Interference Suppression Techniques for Millimeter-Wave Integrated Receiver Front Ends

Chuang Lu

Mixed-Signal Microelectronics group,
Electrical Engineering,
Eindhoven University of Technology,
The Netherlands.

Technische Universiteit
Eindhoven
University of Technology

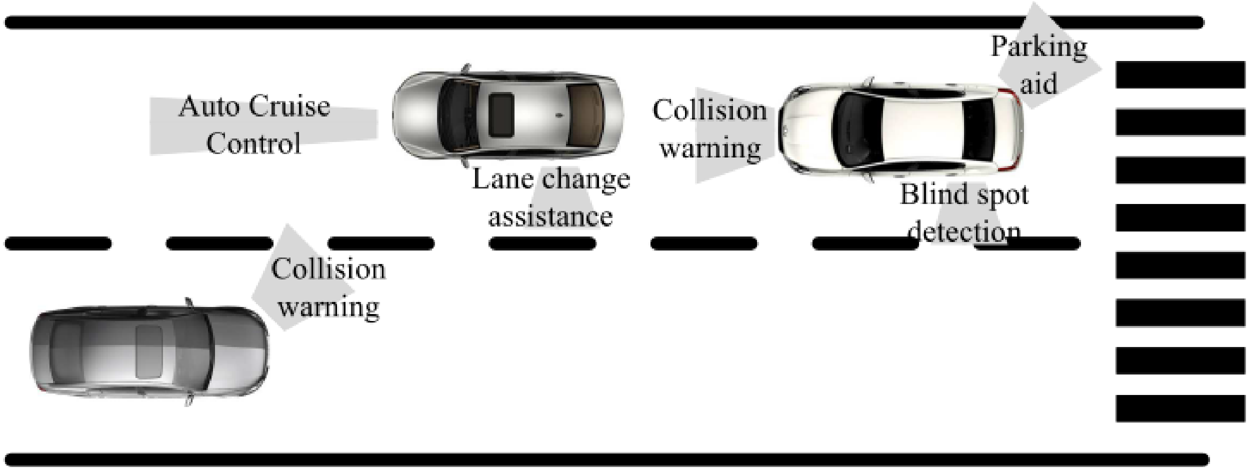
Introduction

- **The demand of higher data rate pushes wireless to mm-wave (>30GHz)**
  - Larger bandwidth;
  - Smaller antennas, etc.
- **Many attractive potential applications.**

Unlicensed 60 GHz band for indoor communication

Introduction

- **The demand of higher data rate pushes wireless to mm-wave (>30GHz)**
  - Larger bandwidth;
  - Smaller antennas, etc.
- **Many attractive potential applications.**



Automotive radar in the 79 GHz band

Introduction

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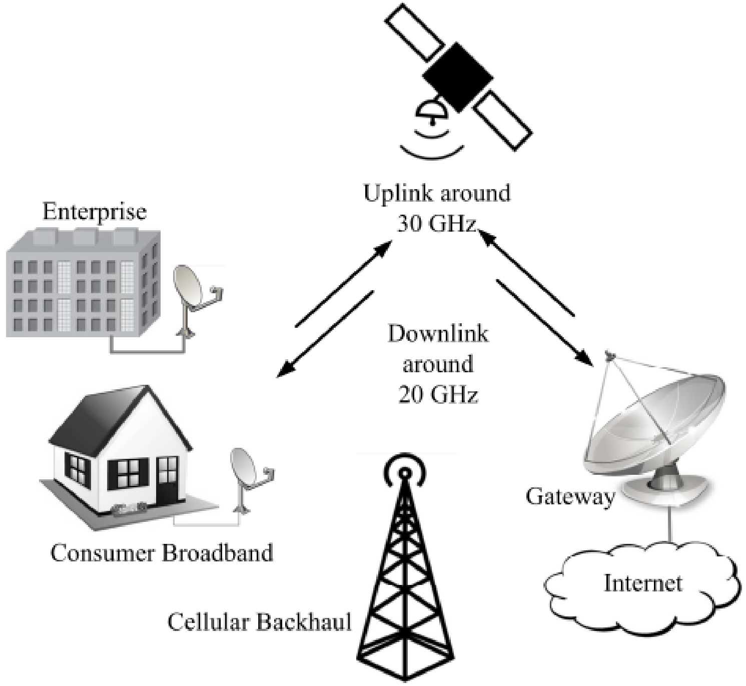
  - Larger bandwidth;
  - Smaller antennas, etc.
- **Many attractive potential applications.**



Satellite Application

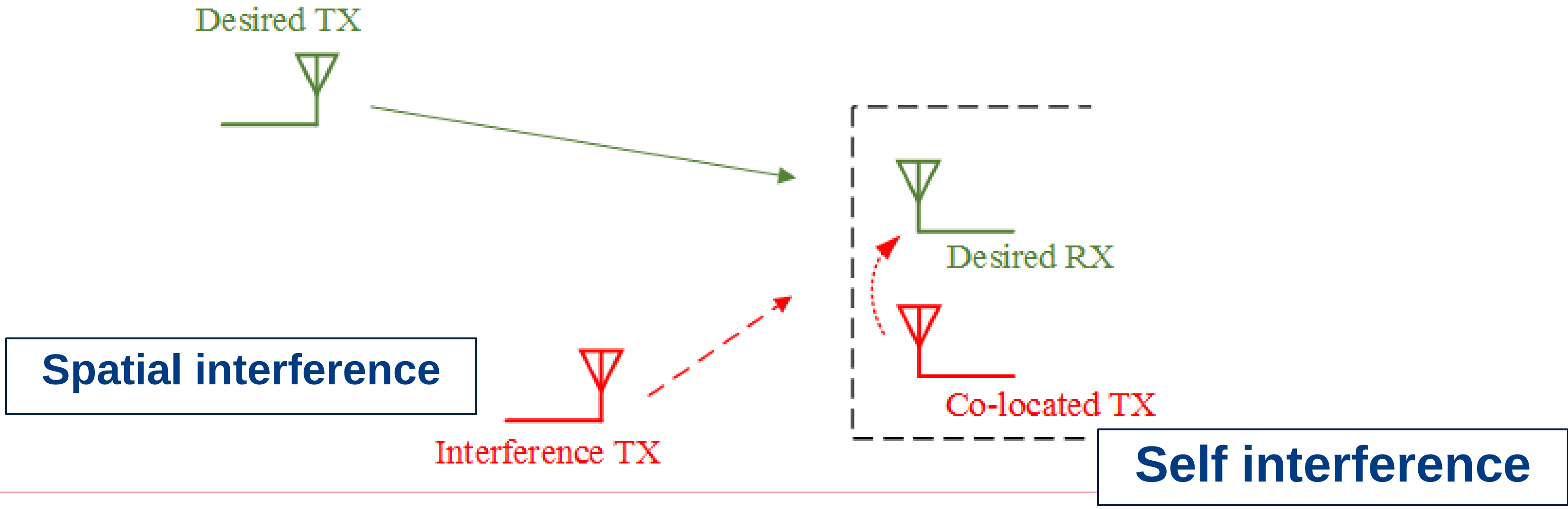
Introduction

- **The demand of higher data rate pushes wireless to mm-wave (>30GHz)**
  - Larger bandwidth;
  - Smaller antennas, etc.
- **Many attractive potential applications.**

And many others, e.g. 5G cellular communication, imaging...

Introduction

- We can envision that mm-wave systems will become popular and common in the future.
- As the number of mm-wave devices, systems or standards will grow dramatically in the future, interference issues will become important for the co-existence of different devices.

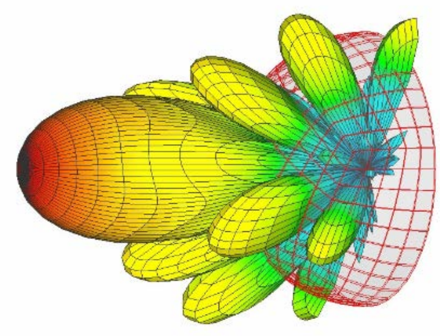


Outline

- Introduction
- Spatial-interference issue
  - Robust null forming phased array
  - High resolution phase shifter design
- Self-interference issue
  - A filtering LNA for VSAT scenario
  - A duplexer for same-band TX/RX scenario
- Conclusions

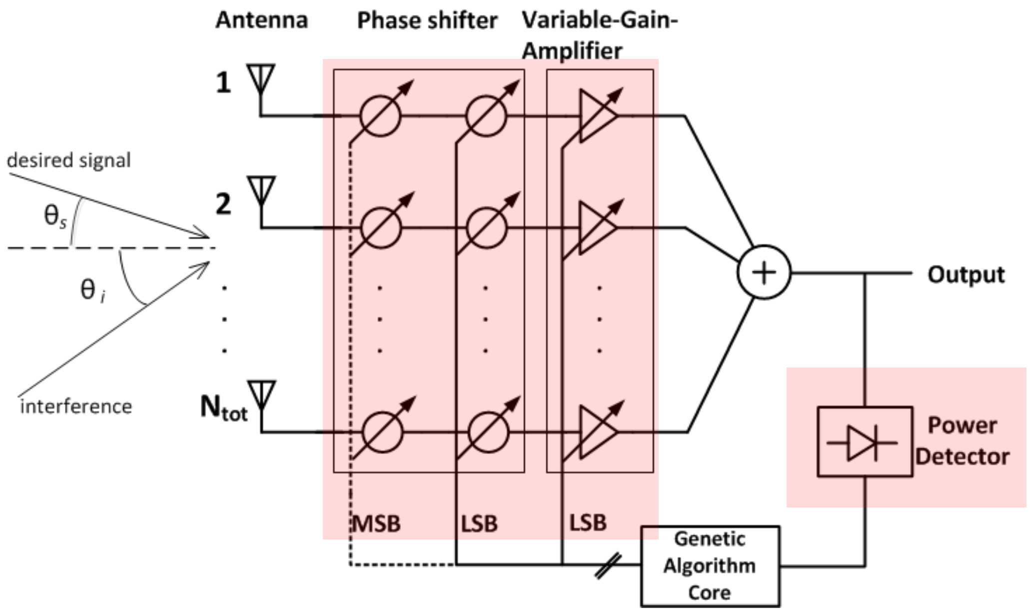
Spatial-interference

- Phased Arrays are commonly used in mm-wave applications.



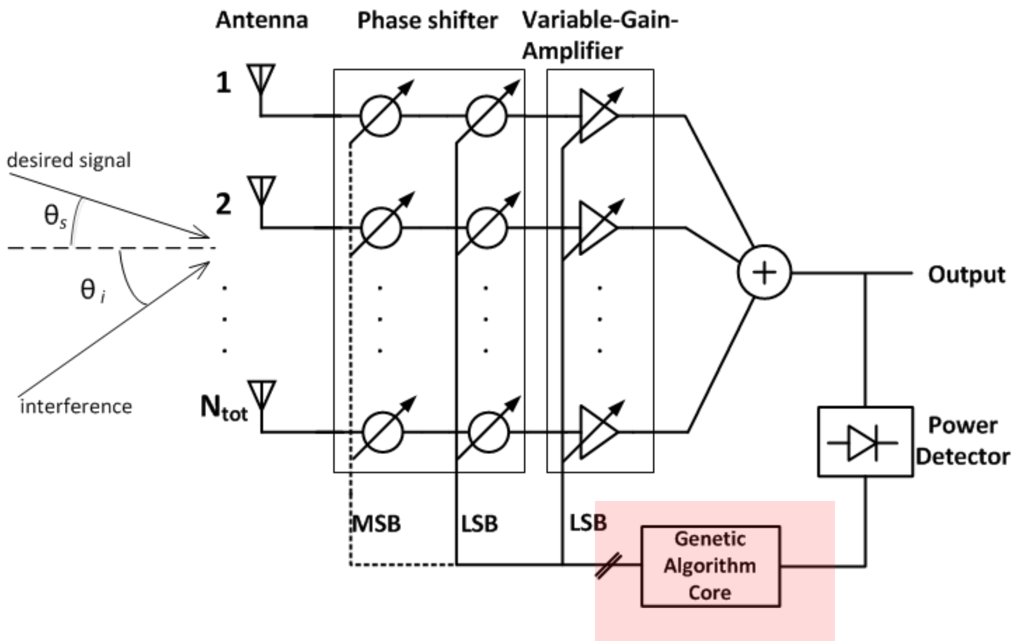
- However, spatial re-use is not fully explored at mm-wave and nulls are not used, because:
  - RF/Analog arrays
  - Limited accuracy
  - Difficult to estimate precise direction, and create accurate null
- A mm-wave null forming array is desired to be: Robust and Efficient

Proposed Robust Null Forming Array



- Discrete phase shifters and VGAs:
  - MSB: Direct mainlobe to the desired signal
  - LSB: Adjust nulls
- Manipulate the LSBs to minimize the total output power.
- Direction of interference is not needed.
- Not sensitive to the weight errors, but fine steps on the phase shifts is desired for convergence.

Proposed Robust Null Forming Array



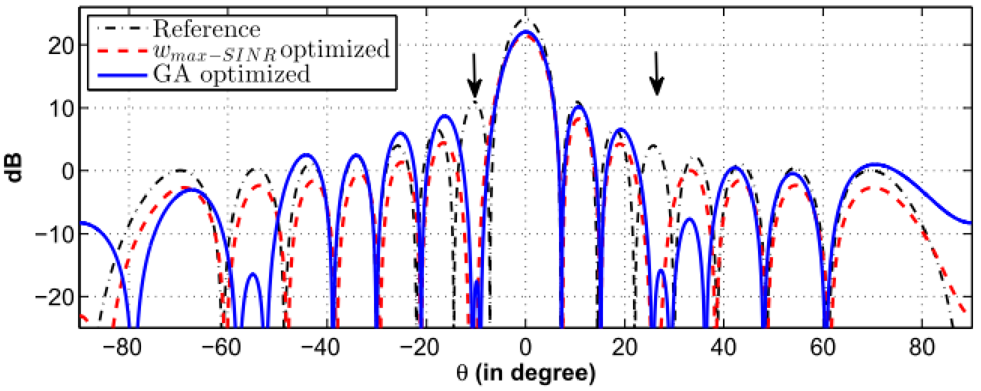
- Genetic Algorithm (GA) is used for the optimization
  - Efficient to find the global optimum.

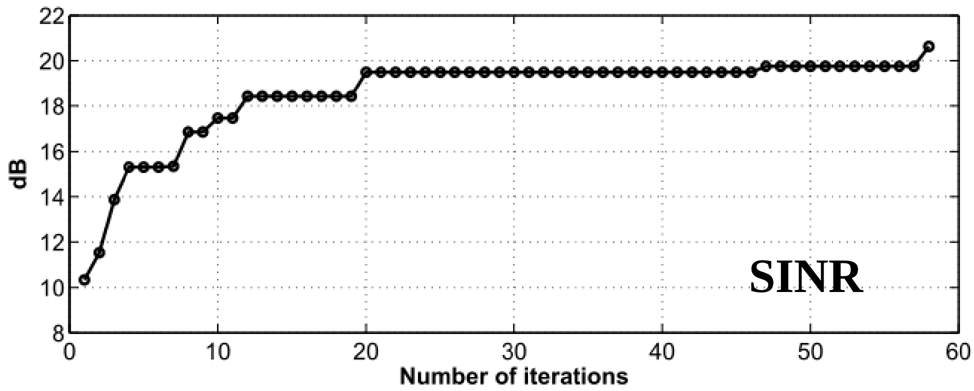
Simulation Results

- Array Pattern Optimization for certain interference scenarios

Assumptions:

- Uniform linear array (ULA): N_{tot} = 16, d=λ/2
- 6-bit Phase Shifter: 4MSB, 2LSB
- 2-bit VGA: 1MSB, 1LSB
- Desired signal power at RX: -64dBm at $\theta_s = 0°$
- Co-channel interferences.





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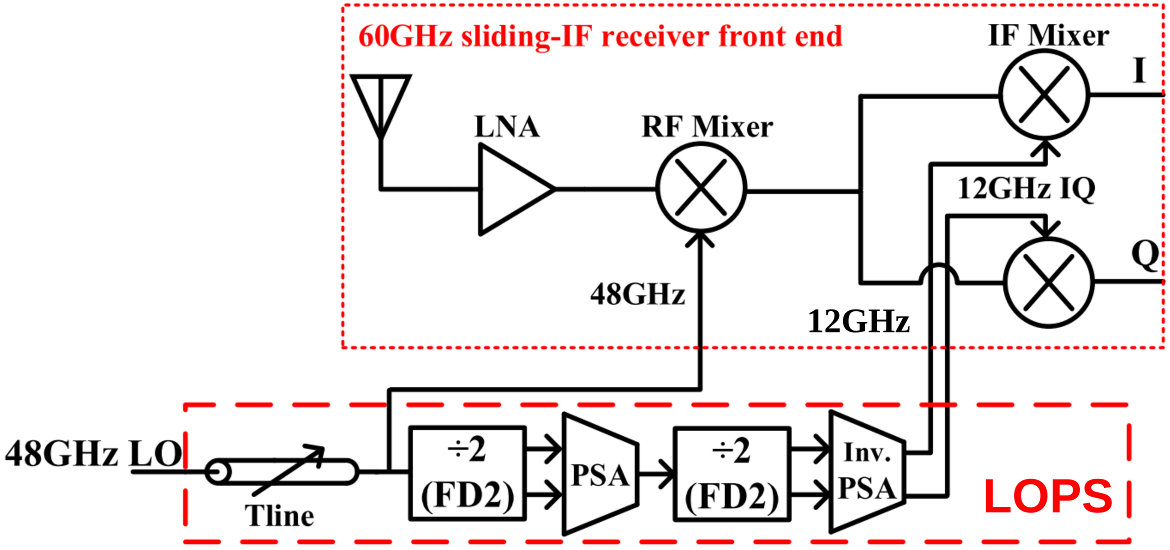
High resolution phase shifter design

- From the null-forming array, high resolution phase shifters are required: Fine steps rather than accuracy.

- To have enough LSB's for optimization.
- 6-bit phase shifter is required.

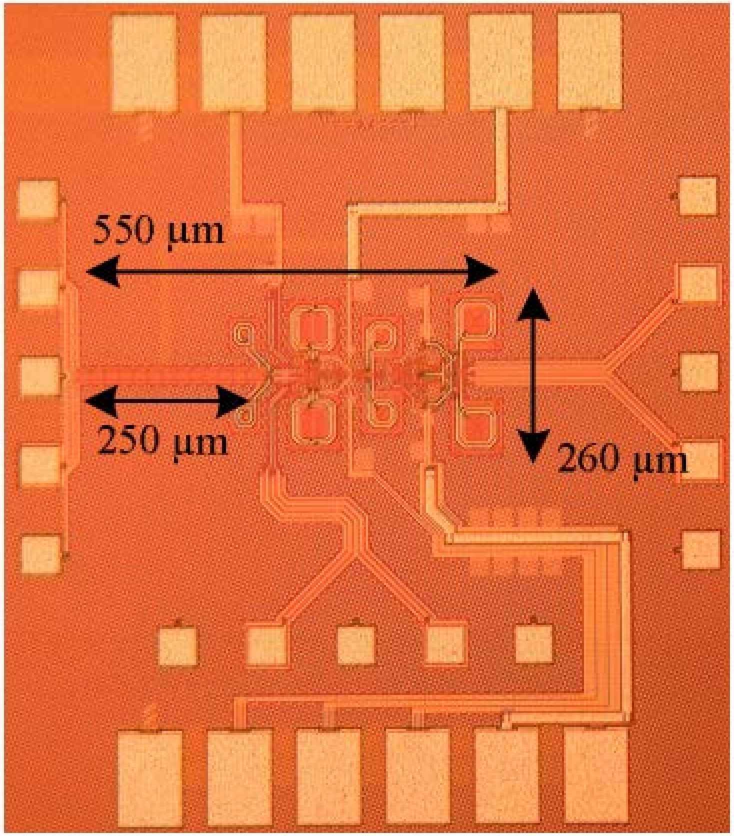
- Two phase shifters are designed and implemented for the null-forming array:
  - LO-path phase shifter
  - Base-band phase shifter

LO-path phase shifter

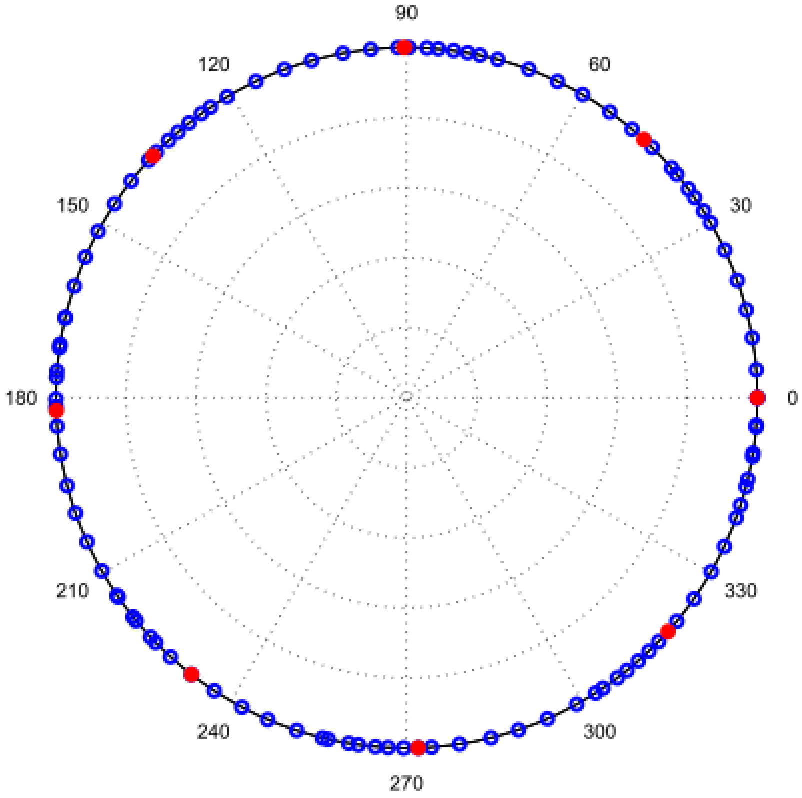


- Phase shifting implemented by Tunable Tline + Divider-by-4.
- Reduced tuning range requirement on the tline.
- In LO path, de-coupled from the signal path.

LO-path phase shifter
Measurement Result

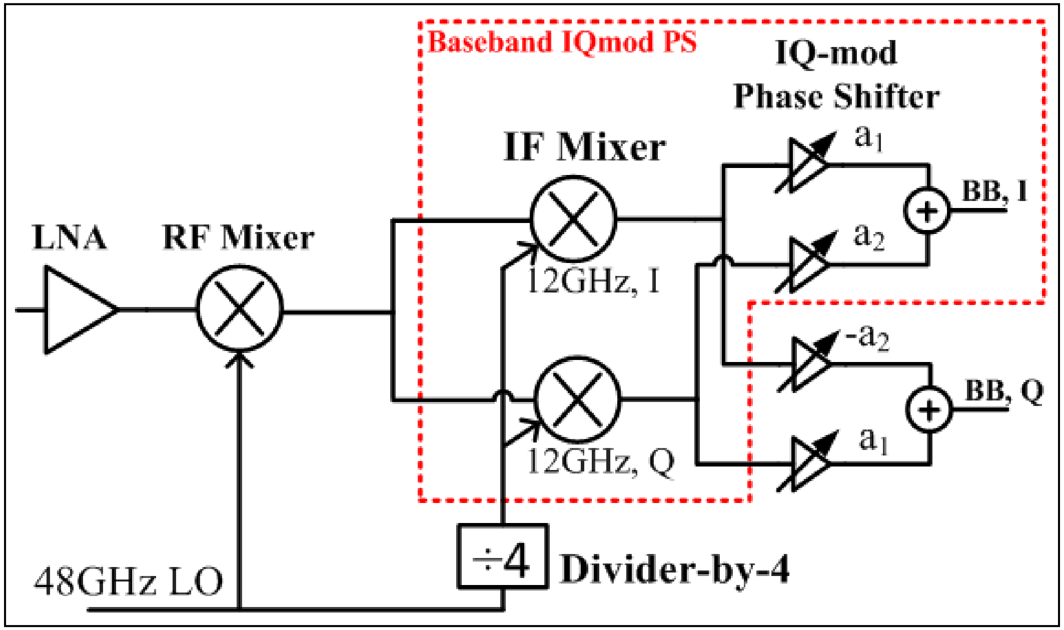


In 40nm CMOS technology



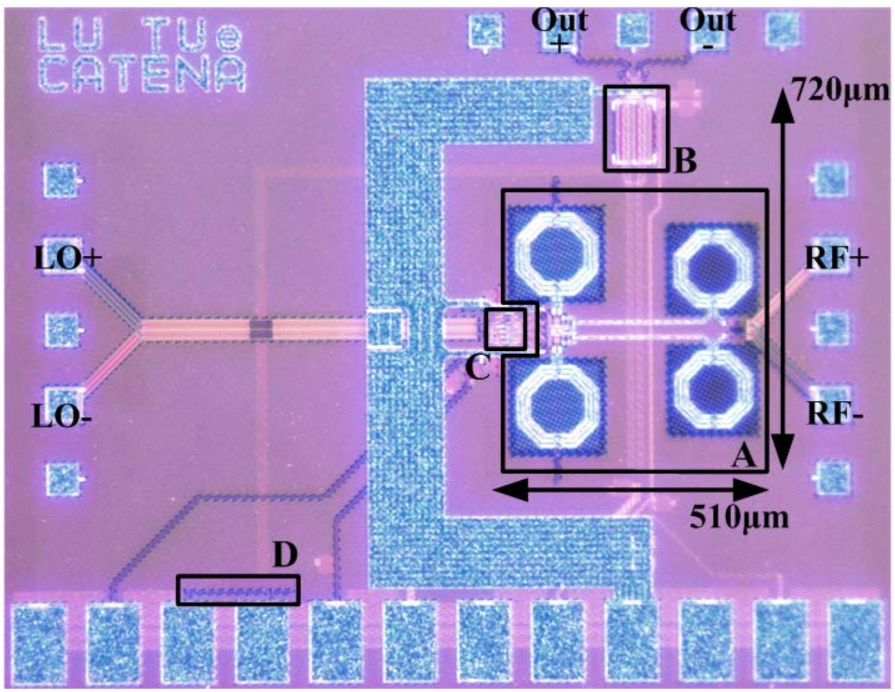
- Average phase step: 3.5º
- Maximum phase step: 5.4º

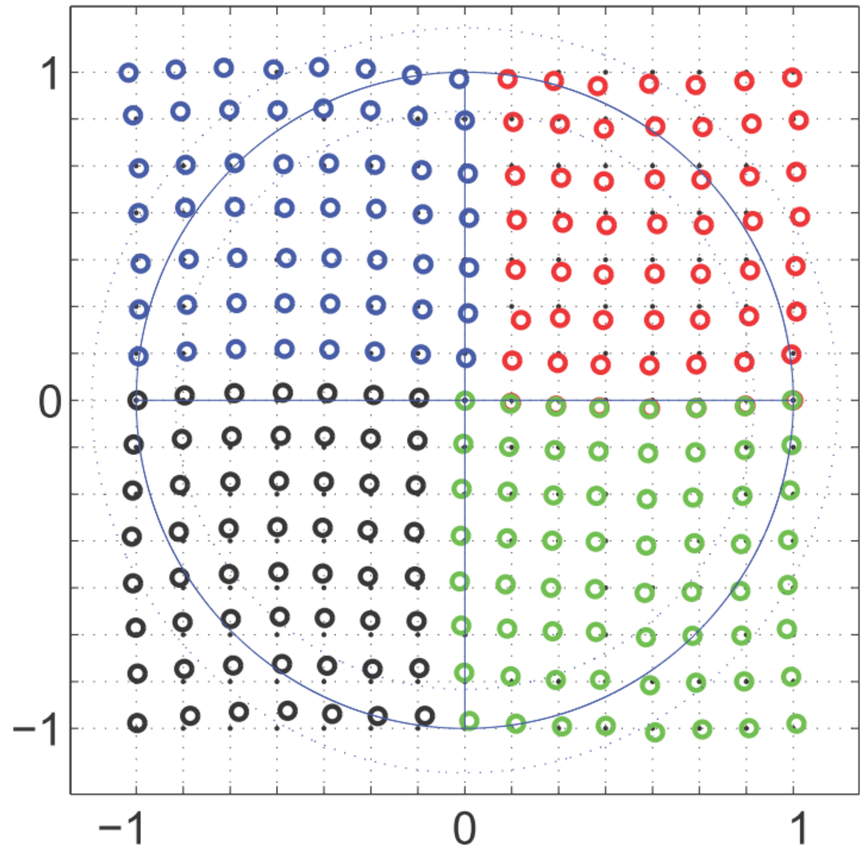
Base-band phase shifter



- Make use of the quadrature signals from the I/Q mixing.
- Combine the I and Q signals with certain amplitudes, to generate output signals with certain phase shifts/amplitudes

Base-band phase shifter
Measurement Result





- 225 points
- Both amplitude and phase tuning.

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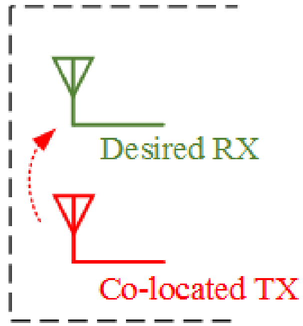
Self-interference issue



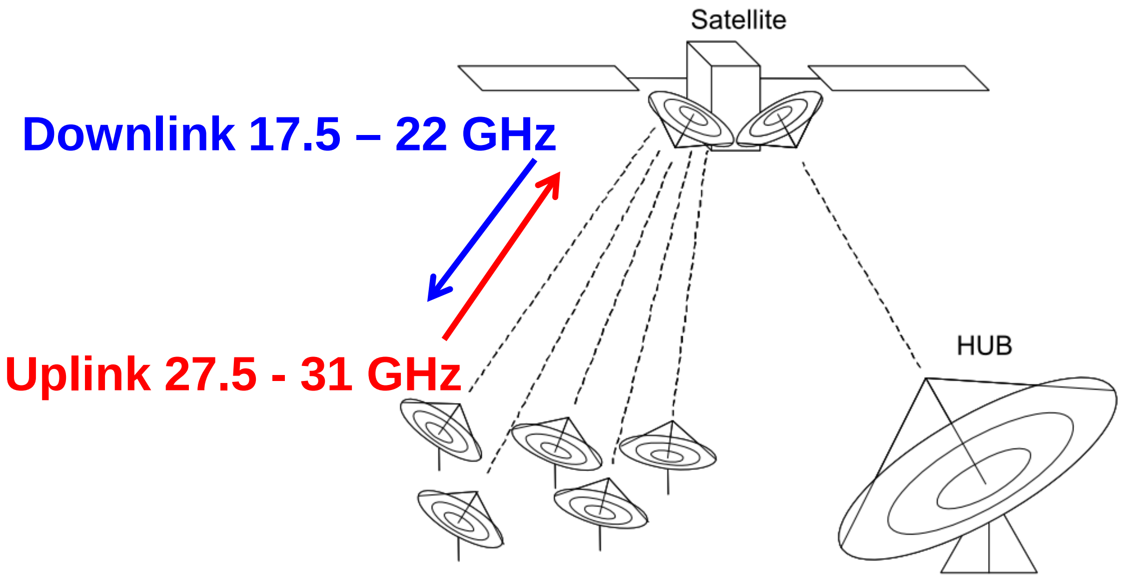
- Between colocated TX and RX.
- High power TX can desensitize and saturate RX.
- Two scenarios:

1. When TX and RX are at relatively seperate frequencies
2. When TX and RX are in the same band

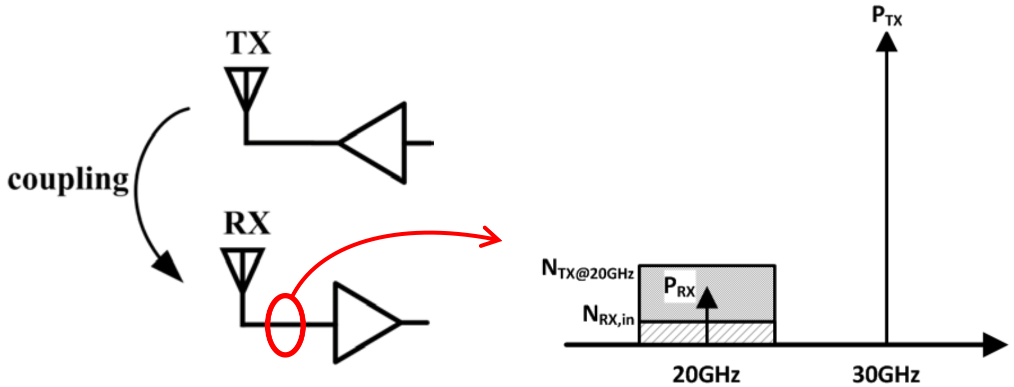
Self-interference issue

1. When TX and RX are at relatively seperate frequencies:

Ka-band Very-Small-Aperture terminals (VSAT) is a typical application.



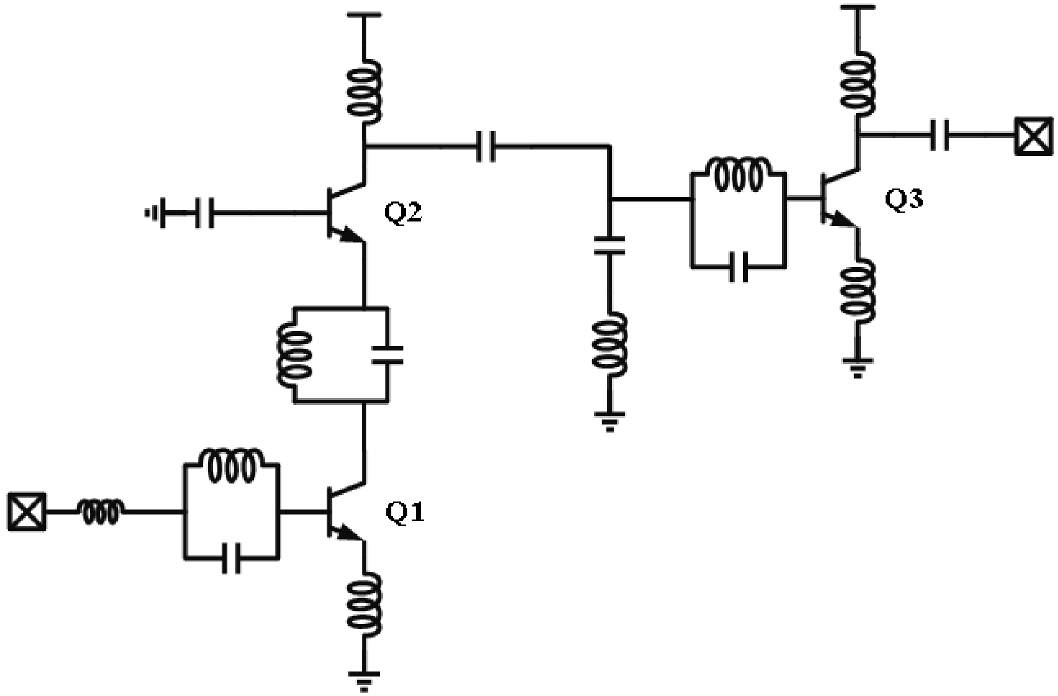
Duplex in VSAT scenario



Challenge:

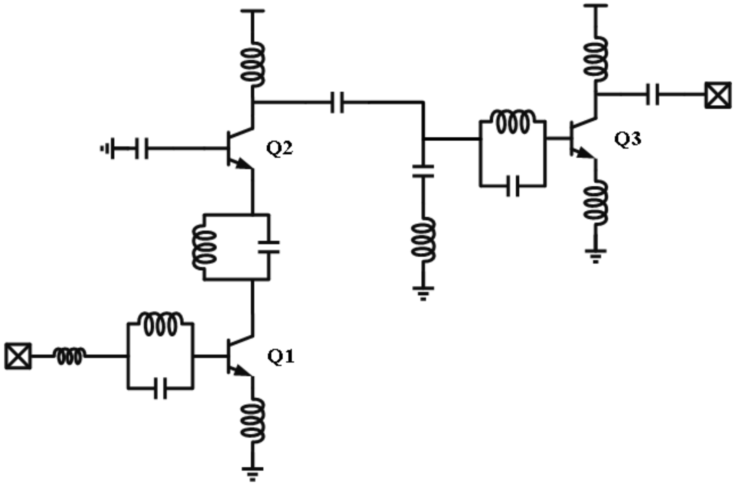
High attenuation @ 30GHz and Low NF @20GHz

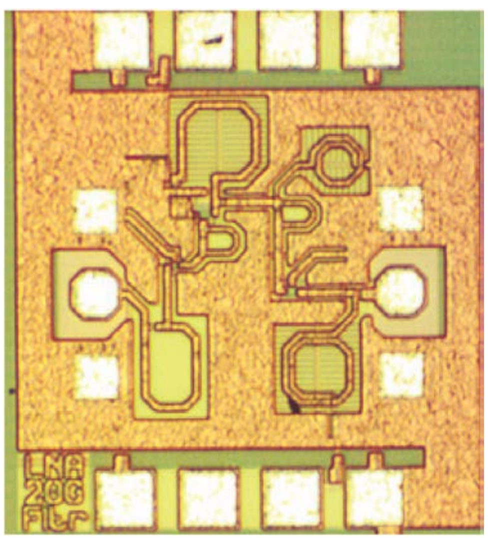
Filtering LNA for VSAT Duplex



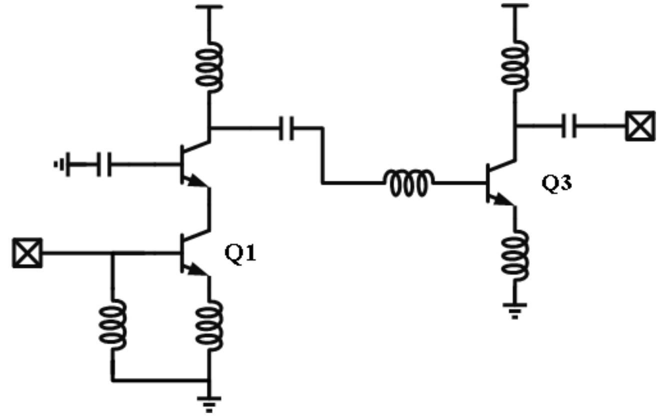
- Distribute filtering at different stages in LNA
- Compression mainly happens after amplifying
- Filtering at later stages contributes less to the total NF

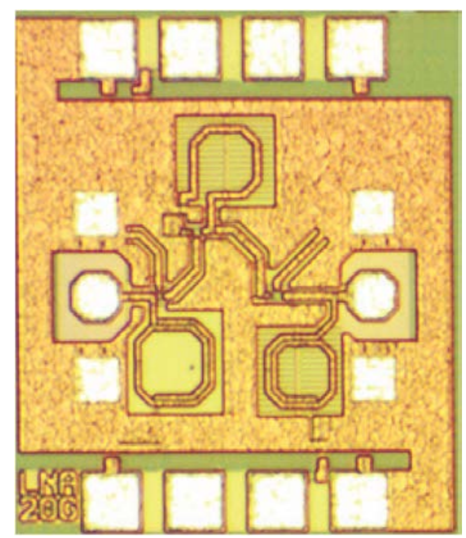
With filtering:





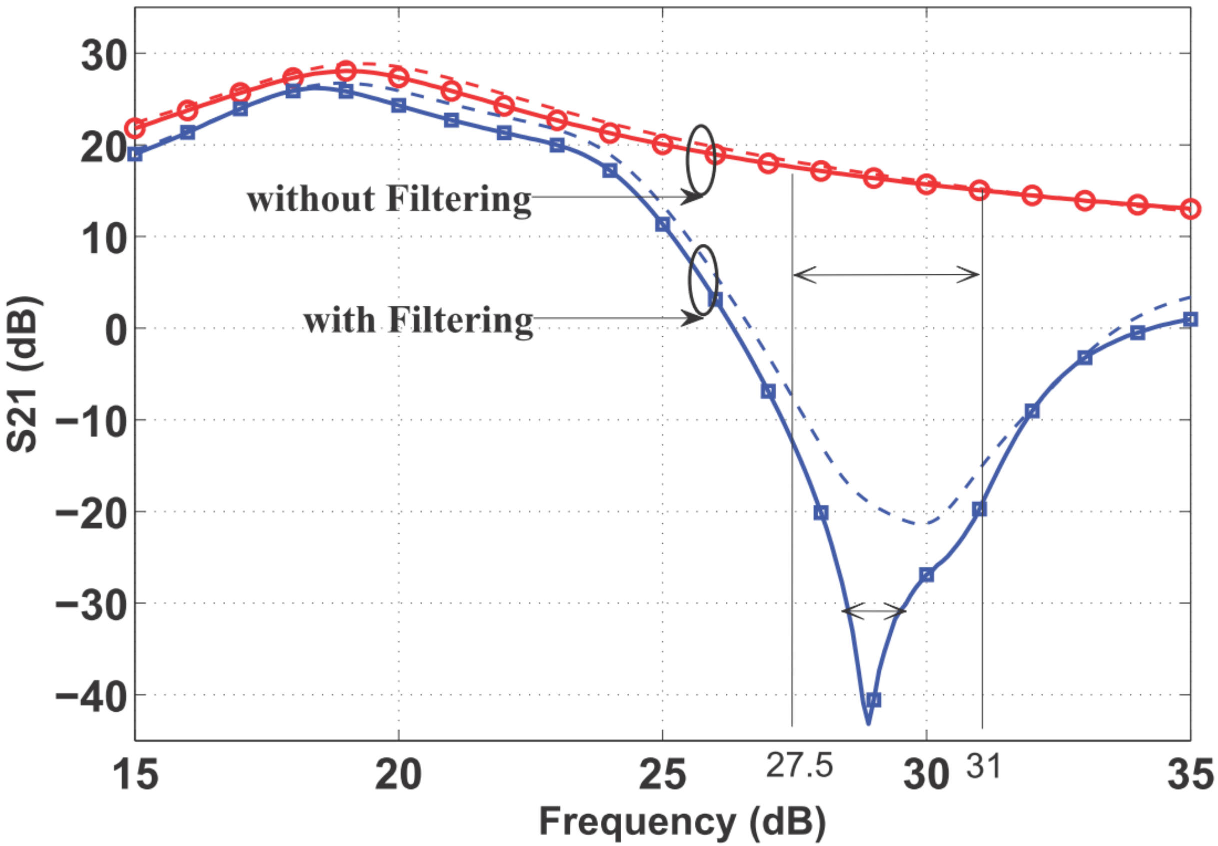
Without filtering: (Reference case)





0.25 µm SiGe:C BiCMOS technology

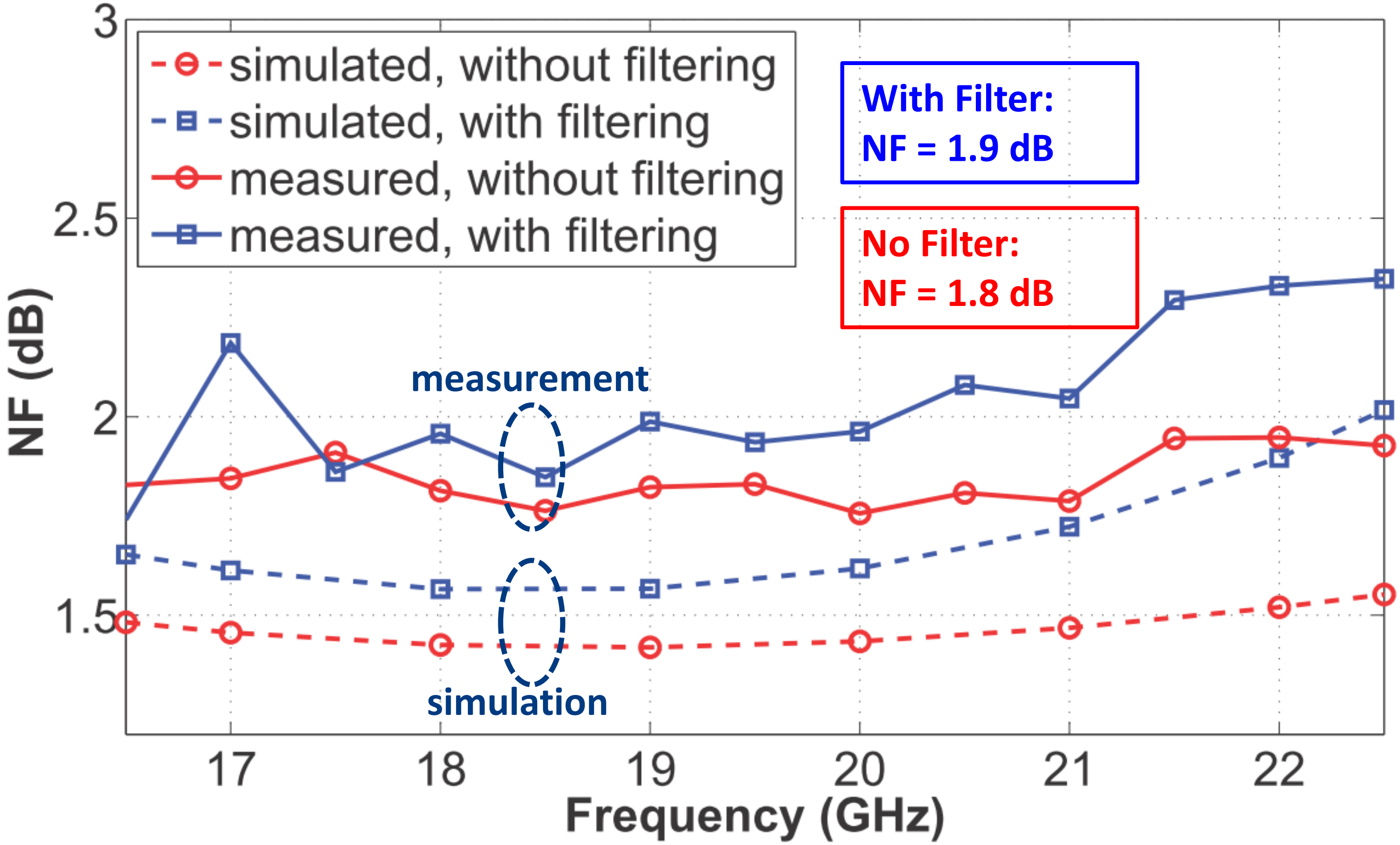
Measurement: Gain



	With Filter	No Filter
S21 (dB) @20GHz	24.3	27
S21 (dB) @17.5GHz	-12.9	17.5
S21 (dB) @31GHz	-20	15.2

More than 30 dB total filtering

Measurement: NF



0.1 to 0.4 dB NF degradation by the filtering LNA

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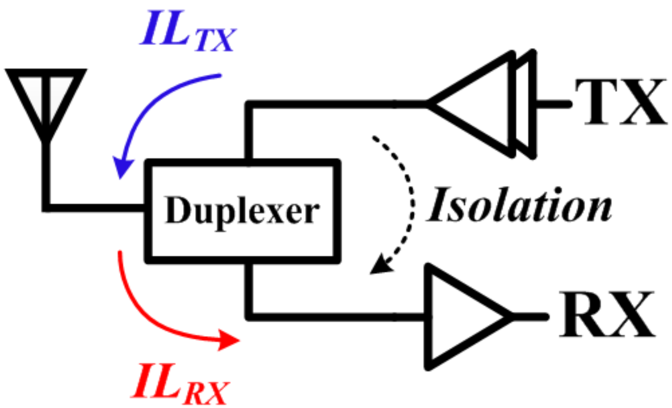
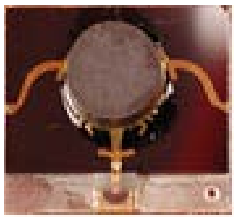
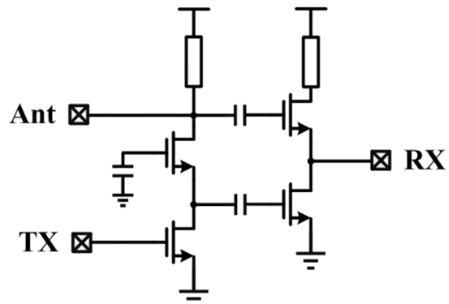
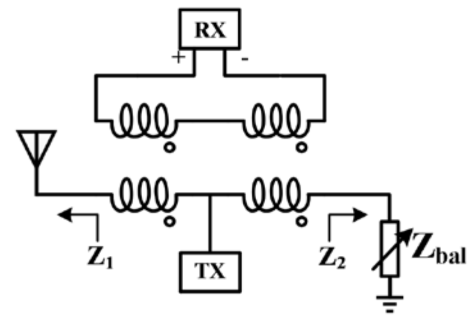
  - **A duplexer for same-band TX/RX scenario**
- **Conclusions**

Self-interference issue
Same-band TX/RX scenario

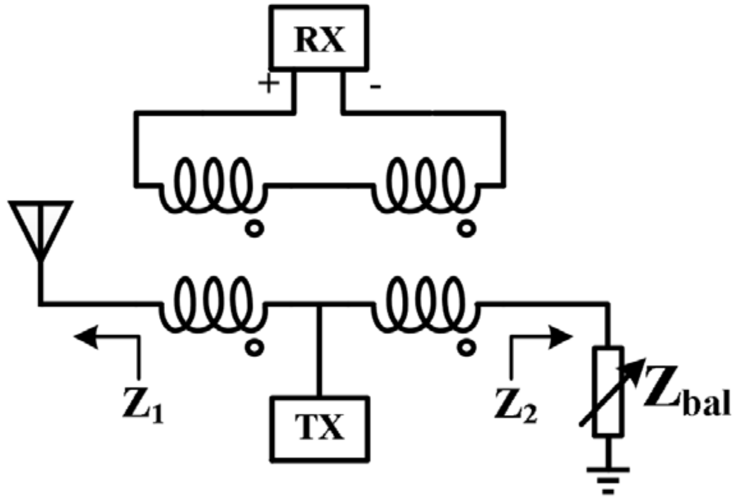
- When the self-interfering TX is in the same band as the RX, lumped filtering is not practical for on-chip solutions.
- Duplexer is typically used to isolate the TX and RX and typically off-chip.
- On-chip duplexers are challenging to be high isolation and low loss at mm-wave.



Possible Duplexer Solutions

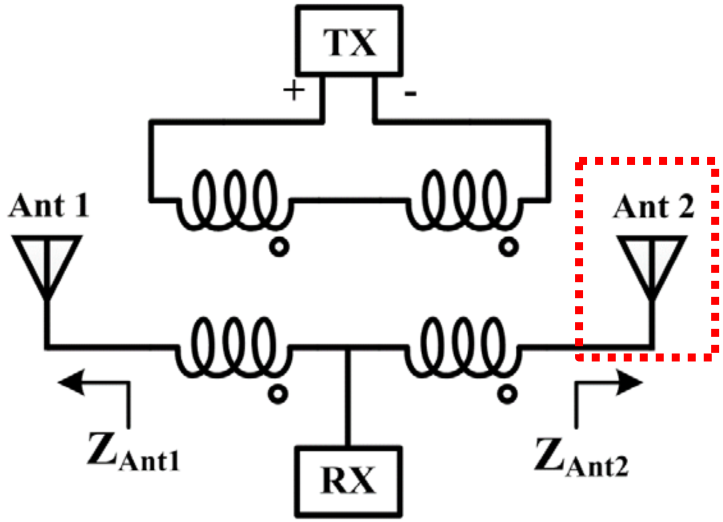
Ferrite based circulators	On-chip active quasi circulator	Hybrid-Transformer
		
Isol>20dB, Loss <0.9dB @30GHz But: — External component, increased area and cost — Limited isolation at mm-wave	On-chip, low-cost But: — High loss and NF — Linearity issue	+ Compact + Tunable + Passive + High Isolation But: - Inherent loss at Z_{bal} (3dB)

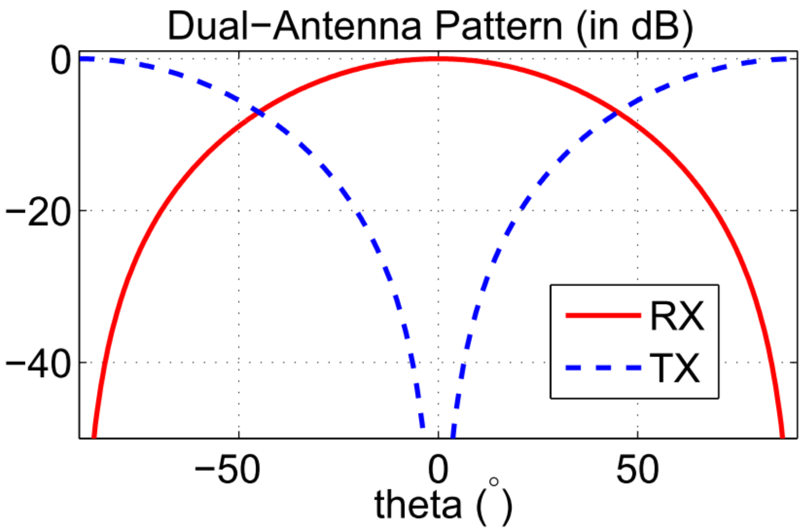
Possible Duplexer Solutions



- Isolation achieved by electrical balance
- Tunable Z_{bal} to balance the impedance for high isolation
- Wideband duplexer with high isolation
- More than 6 dB total loss in link budget

Dual Antenna Hybrid-Transformer Duplexer





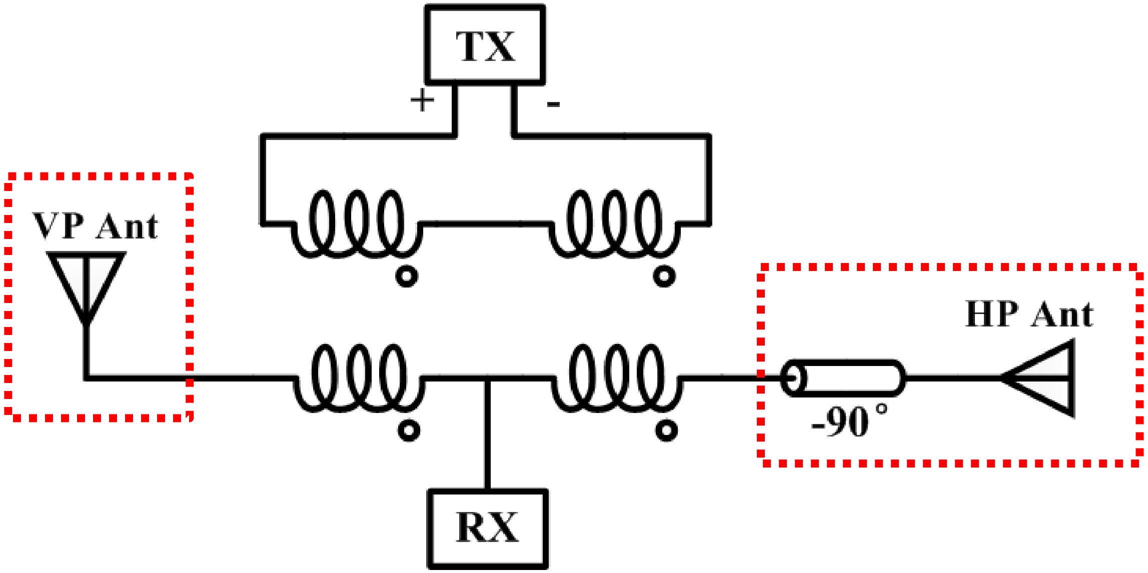
Replace Z_{bal} by an identical antenna?

- Dual antenna duplexed by TX and RX at the same time.
- Avoid the inherent loss
- Wideband impedance balance→ Wideband isolation

However, TX and RX signals at Ant1 and Ant2 are differential and common-mode signals respectively

Dual Antenna Hybrid-Transformer Duplexer

- With Orthogonally Linear-polarized (LP) Antennas

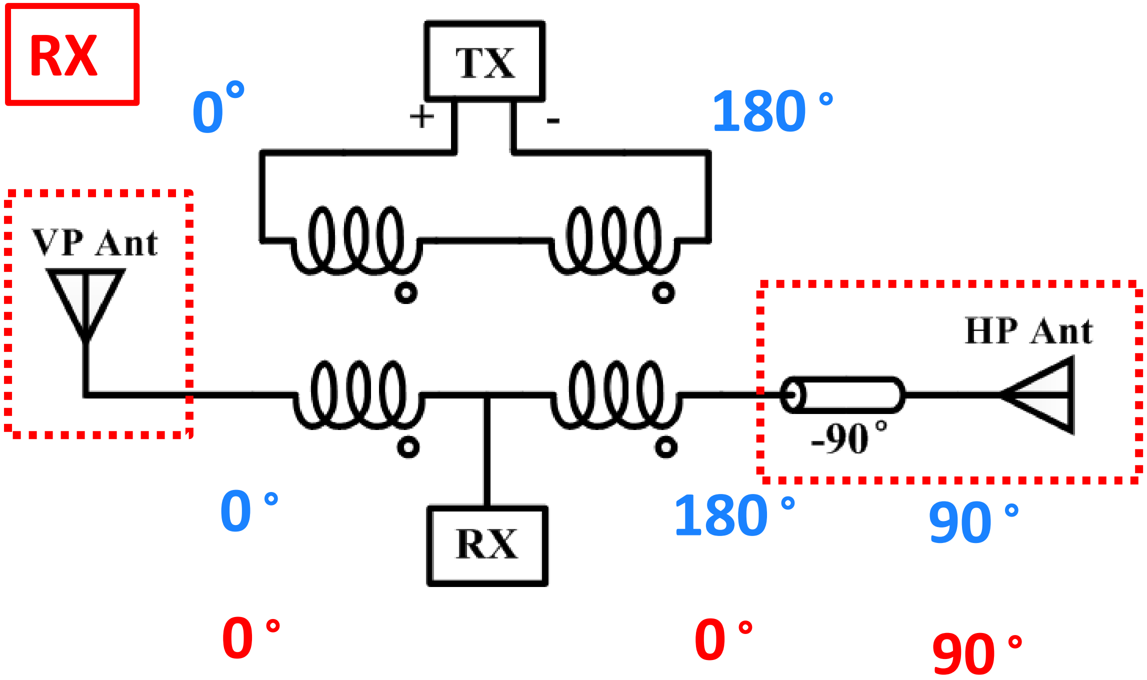


  - Vertically and horizontally polarized antenna's
  - With a $1/4\lambda$ delay line (90º) on one side

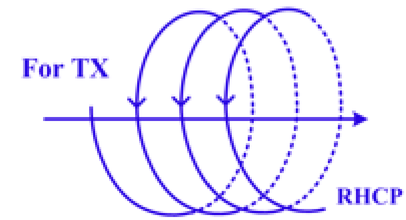
Dual Antenna Hybrid-Transformer Duplexer

TX

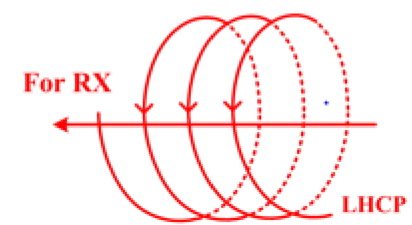
RX



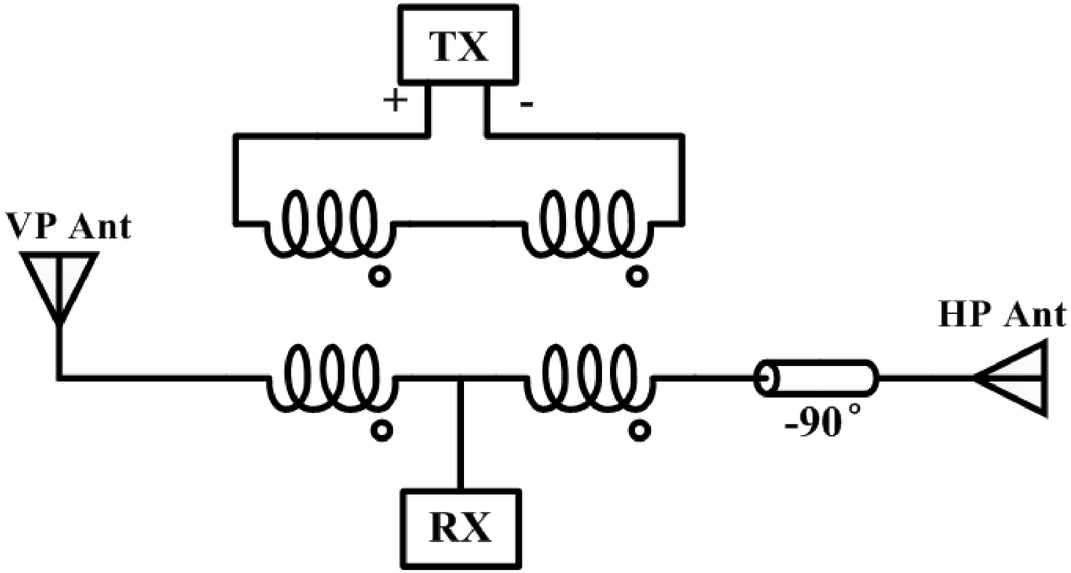
For TX: RHCP



For RX: LHCP



Dual Antenna Hybrid-Transformer Duplexer



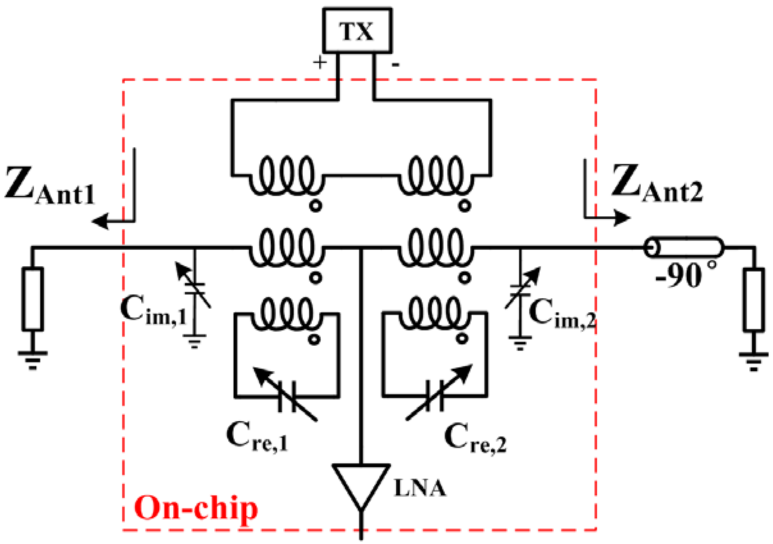
- TX and RX duplexes dual-antenna with orthogonal CP towards and from the same direction
- “Circular polarization duplexer”
- Can be very useful for radar/imaging application

Dual Antenna Hybrid-Transformer Duplexer

Tunable Hybrid-Transformer

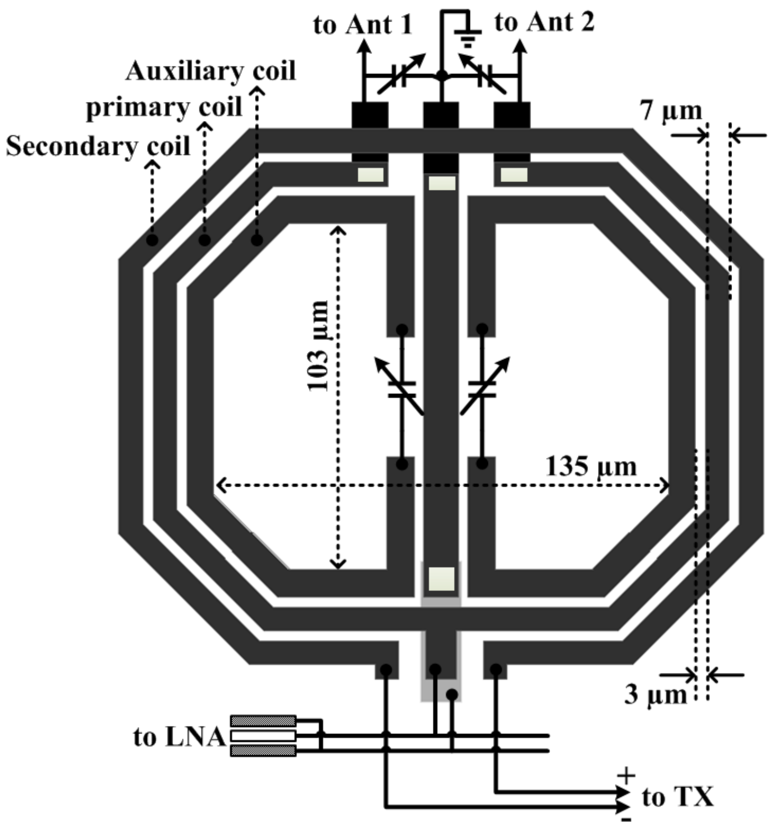
- Why tunable?
  - Impedance transform by the 1/4λ T-line
  - Mismatch between Z_{Ant1} and Z_{Ant2} can degrade the isolation significantly

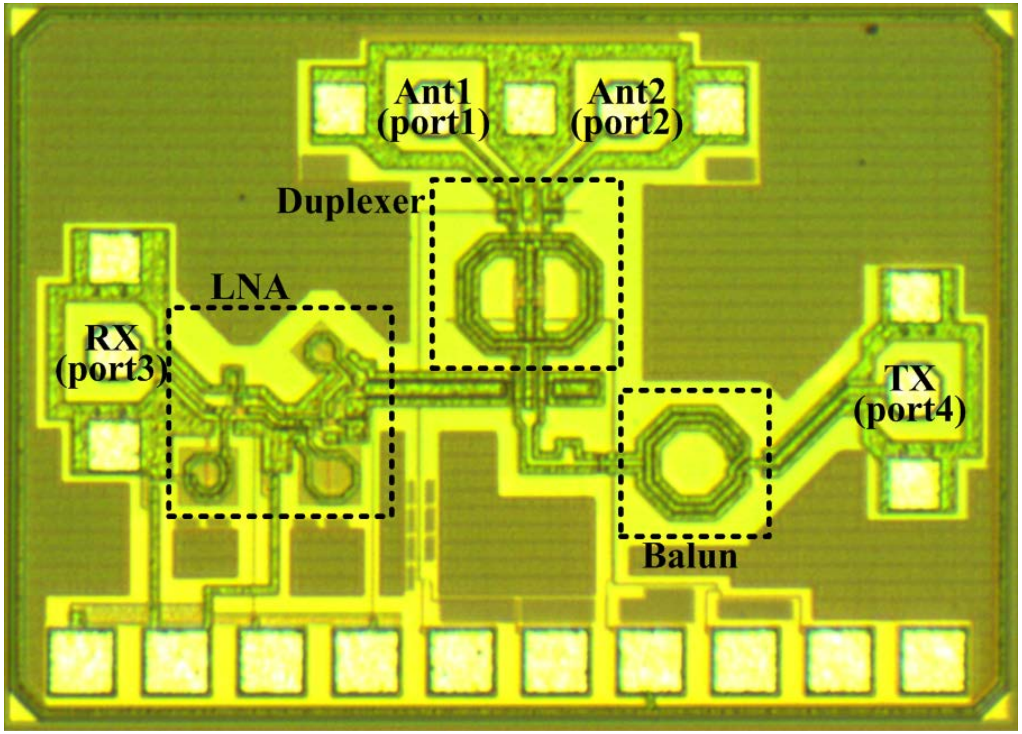
- Impedance imbalance in:
  - Imaginary part
  - Real part
- Compensated respectively by:
  - Shunt varactor
  - Auxiliary coil with series varactor



Dual Antenna Hybrid-Transformer Duplexer

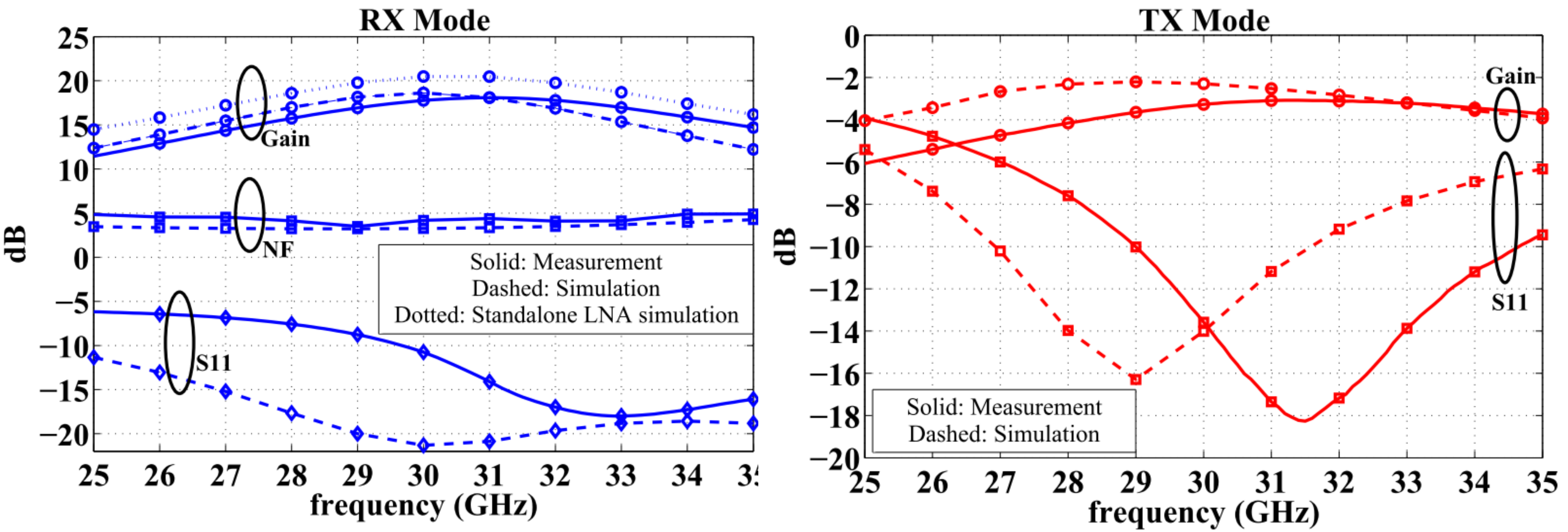
- Chip Implementation in 0.25 μm SiGe:C BiCMOS technology





Dual Antenna Hybrid-Transformer Duplexer

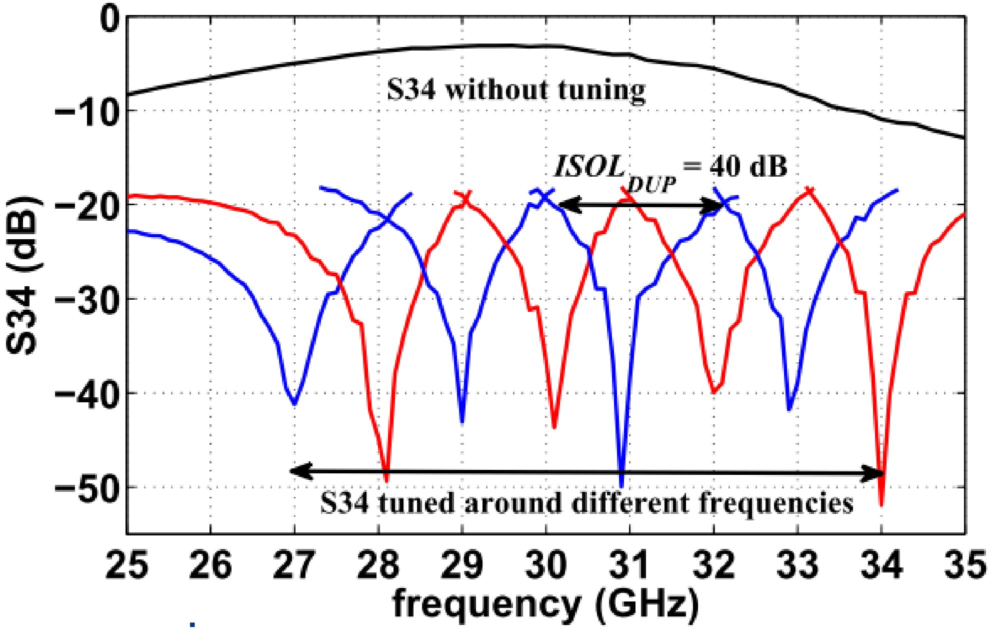
- **Chip Measurement, TX and RX modes.**



RX: Gain=<u>18 dB</u>, NF≈<u>4.1 dB</u>
TX: Loss=<u>3.1 dB</u> (including the balun)
BW_{3dB} from 27.5 GHz to 34.5 GHz

Dual Antenna Hybrid-Transformer Duplexer

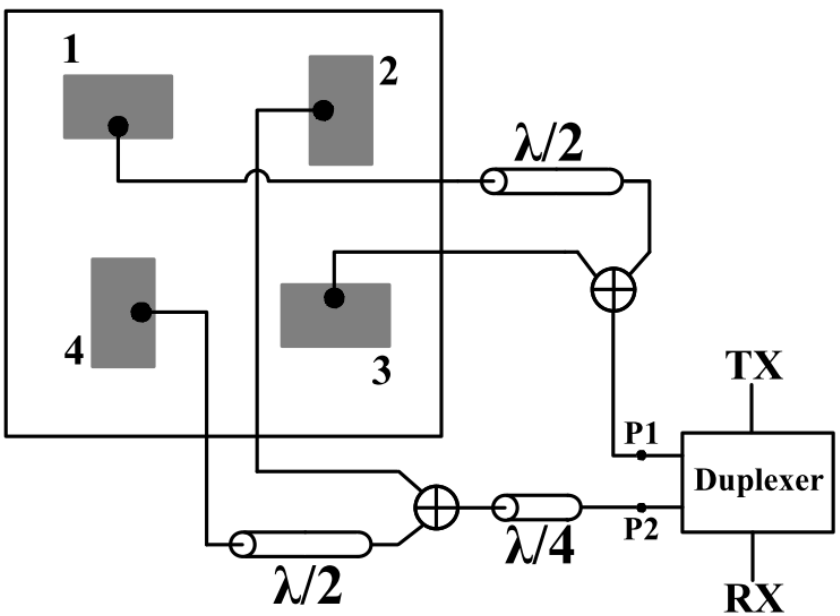
- **Chip Measurement, Isolation.**
- S34 includes gain of LNA (about 20 dB)

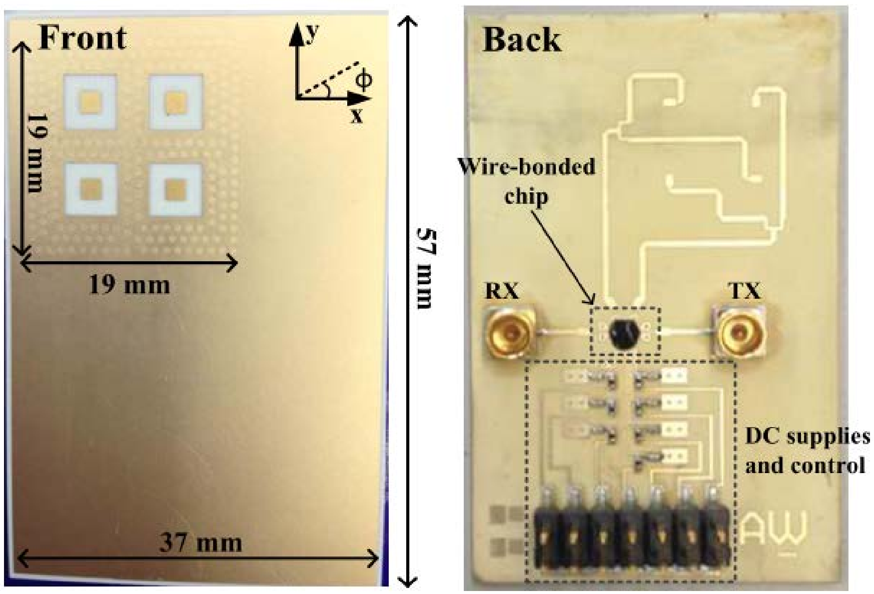


- Without tuning:
  - S34 = -3dB
  - Only 23dB isolation by the duplexer
  - Degraded by the layout non-idealities
- With tuning:
  - Notches tuned for different frequencies
  - S34<-20dB for about 2GHz BW, S34<-30dB for about 1GHz
  - Corresponding to duplexer isolation of 40dB and 50dB.

Dual Antenna Hybrid-Transformer Duplexer

- **Prototype Implementation**

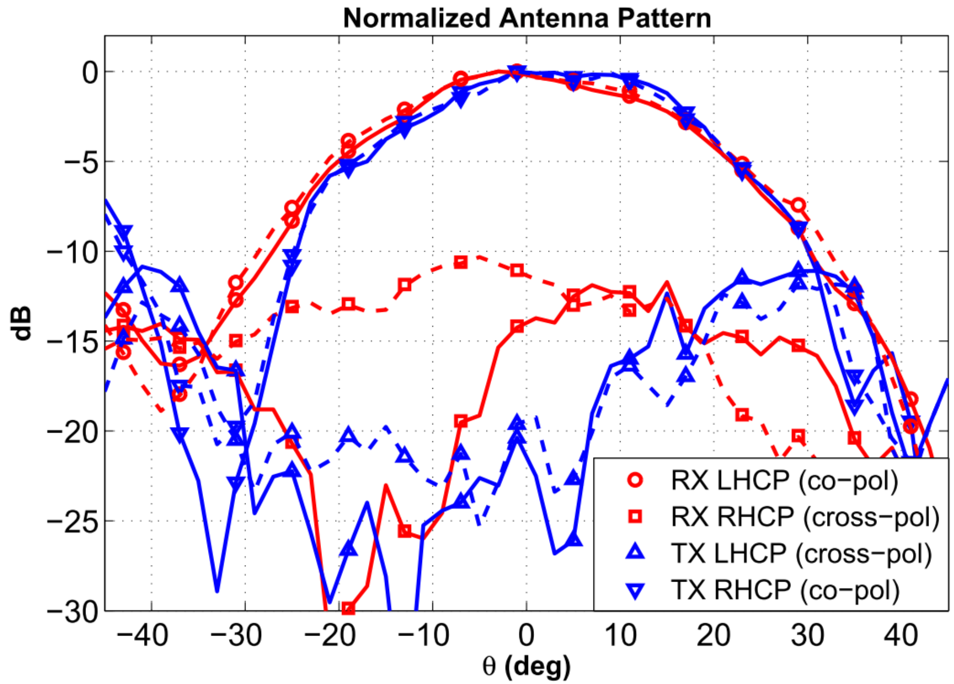




- On-board antennas are made and integrated with the duplexer chip.
- Sequentially rotated linearly-polarized patch antennas.

Dual Antenna Hybrid-Transformer Duplexer

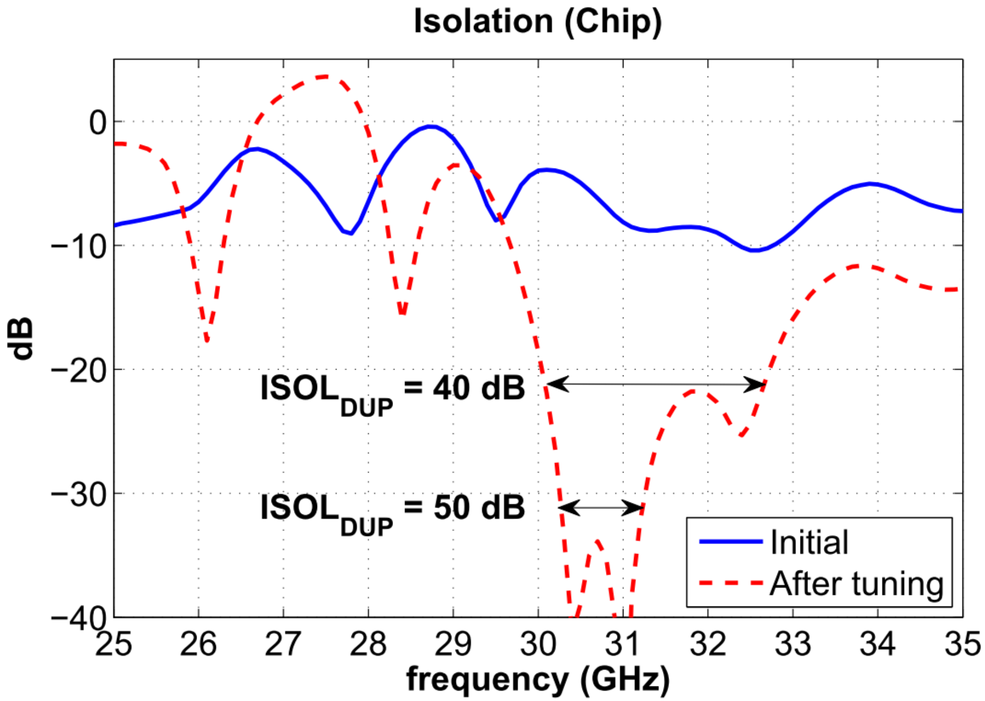
- **Prototype Measurement**



- **Antenna patterns.**
- **RX and TX patterns are orthogonal.**
- **Dashed lines are after tuning for high isolation.**
- **Minor impact on the co-pol of TX and RX.**

Dual Antenna Hybrid-Transformer Duplexer

- **Prototype Measurement**



- **The plotted isolations include the 20 dB gain from the LNA on-chip.**
- **High isolation achieved after tuning.**

Conclusions

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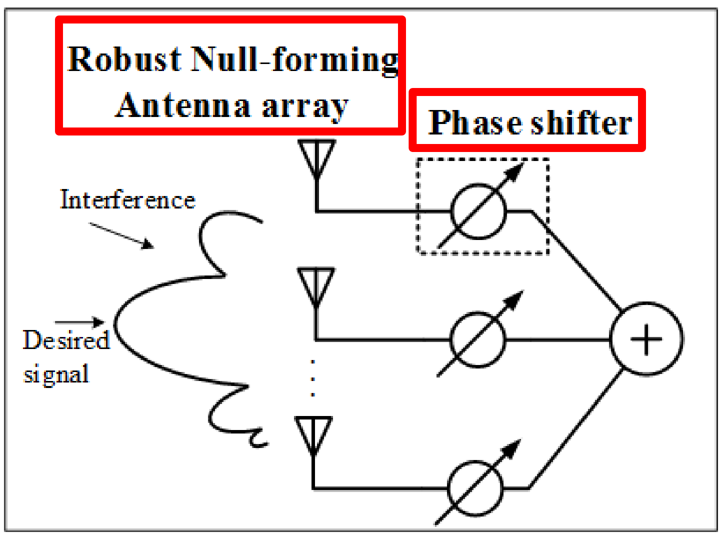
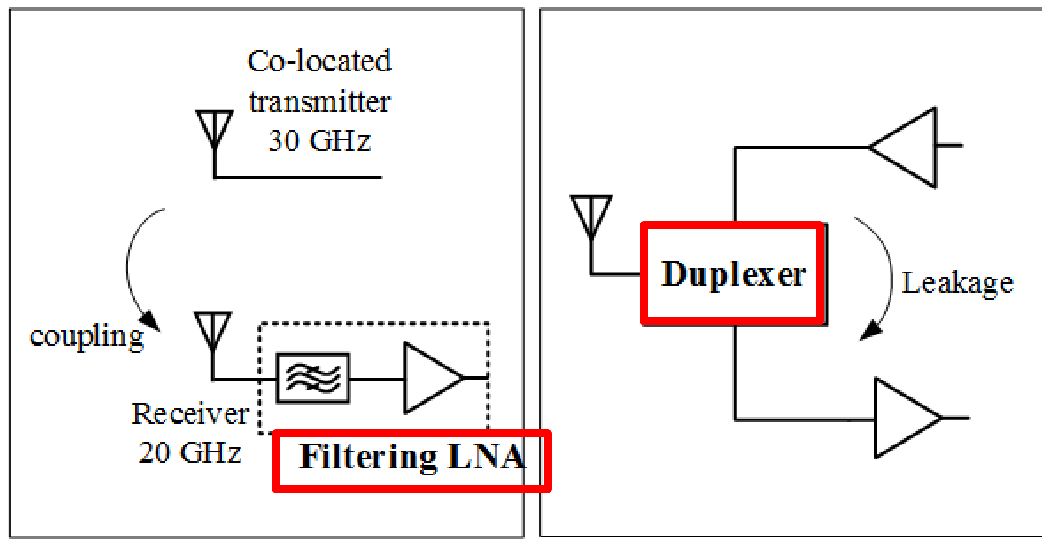
Spatial Interference



Self Interference

Different bands(VSAT scenario) Same band



Interference Suppression Techniques for Millimeter-Wave Integrated Receiver Front Ends

You are warmly welcomed to attend the defense at:

16:00 on 24th November 2015,

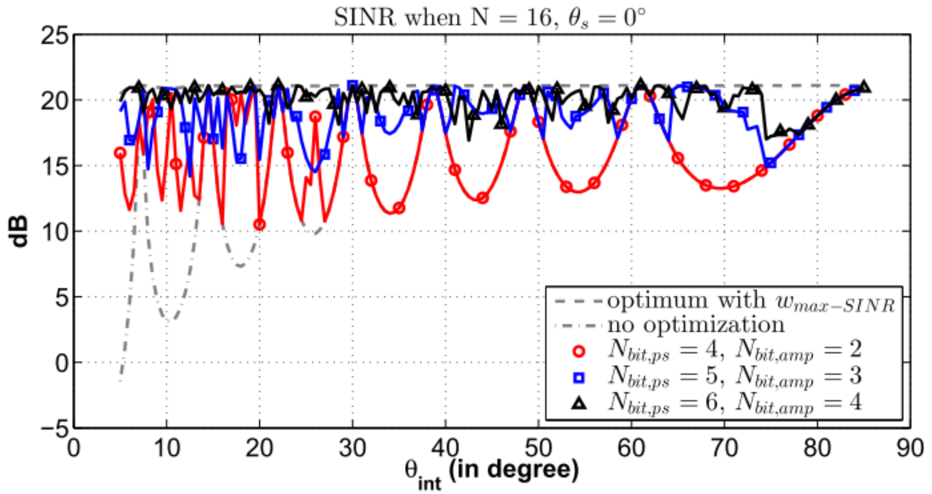
in Collegezaal 4, Auditorium in TU/e

and the reception afterwards.

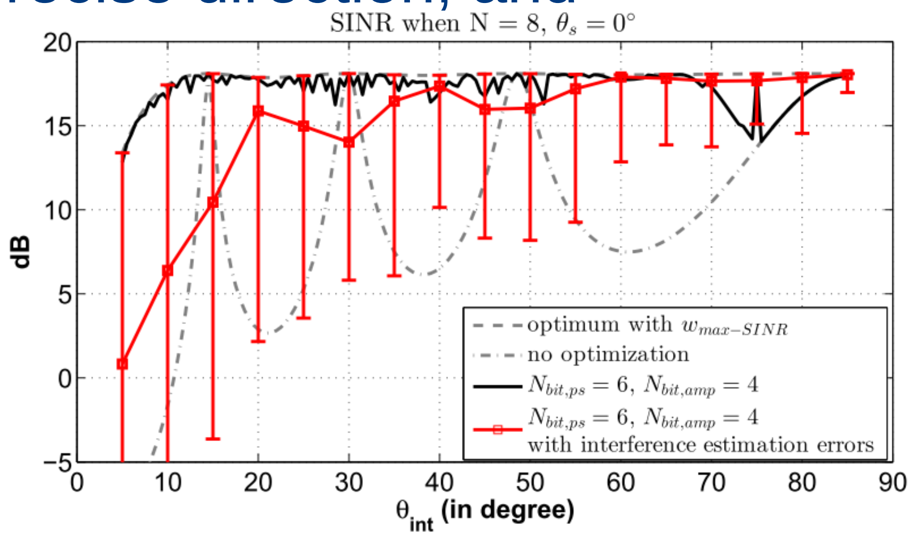
Thank you for your attention!

Appendix

- Limited accuracy



- Difficult to estimate precise direction, and create accurate null



Appendix

- Number of bits for the Null forming array

Table 2.3: The convergence of the algorithm and optimized SINR range by different number of LSBs. The interferences are assumed with power of -60 dBm and with AoAs of -10° and 26° for the 8-path ULA and -21° and 38° for the 8-path ULA.

Set #	Phase Shifter		VGA		8-path ULA		16-path ULA	
	MSB	LSB	MSB	LSB	Average # of iterations	SINR Range (dB)	Average # of iterations	SINR Range (dB)
1	4	1	1	1	>1000	16.7	>1000	17.3 to 18.2
2	4	1	2	1	>1000	7.9	>1000	15.1 to 15.3
3	4	1	1	2	207	16.8 to 17.7	420	20.3 to 20.8
4	4	2	1	1	205	17.4 to 17.7	105	20.3 to 20.8
5	4	2	2	1	>1000	10.1	>1000	19.4 to 19.7
6	4	2	1	2	30	17.4 to 17.8	47	20.3 to 20.8
7	4	3	1	1	140	17.2 to 17.7	48	20.3 to 20.8
8	4	3	1	2	26	17.4 to 17.8	34	20.3 to 20.8