4.3: A 140GHz Transceiver with Integrated Antenna, Inherent-Low-Loss Duplexing and Adaptive Self-Interference Cancellation for FMCW Monostatic Radar

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[5]MIT Lincoln Laboratory, Lexington, MA

Massachusetts
Institute of
Technology

Self Introduction

- **Currently at EECS, MIT**
- **M.S. Degree, EE, Tsinghua University**
- **B.S. Degree, EE, Tsinghua University**
- **Research Interests:**
  - THz integrated electronic systems
  - THz imaging/sensing
  - CMOS electromagnetics/optics

Outline

- **Introduction**
- **140GHz Transceiver Chip Design**
  - Operation Principle
  - Integrated Antenna
  - Adaptive Self-Interference Cancellation (SIC)
  - System Architecture and Functional Circuits
- **Measurement Results**
- **Conclusions**

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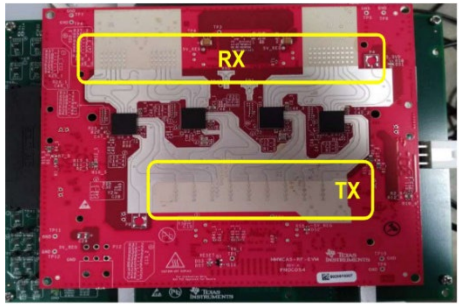
Sub-THz Radars

Microwave Radars



Opportunities and Challenges for Sub-THz Radars!

LiDARs

Microelectronic Devices

LASER/Optical Devices

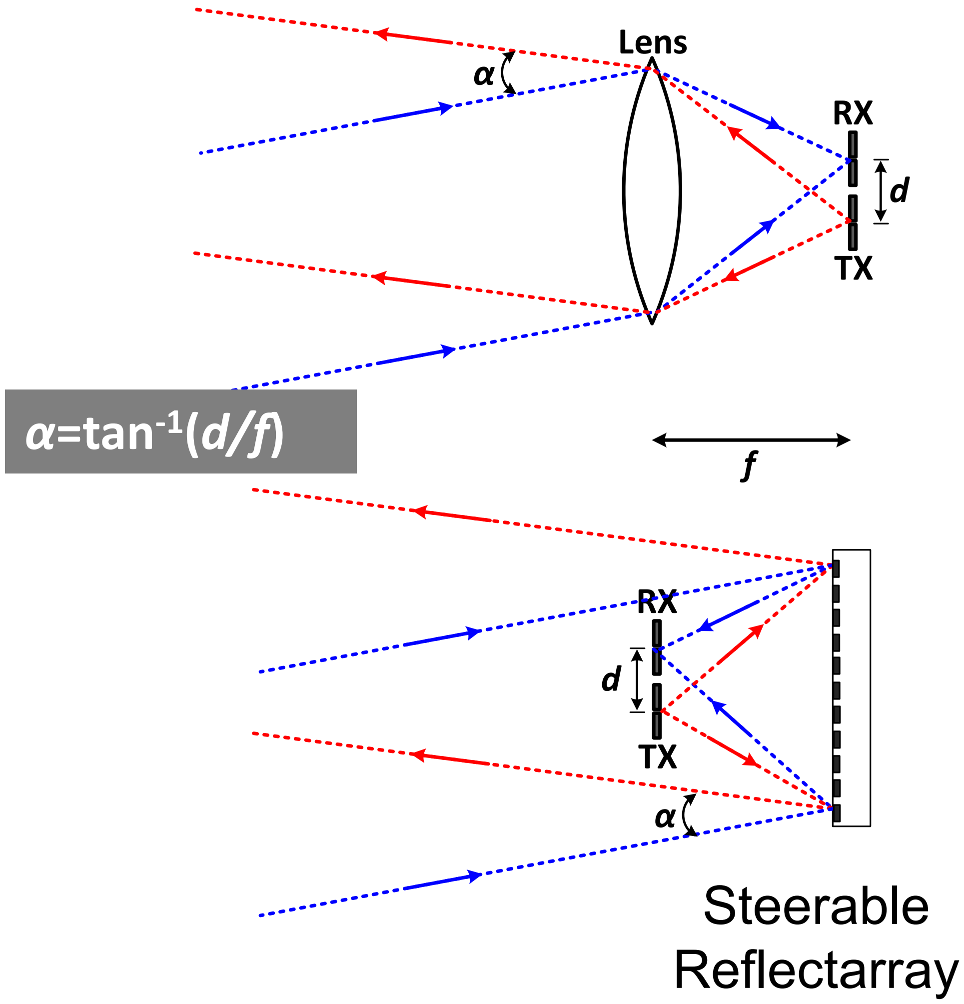
Microwave/mm-Wave | Low-THz/Sub-THz/THz | Visible Range

- Large physical size
- Limited bandwidth

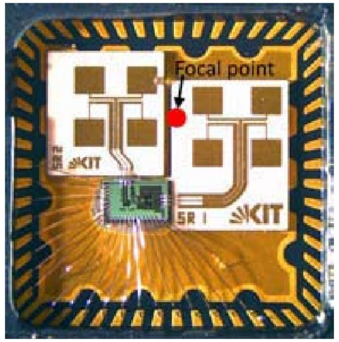
- **Decent bandwidth, angular resolution with small size**

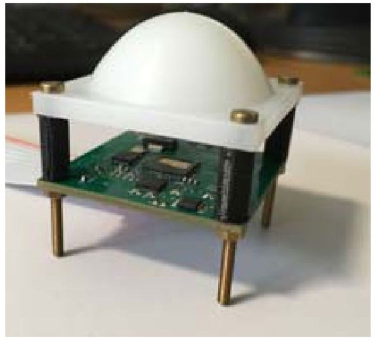
- High angular resolution
- Suffering from bad weather and strong light interference

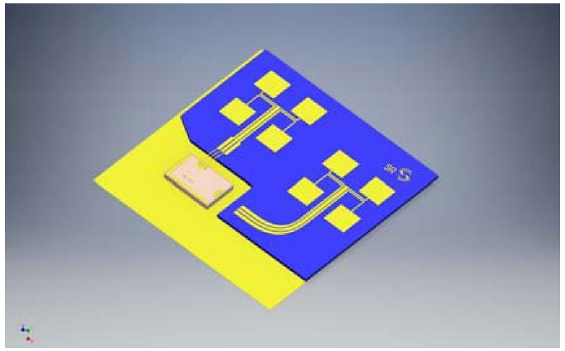
Bistatic Radars: Problem

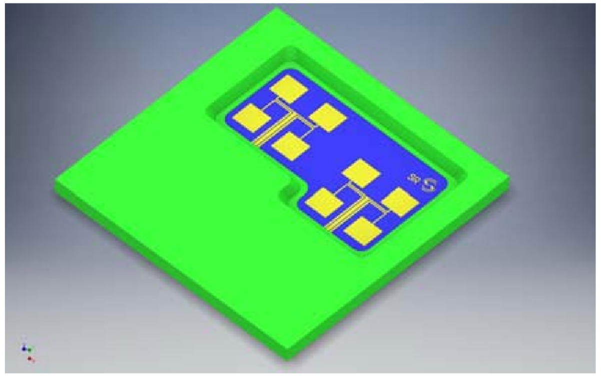


$\alpha = \tan^{-1}(d/f)$

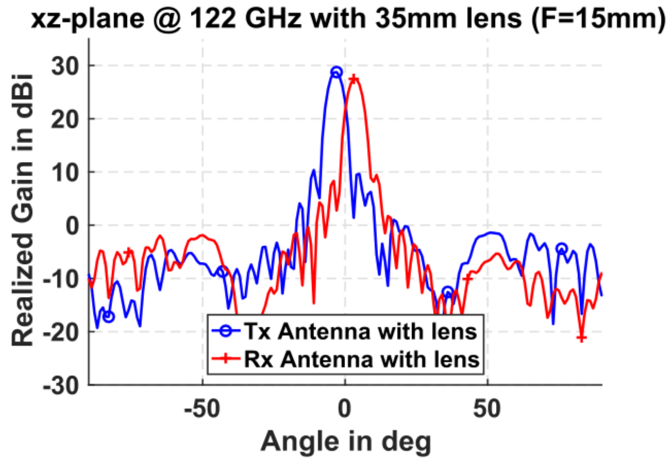






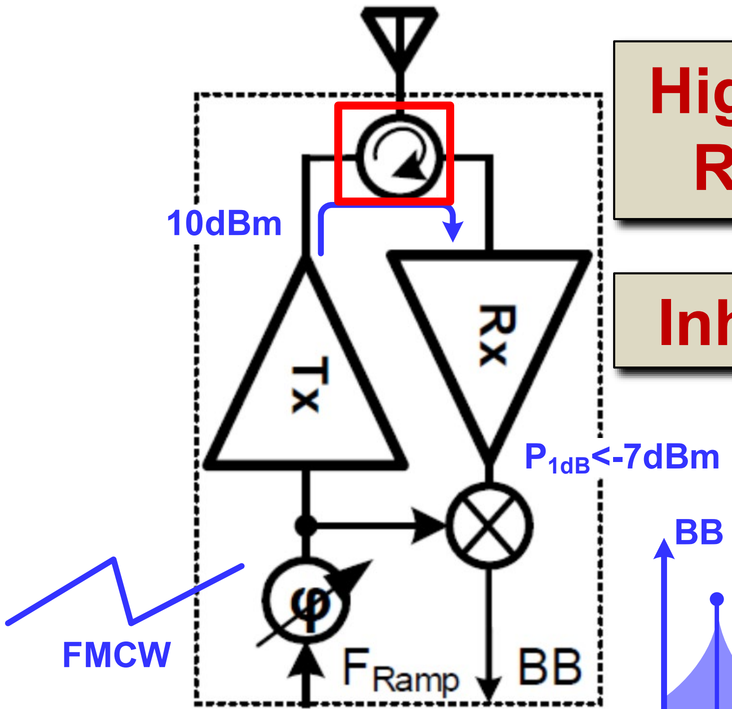


M. Pauli et al., T-MTT, 2017.



- **High TX-RX isolation**
- **Severe TX-RX beam misalignment under high-angular resolution (i.e. large aperture) applications.**

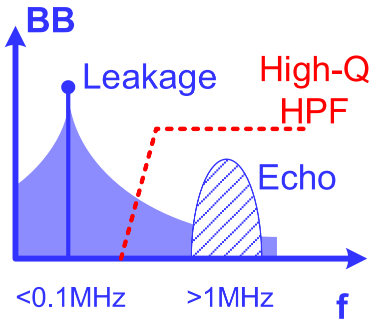
Monostatic Radars: Current Solutions



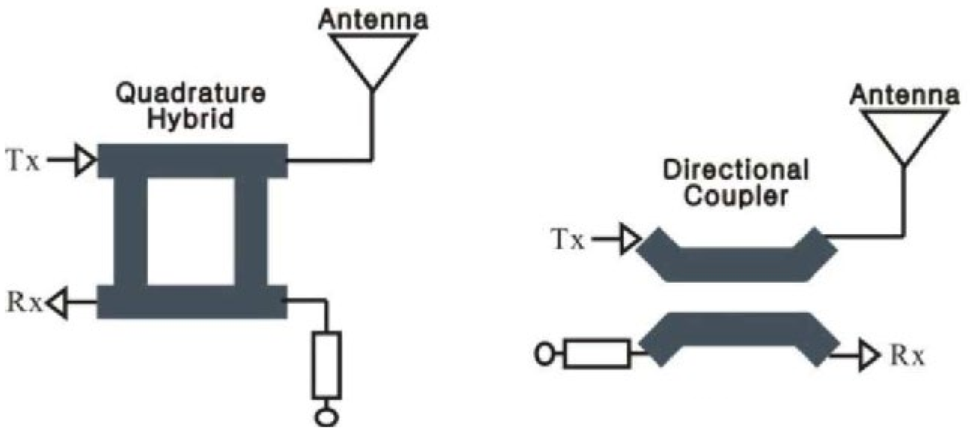
**Single-Ant.
TRx Unit**

High Isolation at RF Interface?

Inherent-Loss-Free?



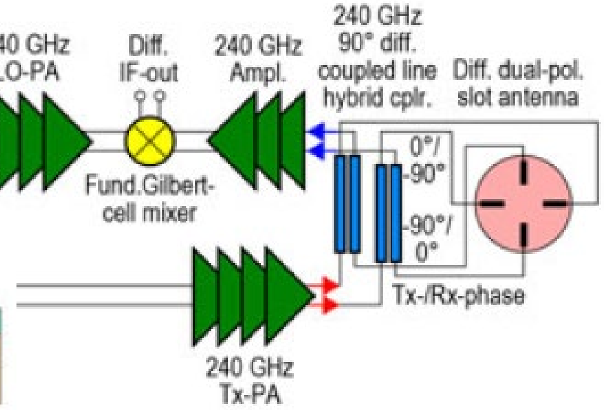
Radar with TX/RX antenna sharing & RX LNA

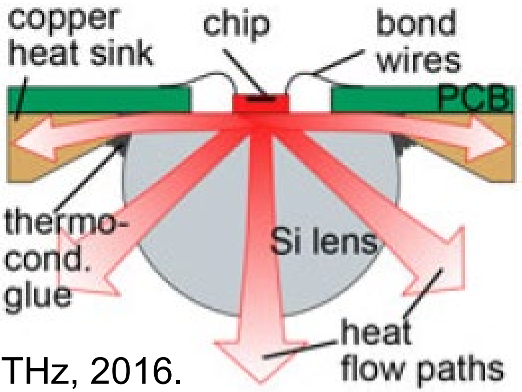


Directional/Quadrature/Hybrid Couplers

(inherent 3dB + 3dB loss to the link budget)

Intrinsic Difference Between TRX waves?





J. Grzyb et al., T-THz, 2016.

Front-Side Radiation?

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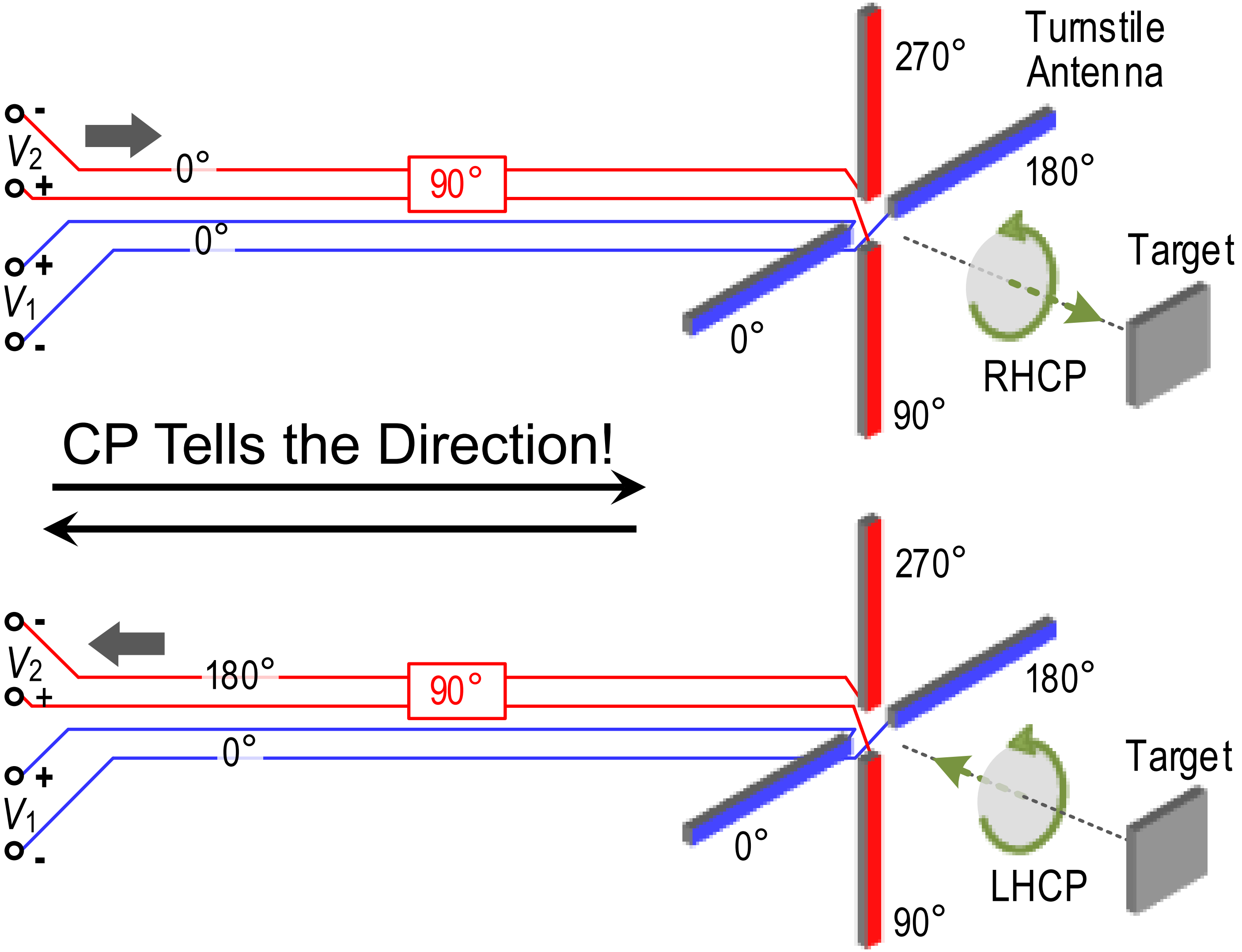
Circular Polarization (CP) Will Tell

Common Mode

$V_1 = V_2$

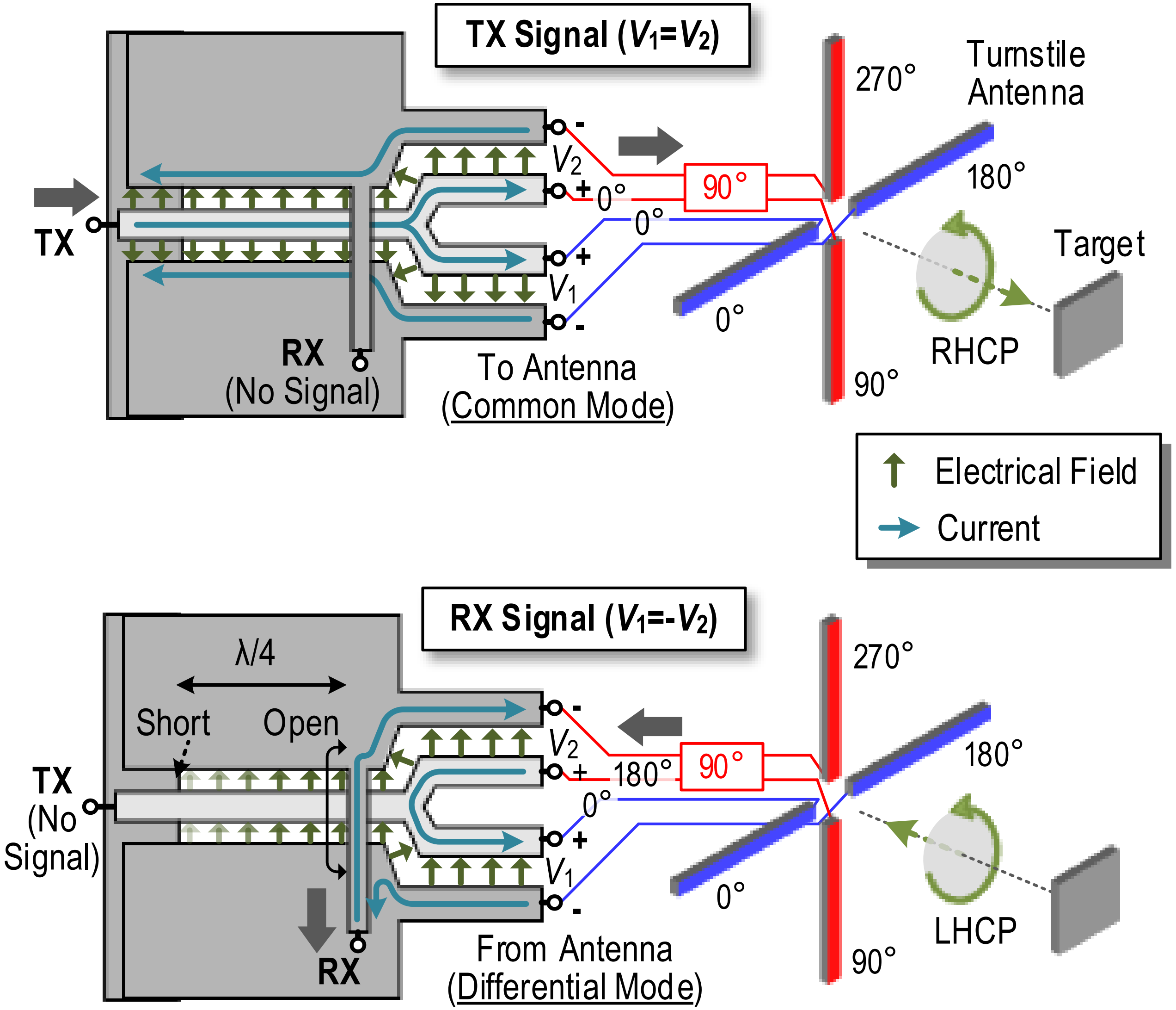
Differential Mode

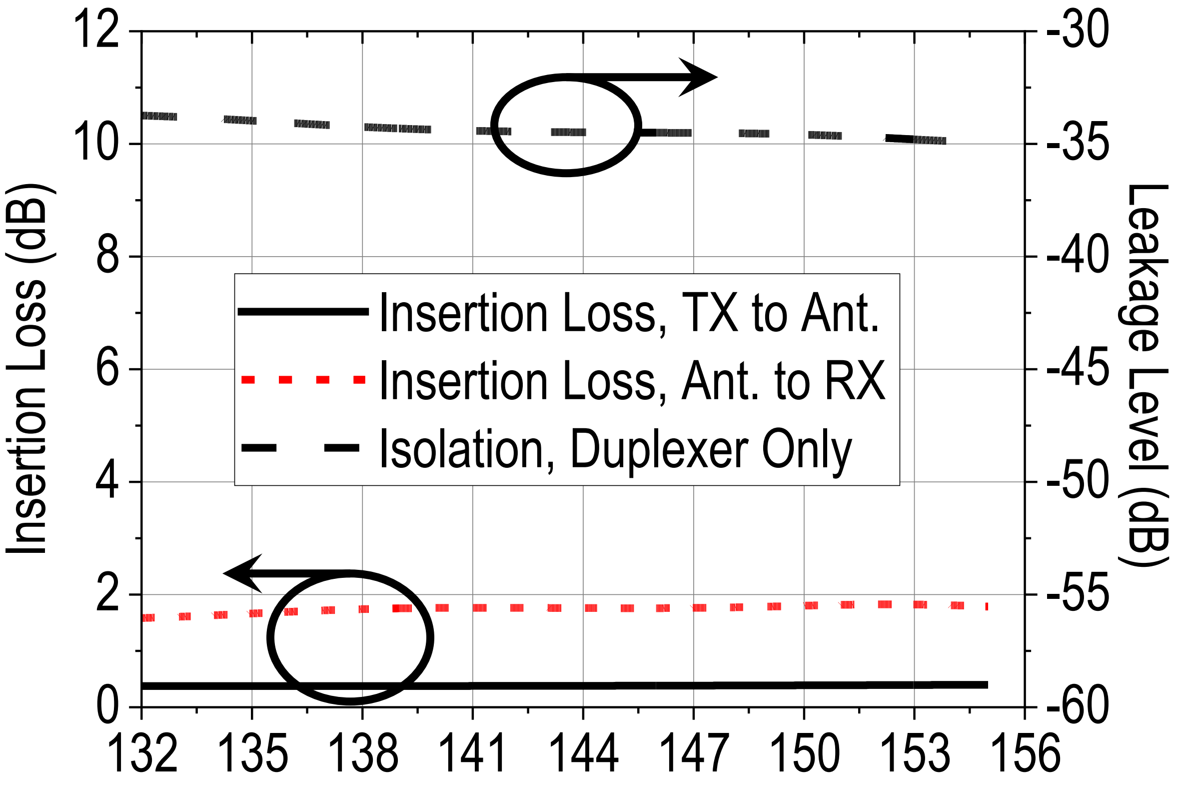
$V_1 = -V_2$



CP Tells the Direction!

Full-Duplexing By Geometrical Symmetry





Simulated Duplexer Loss and Isolation Performances

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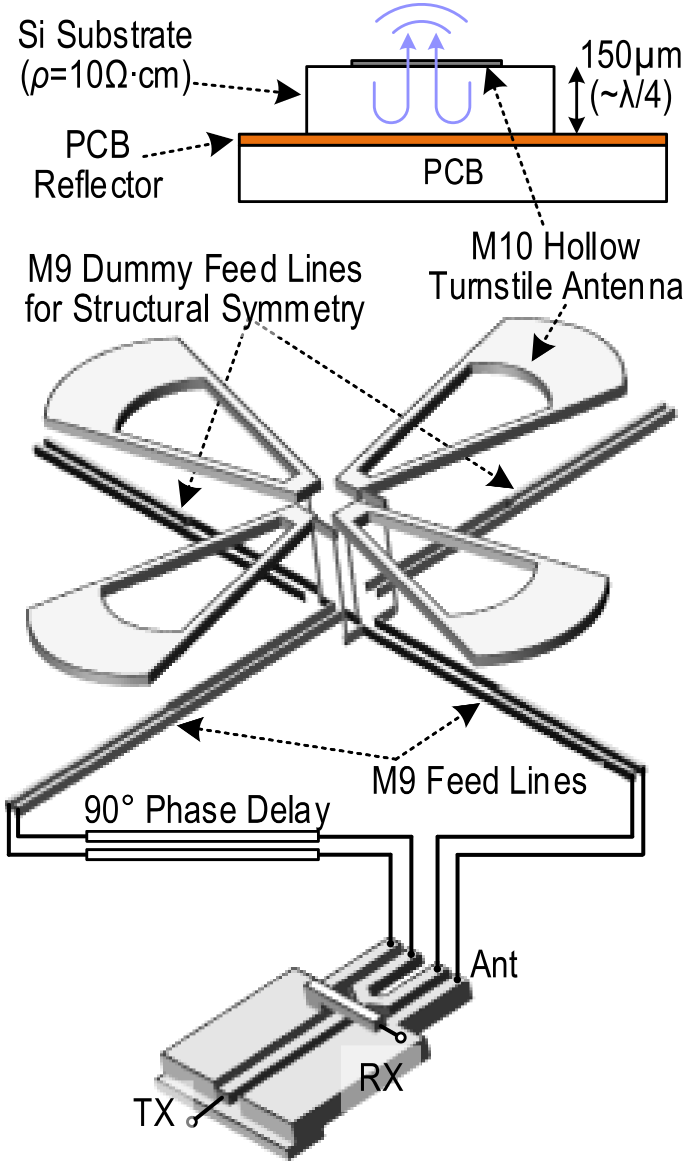
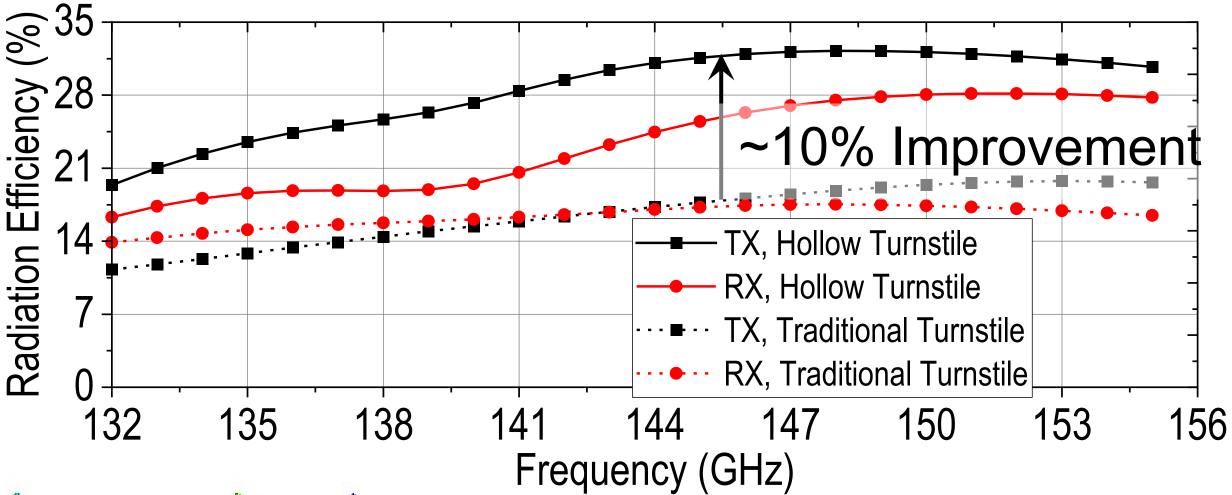
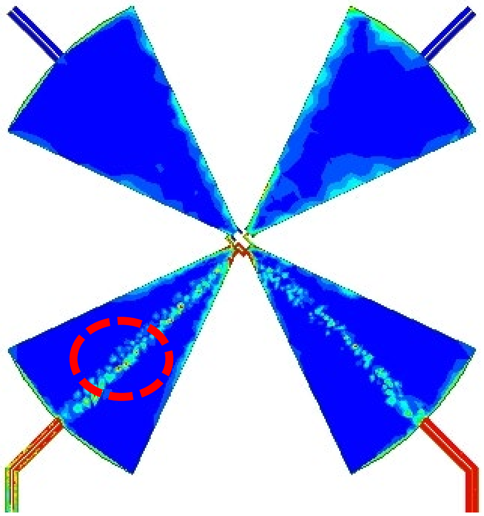
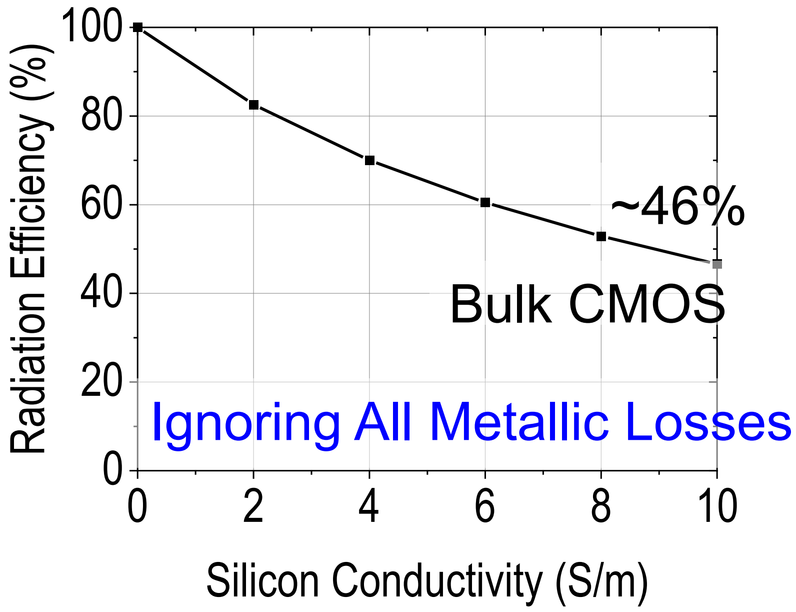
Integrated Hollow Turnstile Antenna



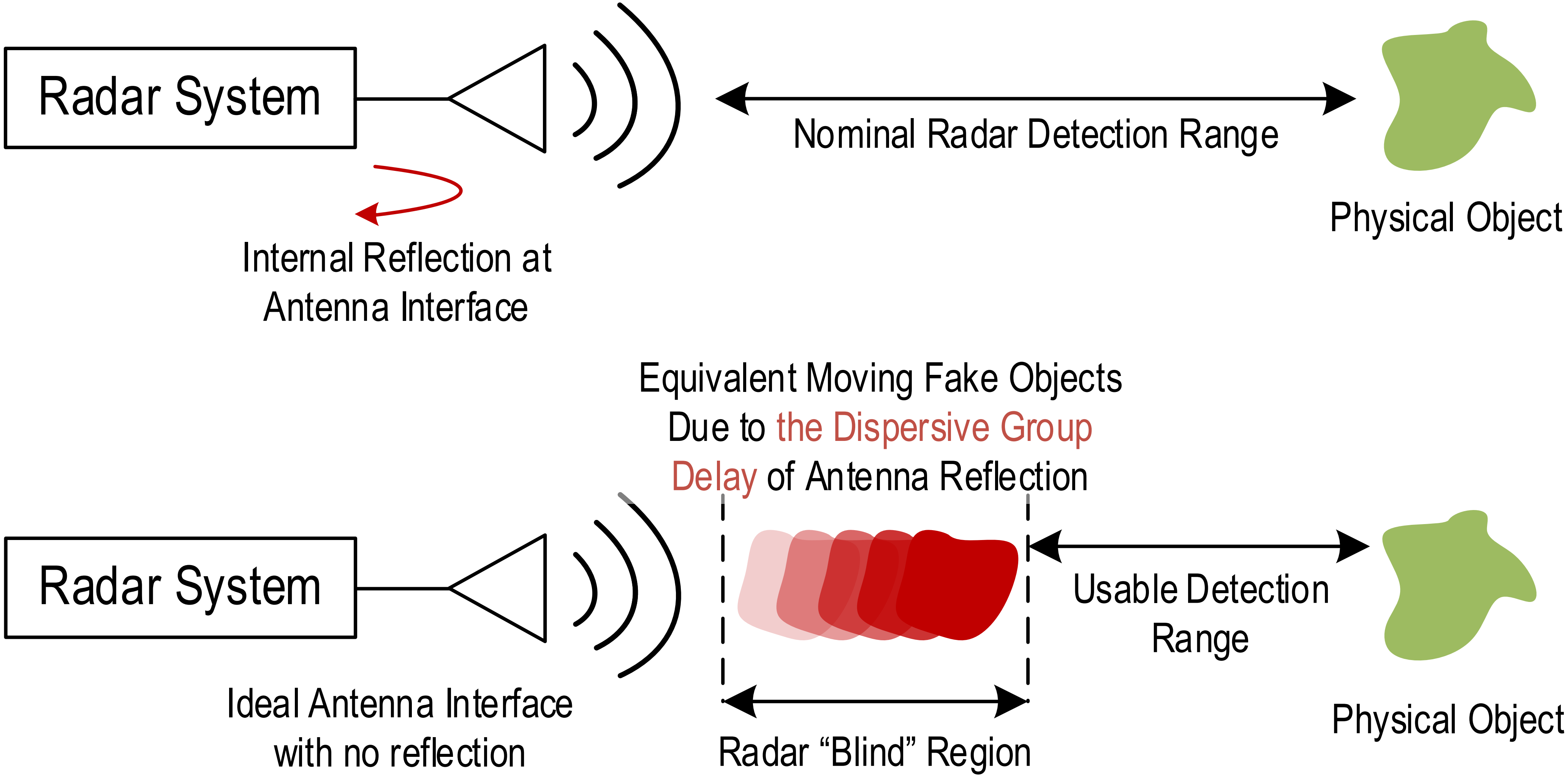




Current Distribution for Traditional Turnstile Antenna



Antenna Mismatch: Dynamic Leakage



Nominal Radar Detection Range

Physical Object

Internal Reflection at Antenna Interface

Equivalent Moving Fake Objects Due to the Dispersive Group Delay of Antenna Reflection

Usable Detection Range

Physical Object

Ideal Antenna Interface with no reflection

Radar “Blind” Region

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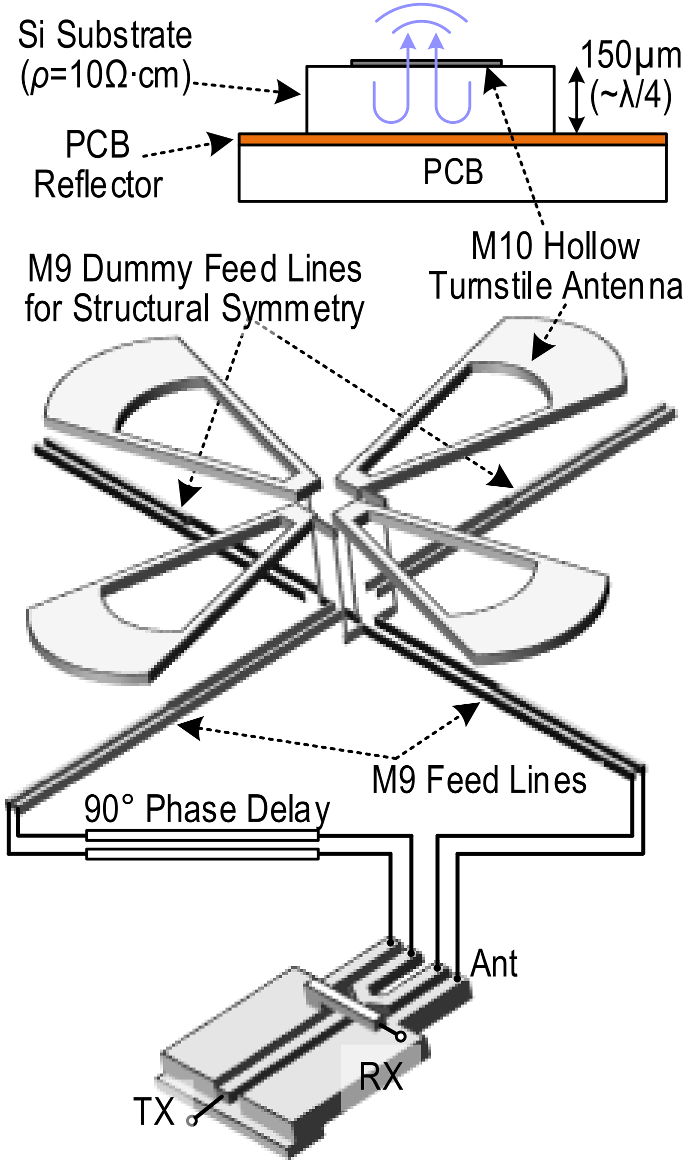
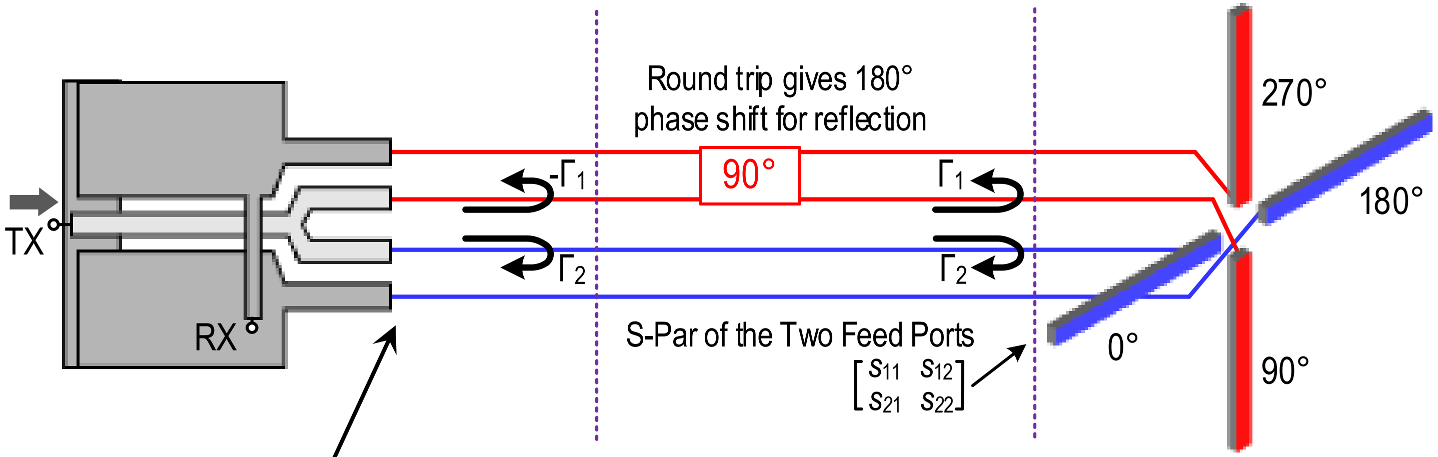
Adaptive SIC Scheme: Observation

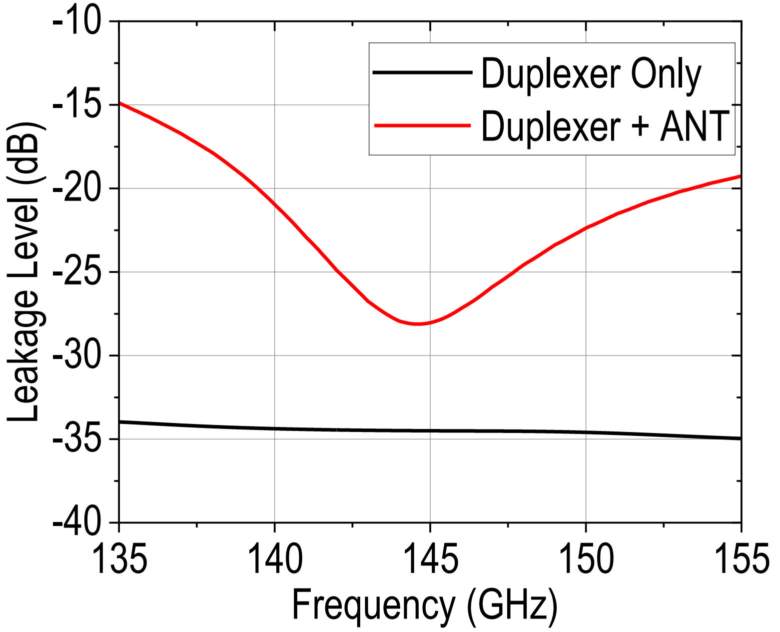




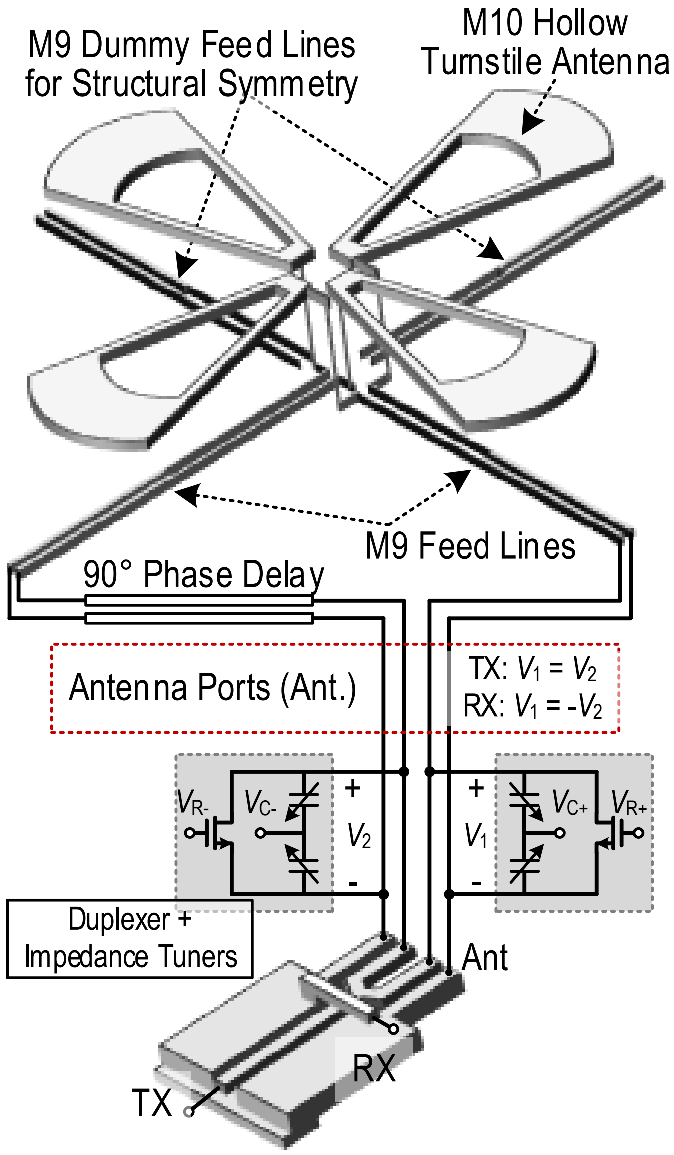
Intentionally add extra unbalanced reflection?

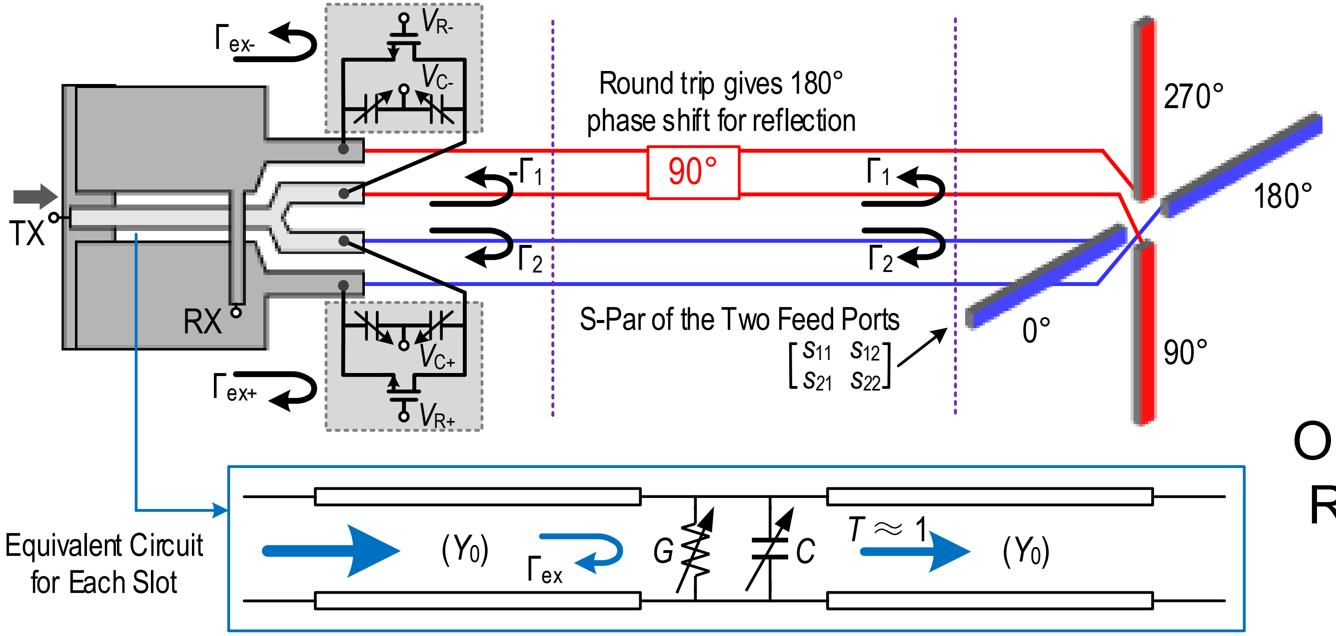
$$S_{RT,0} = [\Gamma_2 - (-\Gamma_1)]/2 = (\Gamma_1 + \Gamma_2)/2 = s_{11}$$

Original Isolation w/o SIC



Adaptive SIC Scheme: Principle





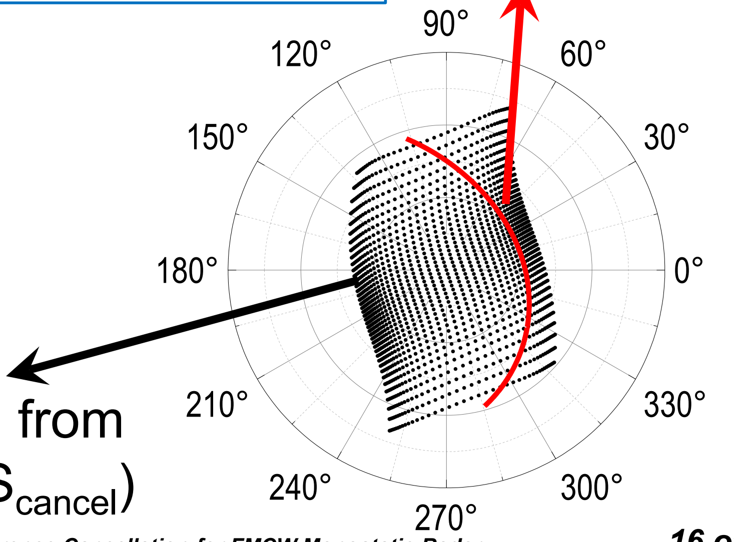
$$S_{RT,0} = [\Gamma_2 - (-\Gamma_1)]/2 = (\Gamma_1 + \Gamma_2)/2 = s_{11}$$

Original Isolation w/o SIC

$$S_{RT} = s_{11} - (\Delta G + j\omega \Delta C)/(2Y_0)$$

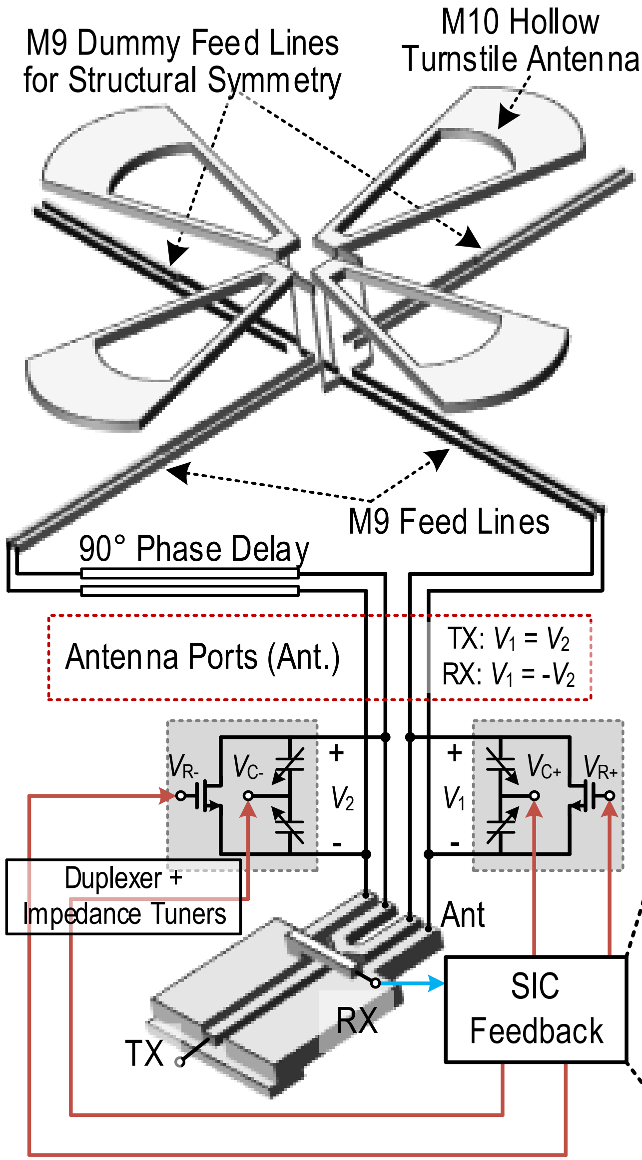
Overall Isolation w/ SIC

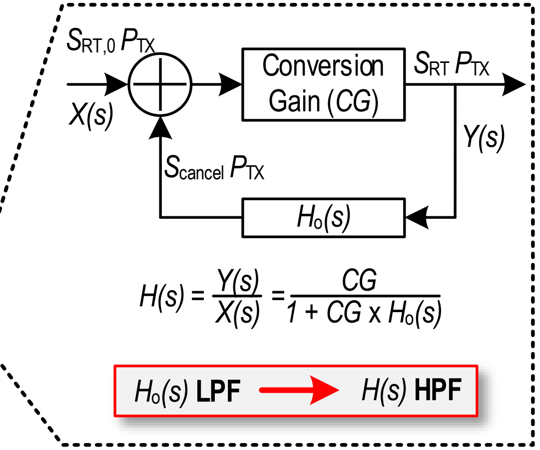
Original TX to RX Leakage ($S_{RT,0}$)



Additional Reflection from Impedance Tuners (S_{cancel})

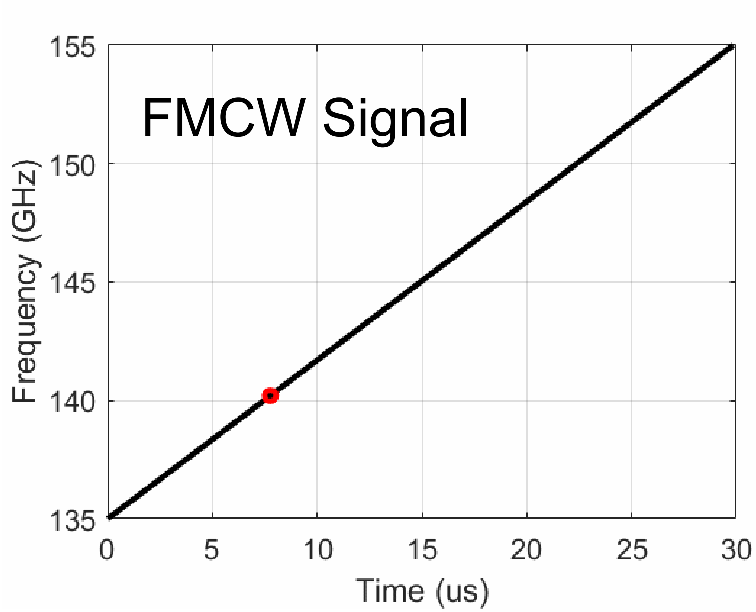
Adaptive SIC Scheme: Behavior

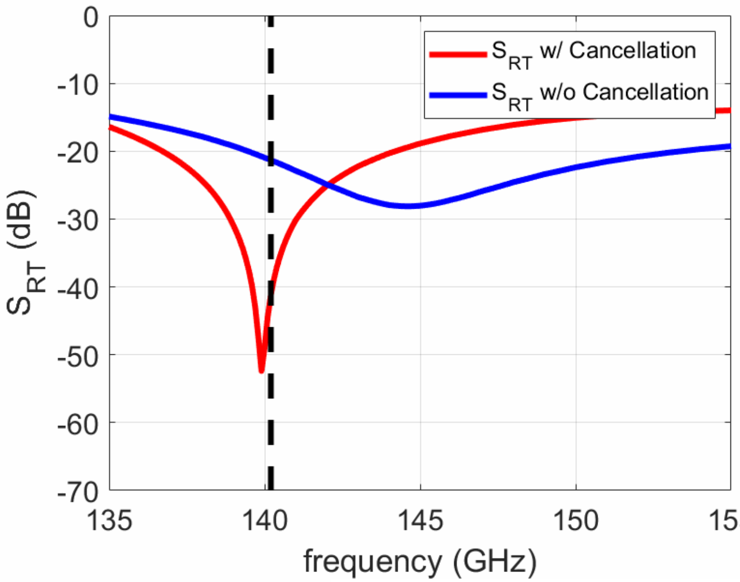


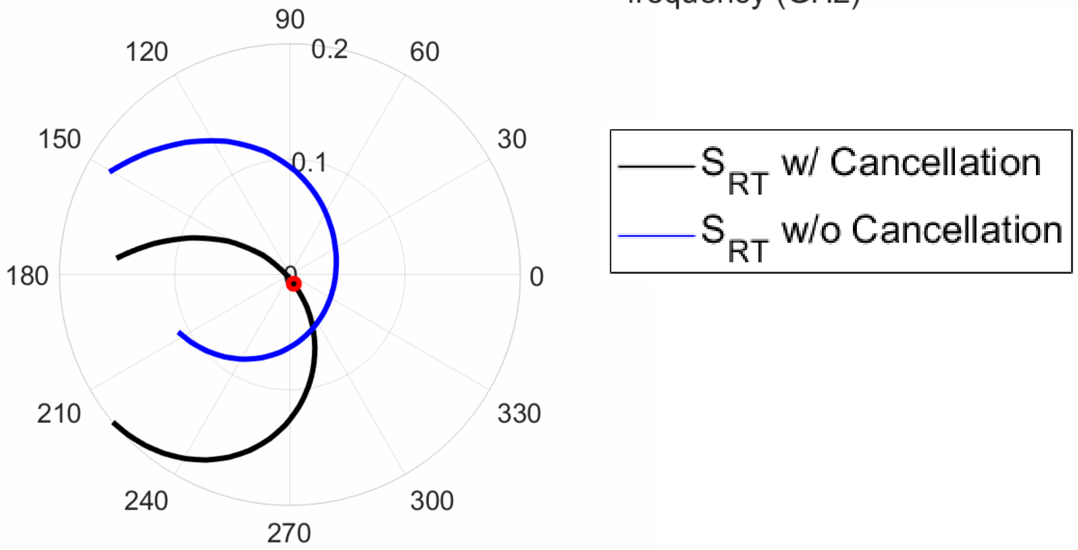


$$H(s) = \frac{Y(s)}{X(s)} = \frac{CG}{1 + CG \times H_0(s)}$$

$H_0(s)$ **LPF** → $H(s)$ **HPF**







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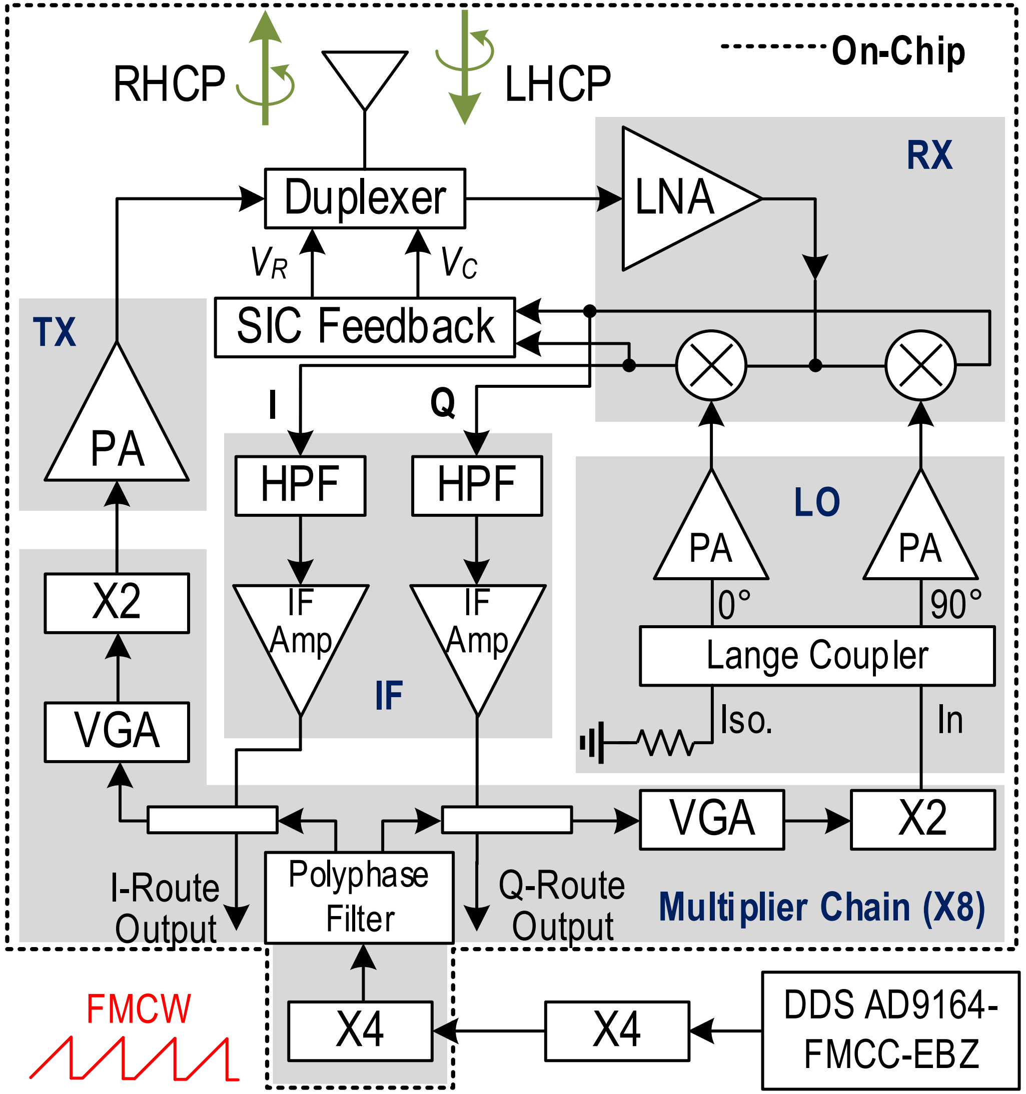
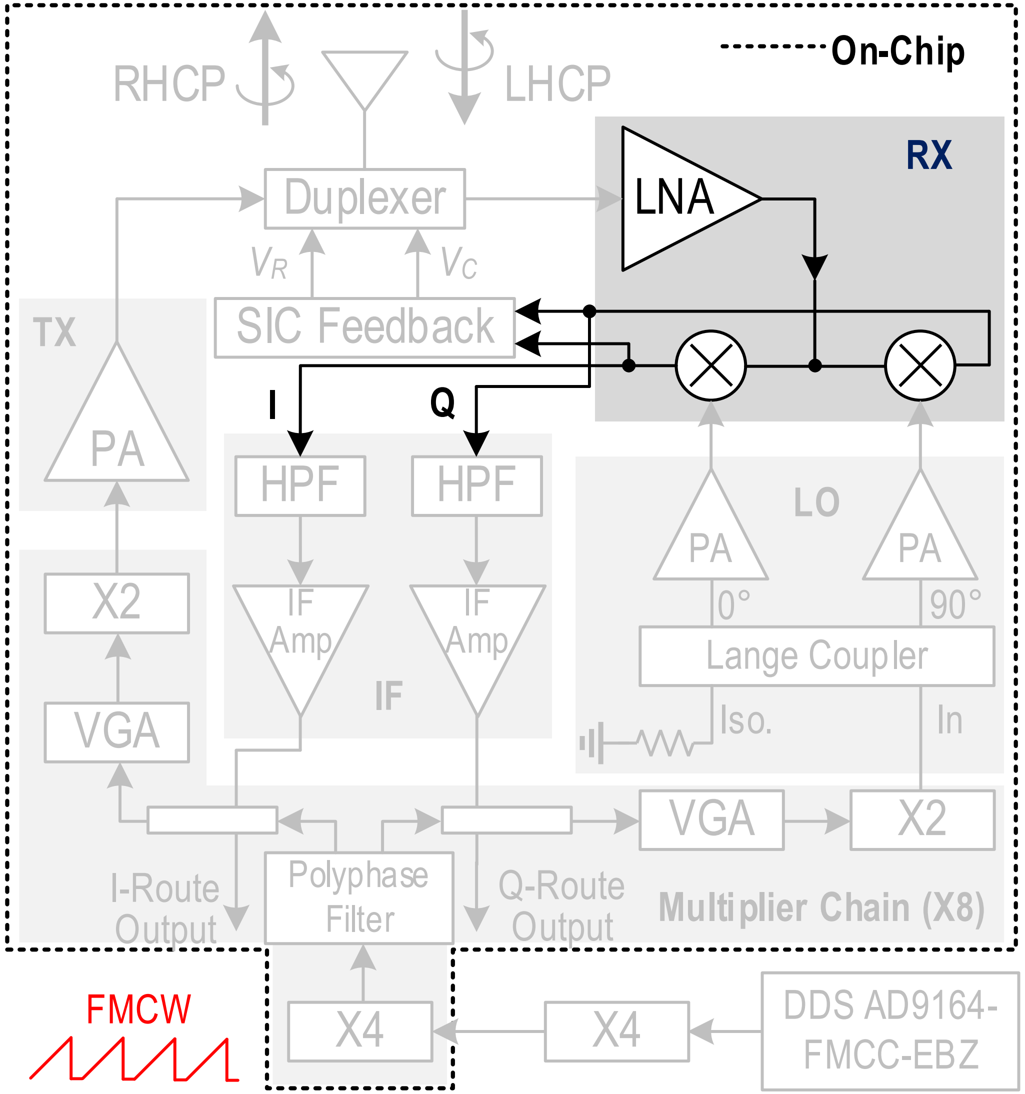
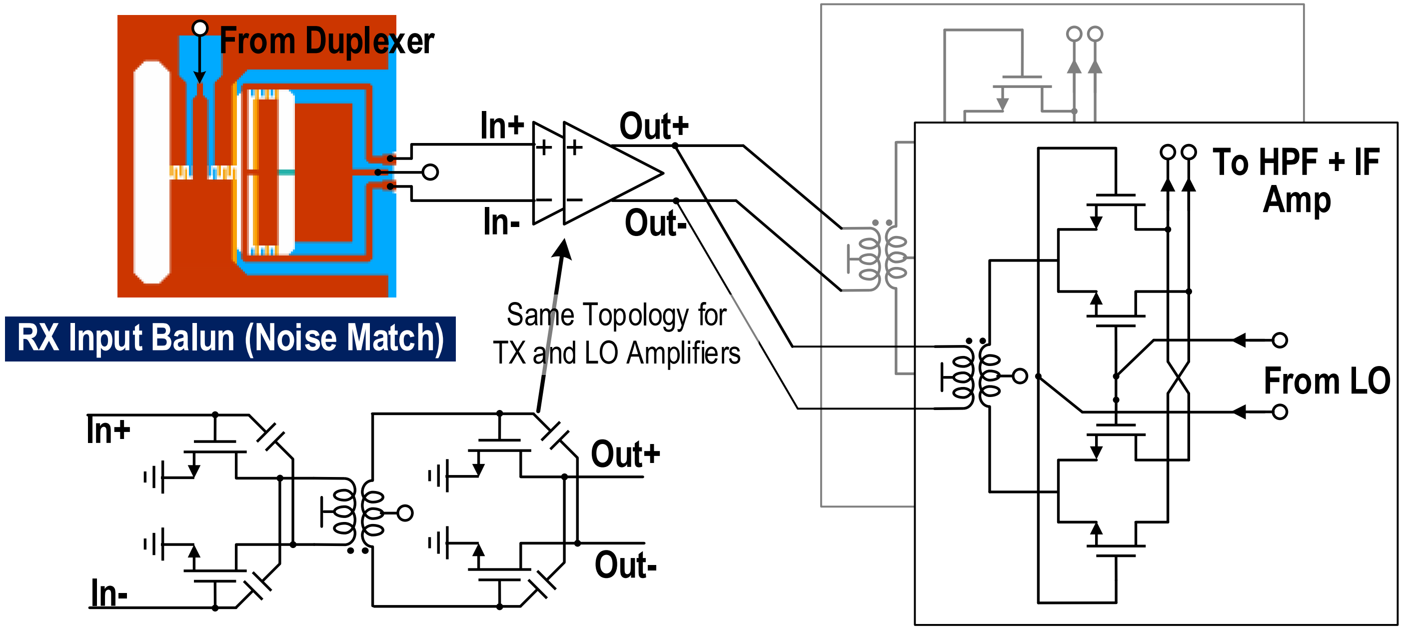
System Architecture



RX Circuits





RX Input Balun (Noise Match)

Two-Stage Noise-Matching LNA

Power Splitter and Passive Mixers

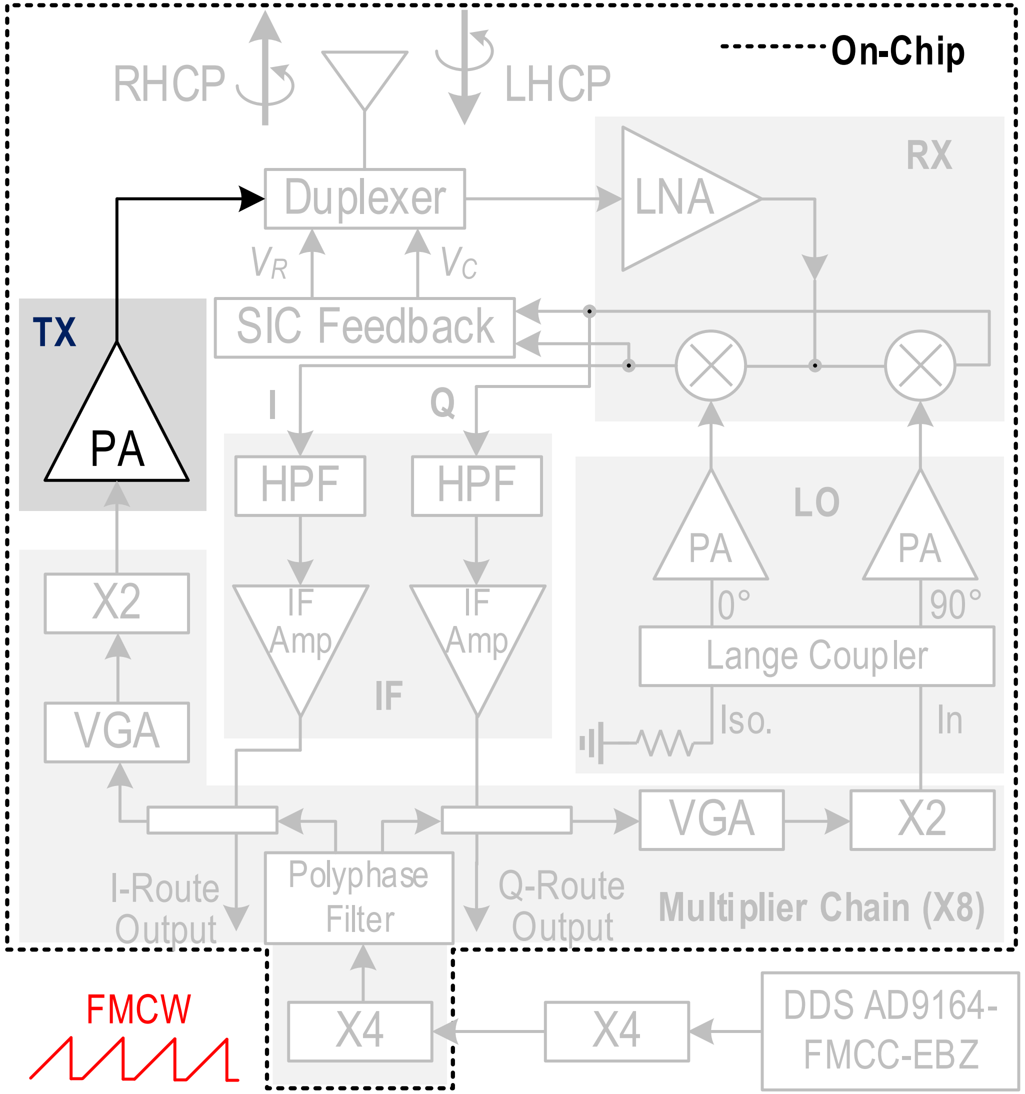
Simulated LNA Gain: 11dB

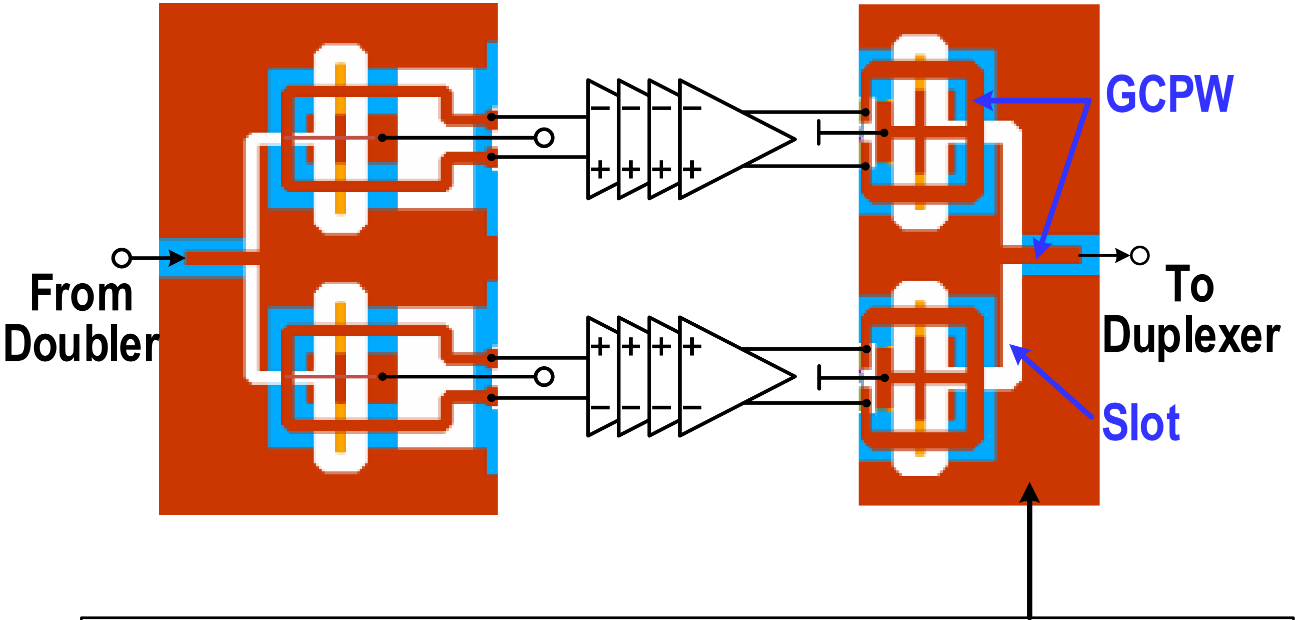
Simulated LNA NF: 7.3dB

Simulated LNA $P_{in,1dB}$: -6.5dBm

Simulated SSB NF: 12dB

TX Circuits





Ultra-Low-Loss Combiner:

X. Li et al., JSSC, 2021.

1. GCPW/slot transition
2. Insertion loss <1dB Across 20GHz BW
3. Full differential mode ensured by the odd-mode field in slots

Simulated TX power >11dBm over 18GHz bandwidth.

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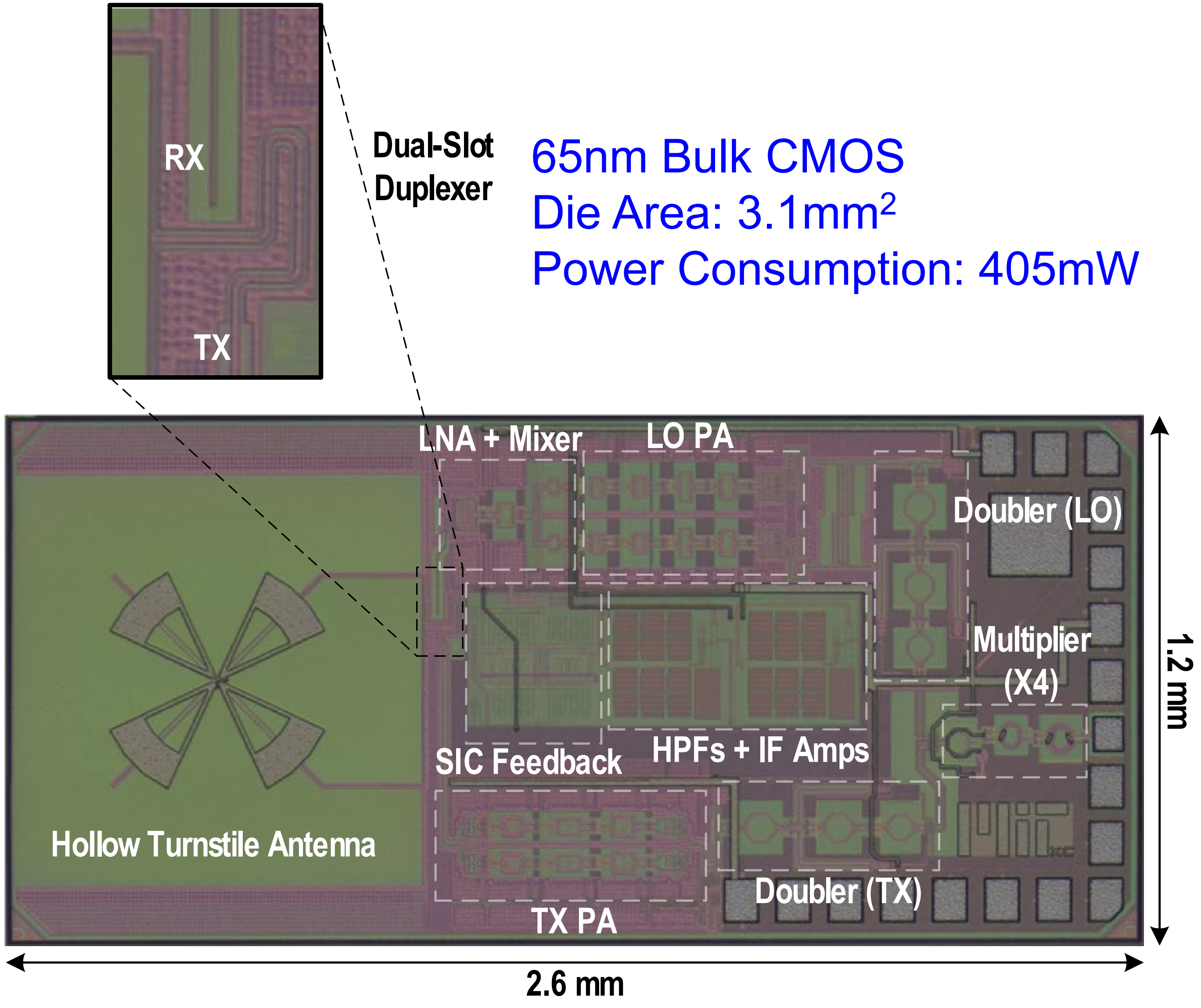
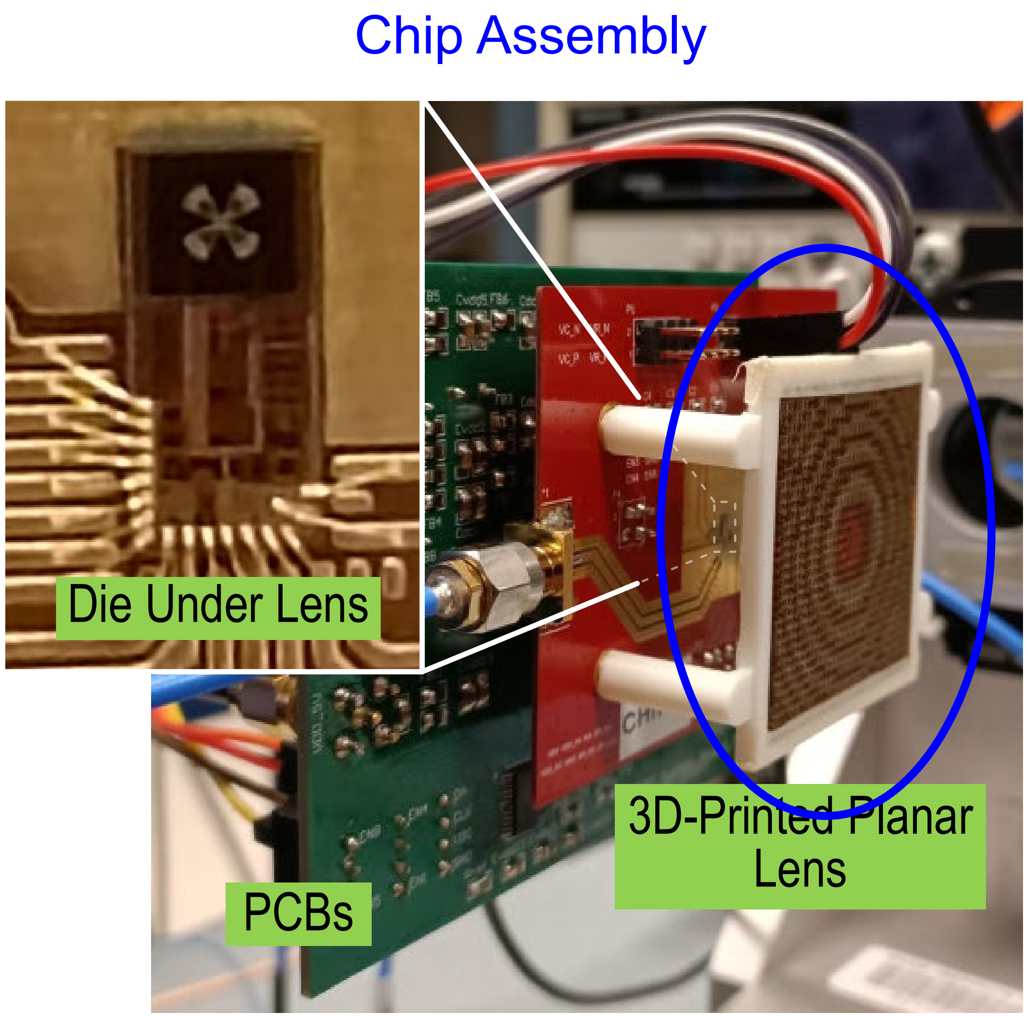
Chip Micrograph and Assembly

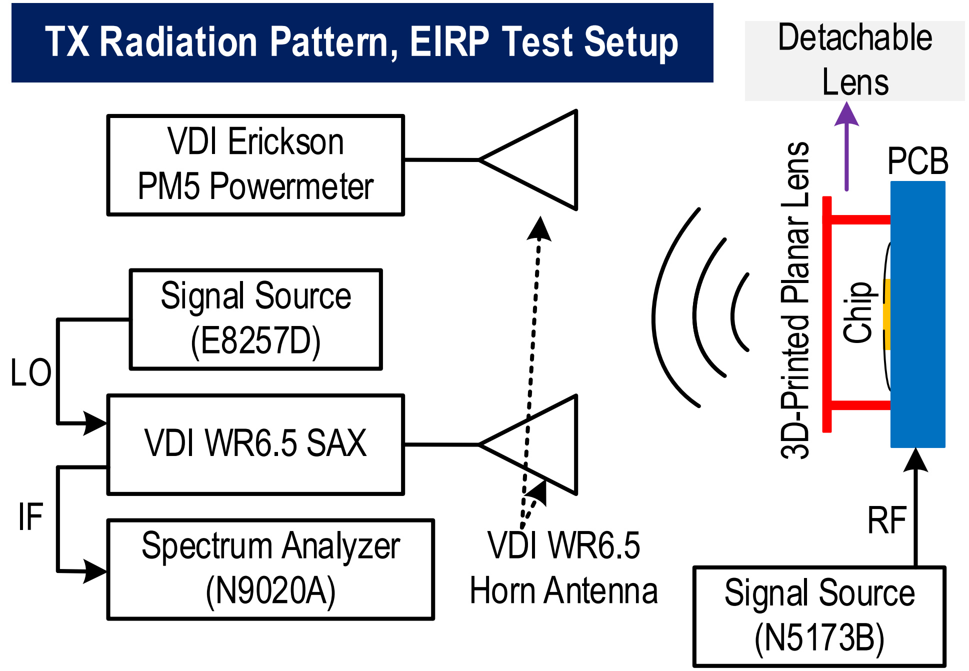
65nm Bulk CMOS
Die Area: 3.1mm^2
Power Consumption: 405mW

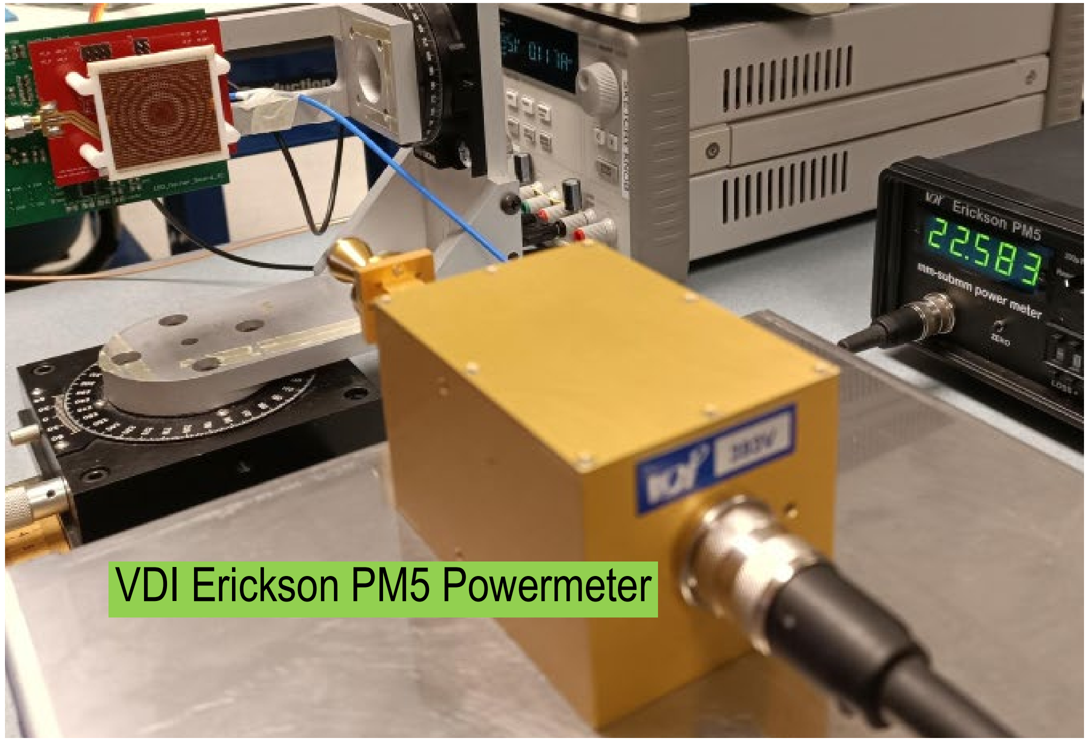


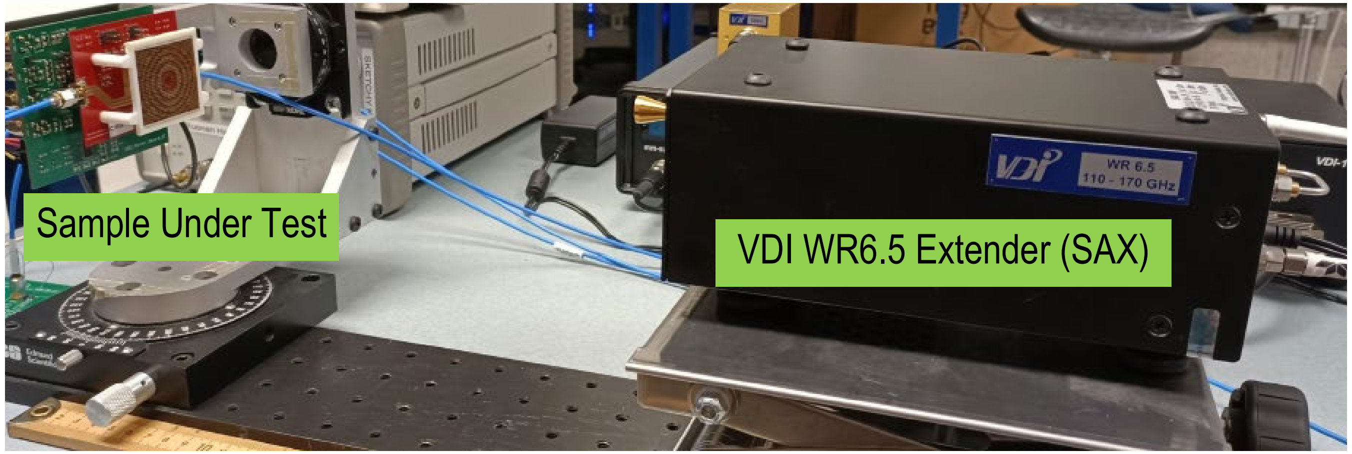

Chip Assembly

TX Test Setups

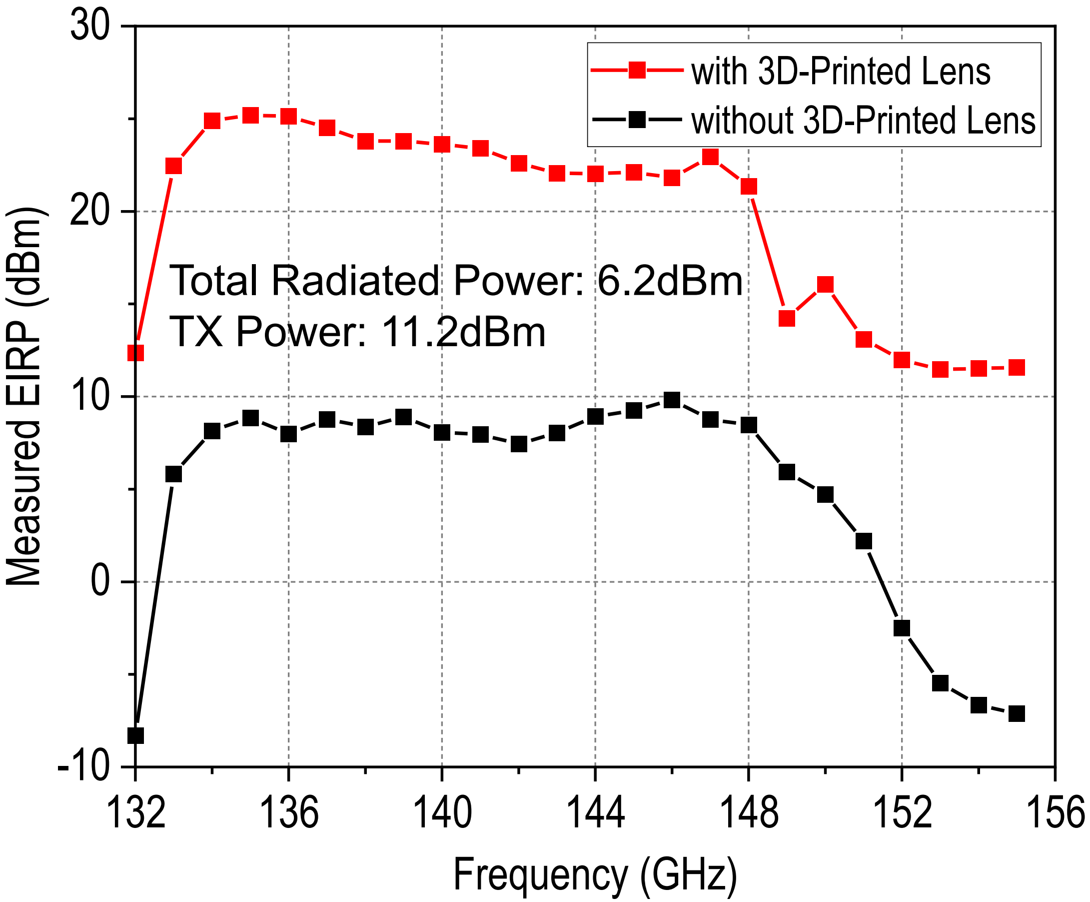
TX Radiation Pattern, EIRP Test Setup





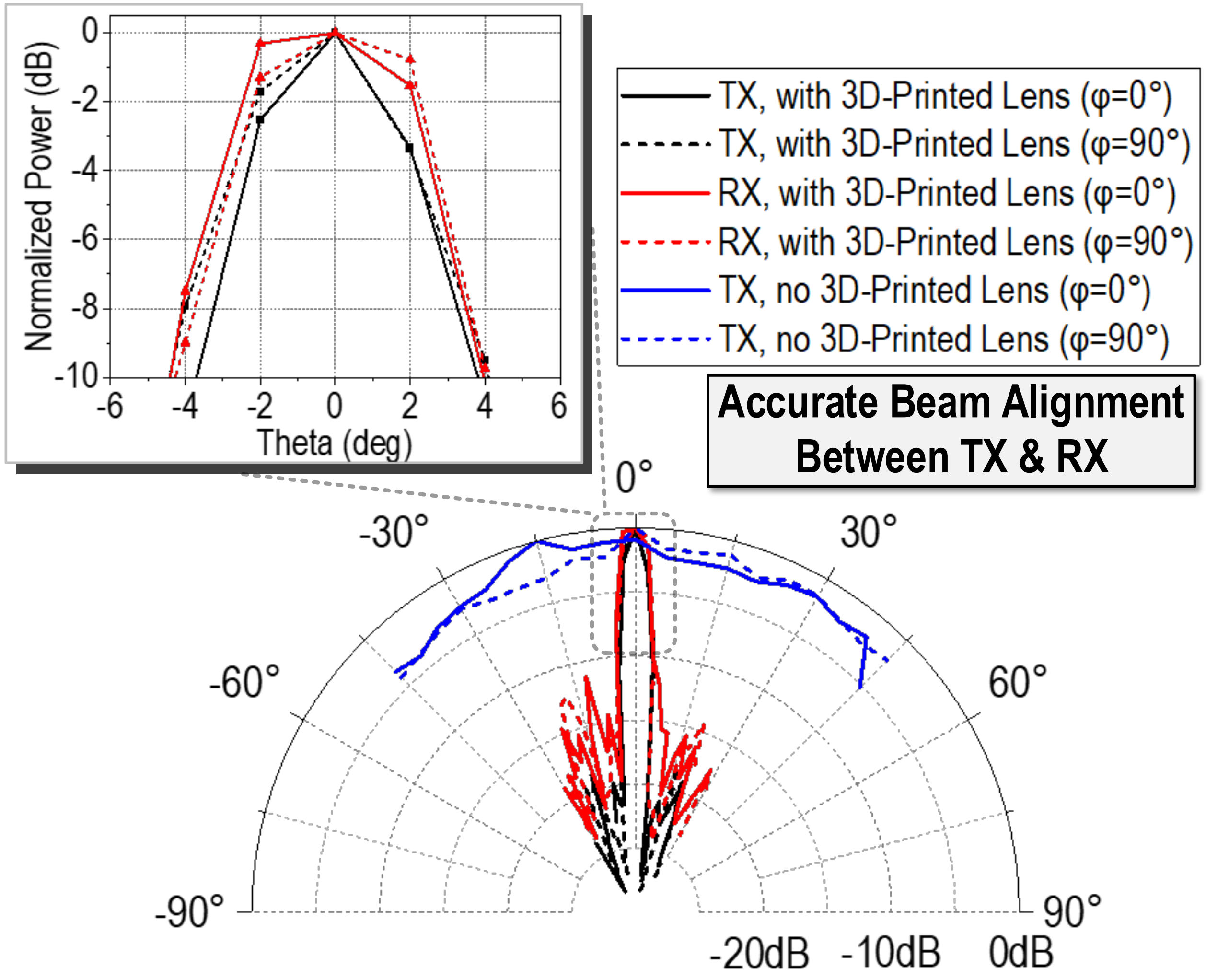


TX Measurement Results



Total Radiated Power: 6.2dBm
TX Power: 11.2dBm

Measured EIRP w/ and w/o the Lens

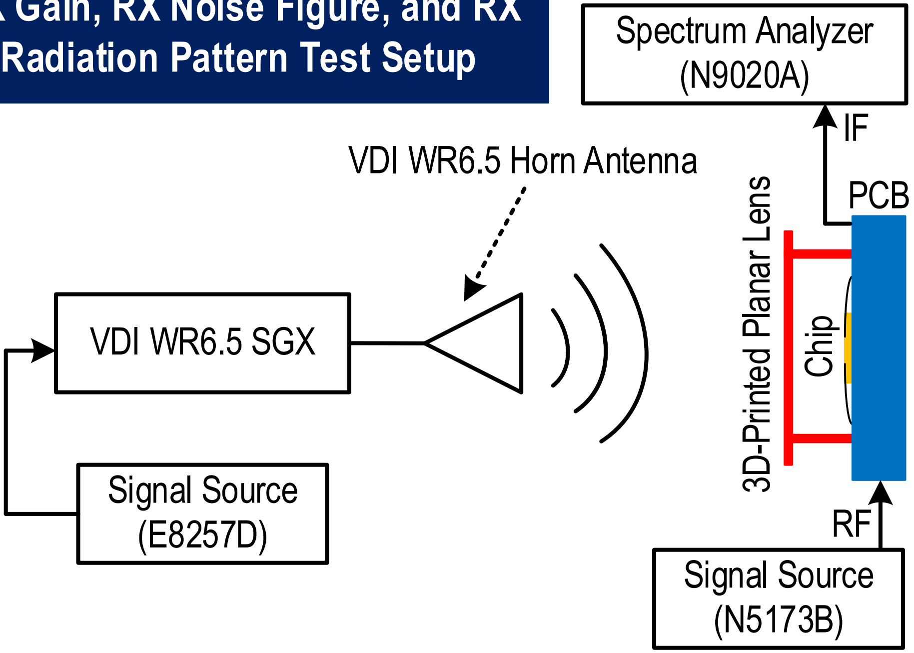


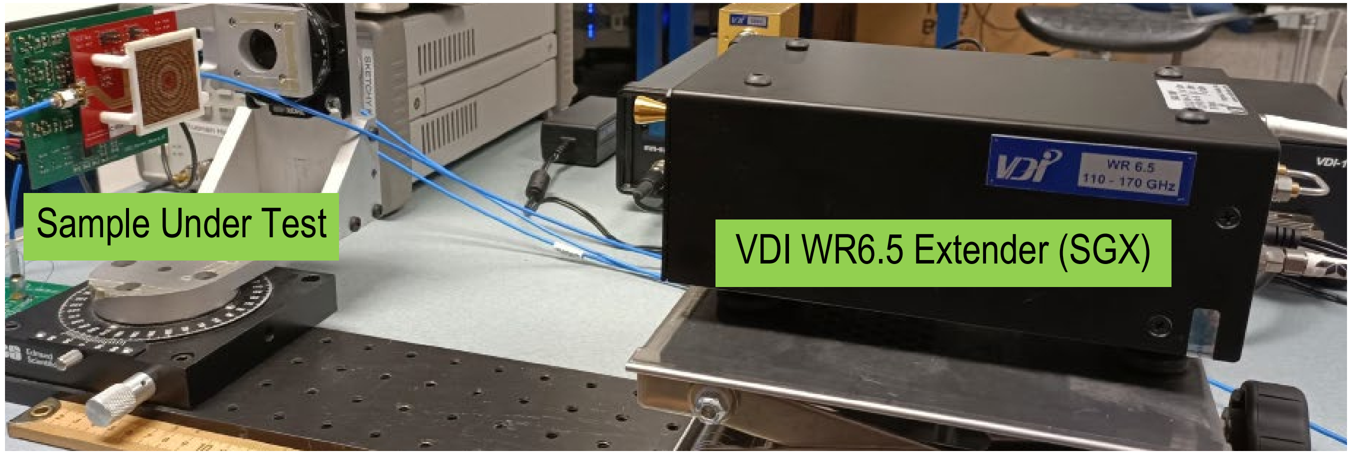
Accurate Beam Alignment Between TX & RX

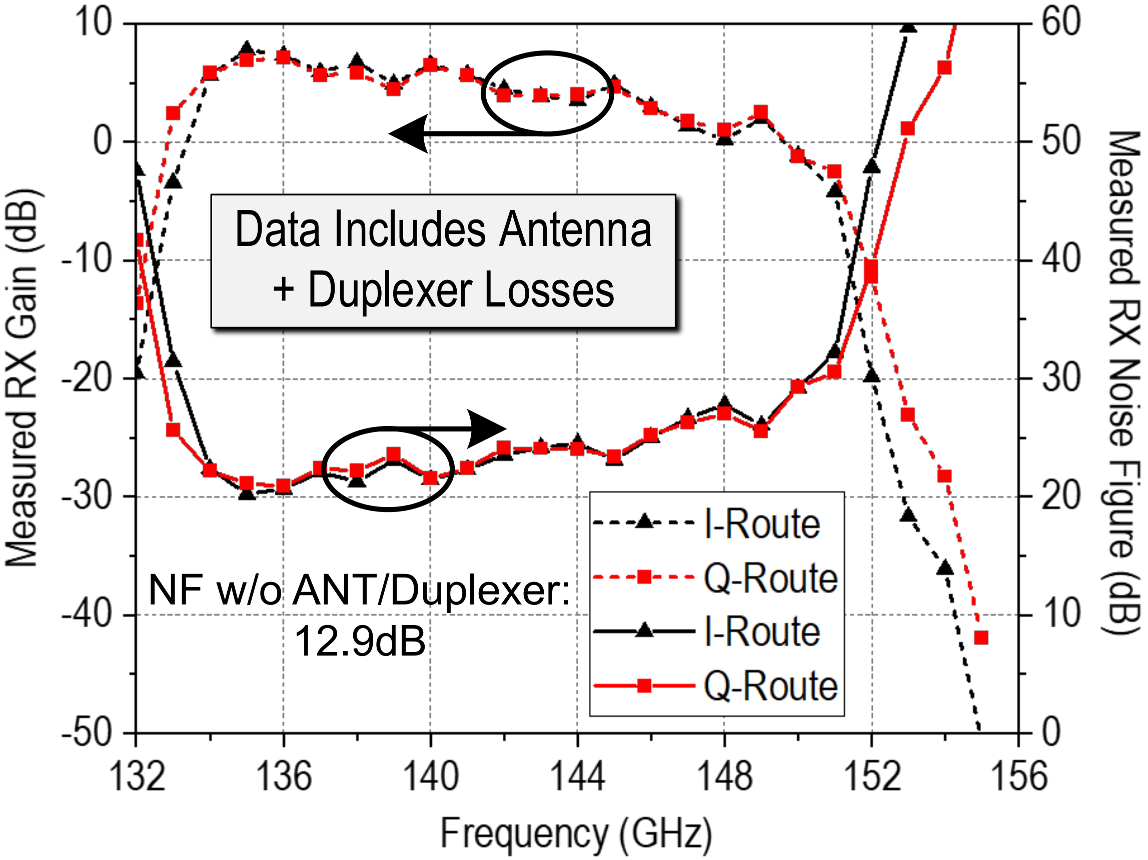
Measured Radiation Patterns

RX Test Setup and Measurement Results

RX Gain, RX Noise Figure, and RX Radiation Pattern Test Setup





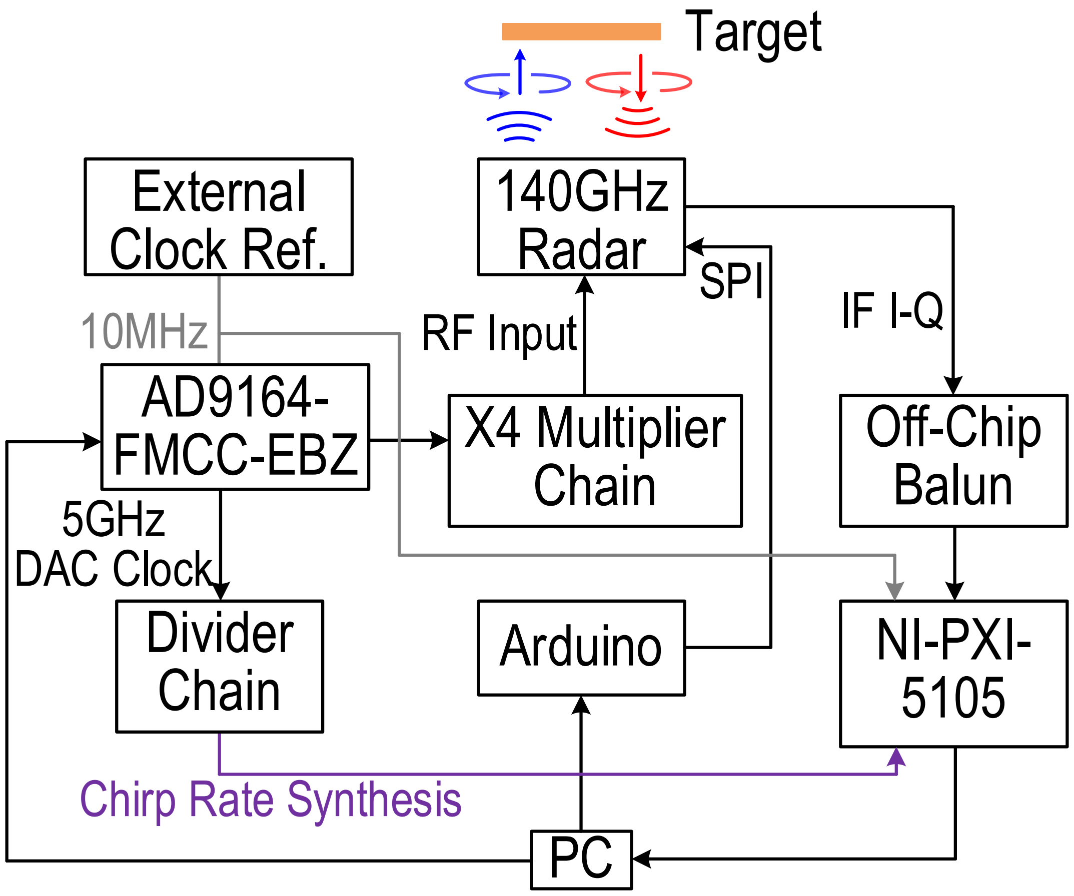


Data Includes Antenna + Duplexer Losses

NF w/o ANT/Duplexer: 12.9dB

Measured RX Gain and NF with Antenna + Duplexer Losses

FMCW Tests



Target

External Clock Ref.

140GHz Radar

10MHz

RF Input

SPI

IF I-Q

AD9164-FMCC-EBZ

X4 Multiplier Chain

Off-Chip Balun

5GHz DAC Clock

Divider Chain

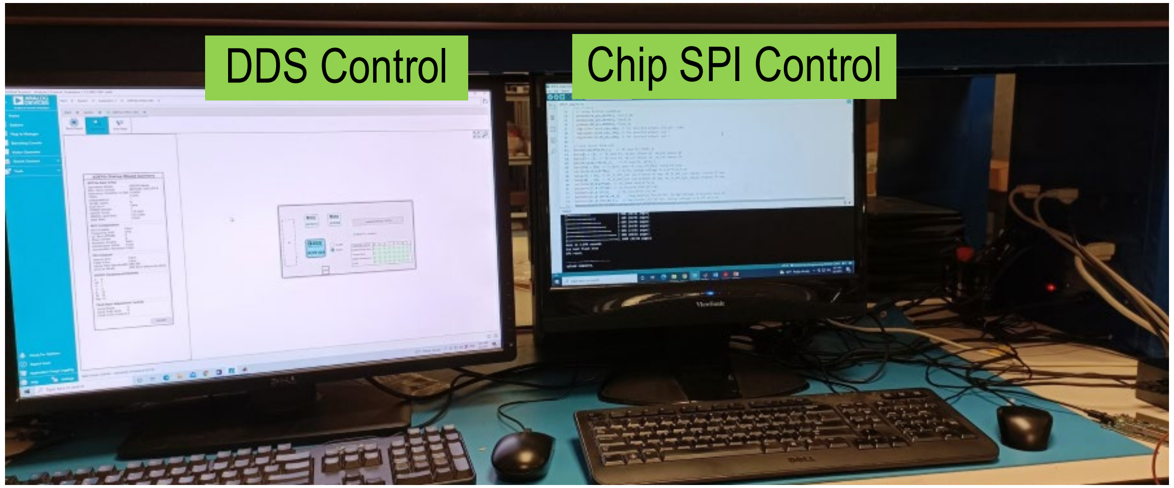
Arduino

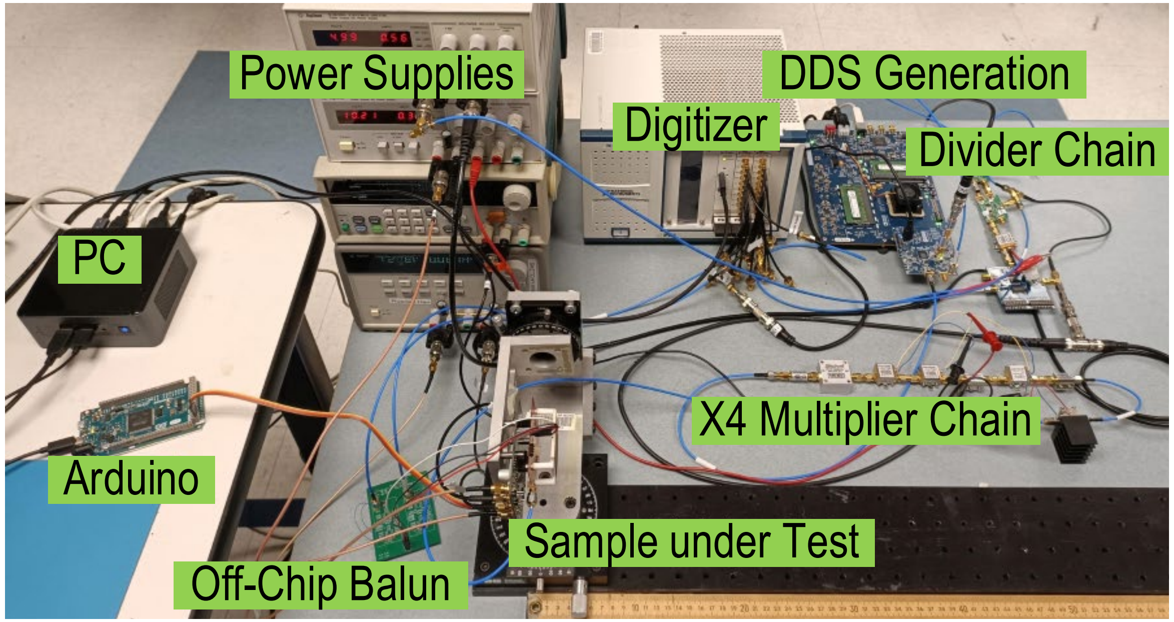
NI-PXI-5105

Chirp Rate Synthesis

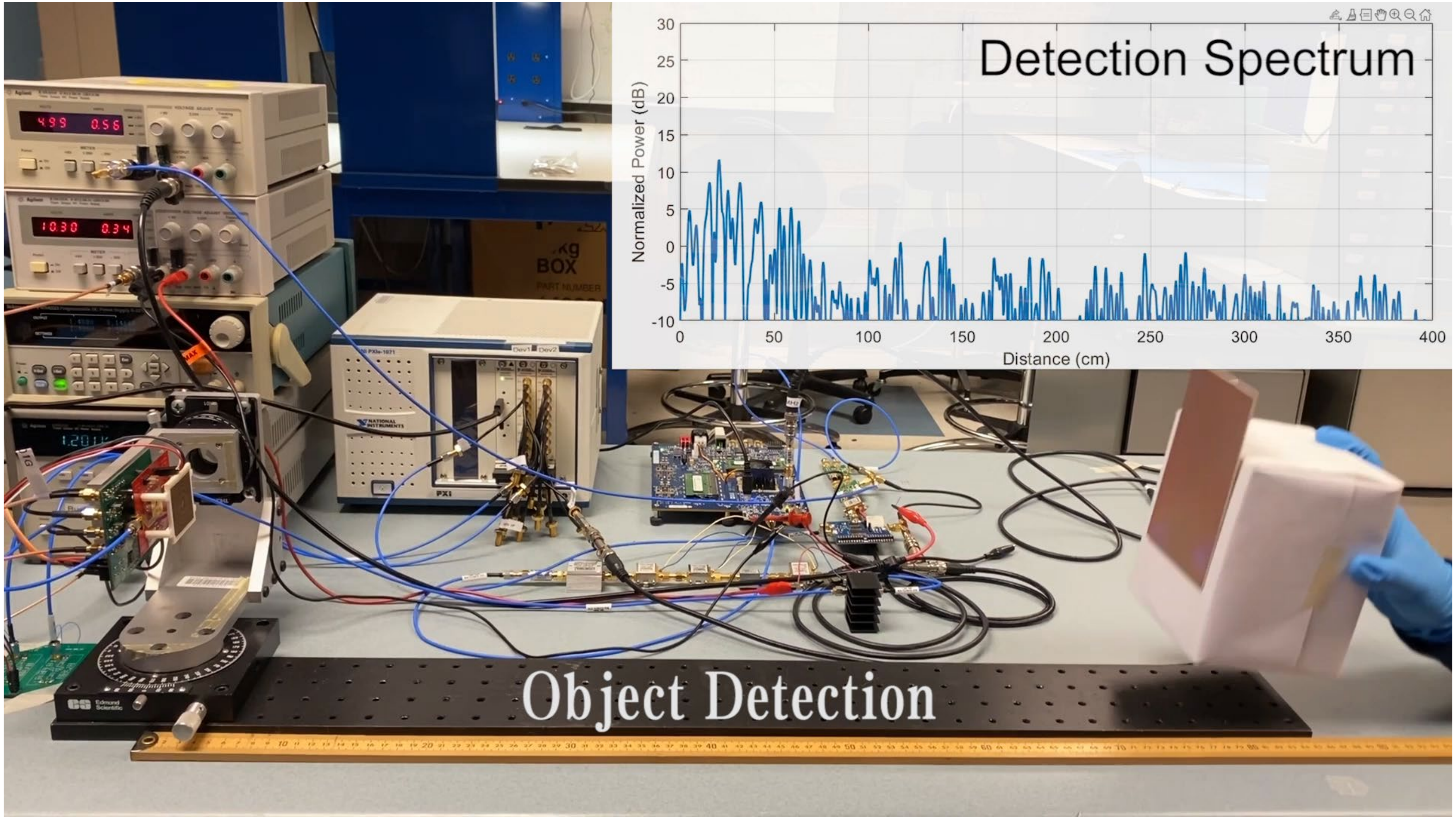
PC

140GHz Radar Detection System Setup

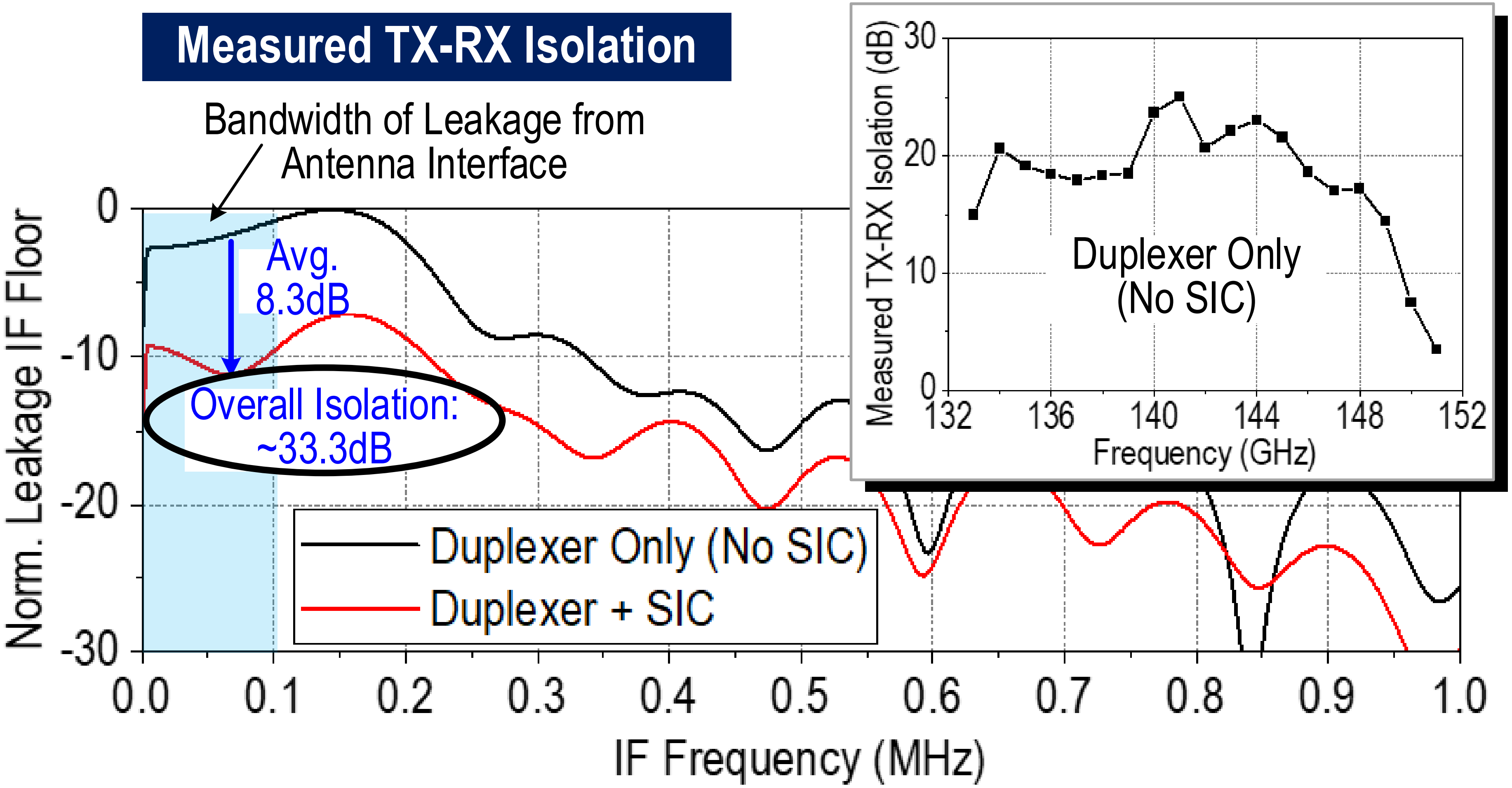




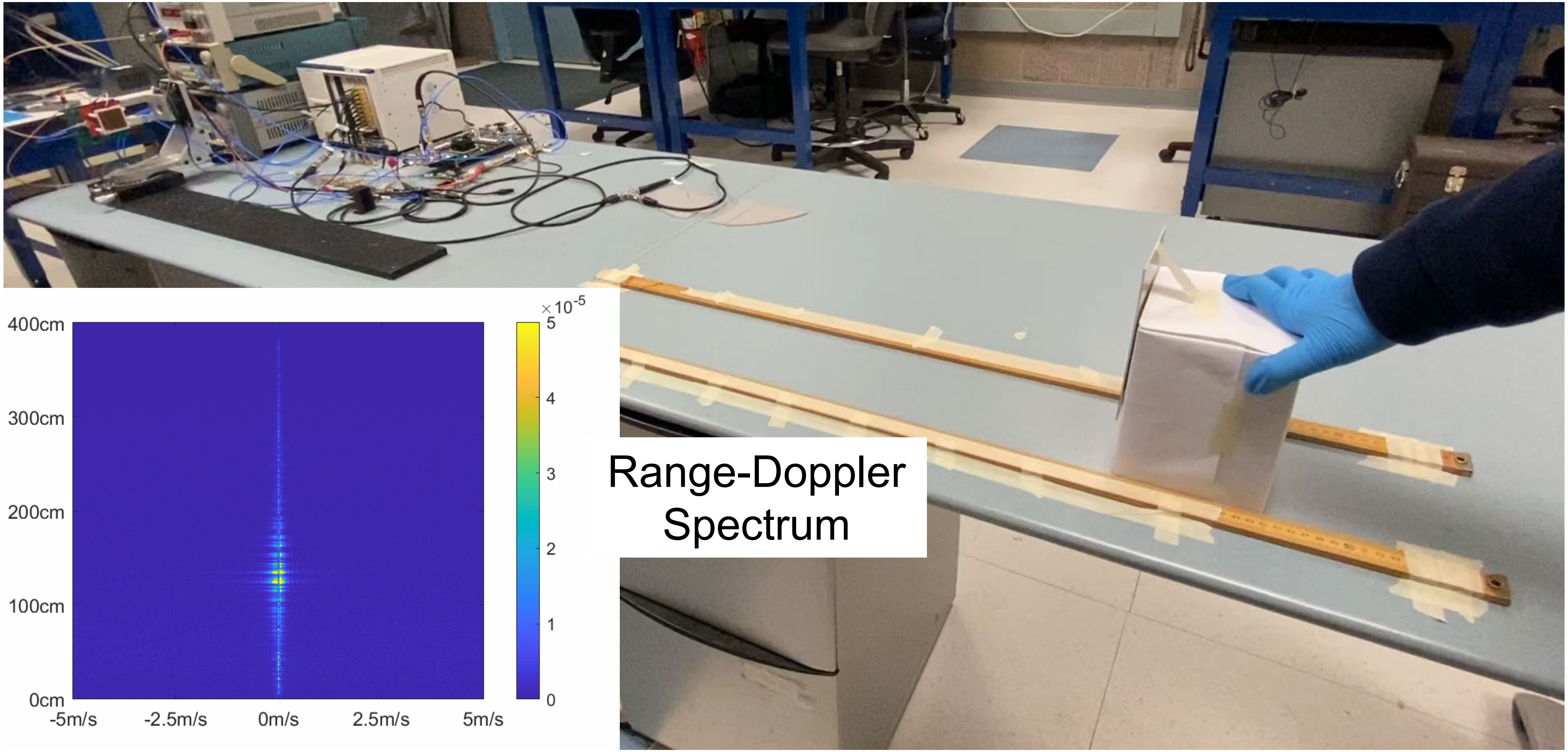
Object Detection



SIC Performance



Range-Doppler Detection*



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Comparison with Other Monostatic Radars

References	This Work	JSSC 2021 [2]	T-THz 2016 [3]	T-MTT 2017 [4]	ISSCC 2020 [5]	T-MTT 2018 [6]
Technology	65nm CMOS	130nm SiGe	130nm SiGe	130nm CMOS	65nm CMOS	130nm SiGe
Frequency (GHz)	134~148	160~178	210~270	23.8~24.5	80~85	150~170
Inherent 6dB Coupler Loss?	No	Yes	No	Yes	Yes	Yes
EIRP (dBm)	9.8, 25.2(a)	8	32.8(e)	N/A	17(g)	32(i)
TX Power (dBm)	11.2(b)	3	N/A	-1.6	2	3
Total Radiated Power (dBm)	6.2	N/A	5	N/A	N/A	N/A
RX NF_{min} (dB)	12.9	15.5	~19	11.6	15	20
Adaptive SIC	Yes	No	No	No	Yes	No
Isolation (dB)	33.3(c)	25	26	47.3(f)	40(h)	17
Antenna Type	On-Chip	On-Chip	On-Chip	Off-Chip	Off-Chip	Off-Chip
Radiation Direction & Antenna Feature	Front-Side with 3D-Printed Planar Lens	Back-Side with Substrate Etching(d)	Back-Side with Silicon Lens	Horn Antenna	4×8 Patch Antenna Array	Dielectric Resonator Antenna
Die Area (mm^2)	3.1	5.4	3.2	1.5	1	1.9
DC Power (mW)	405	860	1600~2000	111	120	N/A

(a) with 3D-printed lens (b) assuming 32% simulated antenna efficiency (c) under 14GHz-wide FMCW chirping
(d) localized backside etching (e) with silicon lens (f) achieved in a narrowband by manual impedance tuning
(g) with off-chip 4×8 patch antenna array (h) reported in a narrowband measurement
(i) with off-chip dielectric-resonator antenna

Conclusions

- 140GHz FMCW monostatic radar transceiver chip
- Full-duplexing based on geometrical symmetry
- Adaptive SIC feedback loop to compensate the antenna mismatch
- >30dB isolation w/o inherent 6dB coupler loss
- Integrated antenna, front-side radiation, with 3D-printed planar lens
- Highest total radiated power

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4.3: A 140GHz Transceiver with Integrated Antenna, Inherent-Low-Loss Duplexing and Adaptive Self-Interference Cancellation for FMCW Monostatic Radar

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