A Single Antenna Full-Duplex Radio using A Non-Magnetic, CMOS Circulator with In-built Isolation Tuning

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Columbia University in the City of New York

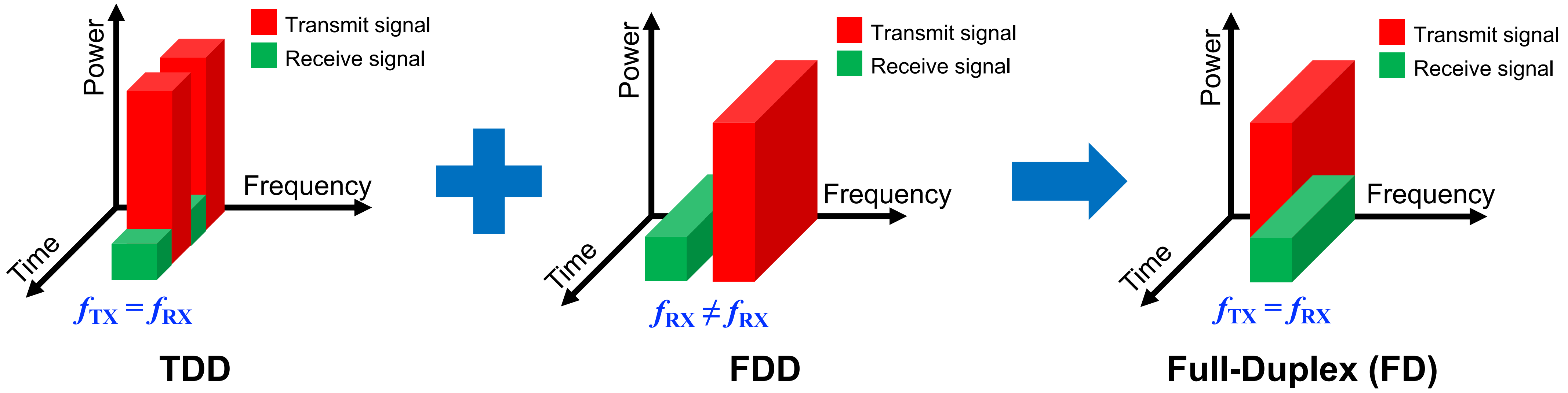
Wireless & Mobile Networking Lab

Columbia high-Speed and Mm-wave IC Lab

Full-Duplex Wireless

- Legacy half-duplex wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

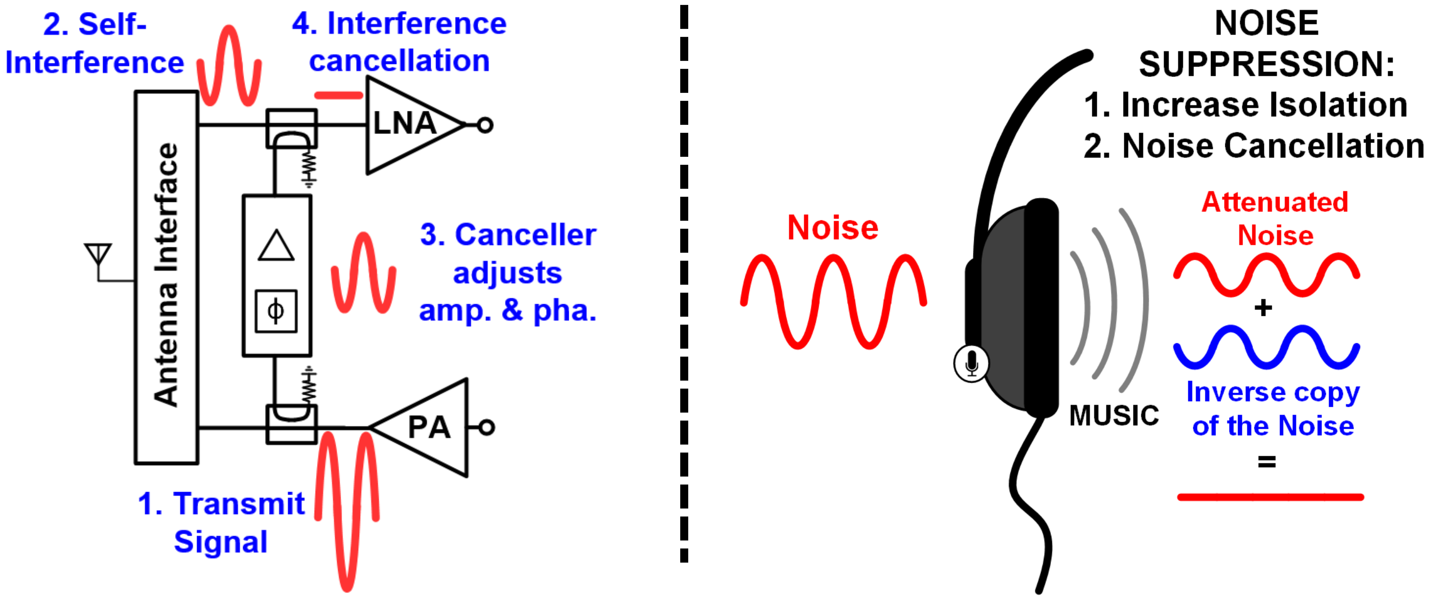
- (Same channel) Full-duplex communication: simultaneous transmission and reception on the same frequency channel



Full-Duplex Wireless

- Benefits of full-duplex wireless:
  - Increased system throughput and reduced latency
  - More flexible use of the wireless spectrum and energy efficiency

- Viability is limited by self-interference
  - Transmitted signal is **billions** of times (**10^9 or 90dB**) stronger than the received signal
  - Requiring extremely powerful self-interference cancellation



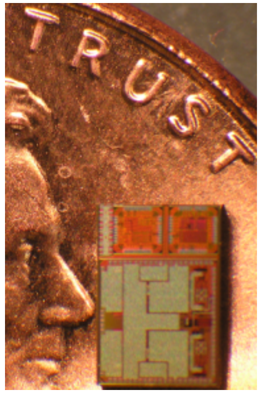
How much is 90dB?

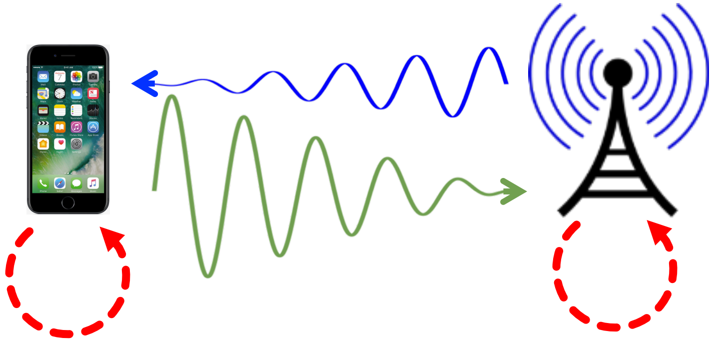
Self-interference (SI)

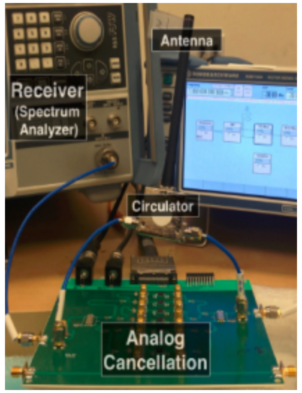
Desired signal

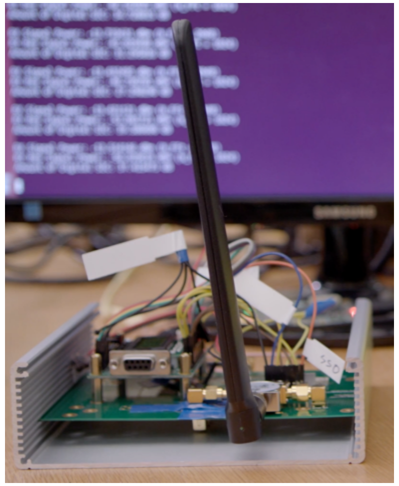
The Columbia FlexICoN Project

- **F**ull-Dup**lex** Wireless: From **I**ntegrated **C**ircuits t**o** **N**etworks (FlexICoN)
  - FD transceiver/system development, algorithm design, experimental evaluation
  - Focus on IC-based implementations (in collaboration w/ the CoSMIC lab led by Prof. Harish Krishnaswamy)
  - Integration of full-duplex capability in the ORBIT and COSMOS testbeds









Full-duplex radios implemented in RFIC (Columbia)

Full-duplex radios using off-the-shelf components (e.g., Stanford)

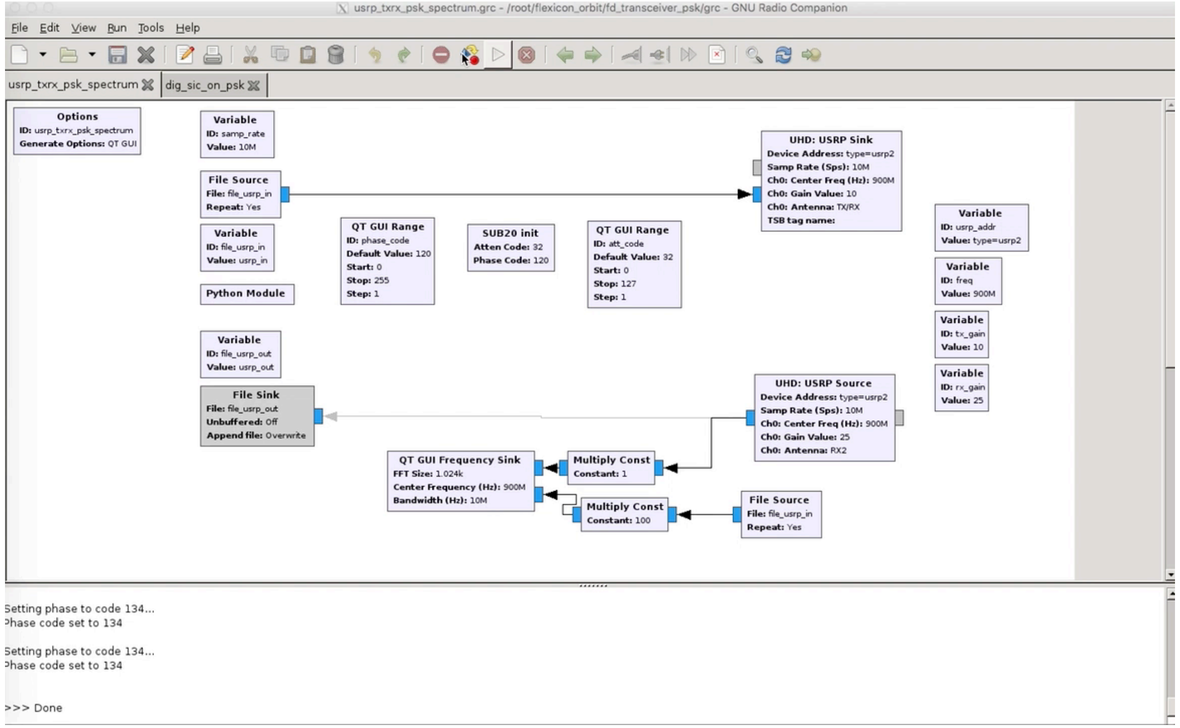
A programmable 1st-generation full-duplex node installed in the open-access ORBIT testbed

- **T. Chen**, J. Zhou, M. Baraani Dastjerdi, J. Diakonikolas, H. Krishnaswamy, and G. Zussman, "Demo abstract: Full-duplex with a compact frequency domain equalization-based RF canceller," in *Proc. IEEE INFOCOM'17*, 2017.
- **T. Chen**, M. Baraani Dastjerdi, G. Farkash, J. Zhou, H. Krishnaswamy, and G. Zussman, "Open-access full-duplex wireless in the ORBIT testbed," *arXiv:1801.03069v2 [cs.NI]*, May 2018. Demo at *IEEE INFOCOM'18*. **Tutorials and code available online at ORBIT/COSMOS wiki and GitHub**

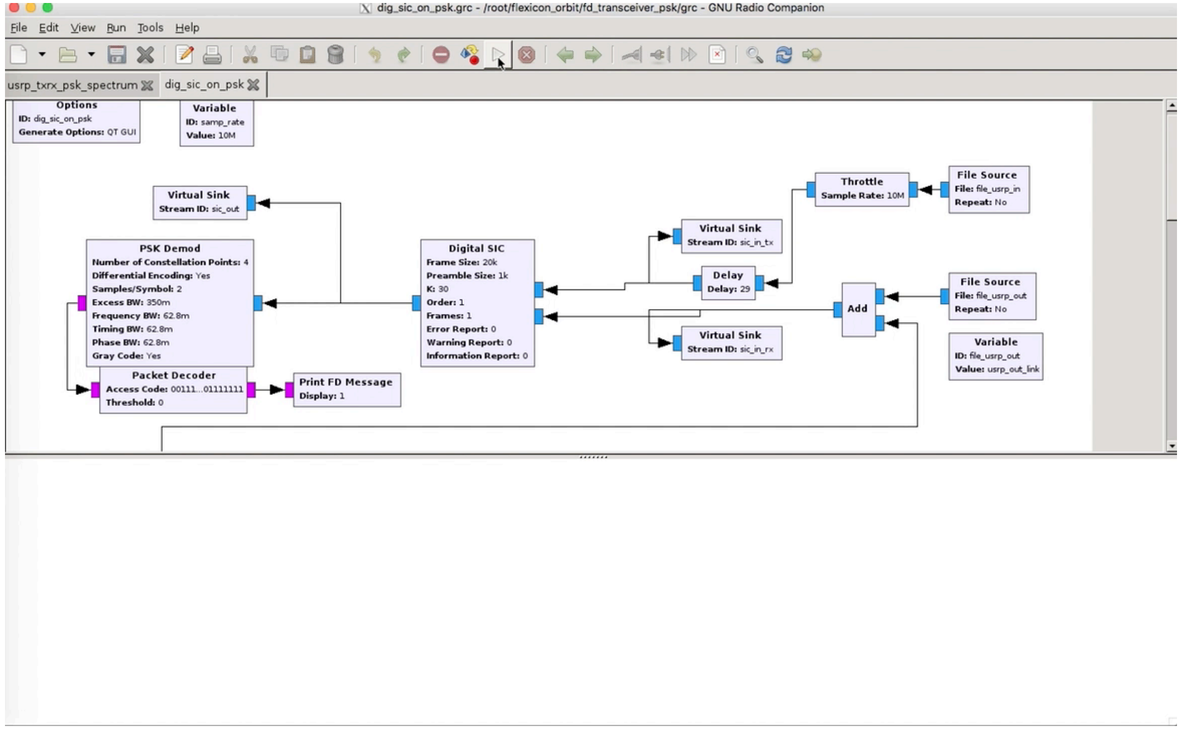
Full-Duplex Wireless in the ORBIT Testbed

- Two example demonstrations

Real-time RF canceller configuration



Packet-level full-duplex communication



- **<u>T. Chen</u>**, J. Zhou, M. Baraani Dastjerdi, J. Diakonikolas, H. Krishnaswamy, and G. Zussman, "Demo abstract: Full-duplex with a compact frequency domain equalization-based RF canceller," in *Proc. IEEE INFOCOM'17*, 2017.
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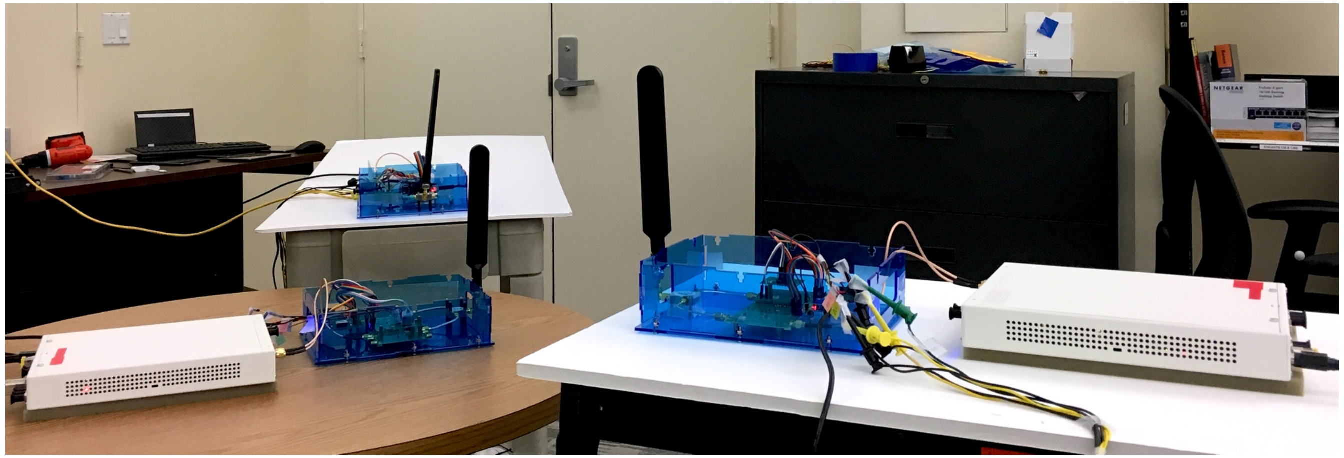
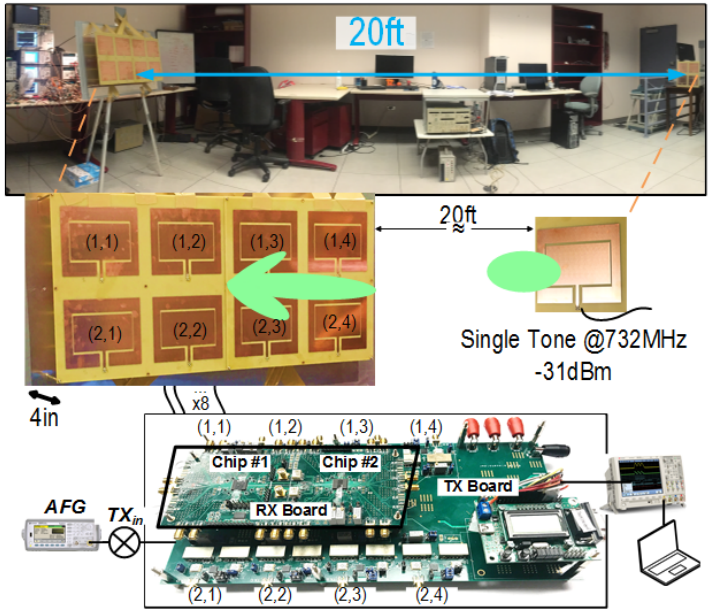
- **F**ull-Dup**lex** Wireless: From **I**ntegrated **C**ircuits t**o** **N**etworks (FlexICoN)
  - FD SISO radios, phased arrays, and MIMO radios
  - Scheduling in heterogenous networks with both HD and FD users



2nd-generation wideband full-duplex nodes



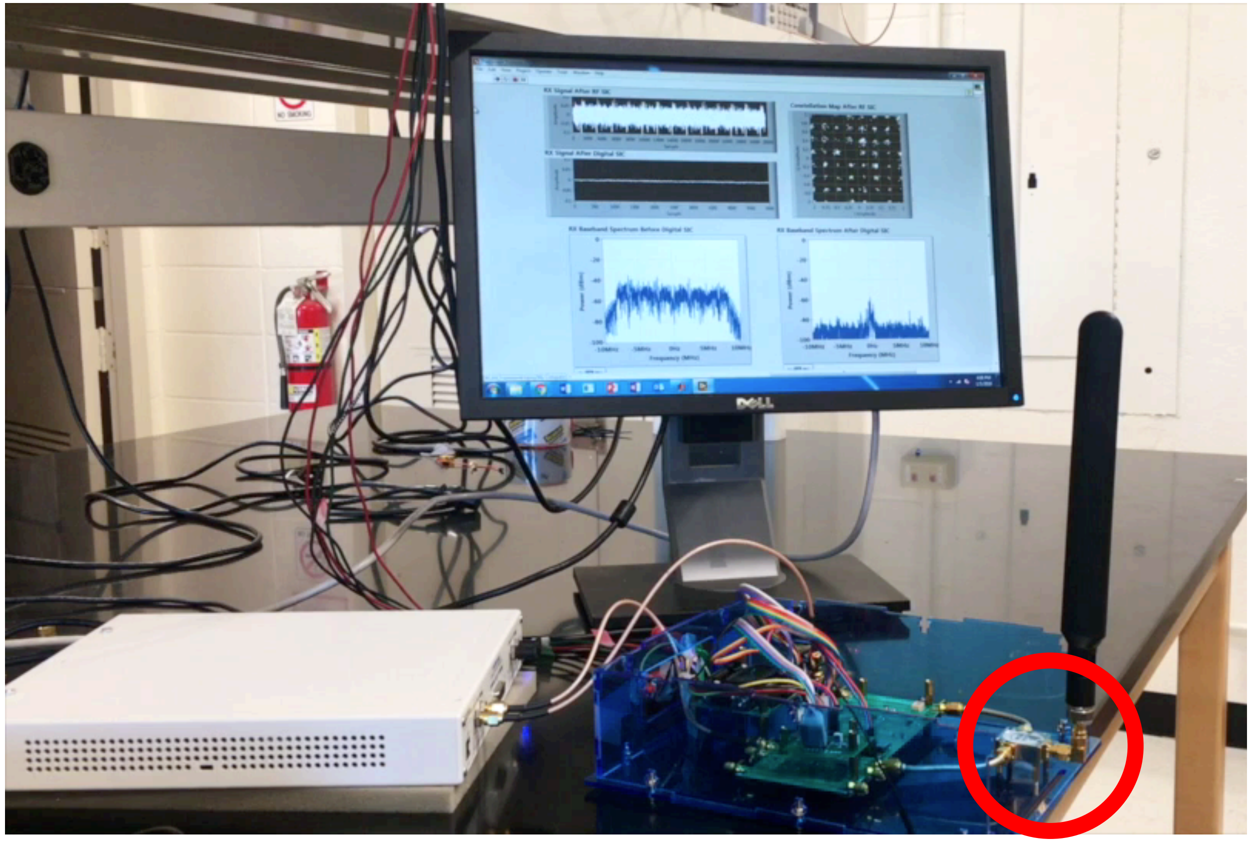
An 8-element IC-based FD phased array

- **T. Chen**, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MobiCom'19 (to appear)*, 2019.
- **T. Chen**, M. Baraani Dastjerdi, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex phased array with joint transmit and receive beamforming: Optimization and rate gains," in *Proc. ACM MobiHoc'19 (to appear)*, 2019.
- **T. Chen**, J. Diakonikolas, J. Ghaderi, and G. Zussman, "Hybrid scheduling in heterogeneous half- and full-duplex wireless networks," in *Proc. IEEE INFOCOM'18*, 2018.
- M. Baraani Dastjerdi, N. Reiskarimian, **T. Chen**, G. Zussman, and H. Krishnaswamy, "Full duplex circulator-receiver phased array employing self-interference cancellation via beamforming," in *Proc. IEEE Radio Frequency Integrated Circuits Symposium (RFIC'18)*, 2018.

2nd-Generation Wideband (Compact) Full-Duplex Node

NI LabVIEW

NI USRP SDR

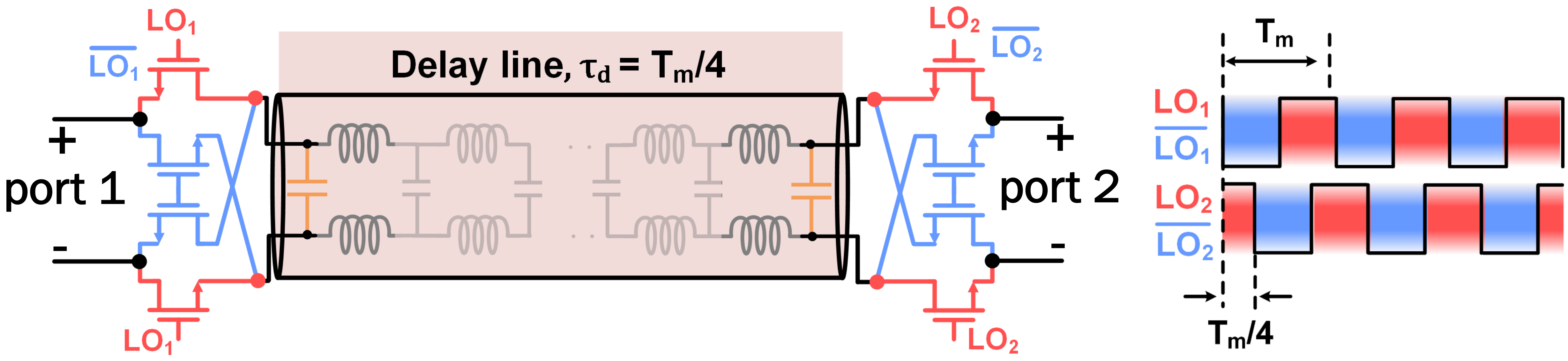


Magnetic Circulator

- OFDM PHY w/ 20MHz real-time RF BW
- Modulation schemes: from BPSK to 64QAM
- TX power: +10dBm
- RX noise floor: -85dBm
- Overall SIC: 95dB
- RF SIC: 52dB
- Digital SIC: 43dB
- Adaptive RF canceller configuration

- **T. Chen**, M. Baraani Dastjerdi, J. Zhou, H. Krishnaswamy, and G. Zussman, "Wideband full-duplex wireless via frequency-domain equalization: Design and experimentation," in *Proc. ACM MobiCom'19 (to appear)*, 2019.

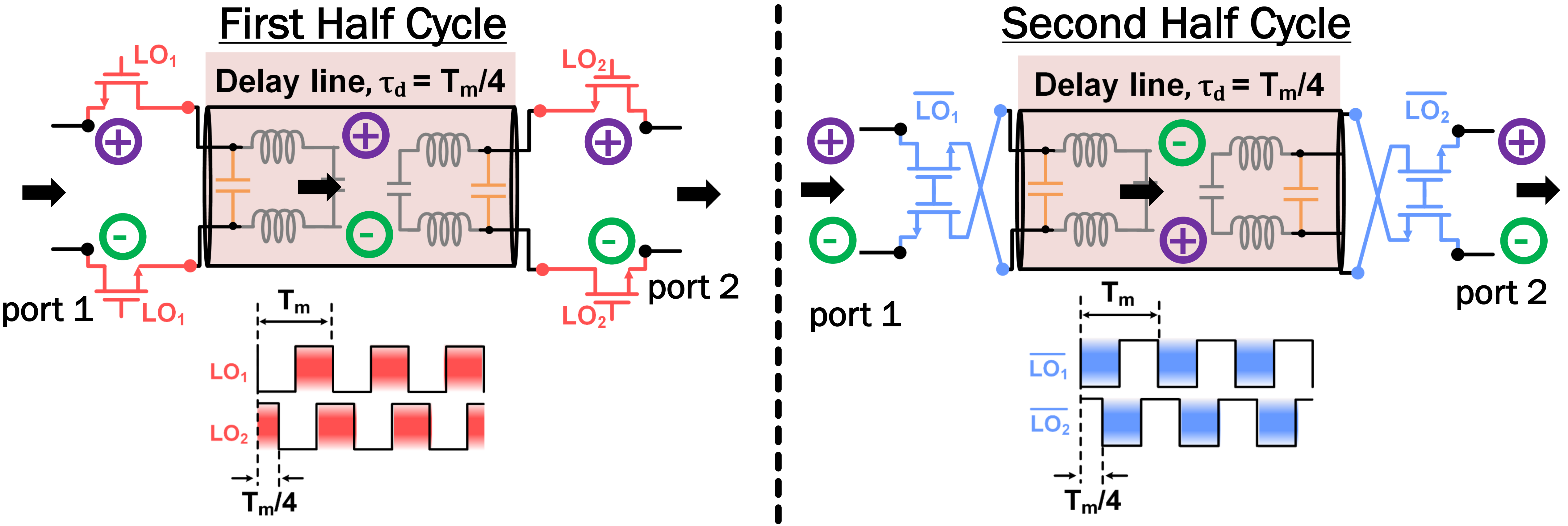
Ultra-Wideband Switched Delay Line Gyrator



- 50% duty cycle square waves with time period $\mathbf{T}_m$
- Right-hand side switches are delayed with respect to left-hand side switched by $\mathbf{T}_m/4$
- Delay of the transmission line is $\mathbf{T}_m/4$

Ultra-Wideband Switched Delay Line Gyrator

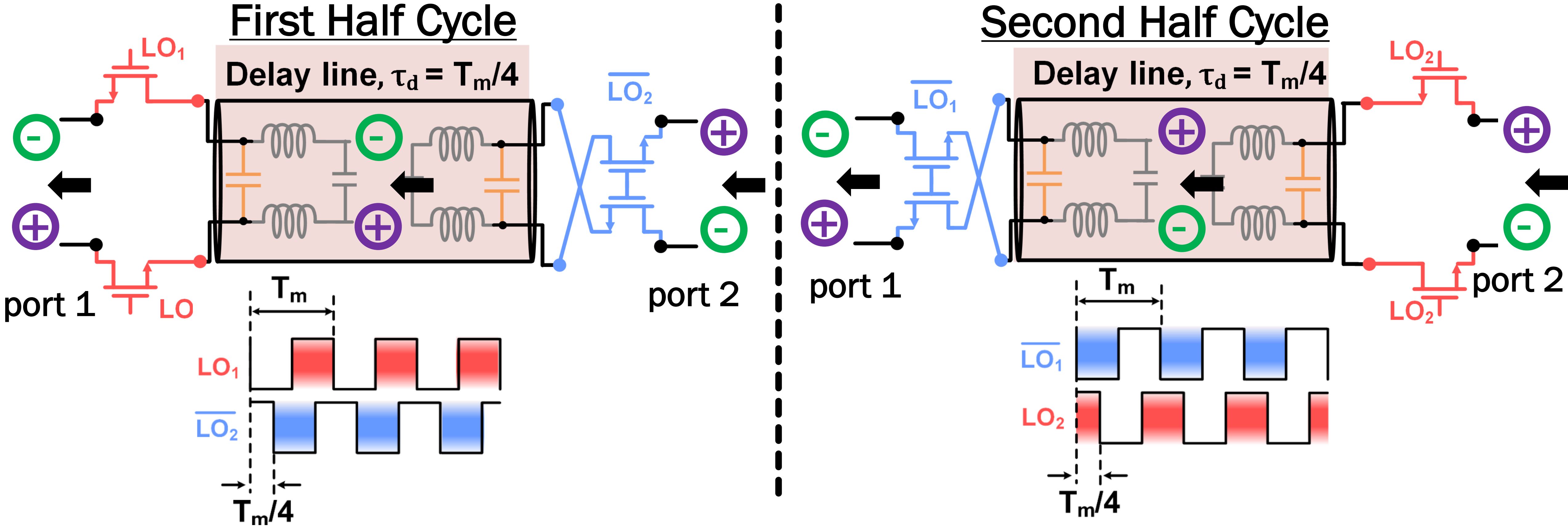
- Operation in the ***forward*** direction



- The signal in the forward direction experiences just the delay of the transmission line

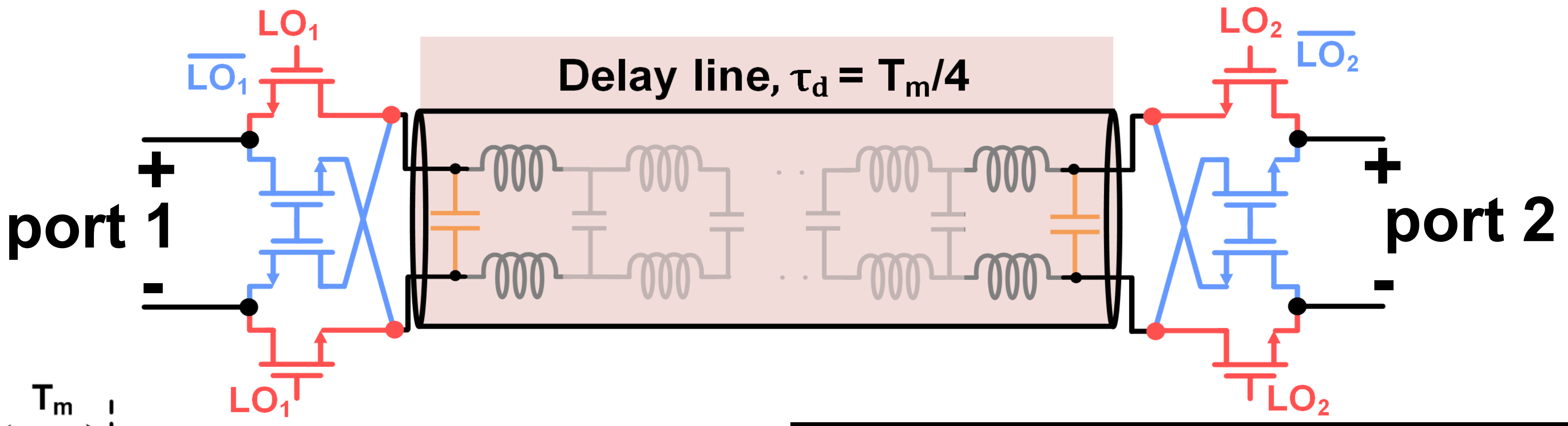
Ultra-Wideband Switched Delay Line Gyrator

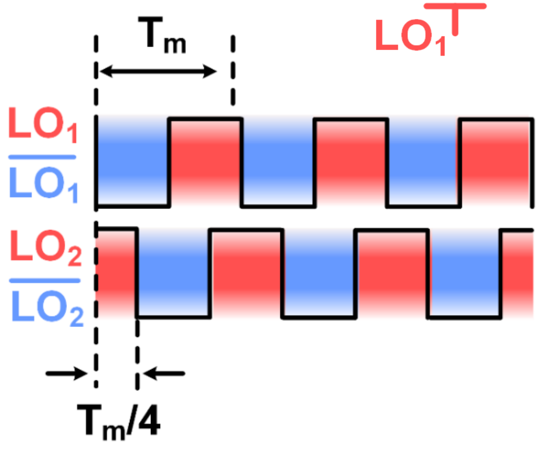
- Operation in the ***reverse*** direction



- The signal in the reverse direction experiences the delay of the transmission line **w/ an additional sign flip**

Ultra-Wideband Switched Delay Line Gyrator

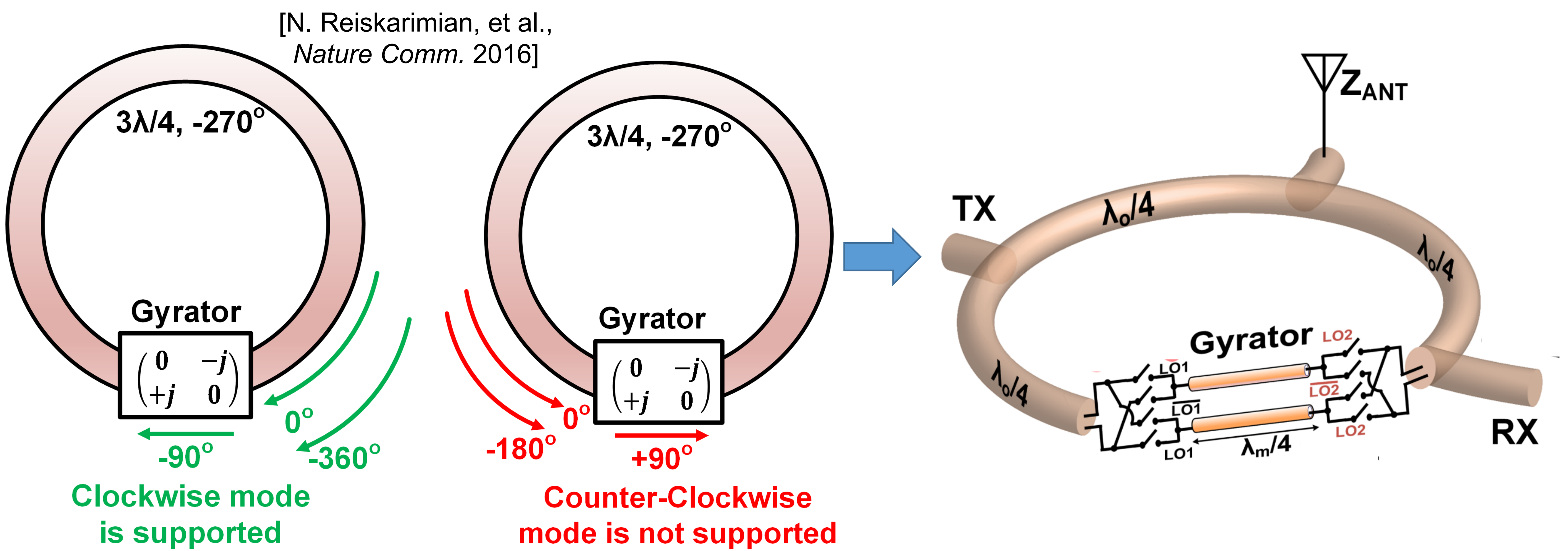




$$\mathbf{S} = \begin{pmatrix} 0 & -e^{-\frac{j\omega T_m}{4}} \\ +e^{-\frac{j\omega T_m}{4}} & 0 \end{pmatrix}$$

- This structure provides perfect matching and lossless transmission with non-reciprocal phase shift of 180° across infinite bandwidth

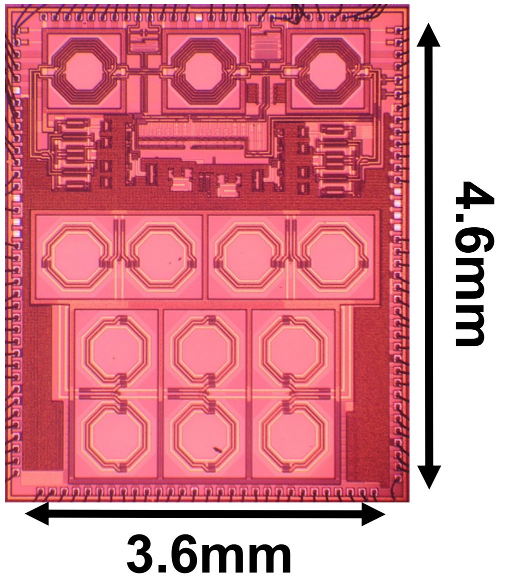
Converting the Gyrator into a Circulator

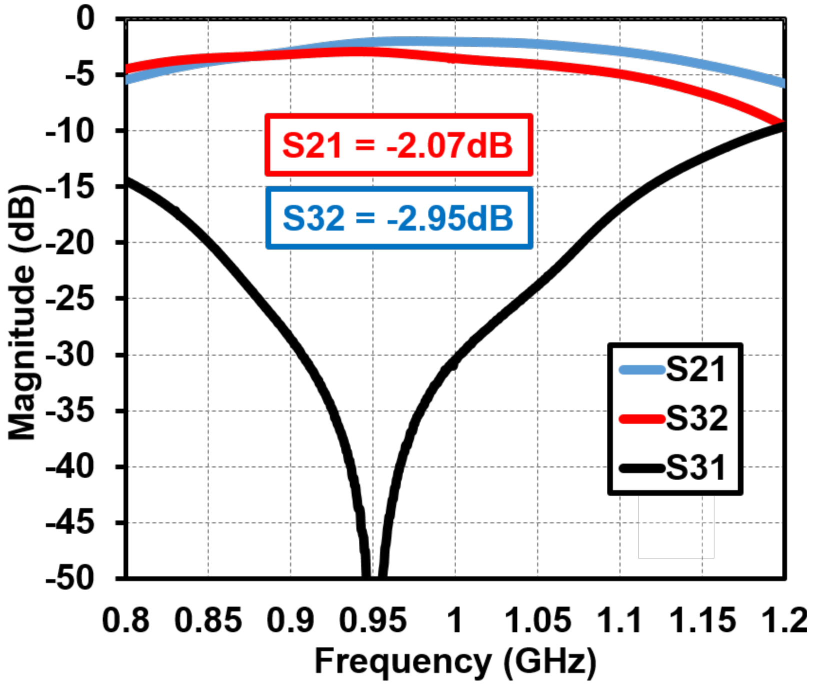


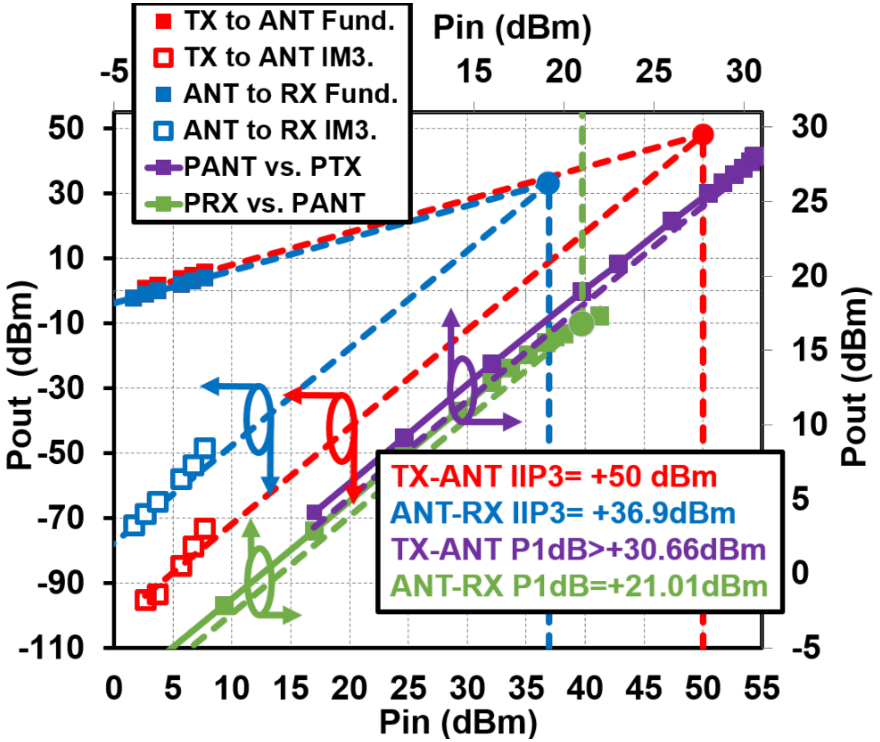
- A $3\lambda/4$ ring is wrapped around the gyrator to realize a circulator with non-reciprocal wave propagation

- A. Nagulu, A. Alu, and H. Krishnaswamy, "Fully-Integrated Non-Magnetic 180nm SOI Circulator with >1W P1dB, >+50dBm IIP3 and High Isolation Across 1.85 VSWR." in *Proc. IEEE Radio Frequency Integrated Circuits Symposium (RFIC'18)*, 2018. **Best Student Paper Award – 1st place**

Performance Measurements



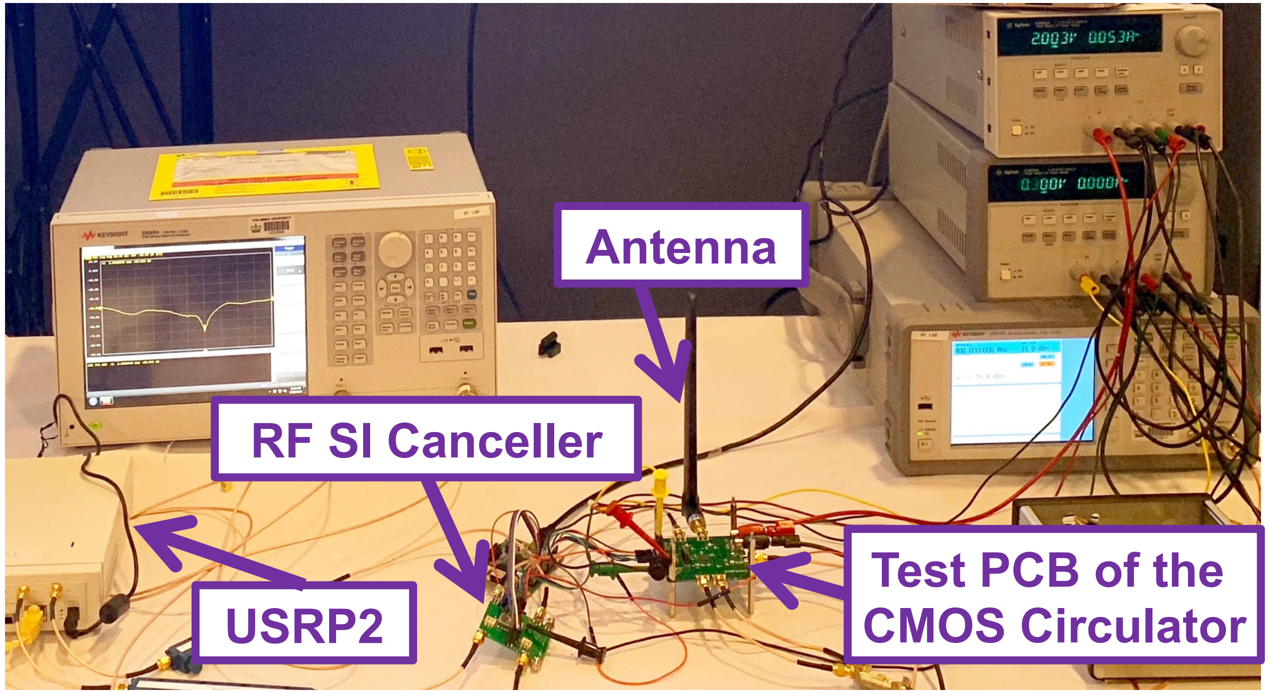


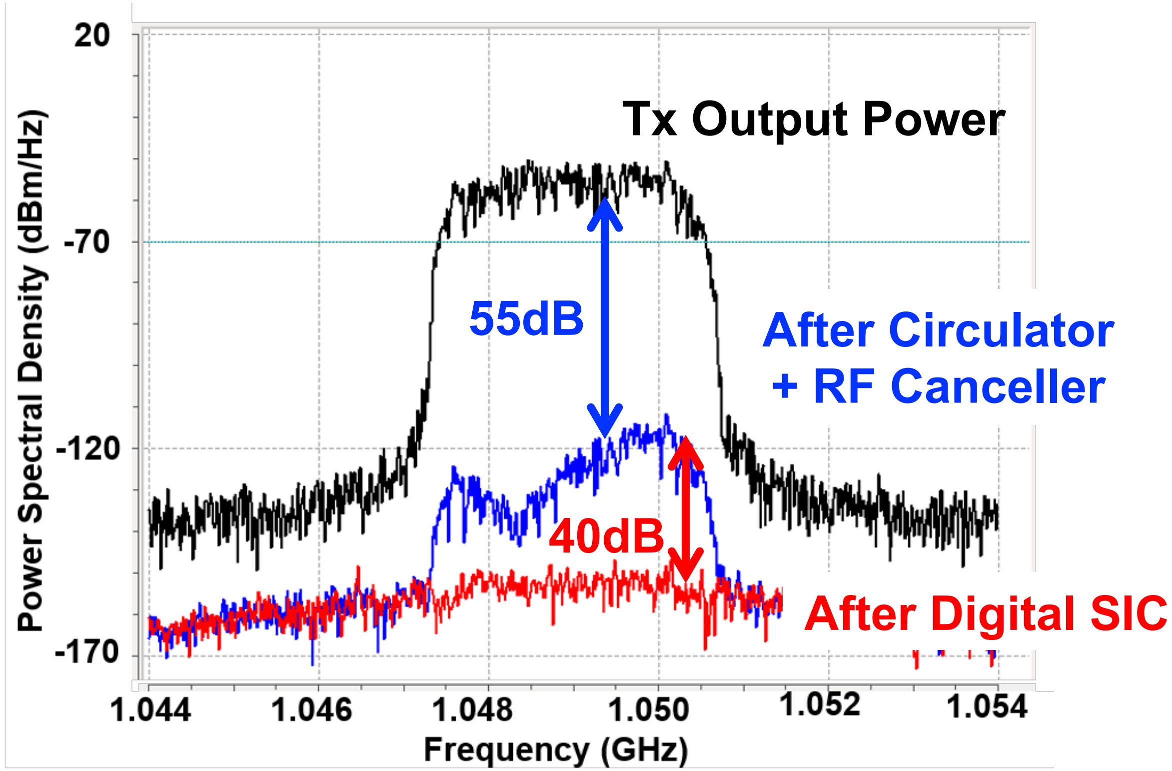


- **~100x** smaller in size than a ferrite magnetic coaxial circulator
- Measured insertion losses of **2.1 dB** and **2.9 dB**, and isolation **>40 dB**
- Measured TX-ANT IP_{1dB} **> +30.66 dBm** (i.e., 1 Watt of Tx power), TX-ANT IIP3 is **+50 dBm**

- A. Nagulu, A. Alu, and H. Krishnaswamy, "Fully-Integrated Non-Magnetic 180nm SOI Circulator with >1W P1dB, >+50dBm IIP3 and High Isolation Across 1.85 VSWR." in *Proc. IEEE Radio Frequency Integrated Circuits Symposium (RFIC'18)*, 2018. **Best Student Paper Award – 1st place**

A Full-Duplex Radio Prototype with a CMOS Circulator





- A QPSK signal with 10 MSa/s sampling rate at +15 dBm TX power level
- An overall SIC of 95—100 dB is achieved

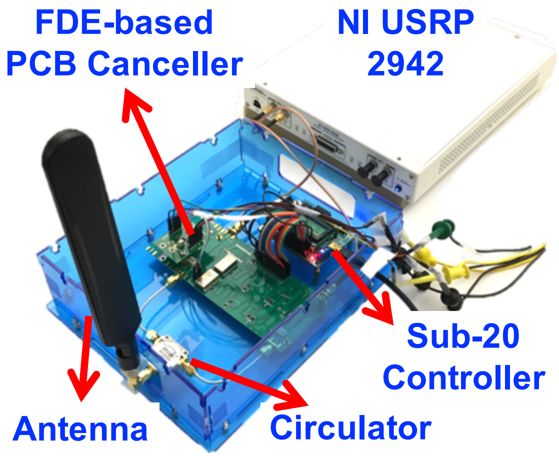
A Real-Time Full-Duplex Wireless Link Demo

- Up to 20 MHz real-time OFDM PHY using the GNU Radio software with customized DSP blocks (in C++) and packet-level demodulation and decoding

Summary

- The Columbia FlexICoN project and the open-access full-duplex radio in the ORBIT testbed
- Design and implementation of a non-magnetic, CMOS circulator with high isolation and high power handling, and its integration with a software-defined radio
- Future directions:
  - Development of efficient tuning algorithms for the CMOS circulator and its performance evaluation
  - Integration of the wideband RF canceller in the COSMOS testbed
  - Development of more advanced example experiments using the testbed (novel digital SIC algorithms, PHY layer security, evaluation of capacity gains, etc.)

Open-access FD radio



Gen-2 wideband FD radio

The city-scale PAWR COSMOS testbed in NYC

Thank you!

tingjun@ee.columbia.edu

http://www.ee.columbia.edu/~tc2668

Aravind Nagulu, Tingjun Chen, Gil Zussman, Harish Krishnaswamy
"A Single Antenna Full-Duplex Radio using A Non-Magnetic, CMOS Circulator with In-built Isolation Tuning".

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