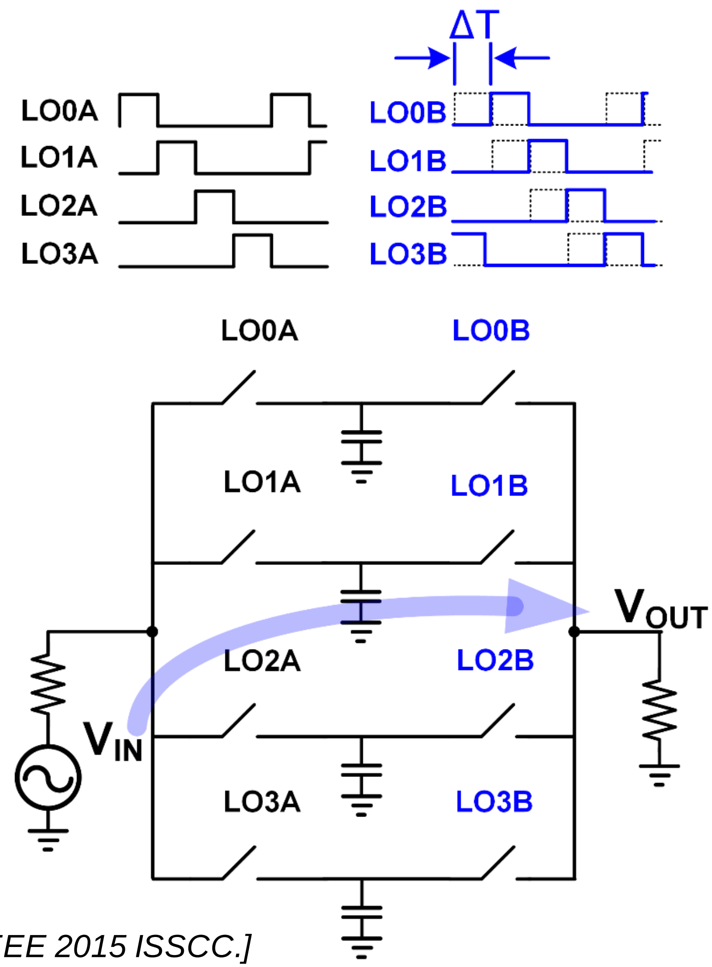
Inspired by Faraday rotation, phase non-reciprocity can be achieved by using staggered commutation.

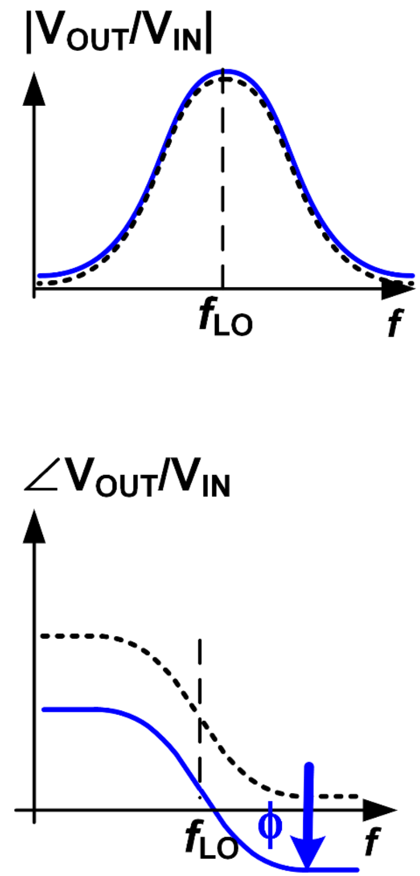
Two-Port CMOS N-Path Filters



- N-path filters are the electronic realization of commutating networks.

Phase Shift in N-Path Filters





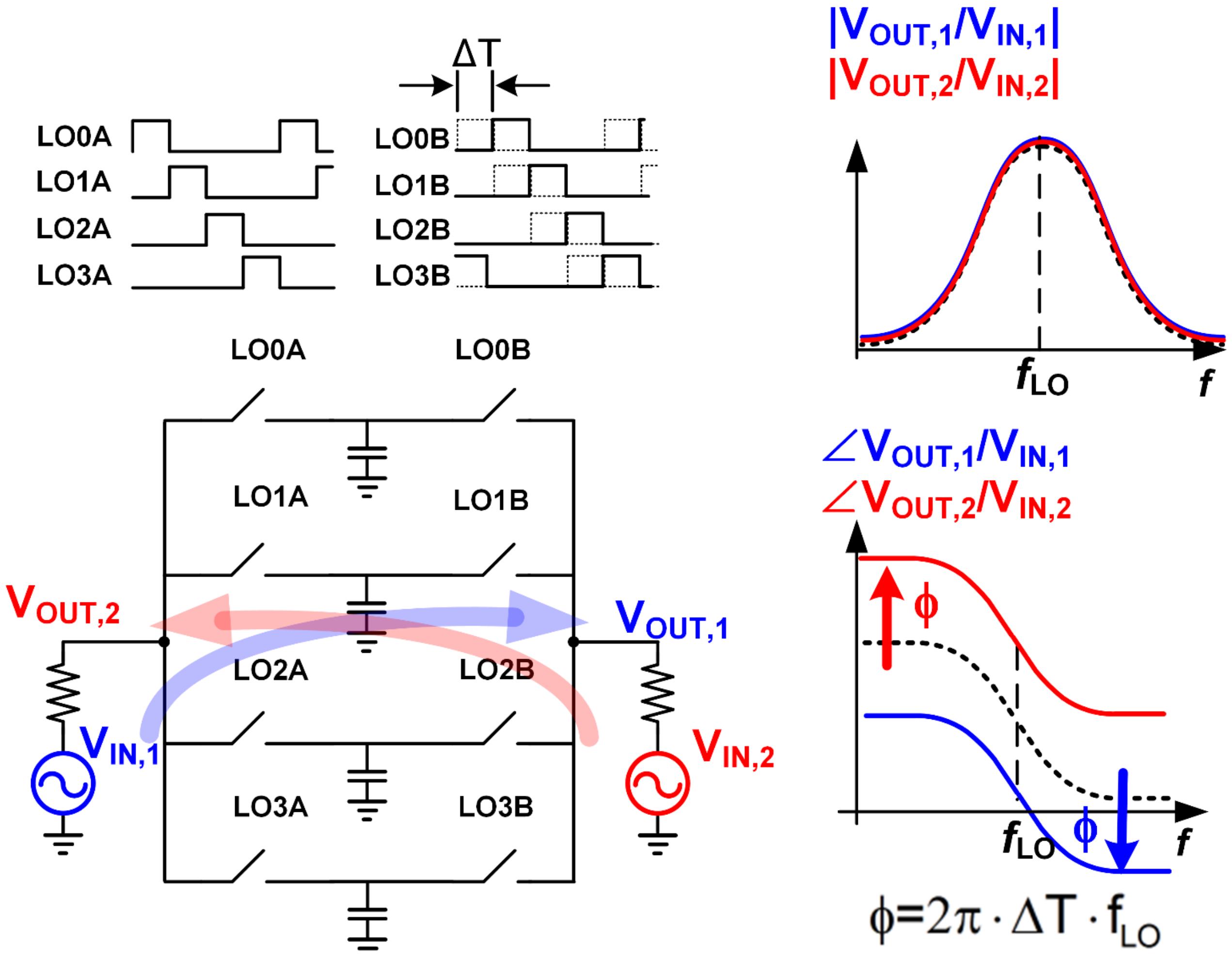
$$\phi = 2\pi \cdot \Delta T \cdot f_{LO}$$

[Ref: J. Zhou, et al., IEEE 2015 ISSCC.]

[Ref: N. Reiskarimian, et al., IEEE 2016 TCAS-II.]

- Our previous work revealed phase shifts can be embedded in the N-path filter by phase shifting the clocks – essentially staggering the commutation.

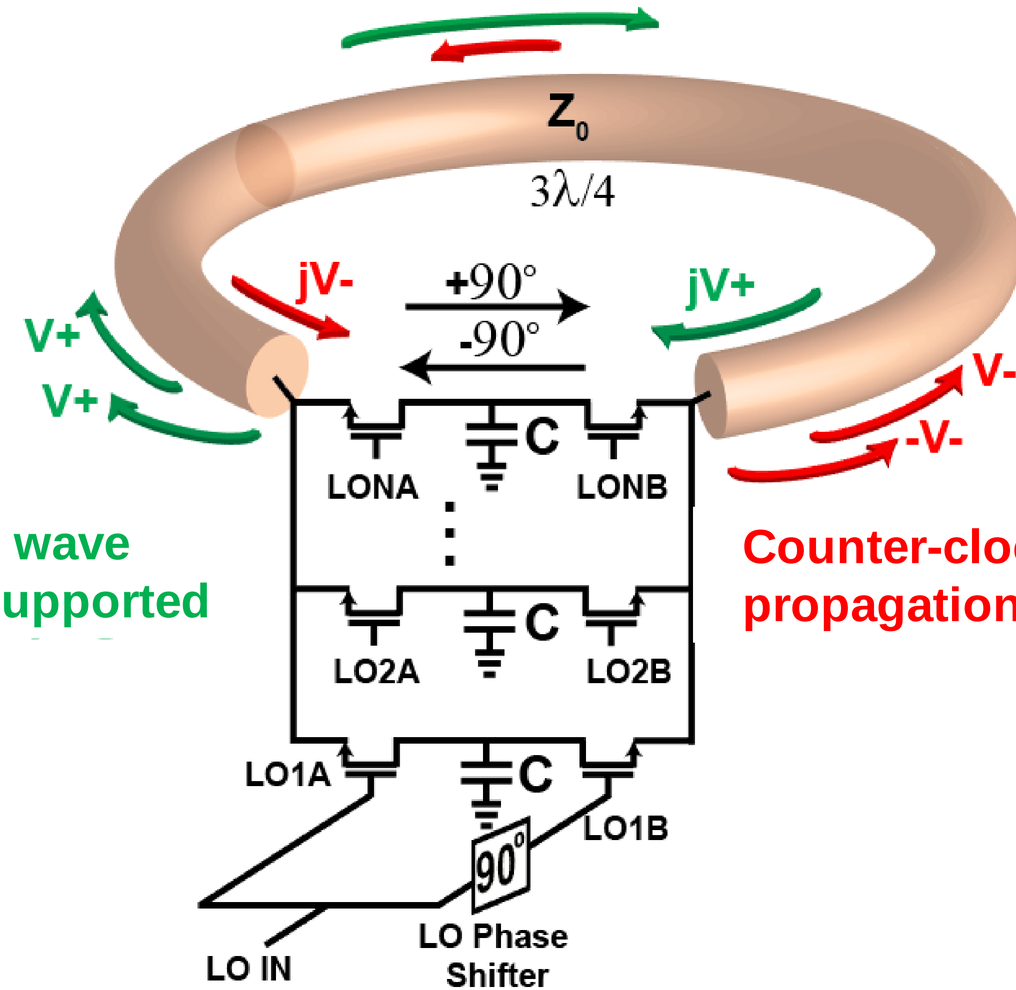
Passive Phase Non-Reciprocity



$$\phi = 2\pi \cdot \Delta T \cdot f_{LO}$$

Phase-shifts applied to signals near f_{LO} traveling in opposite directions have opposite signs.

Non-Reciprocal Wave Propagation

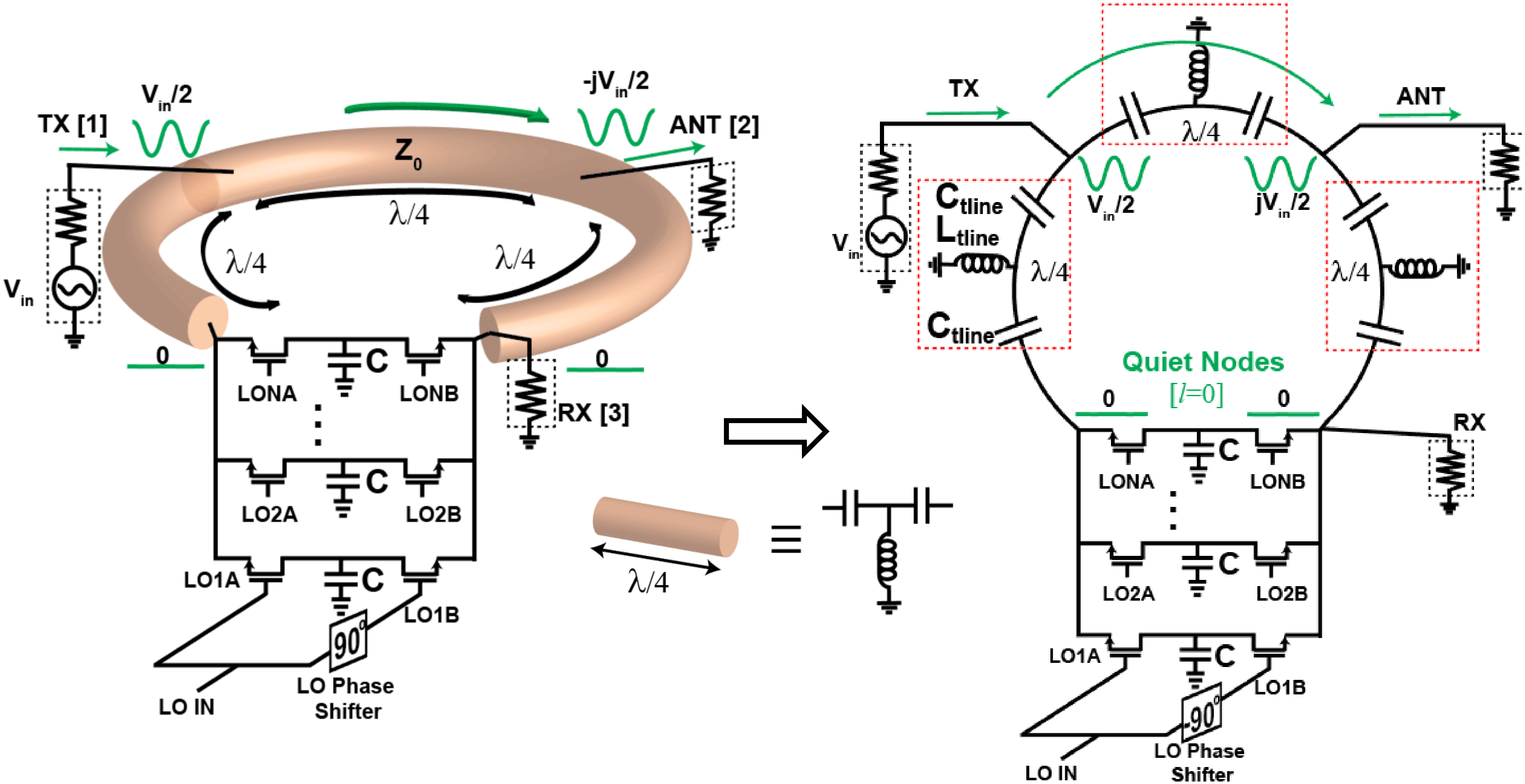


Clockwise wave propagation supported

Counter-clockwise wave propagation suppressed

In the counter-clockwise direction, signals add destructively. Non-reciprocal wave propagation is achieved!

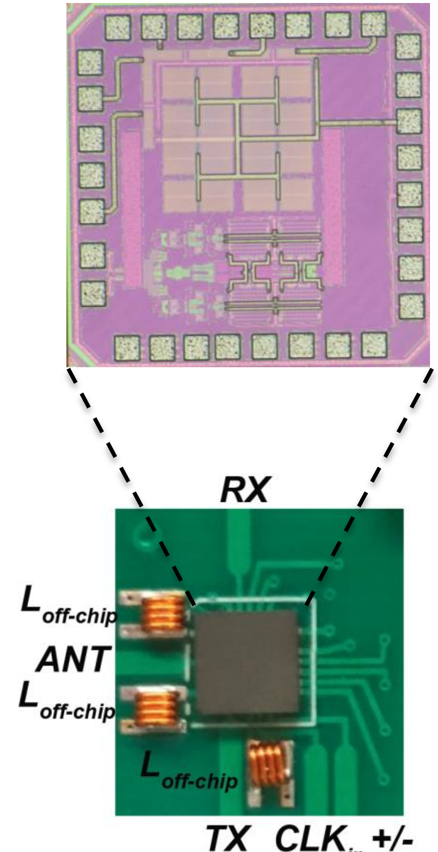
Compact Highly Linear Circulator



- The RX port is placed next to the N-path filter resulting in high linearity to excitations at the TX.
- The 3λ/4 line is miniaturized using three CLC networks for a compact implementation.

65nm CMOS Circulator Breakout

25 X >

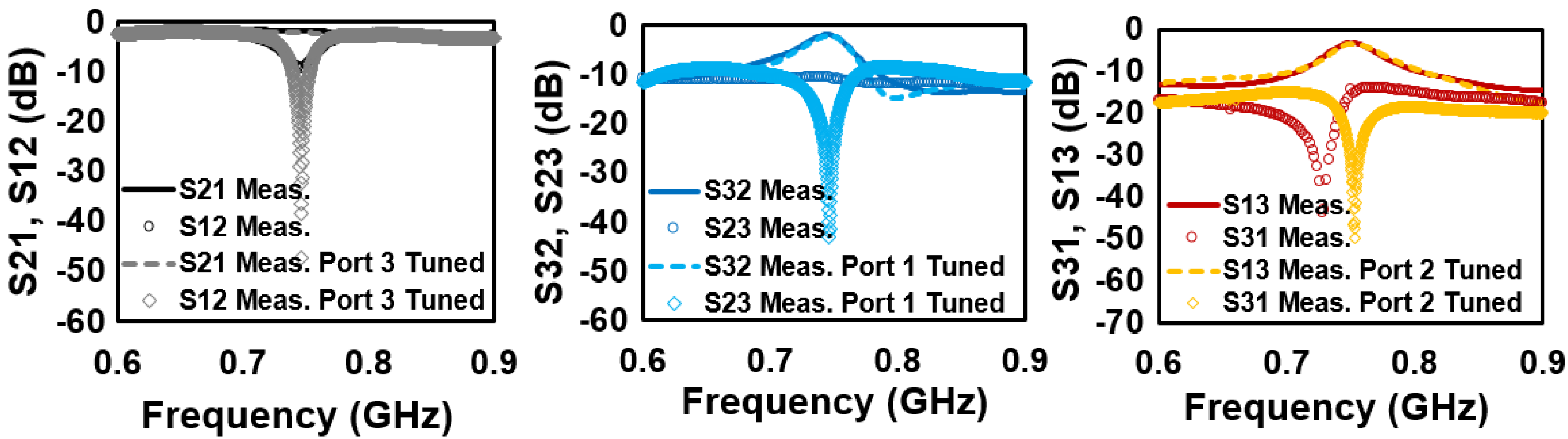


This is the first CMOS magnetic-free passive non-reciprocal circulator IC.

nature COMMUNICATIONS

*N. Reiskarimian, and H. Krishnaswamy, "Magnetic-free Non-Reciprocity Based on Staggered Commutation," *Nature Communications* 7:11217 doi: 10.1038/ncomms11217 (2016).

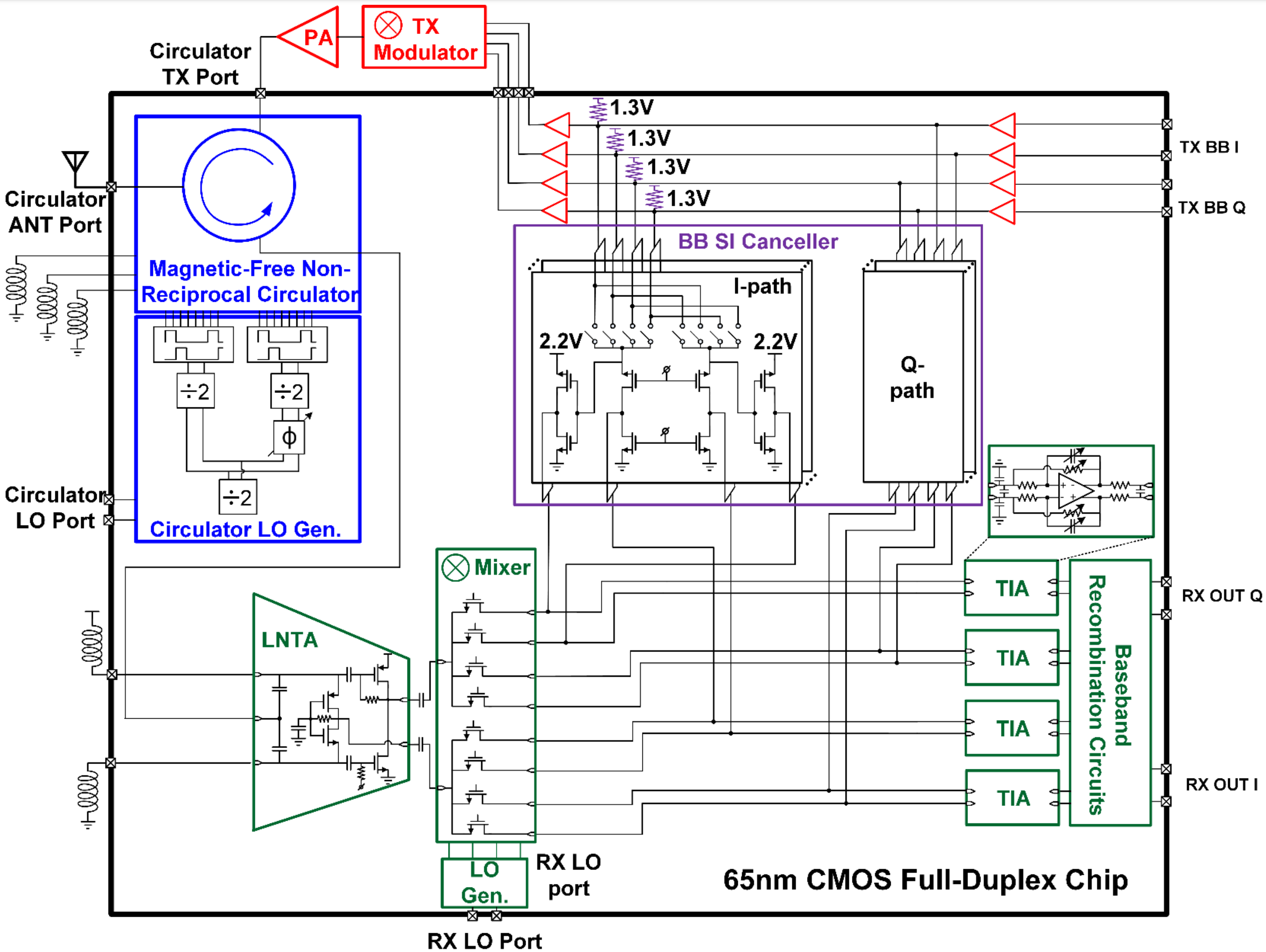
Circulator S-Parameters



- The ANT-RX path sees the filtering profile of the N-path filter.
- Here, tuning is exploited to achieve very high (>50dB) narrowband isolation.

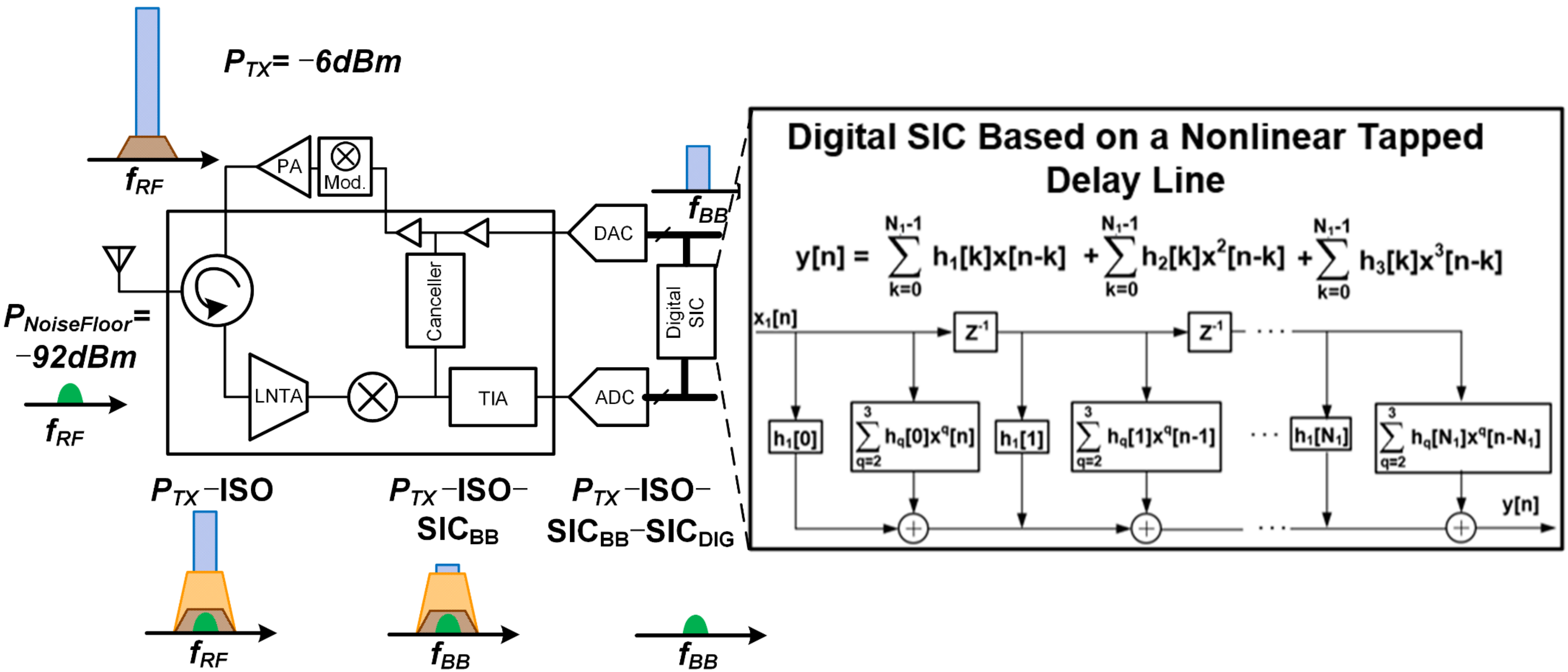
Measurements show very low loss (1.7dB) in both TX-ANT and ANT-RX paths and strong isolation.

Full Duplex Radio



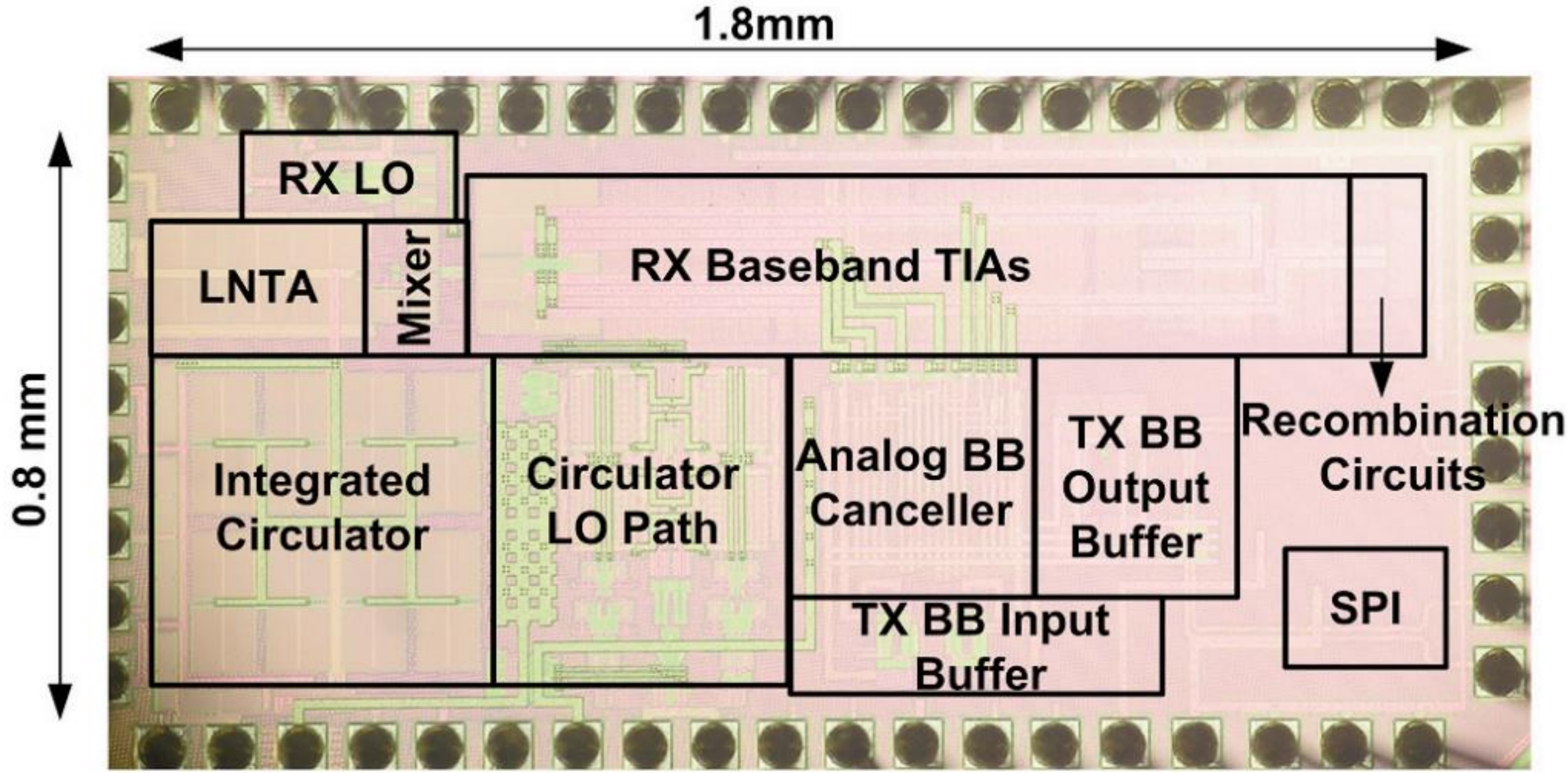
- The full-duplex radio integrates the magnetic-free circulator, a noise-cancelling receiver, transmitter baseband buffers, and an analog SI canceller.

Digital SI Canceller



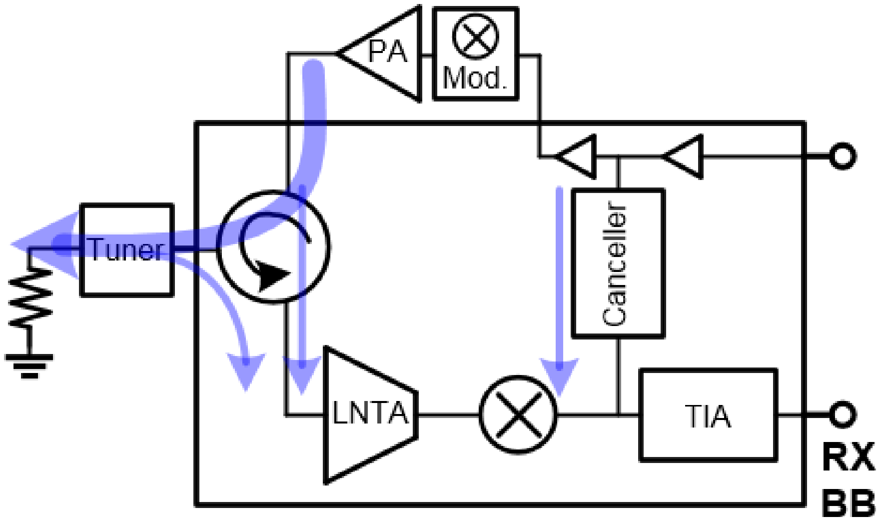
- A nonlinear tapped delay-line-based digital canceller cancels not only the main SI but also the IM3 distortion generated on the SI.

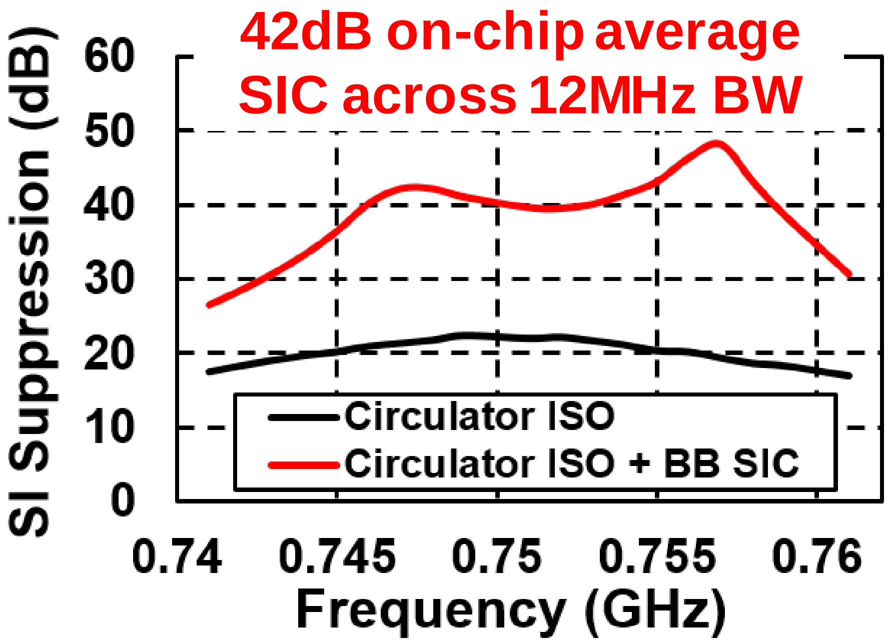
65nm CMOS FD Radio Prototype



Jin Zhou, Negar Reiskarimian and Harish Krishnaswamy, "Receiver with integrated magnetic-free N-path-filter-based non-reciprocal circulator and baseband self-interference cancellation for full-duplex wireless," in *2016 IEEE ISSCC Digest of Technical Papers*, pp. 178 – 180, Feb. 2016.
Negar Reiskarimian, Jin Zhou and Harish Krishnaswamy "A CMOS Passive LPTV Non-Magnetic Circulator and Its Application in a Full-Duplex Receiver," *IEEE JSSC*, vol. 52, no. 5, pp. 1358-1372, May 2017.

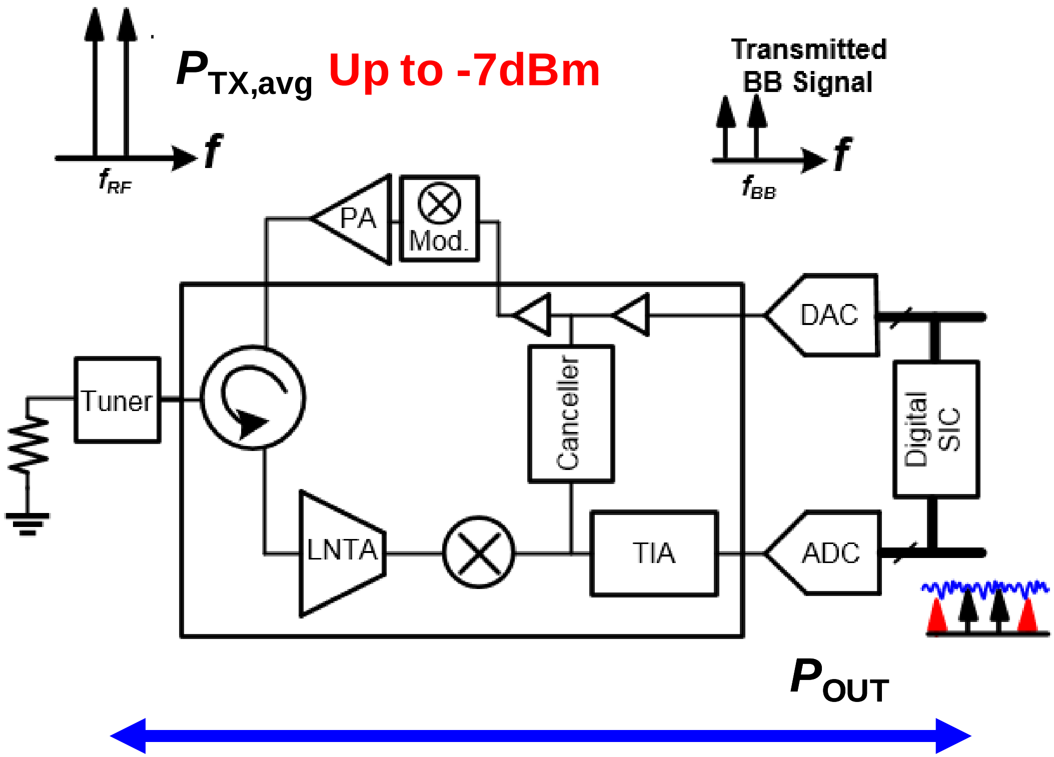
SIC Across ANT and Analog BB



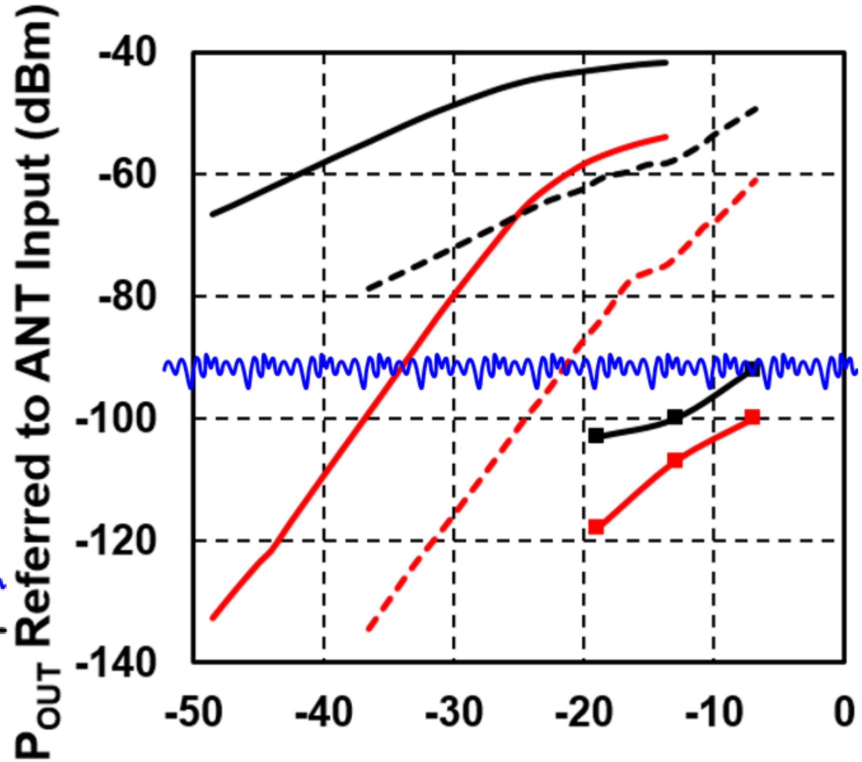


- Joint-optimization of SIC BW across the antenna tuner, circulator and analog baseband canceller enables 42dB on-chip average SIC across 12MHz BW.

SIC across ANT, Analog BB, Digital

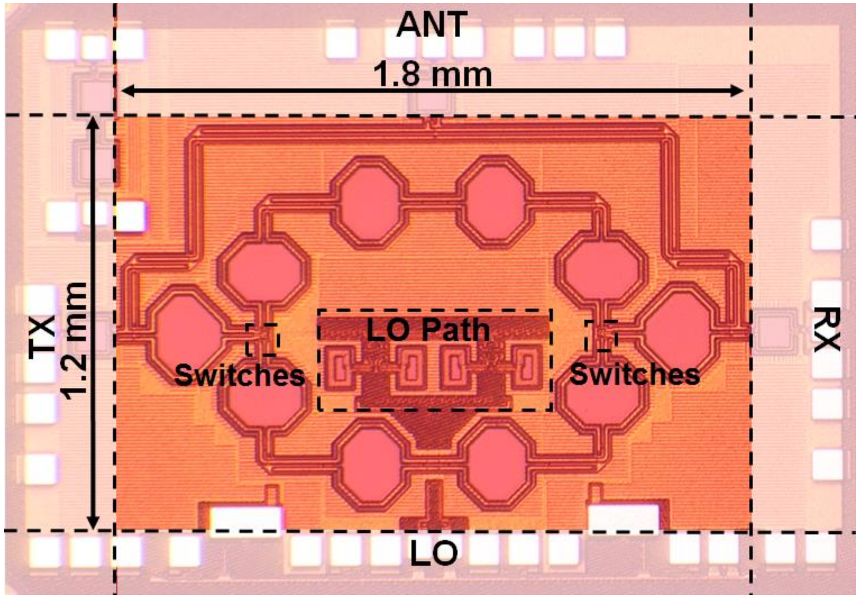


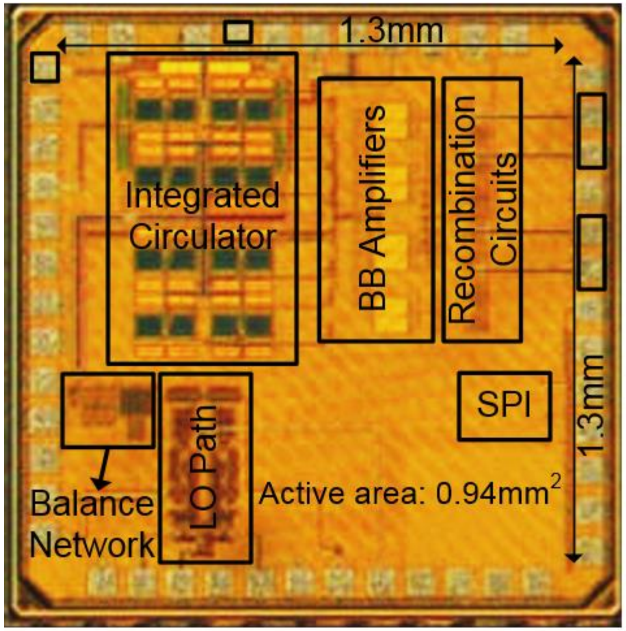
85dB Overall Self-Interference Cancellation



First full-duplex link demonstration with –7dBm TX average output power and –92dBm noise floor.

Some Recent Results at ISSCC'17





A 28GHz circulator in 45nm SOI CMOS based on Spatio-Temporal Conductivity Modulation

A merged circulator-RX with improved (~8dBm) power handling, NF, power dissipation

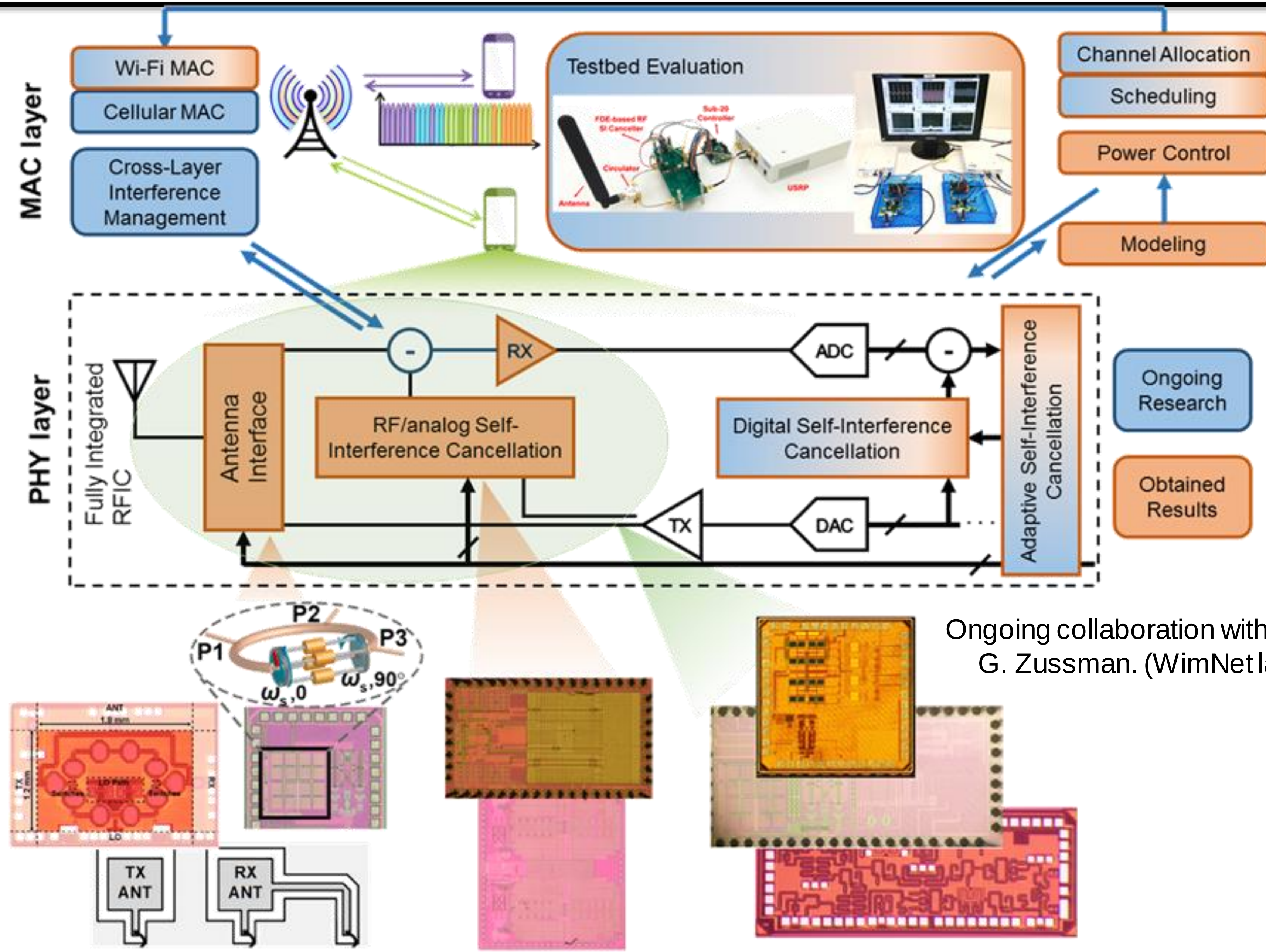
Tolga Dinc and Harish Krishnaswamy, "A 28GHz Magnetic-Free Non-reciprocal Passive CMOS Circulator Based on Spatio-Temporal Conductance Modulation", in the *2017 IEEE ISSCC*, pp. 294-295, Feb. 2017.

Negar Reiskarimian, Mahmood Baraani Dastjerdi, Jin Zhou and Harish Krishnaswamy, "Highly-Linear Integrated Magnetic-Free Circulator-Receiver for Full-Duplex Wireless," in the *2017 ISSCC*, pp. 316-317, Feb. 2017.

Overview

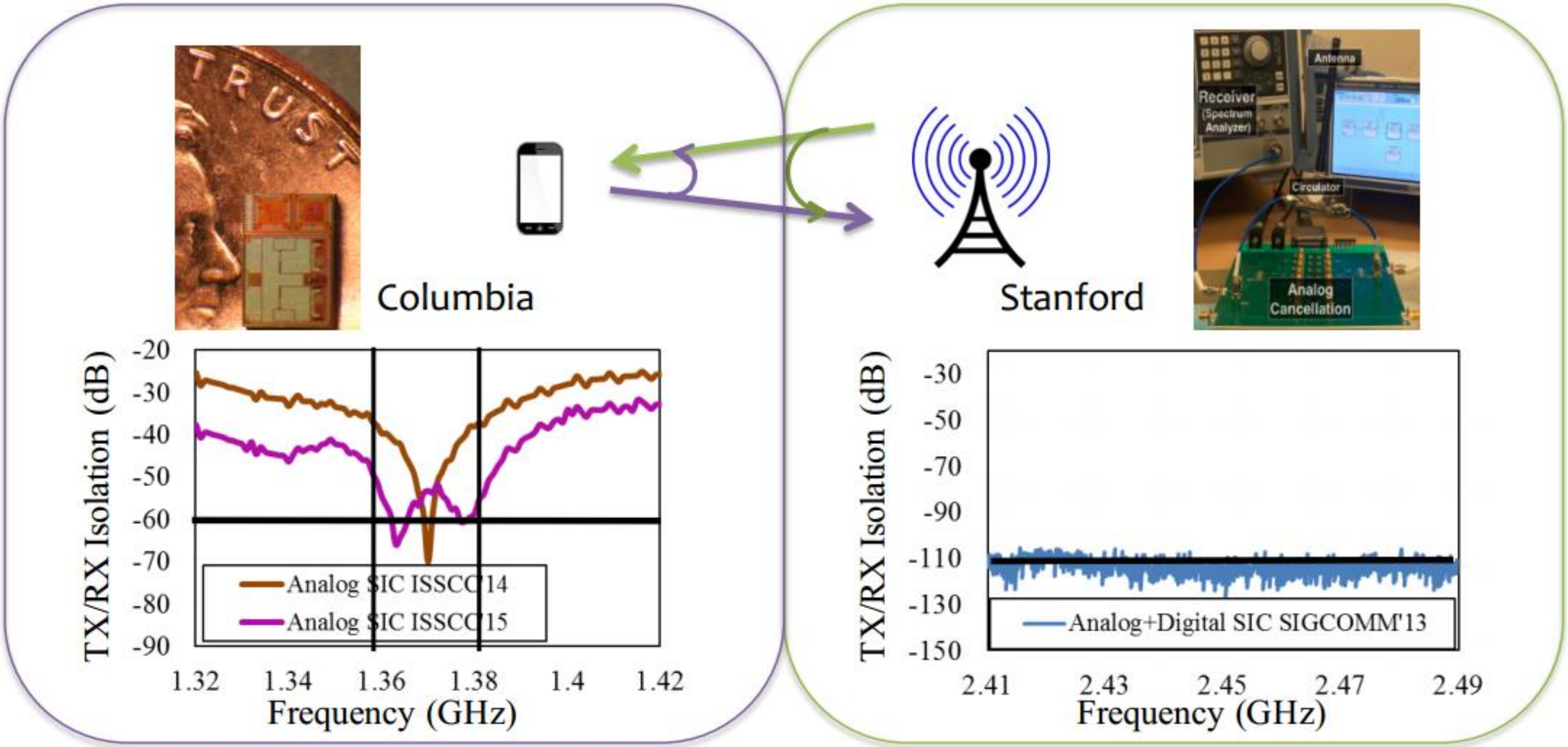
- Introduction
- Full Duplex Wireless
- **FD at the Higher Layers**
- Conclusion

Columbia's FlexICoN Project



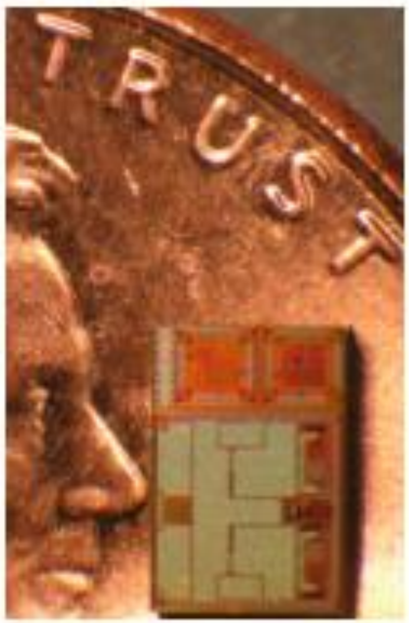
Ongoing collaboration with Prof. G. Zussman. (WimNet lab)

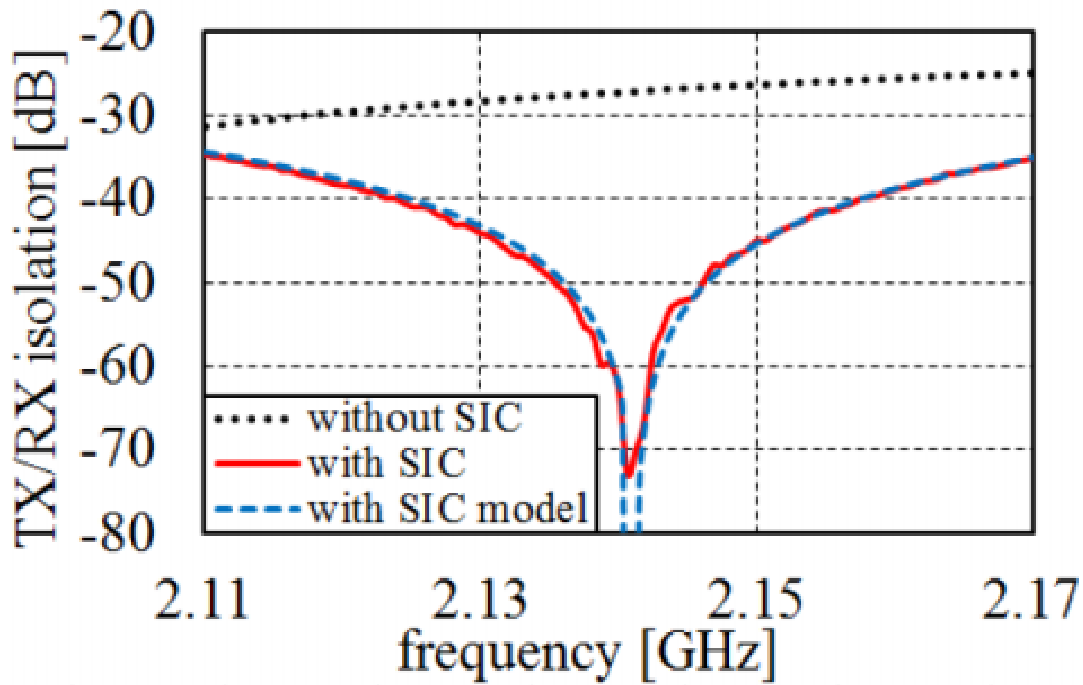
Imperfect Self-Interference Canc.



- Prior work on the resource allocation and rate gain characterization of full-duplex wireless assumes perfect self-interference cancellation.
- We model the imperfect self-interference cancellation at the MS.

Modeling Canc. at Integrated MSs

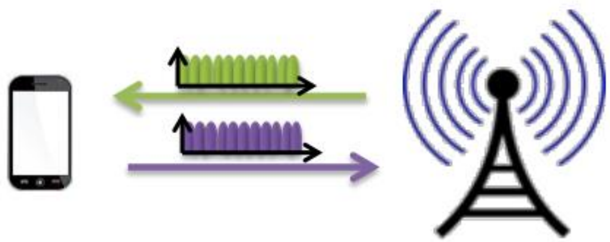




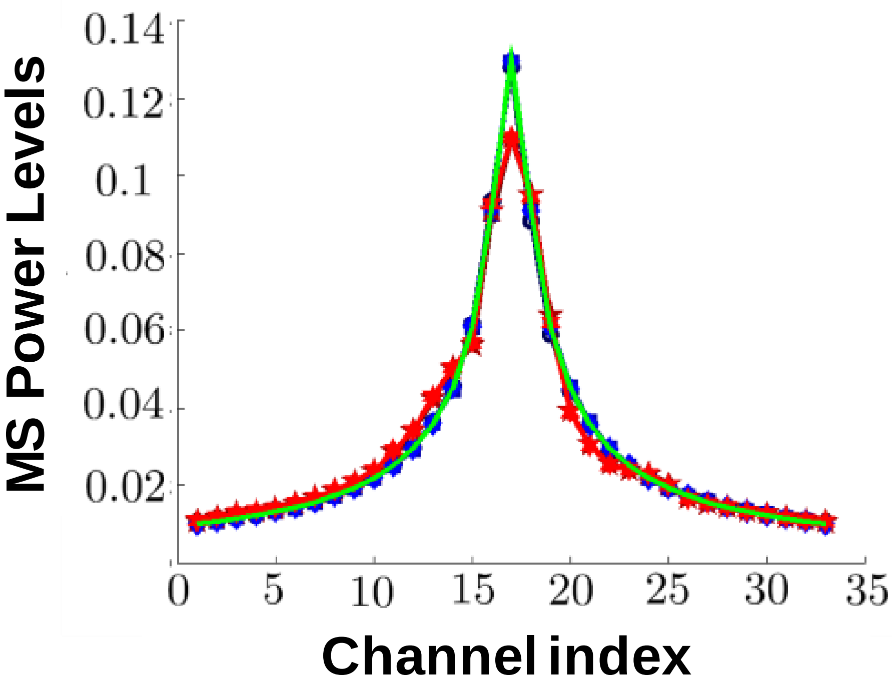
$$
\begin{aligned}
RSI_{m,k} &= 2|H_A|^2 P_{m,k} \left(1 - \cos(2\pi\tau(f_k - f_c))\right) SIC_D^{-1} \\
&= \text{const.} \cdot (f_k - f_c)^2 \cdot P_{m,k}
\end{aligned}
$$

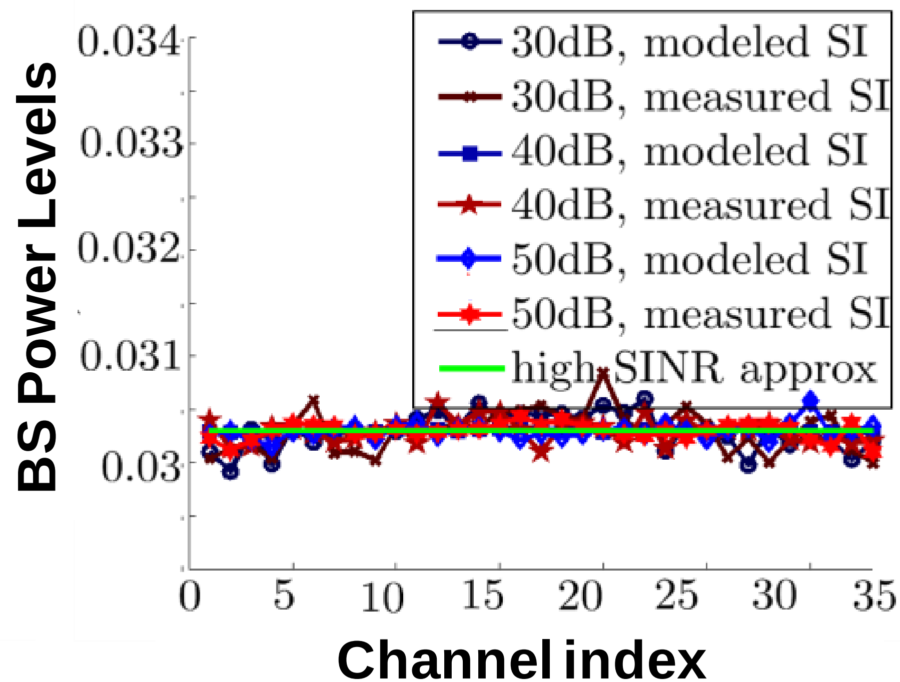
- A mathematical model is developed to model the self-interference cancellation obtained from a frequency-flat self-interference canceller.

Power Allocation Under High SINR

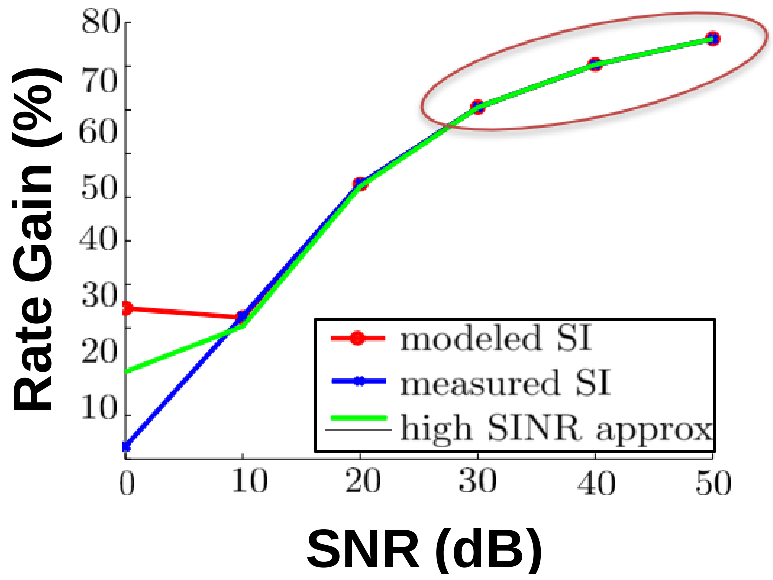


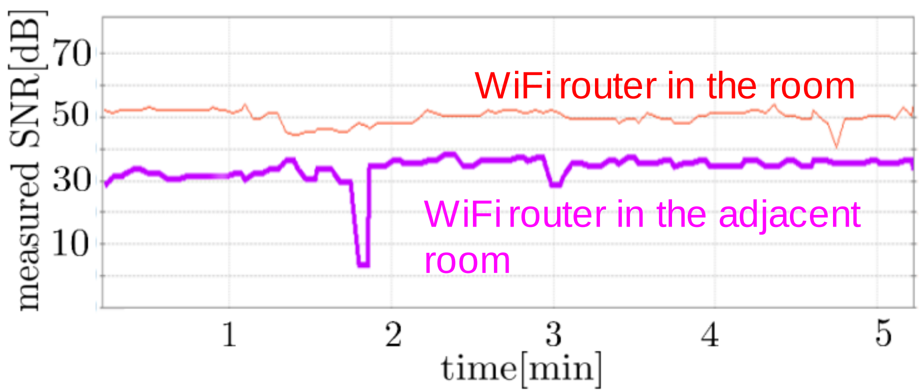
- A bidirectional link between a BS and a MS.
- 33 channels on a 20MHz bandwidth.





Rate Improvements





Significant – over 60% throughput gains – are achieved in the high SNR regime.

Higher Layer References

- J. Marašević, J. Zhou, H. Krishnaswamy, Y. Zhong, and G. Zussman, “Resource Allocation and Rate Gains in Practical Full-Duplex Systems,” *IEEE/ACM Transactions on Networking*, vol. 25, no. 1, pp. 292-305, Feb. 2017.
- J. Marašević, J. Zhou, H. Krishnaswamy, Y. Zhong, and G. Zussman, “Resource Allocation and Rate Gains in Practical Full-Duplex Systems,” in *Proc. ACM SIGMETRICS'15*, 2015.

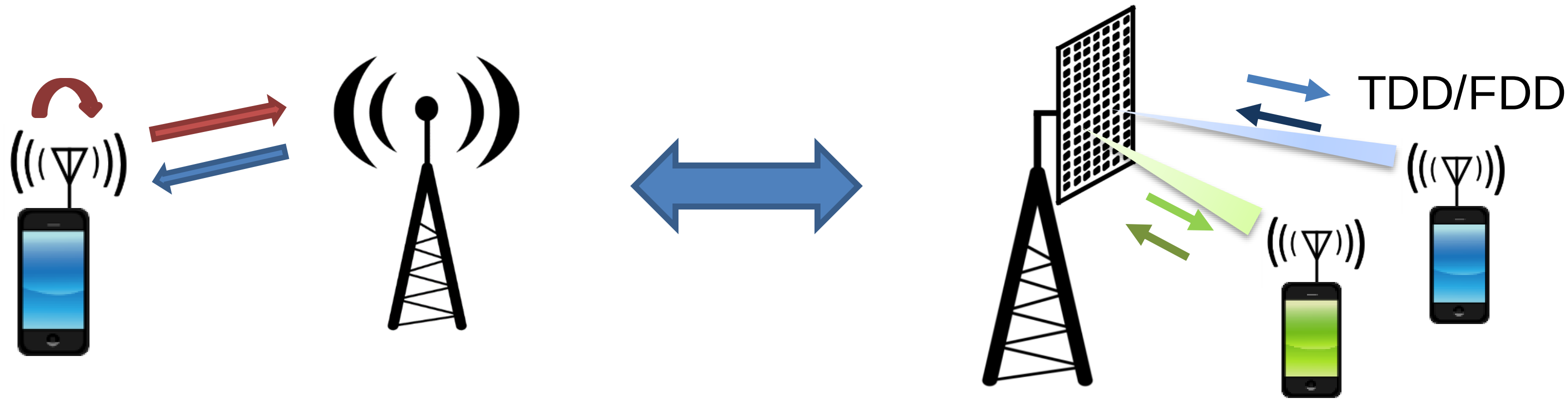
For newer work that computes resource allocation and rate gains using the frequency-domain equalization (FDE) based canceller:

- J. Marašević and G. Zussman, “On the Capacity Regions of Single-Channel and Multi-Channel Full-Duplex Links,” in *Proc. ACM MobiHoc'16*, 2016.

Full-Duplex Massive MIMO

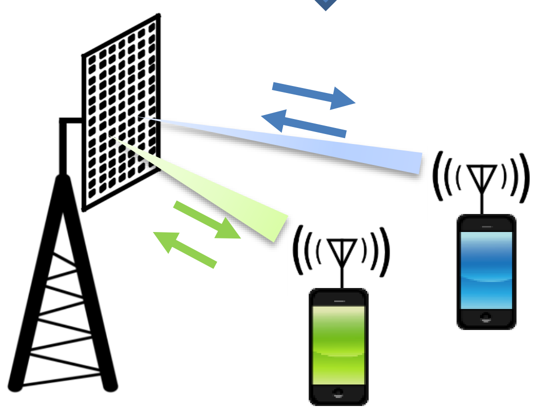
5G Emerging Technologies

Full-Duplex | **Massive MIMO**



- Can these technologies work in conjunction with each other?

Full-Duplex massive MIMO



Additional benefits:

1. Massively increased throughput
2. Reduced interference
3. Higher reliability

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Conclusion

- Rethinking the functional boundaries of the conventional radio *through creative circuit design* enables the movement of complex signal processing functionalities to the RF front-end (*and even within the antenna*).

- Linear periodically time-varying circuits enable breaking of time-reversal symmetry and magnetic-free non-reciprocity in CMOS for the first time.

- The resultant *order-of-magnitude* performance enhancements enable new communication paradigms, such as full-duplex radio. *The first full-duplex RF and mmWave radio ICs have been demonstrated.*

- Topics for future research include cross-layer co-design of PHY and MAC layers, and hardware implementations of full-duplex MIMO.