RMo1A-4

Student Paper Finalist

A Blocker-Tolerant mm-Wave MIMO Receiver with Spatial Notch Filtering Using Non-Reciprocal Phase-Shifters for 5G Applications

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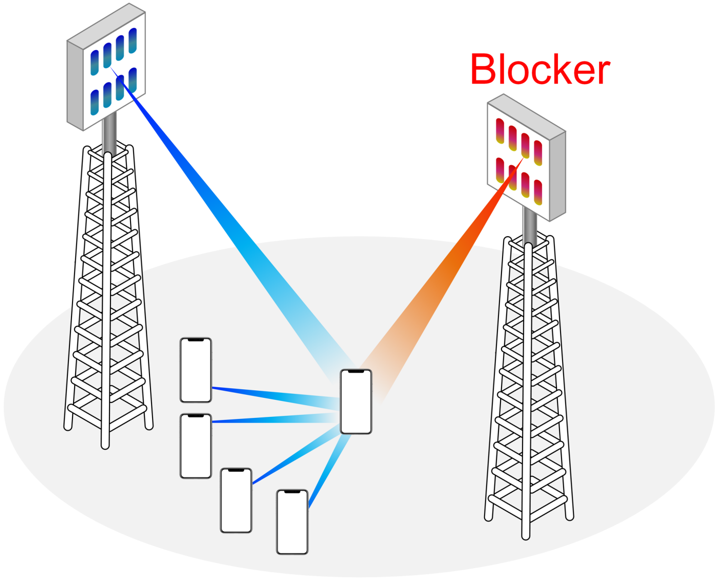
Radius Lab, Massachusetts Institute of Technology

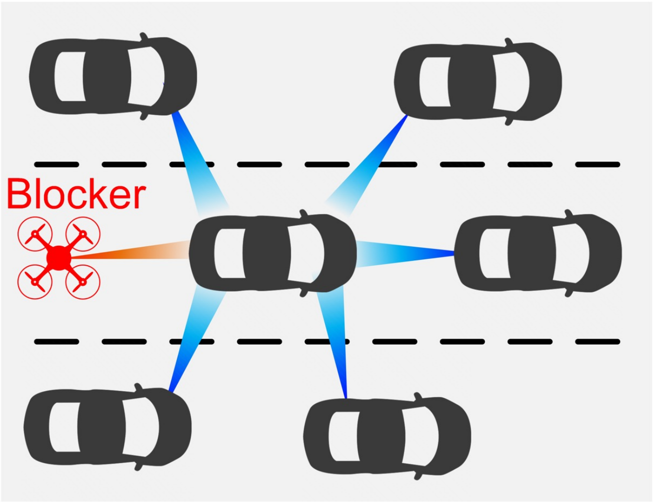
Outline

- Motivation and Introduction
- Proposed RX Architecture with Spatial Notch Filter
- Proposed Non-Reciprocal Phase-Shifter
- Implementation
- Measurement Results
- Conclusion

Motivation

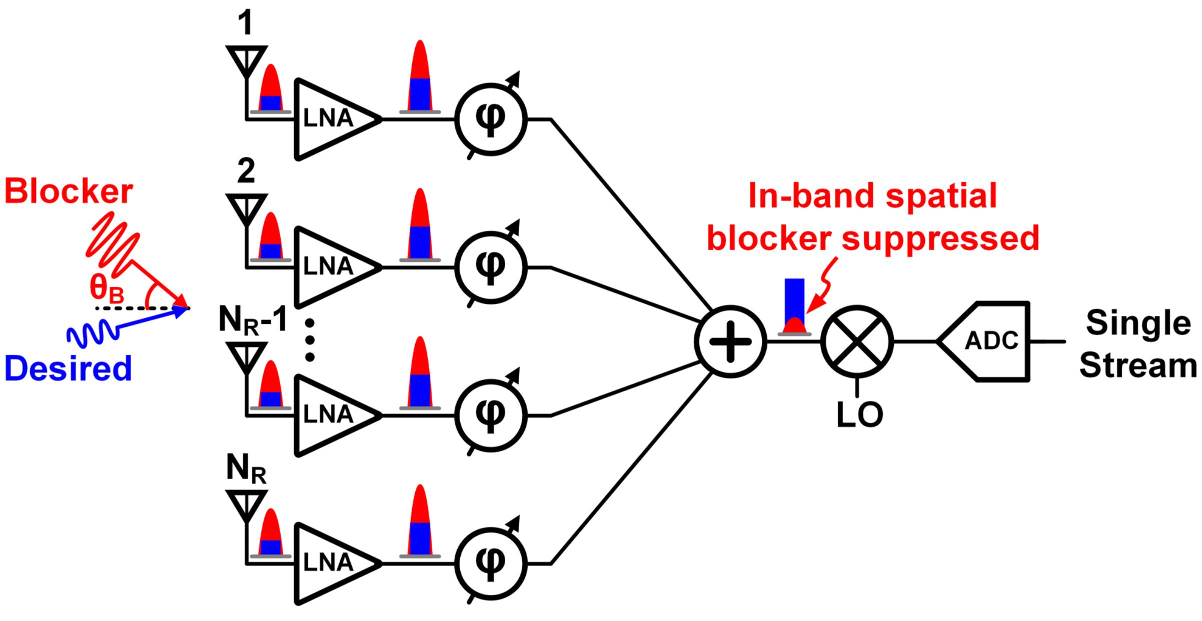
- mm-Wave Transceiver
  - High RF bandwidth
  - On-chip beamforming
  - Spatial multiplexing
- Application
  - 5G New Radio
  - Automotive radar
  - Satellite communication





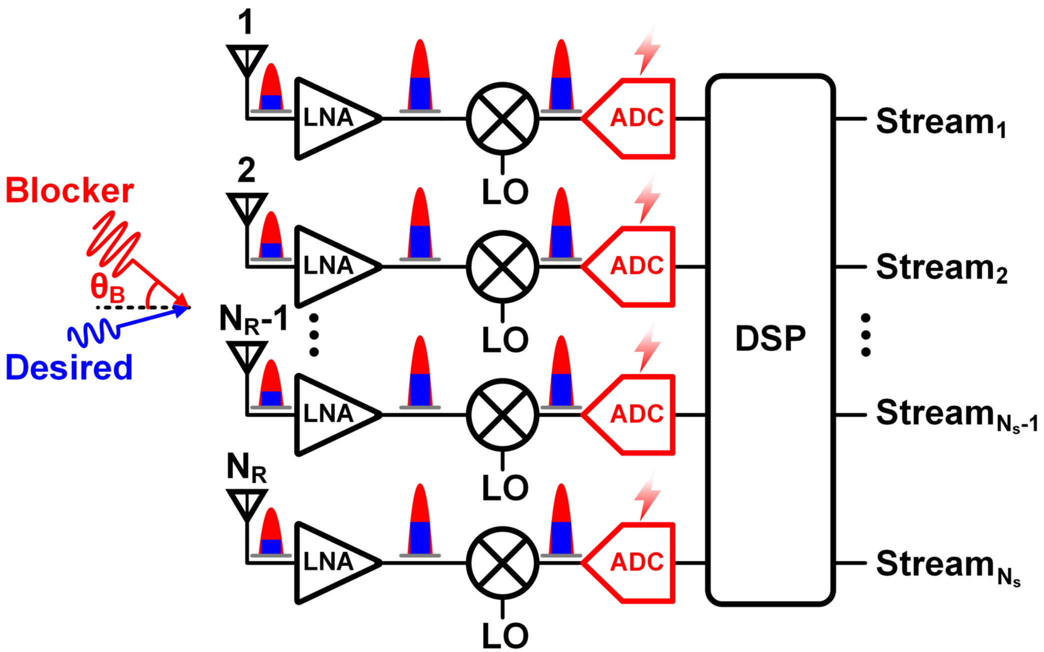
Beamforming RX Structures

Analog Beamforming



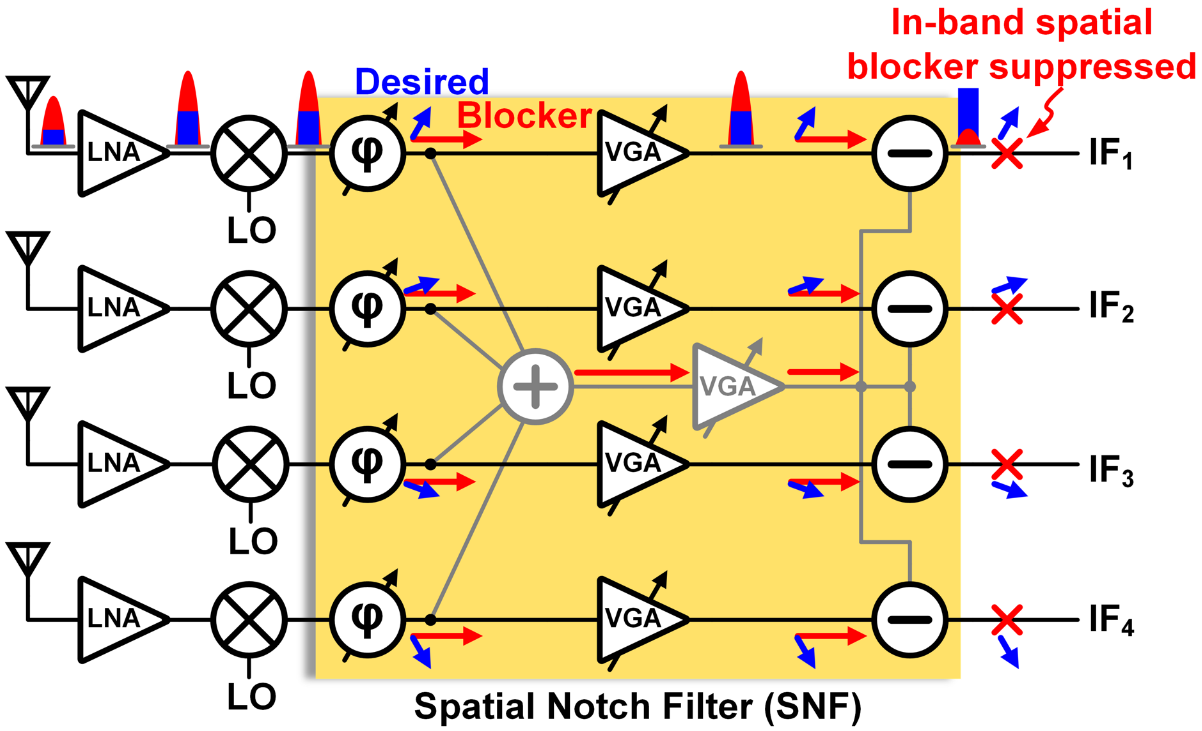
In-band spatial blocker suppressed

Digital Beamforming



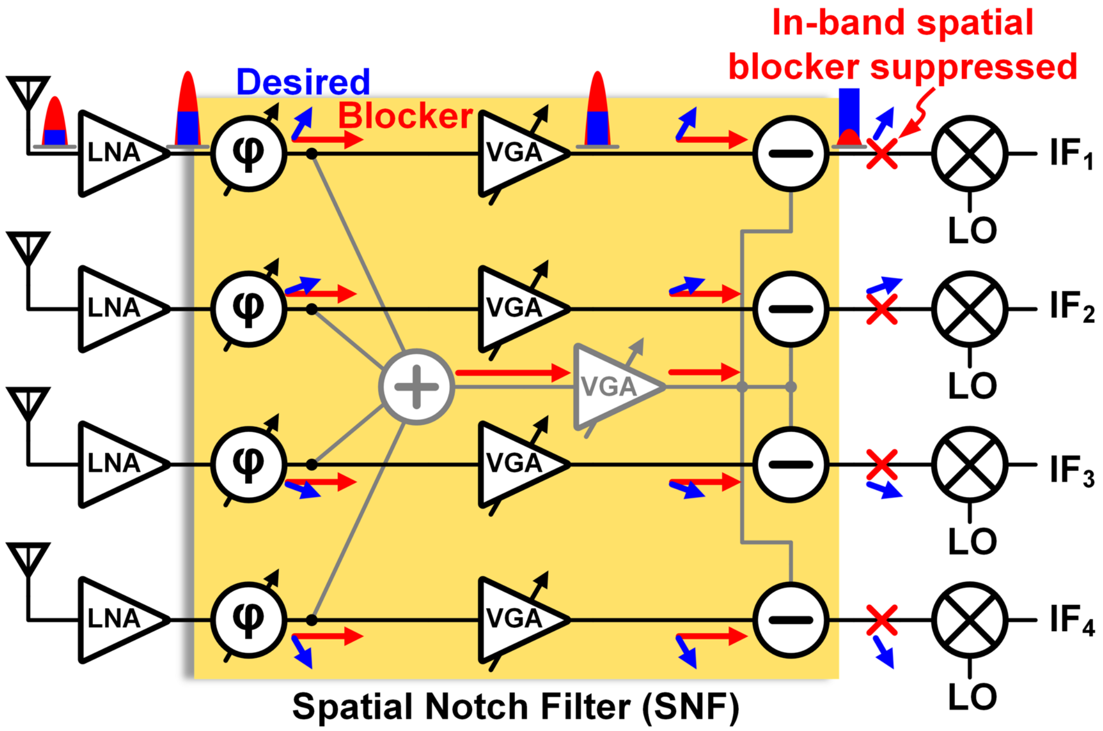
	Analog Beamformer	Digital Beamformer
Support Multiple Streams	✗ No	✓ Yes
Power Consumption	✓ Low	✗ High
Resistant to Spatial Blockers	✓ Yes	✗ No

mm-Wave RX with SNF



Spatial Notch Filter (SNF)

[M. Huang, JSSC '19]



Spatial Notch Filter (SNF)

[M. Huang, TMTT '18]

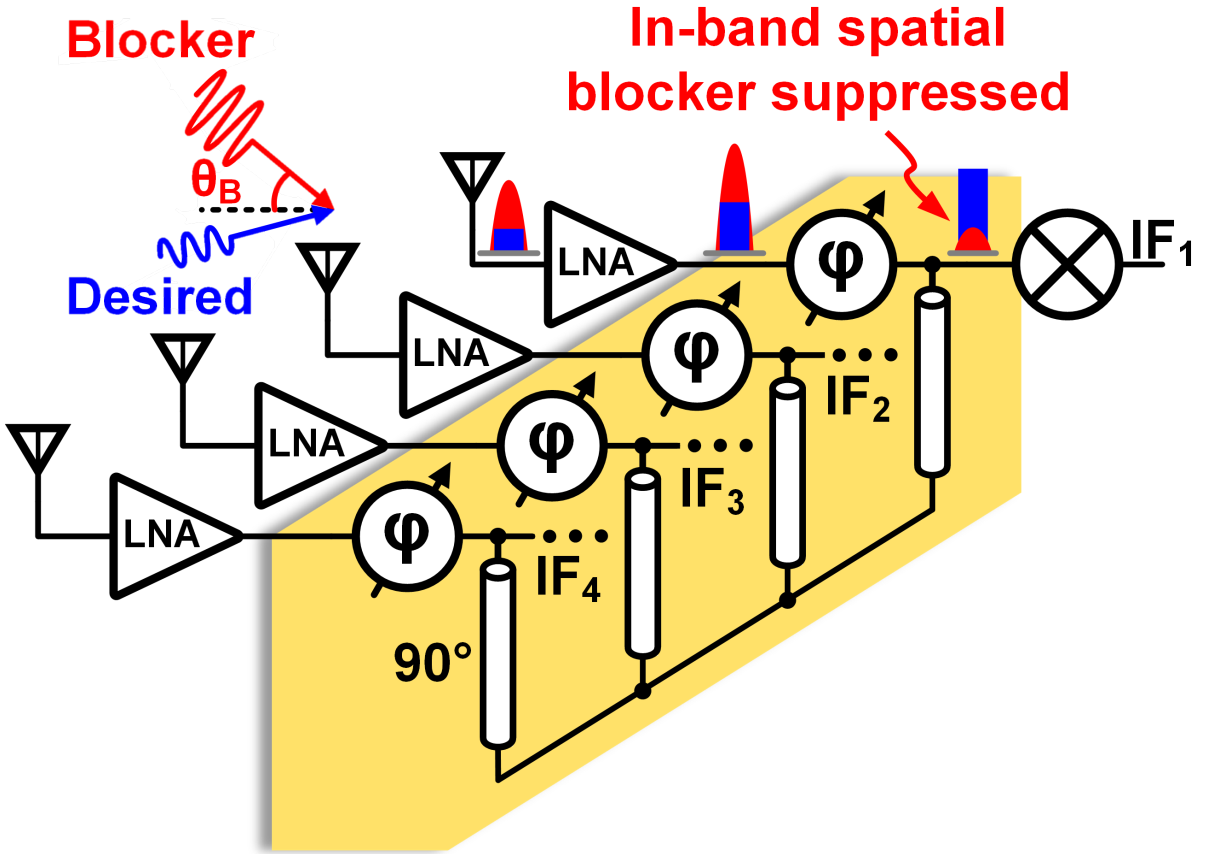
	M. Huang, JSSC '19	**M. Huang, TMTT '18**
Blocker Suppression Frequency	✗ IF	✓ mm-Wave
Power Consumption	✗ High	✗ High
Susceptible to Spatial Blockers	✗ LNAs, Mixers, PSs and VGAs	✗ LNAs, PSs and VGAs

mm-Wave RX with SNF

✓ Spatial notch filtering at the output of PSs.

× Amplified spatial blockers appear at the LNA outputs limiting the in-notch P_{1dB}.

× PS inputs are susceptible to amplified spatial blockers.



Spatial Notch Filter [L. Zhang, ISSCC '22]

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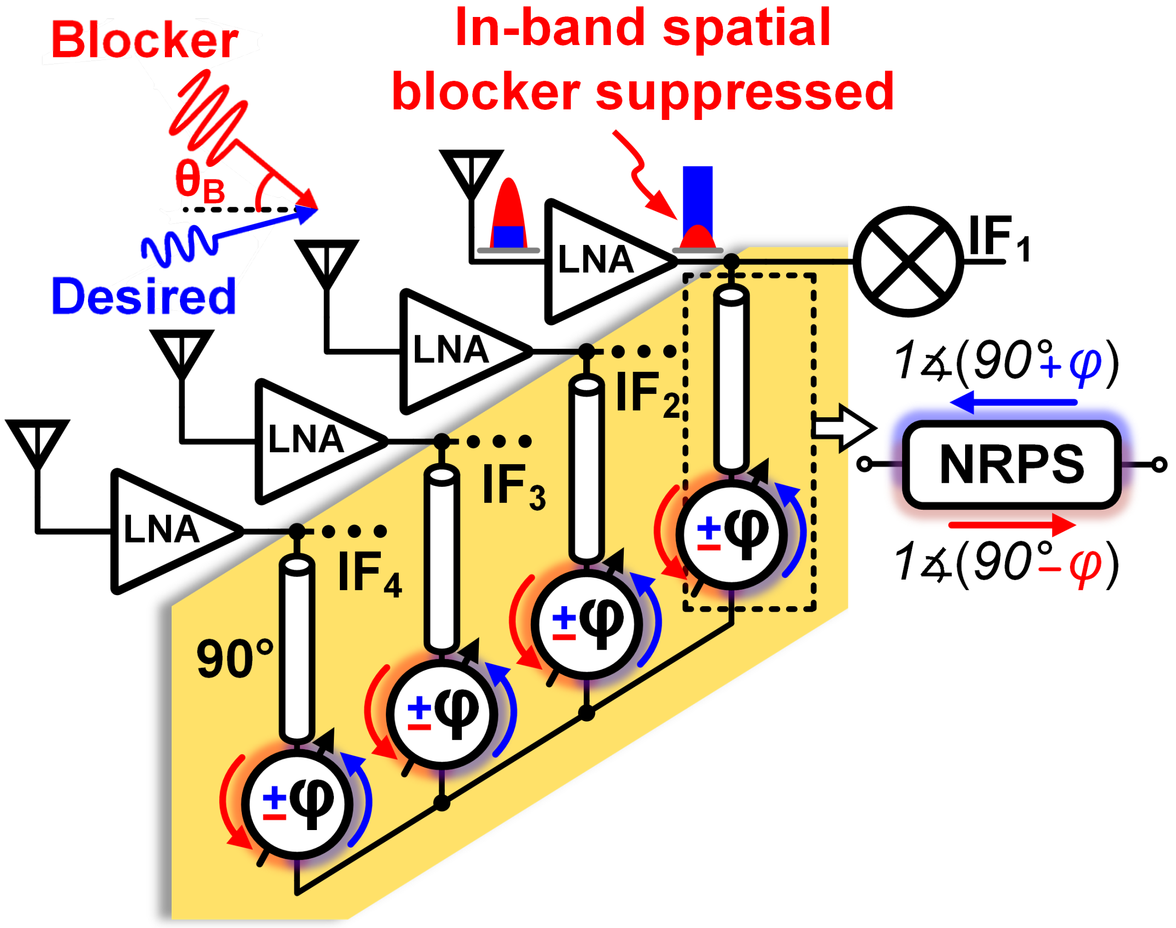
Proposed Architecture

- Support MIMO
- **Blocker-resilient** due to the spatial filtering
- **Highly-linear** due to the blocker cancellation at the **output of LNAs**
- SNF can be turned off in the absence of blockers, reducing the number of components in the **main path**.



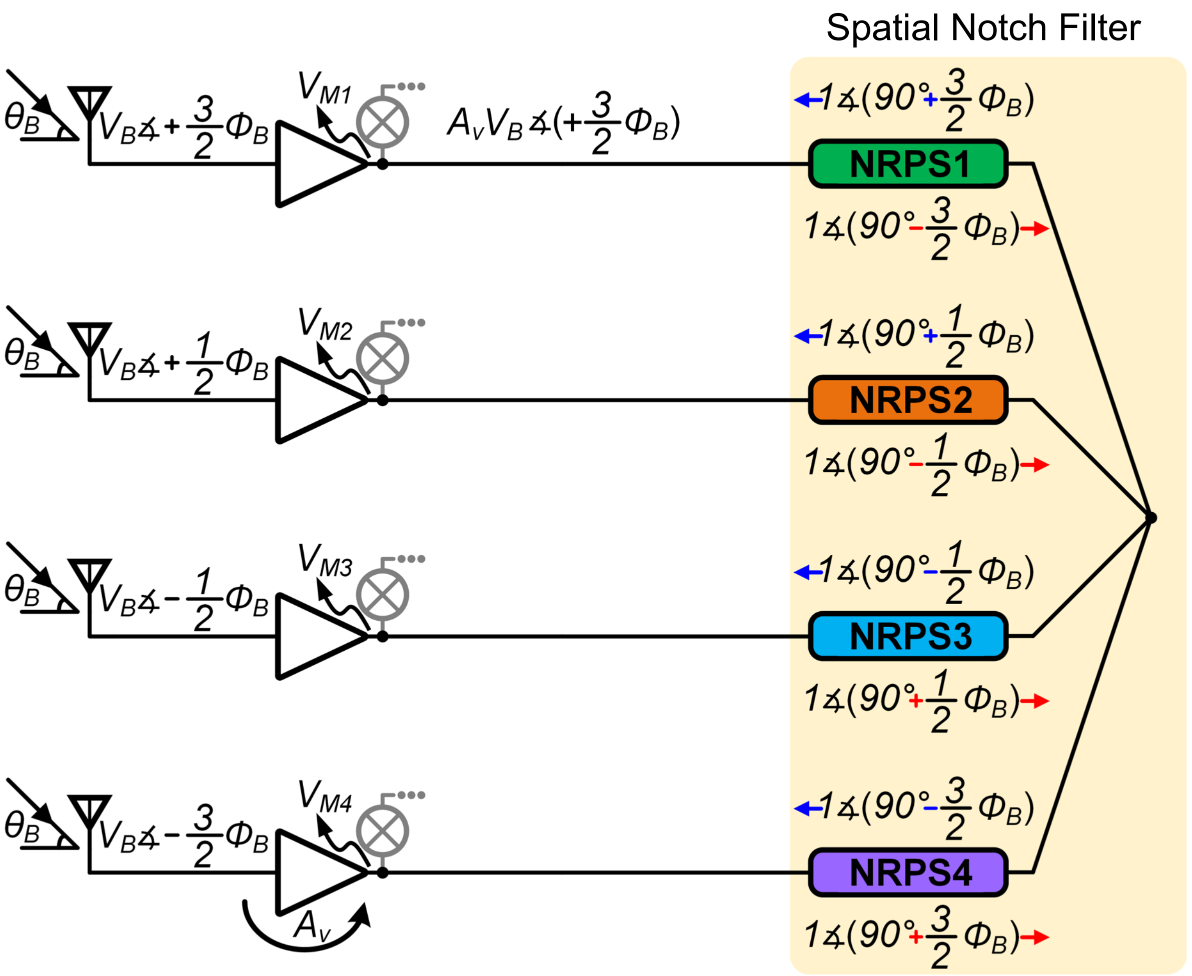
Proposed Spatial Notch Filter

Blocker-Cancellation Operation

- Antennas are spaced by $\frac{\lambda}{2}$.
- θ_B : Incident angle
- φ_B : Phase difference

- Relative phase is used

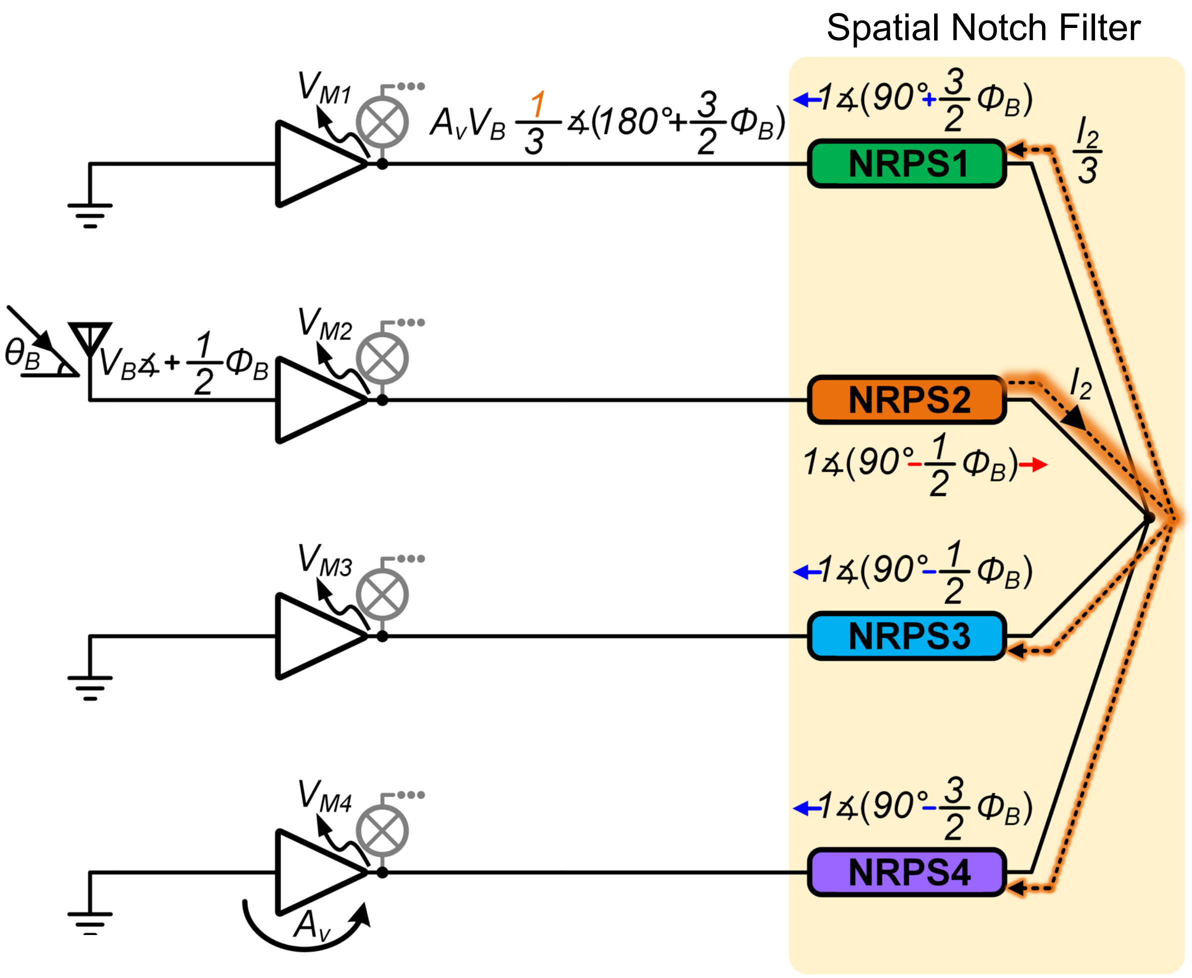
$$\boxed{\Phi_B=\pi \sin(\theta_B)}$$



Blocker-Cancellation Operation

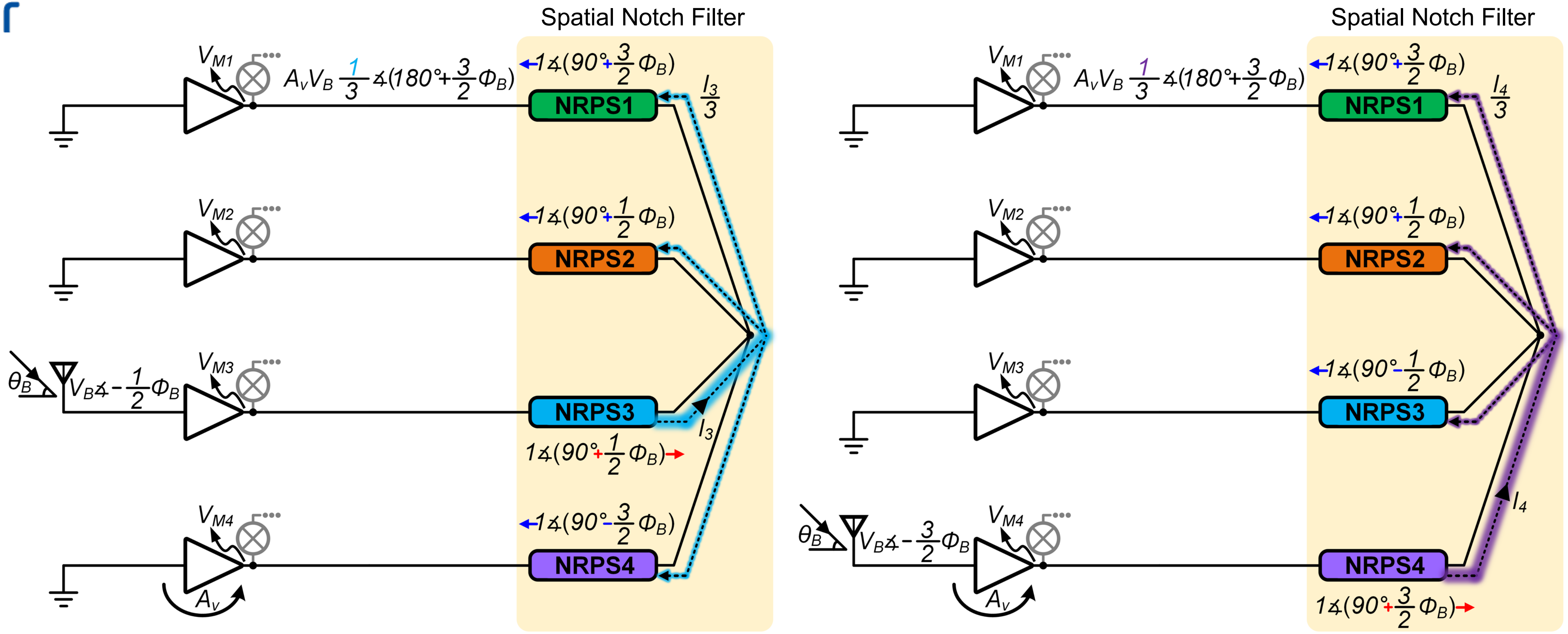
- The first and second phase shifters rotate the phase of the second input signal by $\phi_B + 180°$.
- Voltage contribution of the second input signal at the first LNA output:

$$\frac{1}{3}A_V V_B \measuredangle\left(\frac{1}{2}\phi_B + 90° - \frac{1}{2}\phi_B + 90° + \frac{3}{2}\phi_B\right)$$



Superposition of incoming signals

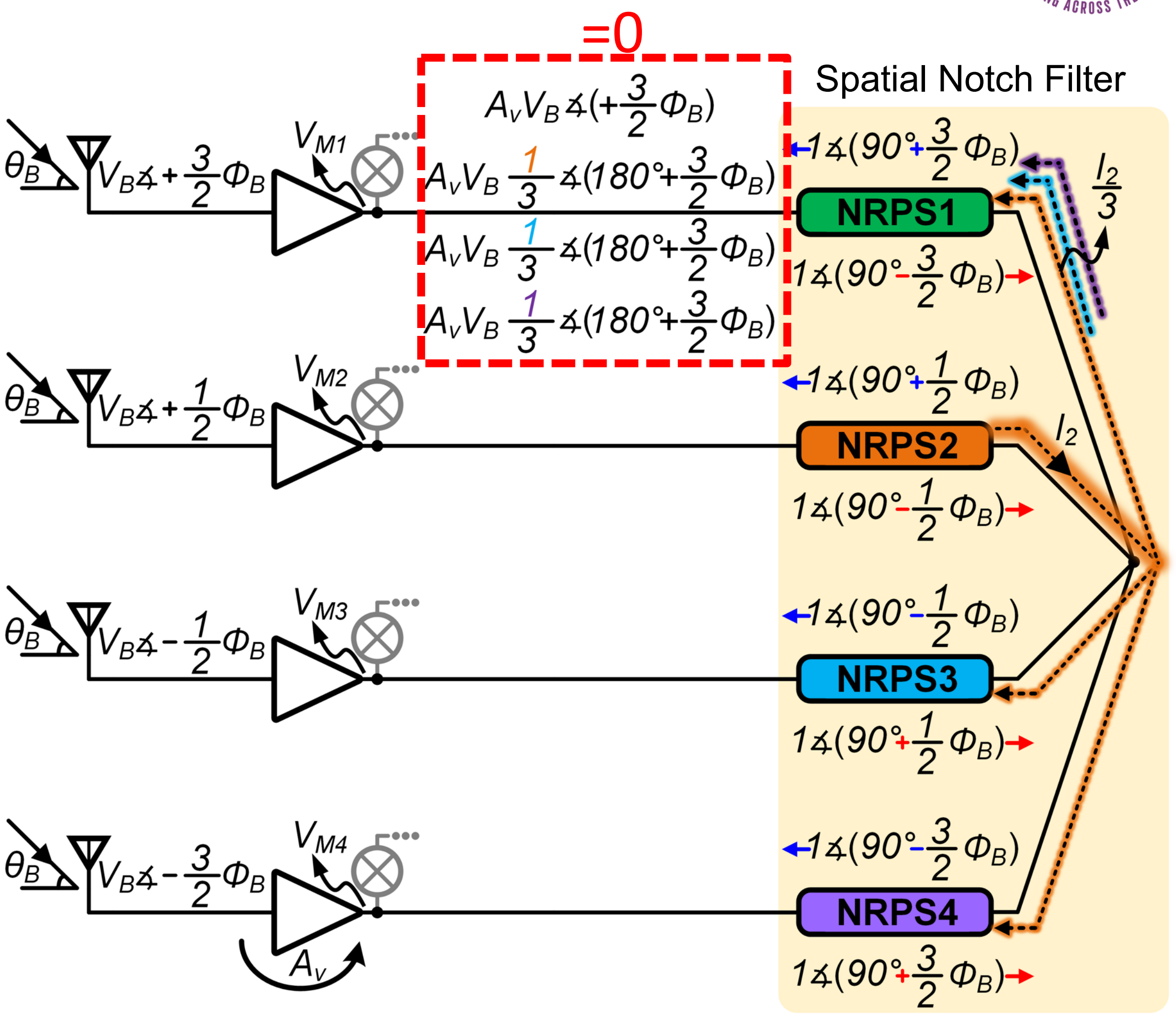
Blocker-Cancellation Operation



Superposition of incoming signals

Blocker-Cancellation Operation

- Blockers **cancelled** at LNA outputs.
- Requires **lossless non-reciprocal** phase-shifters.
  - Lossy PSs result in partial spatial blocker cancellation



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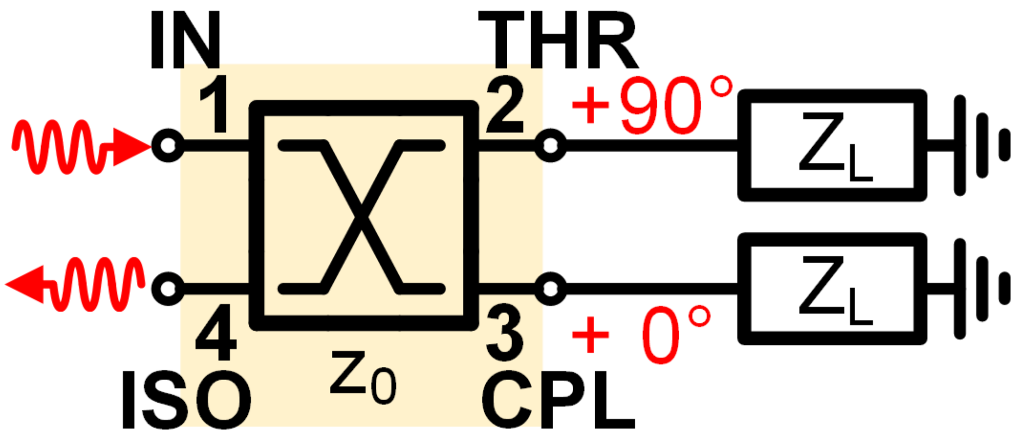
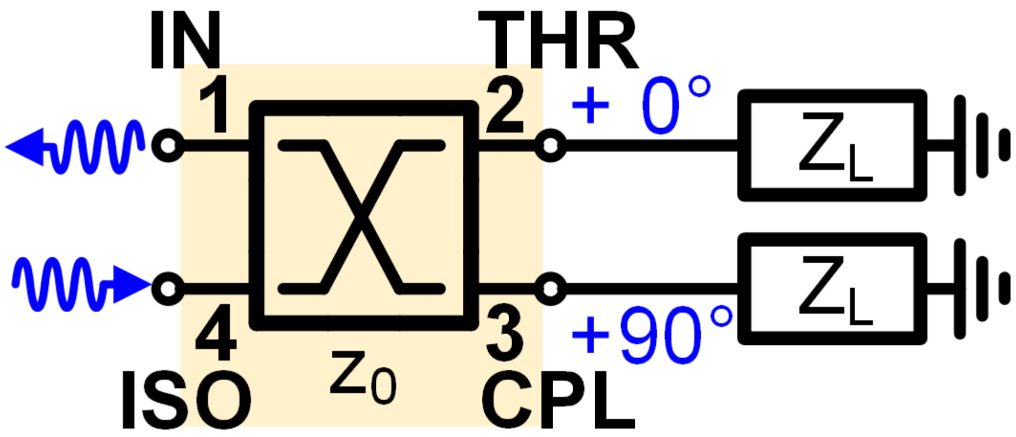
Quadrature Hybrid



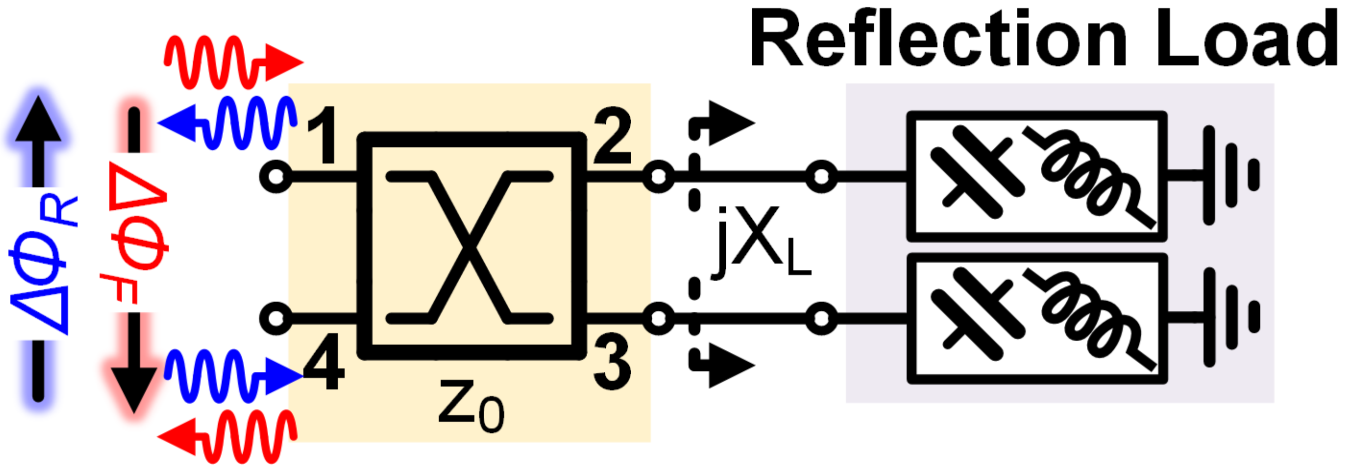


$\phi_2 - \phi_3 = +90°$

$\phi_2 - \phi_3 = -90°$

Depending on the excitation port, either the IN or ISO port, the phase difference between THR and CPL ports is different.

Reflection-Type Phase-Shifter



$$\Delta\phi_F = \Delta\phi_R = 90^\circ + 2\tan^{-1}\left(\frac{Z_0}{X_L}\right)$$

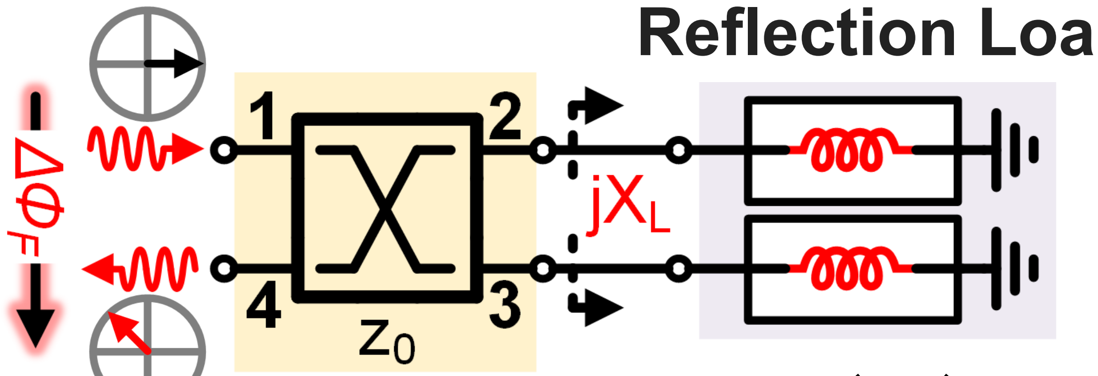
X_L: Reactance of the load

An RTPS provides a reciprocal phase-shift with a value dependent on the imaginary load.

Non-Reciprocal Phase-Shifter

Goal

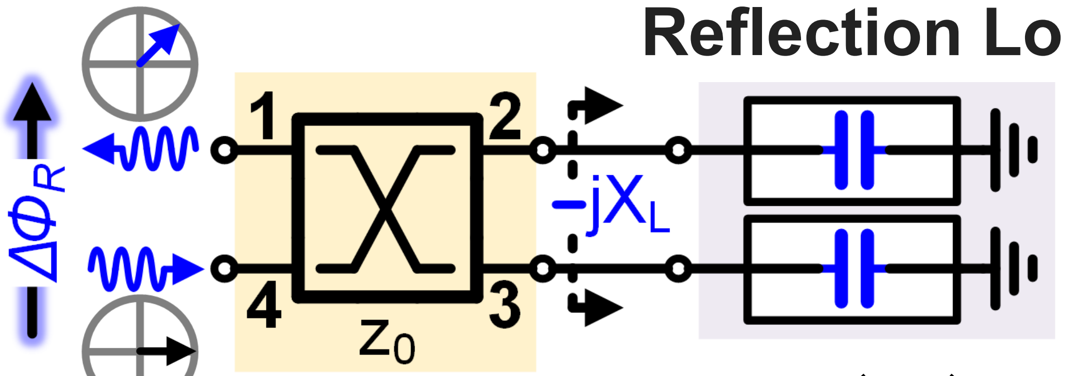
Inductive Reflection Load



$$\Delta\phi_F = 90° + 2\tan^{-1}\left(\frac{Z_0}{X_L}\right)$$

Forward Path

Capacitive Reflection Load

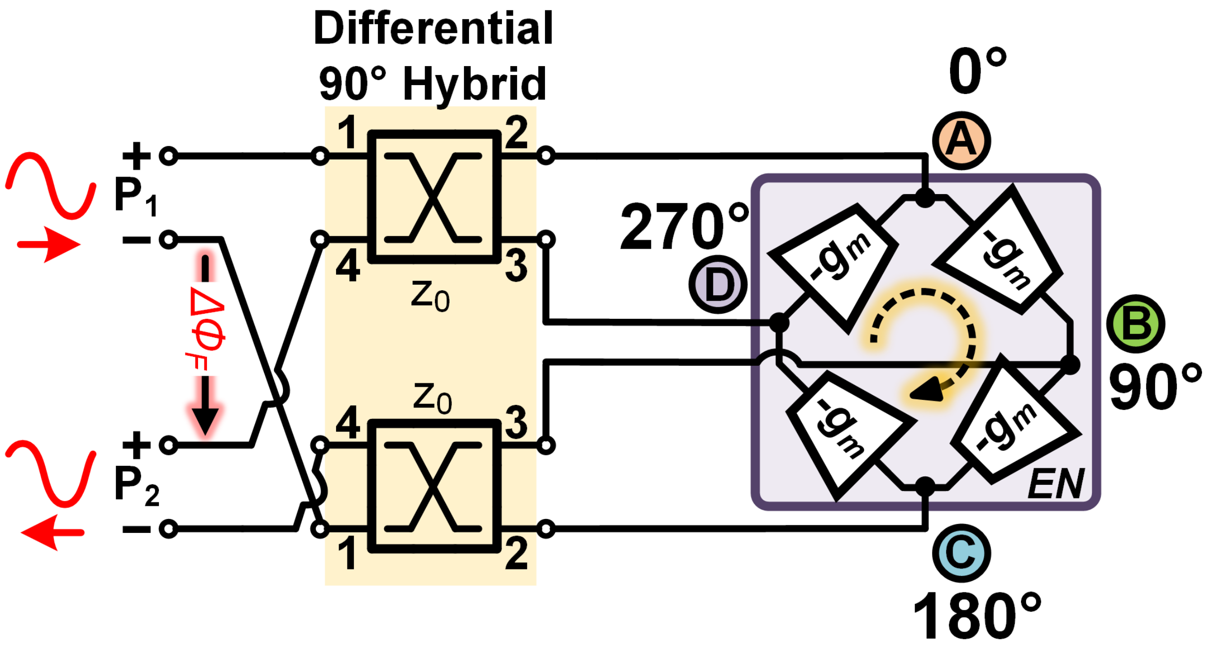


$$\Delta\phi_R = 90° - 2\tan^{-1}\left(\frac{Z_0}{X_L}\right)$$

Reverse Path

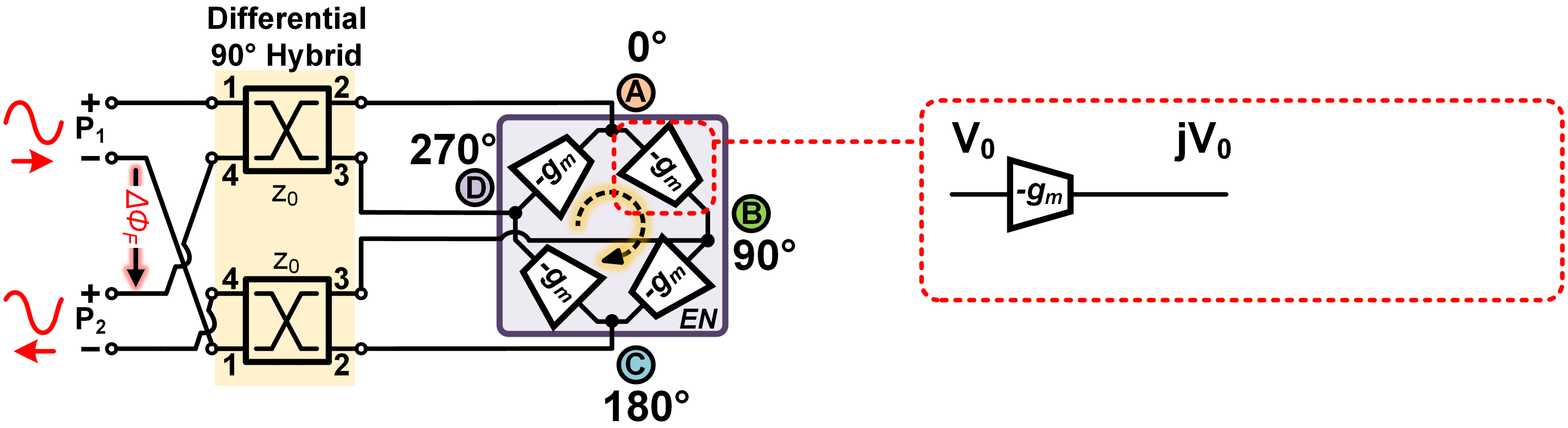
Can we make an NRPS by using a load dependent on the direction of the incoming signal?

Forward Phase-Shift

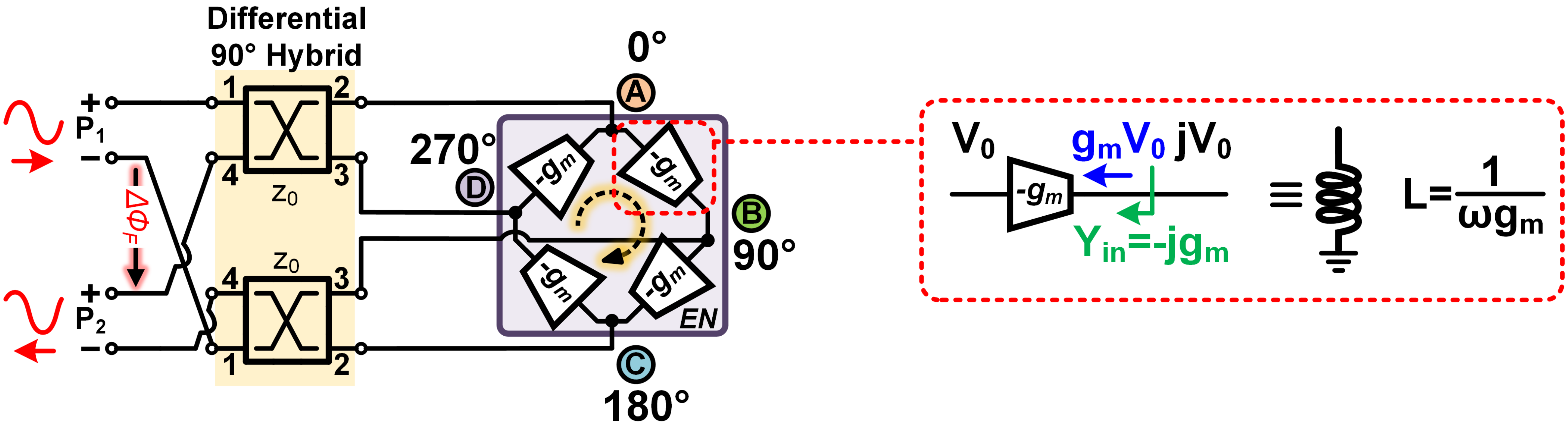


Applying an input signal to P_1.

Forward Phase-Shift

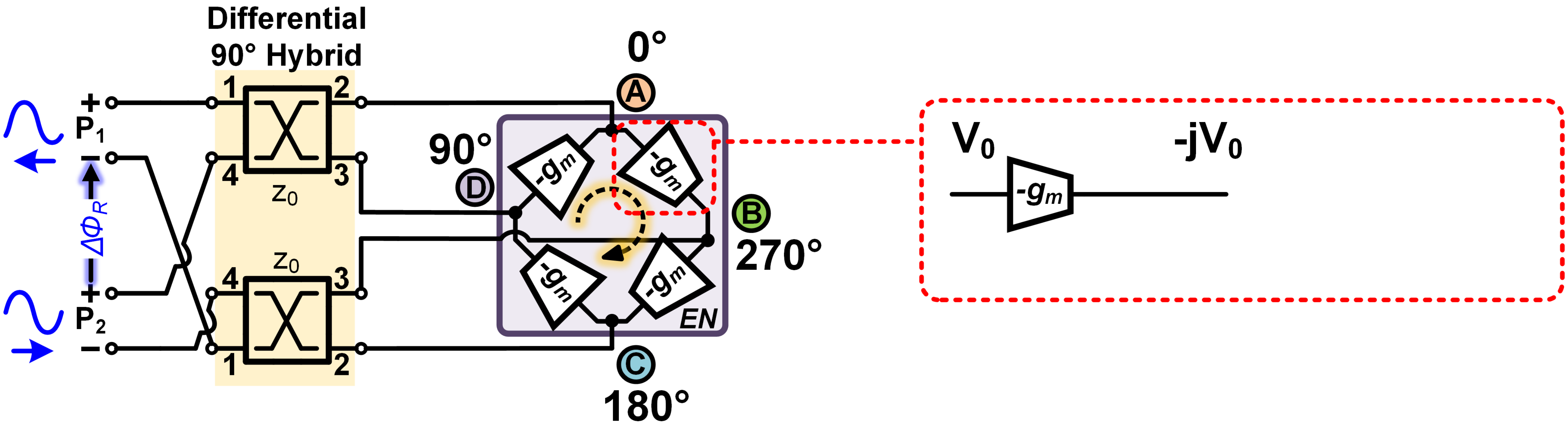


Forward Phase-Shift



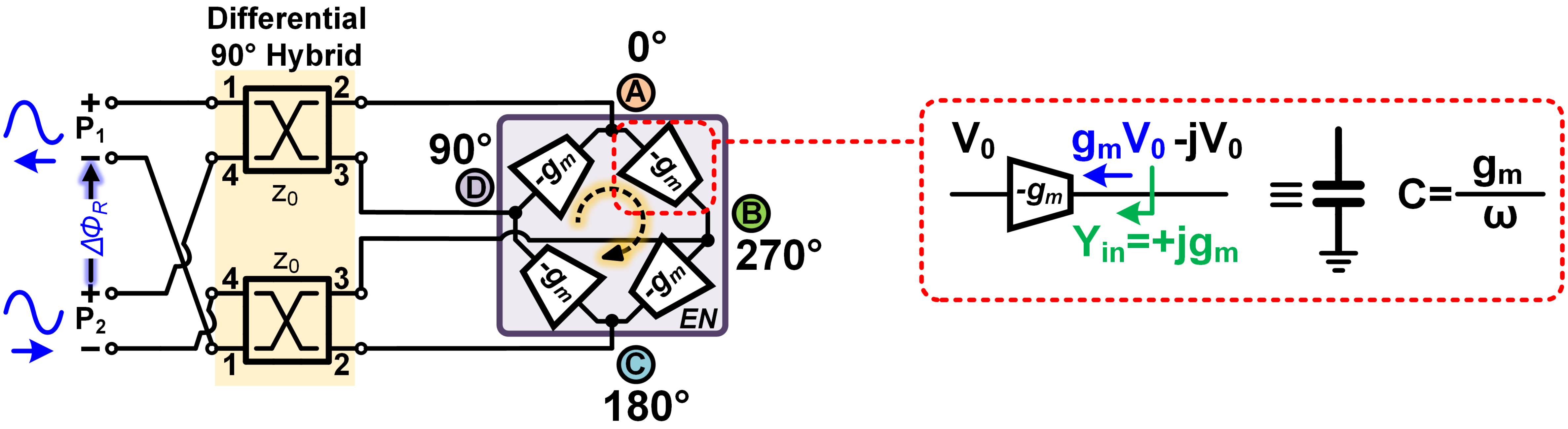
$$\Delta\phi_F = 90° + 2\tan^{-1}(z_0 g_m)$$

Reverse Phase-Shift



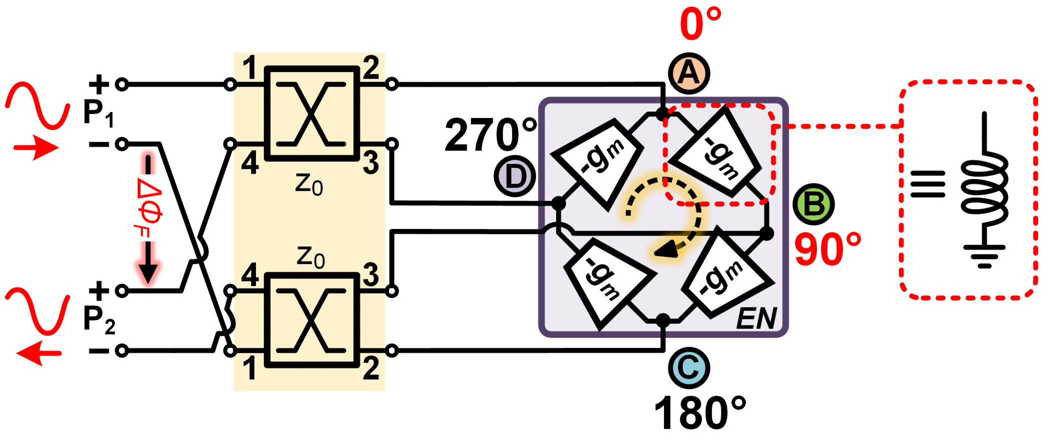
Applying an input signal to P_2.

Reverse Phase-Shift

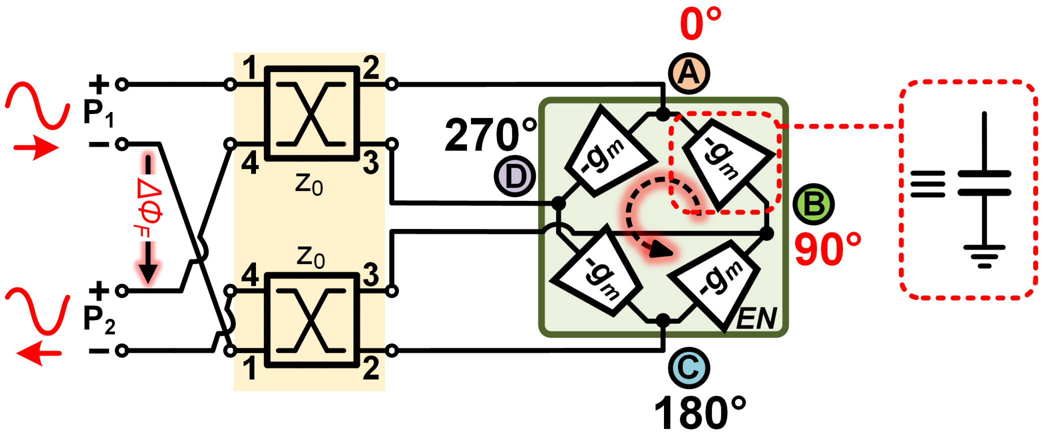


$$\Delta\phi_R = 90° - 2\tan^{-1}(z_0 g_m)$$

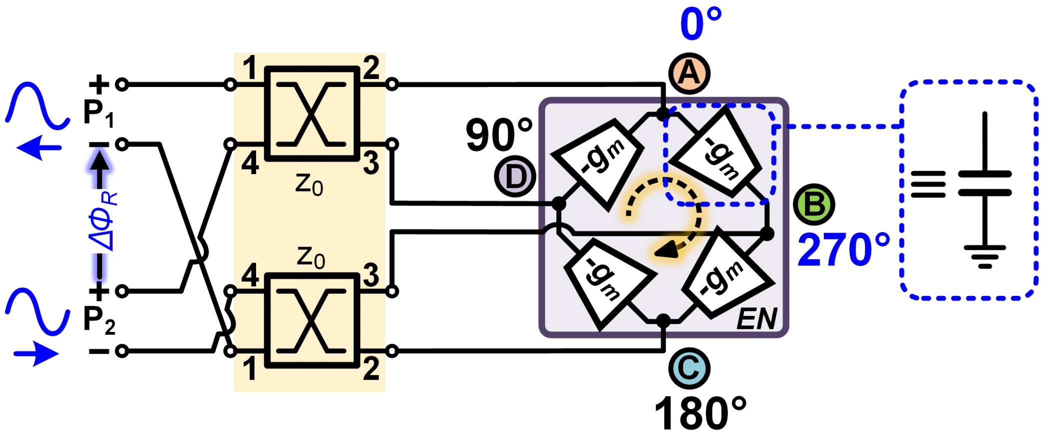
Non-Reciprocal Phase-Shifter



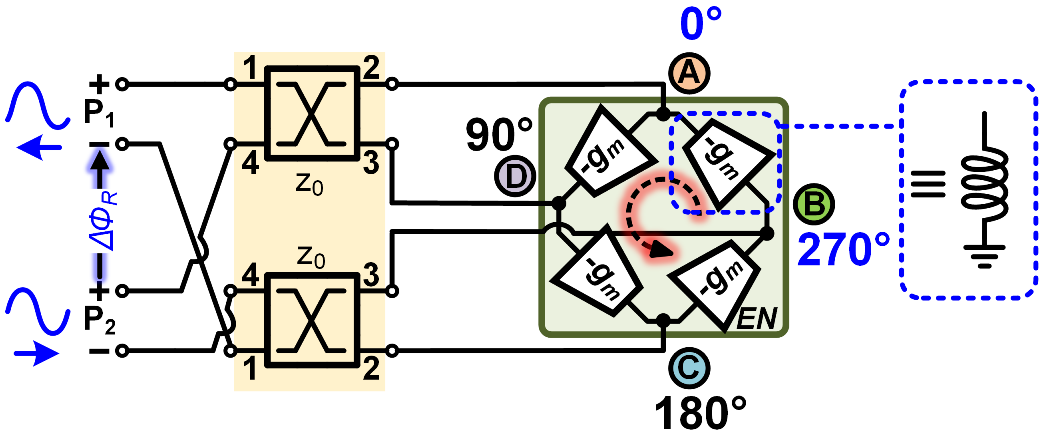
$\Delta\phi_F \geq 90°$



$\Delta\phi_F \leq 90°$



$\Delta\phi_R \leq 90°$



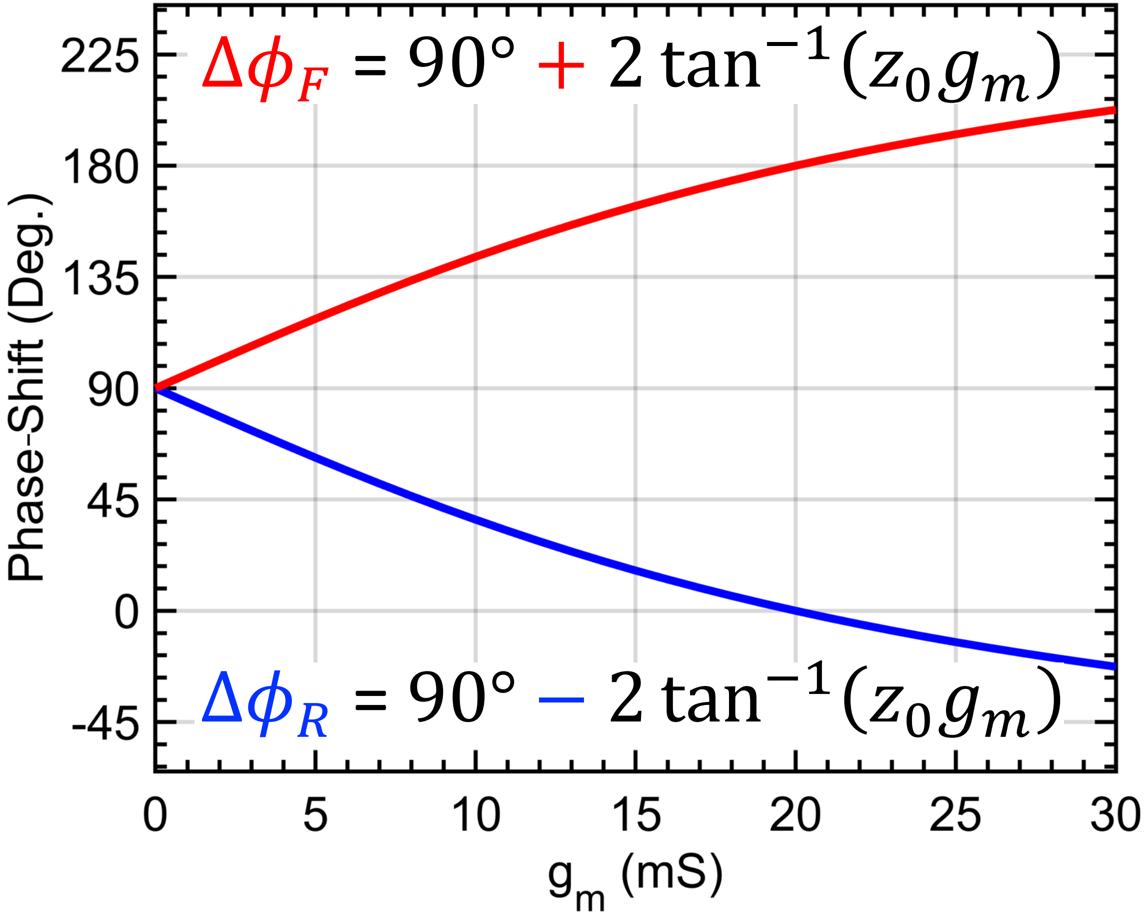
$\Delta\phi_R \geq 90°$

Non-Reciprocal Phase-Shifter

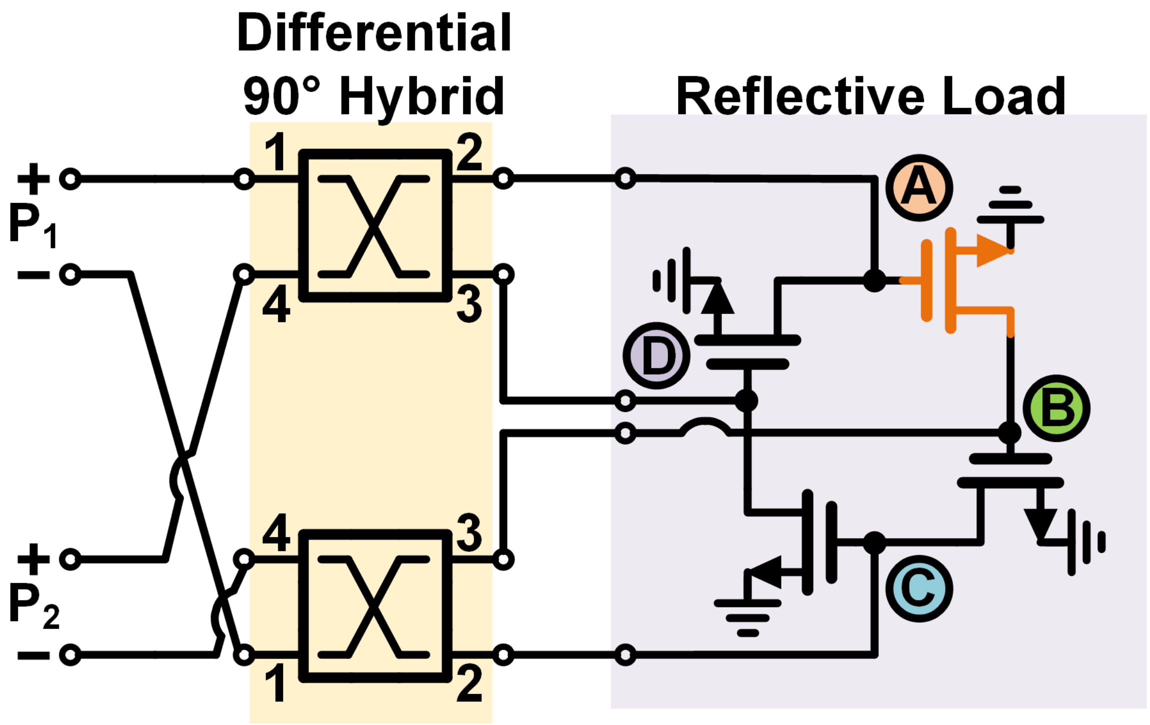
NRPS	Dinc, JSSC17	This Work
Freq. Range [GHz]	23 to 27	**27 to 31**
Tunable	No	**Yes**
Area [mm^2]	1.3[1]	**0.21**
Power [mW]	78	**<14**
IL [dB]	-4.5[2]	**-0.8 to 0**[2]

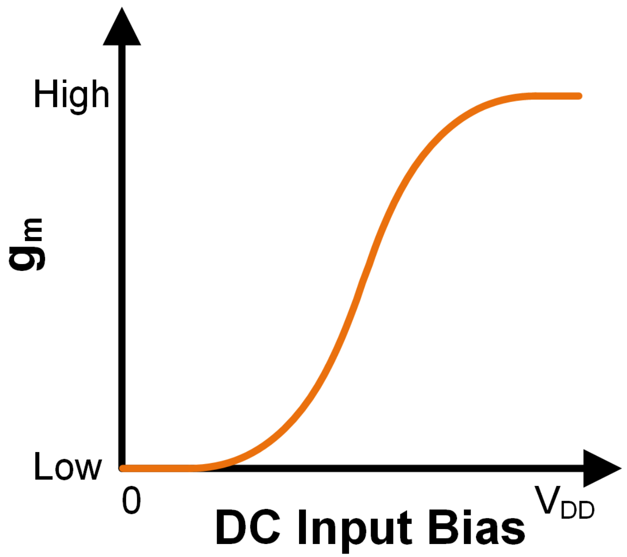
[1] Estimated from figures.

[2] From simulation.



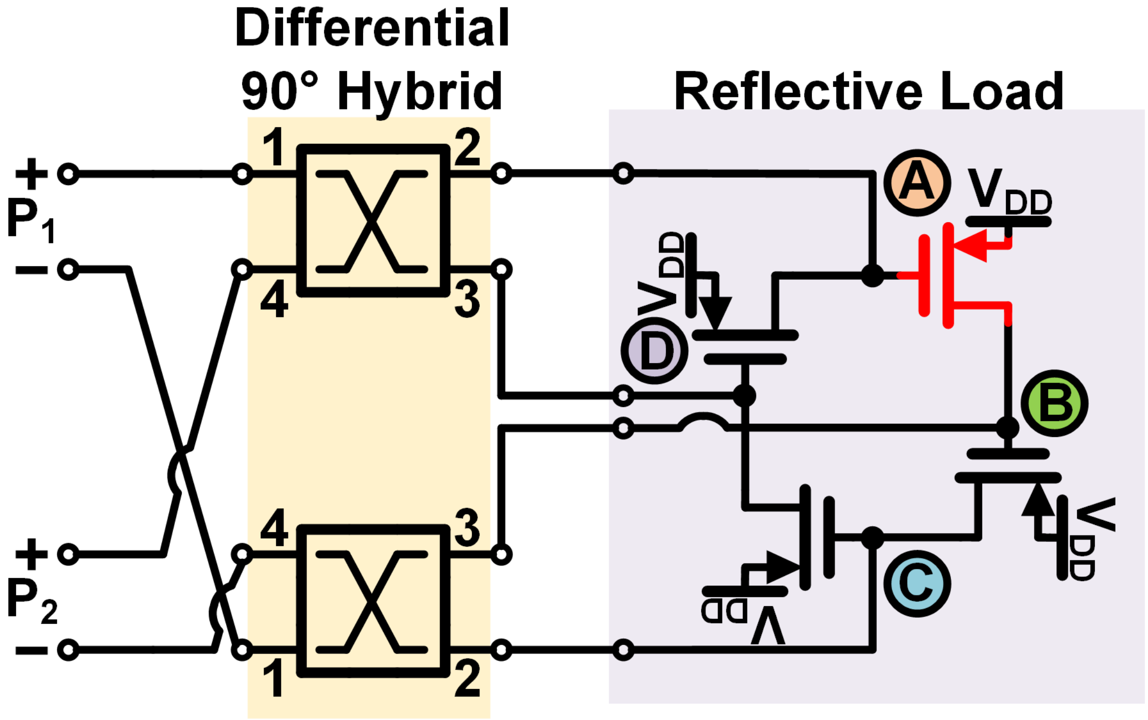
Inverter-Based Phase-Shifter

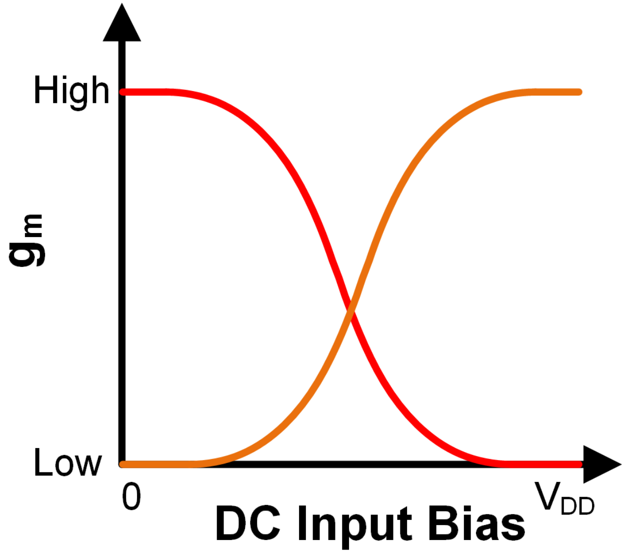




[D. Murphy, JSSC 2012]

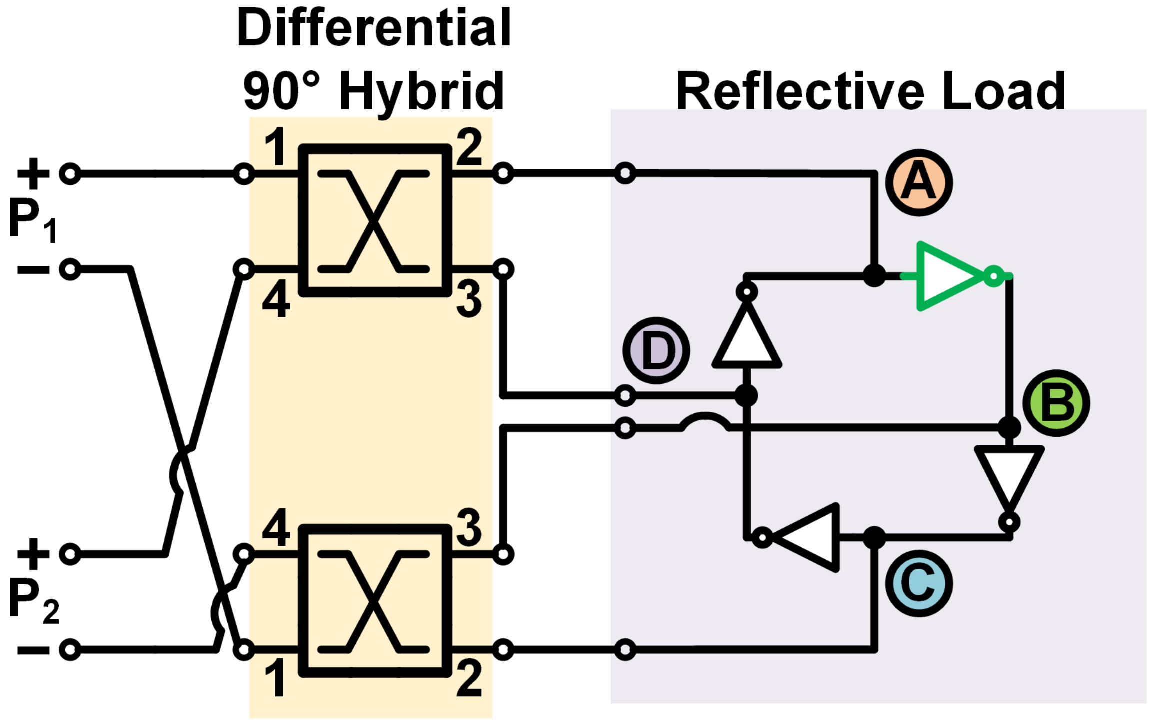
Inverter-Based Phase-Shifter

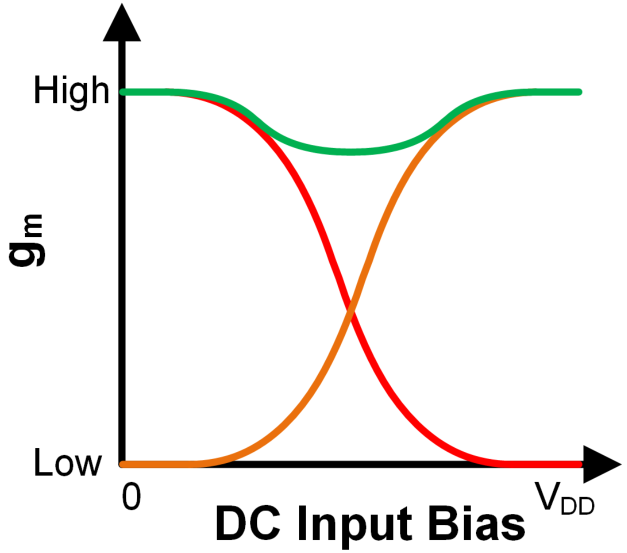




[D. Murphy, JSSC 2012]

Inverter-Based Phase-Shifter

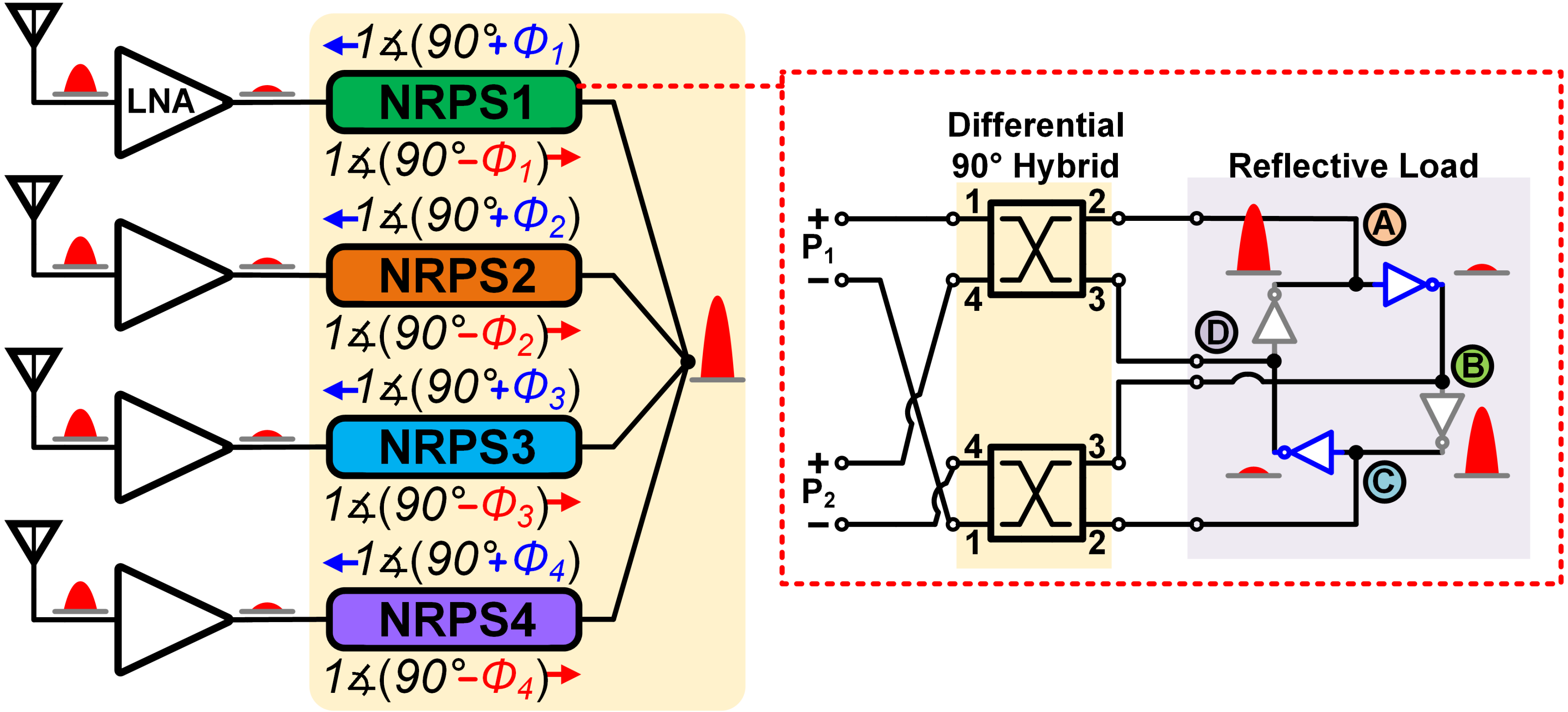


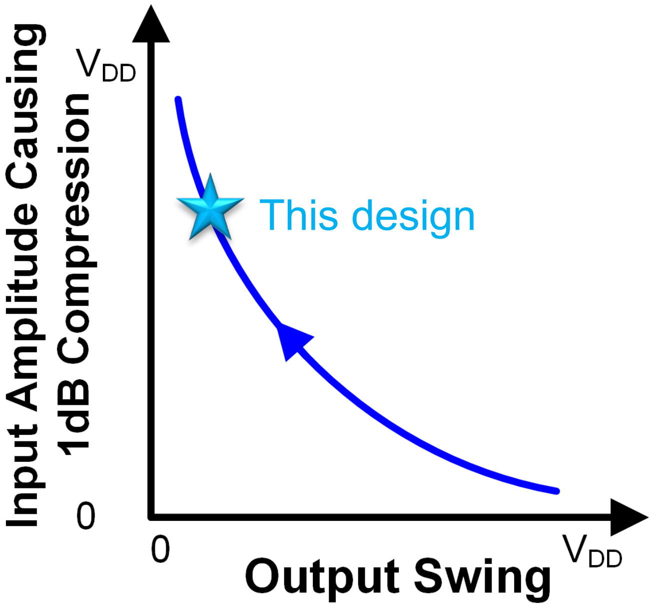


[D. Murphy, JSSC 2012]

Linearity performance can be improved by using inverters.

Inverter-Based Phase-Shifter



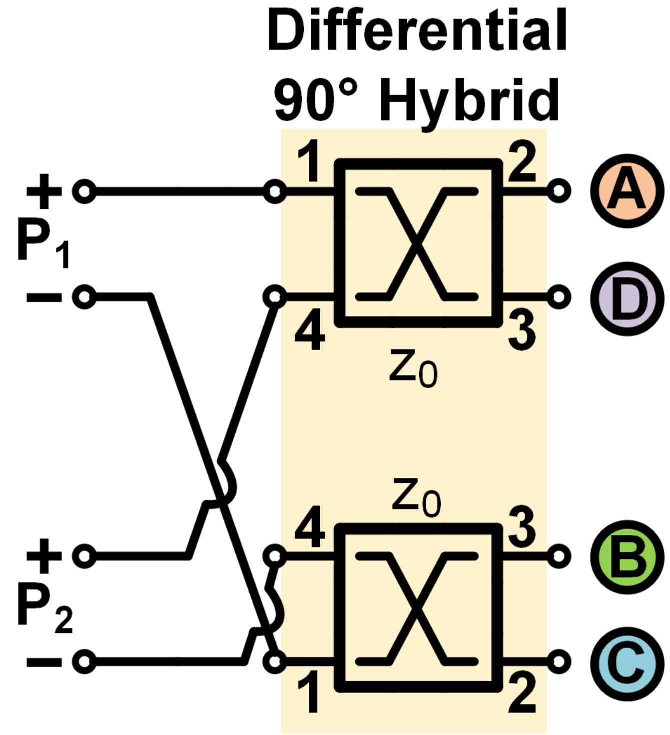


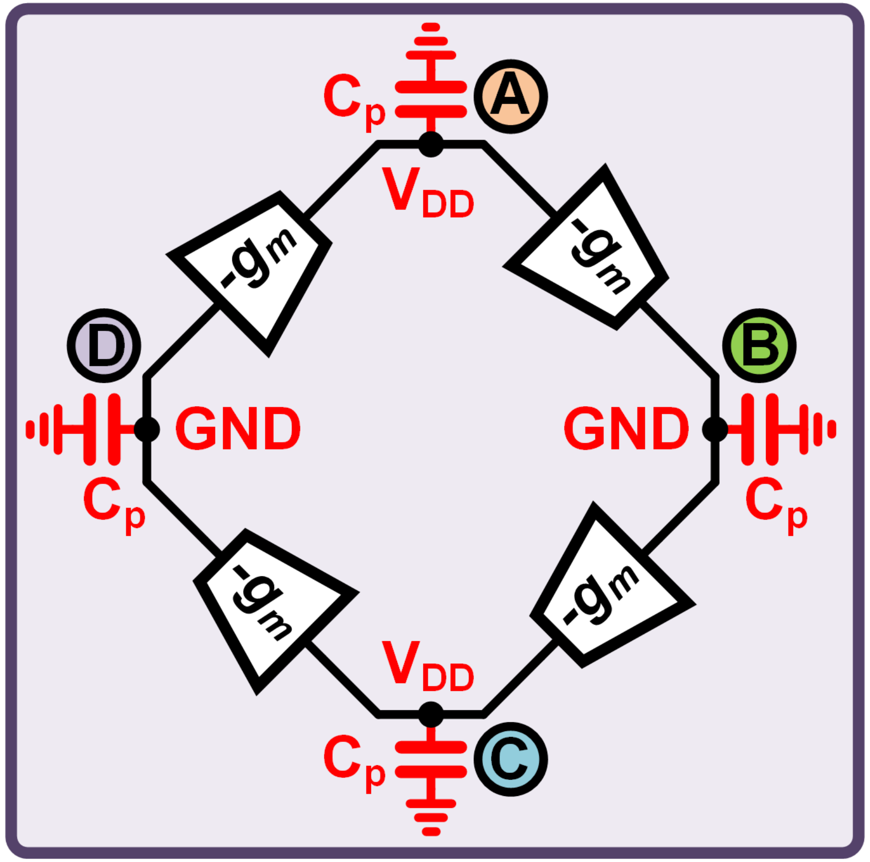
[D. Murphy, JSSC 2012]

Blue inverters operate in the linear region due to their small output swing.

Gray inverters do not contribute non-linearity as their input is silent.

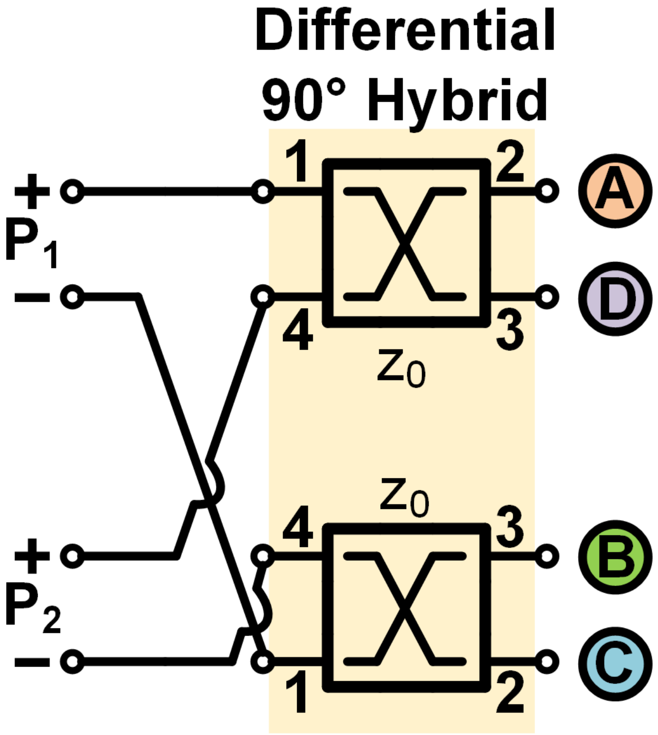
Bias Circuit

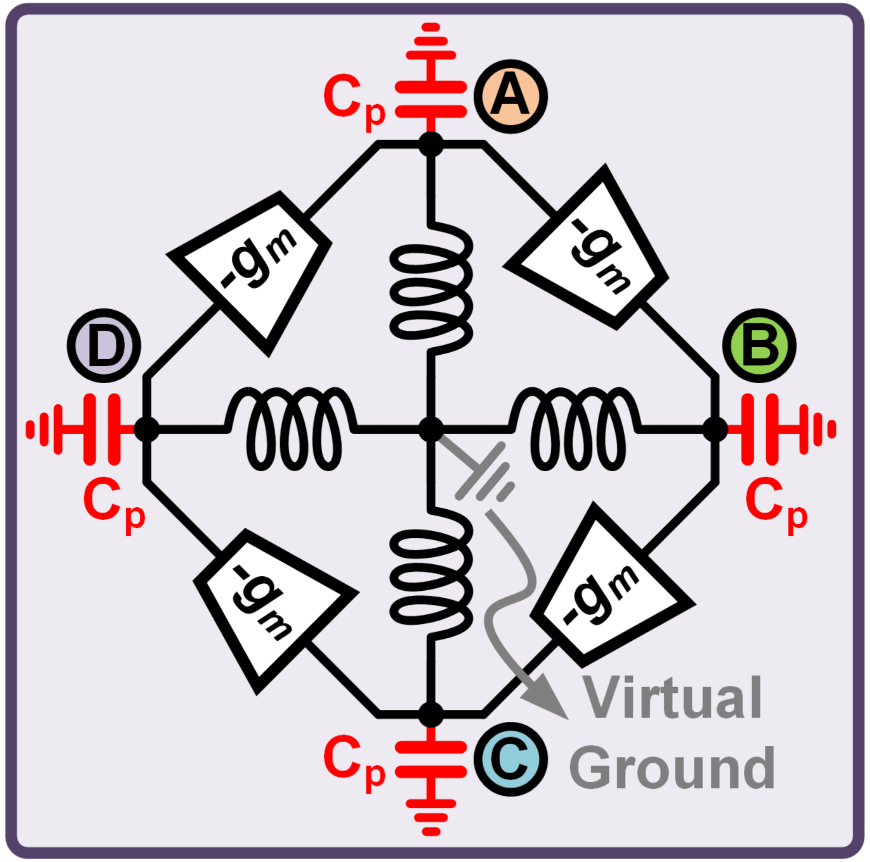




Phase shift is offset by parasitic capacitors.

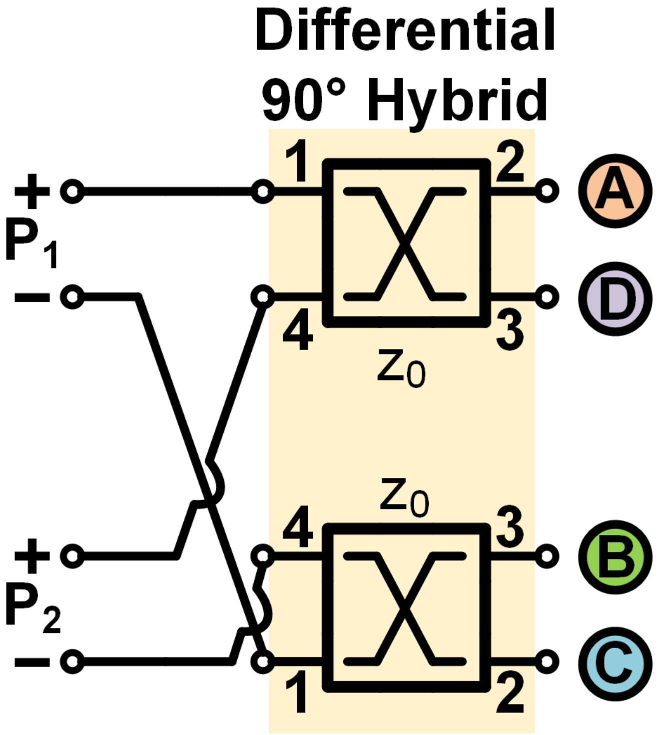
Bias Circuit

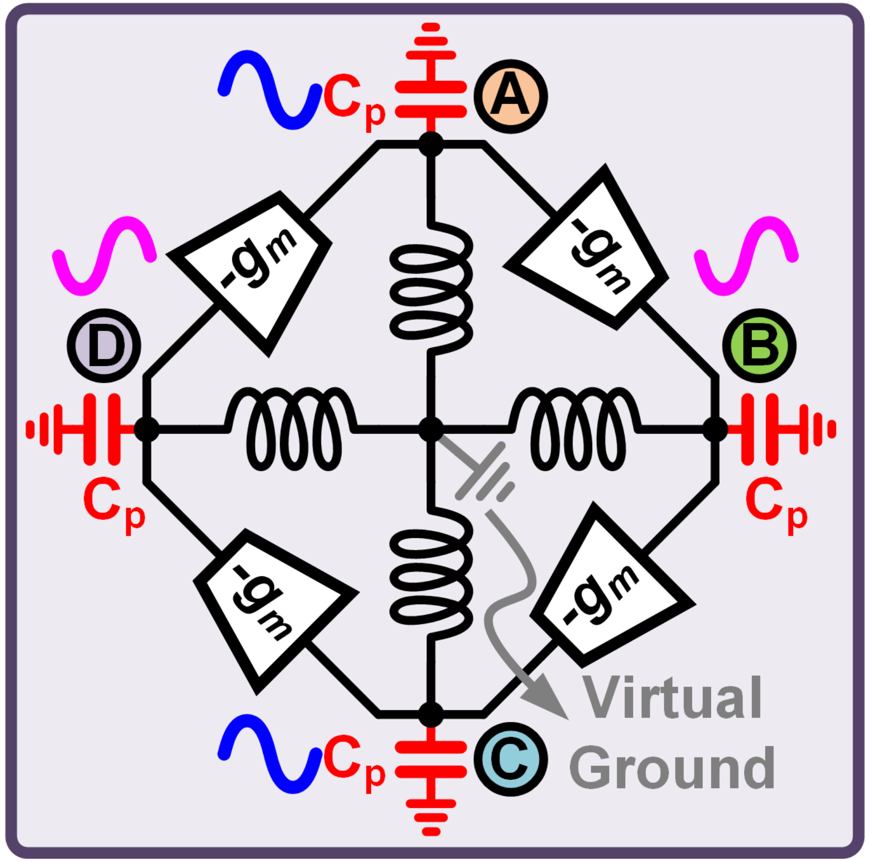




Parallel inductors can resonate with the parasitic capacitors.

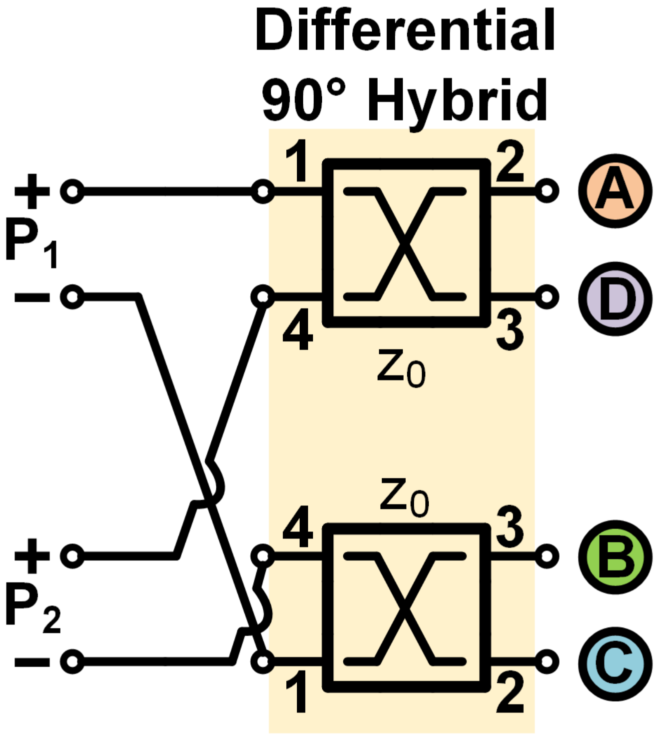
Bias Circuit

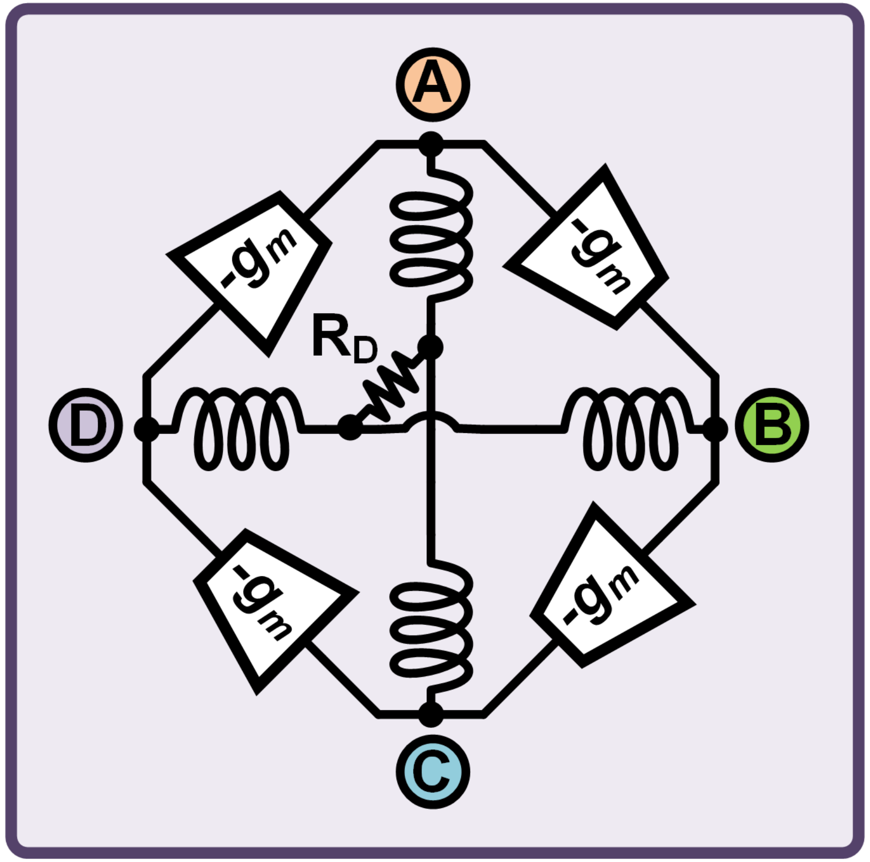




Adding inductors can create an LC oscillator.

Bias Circuit





We can add a resistor to solve the problem.

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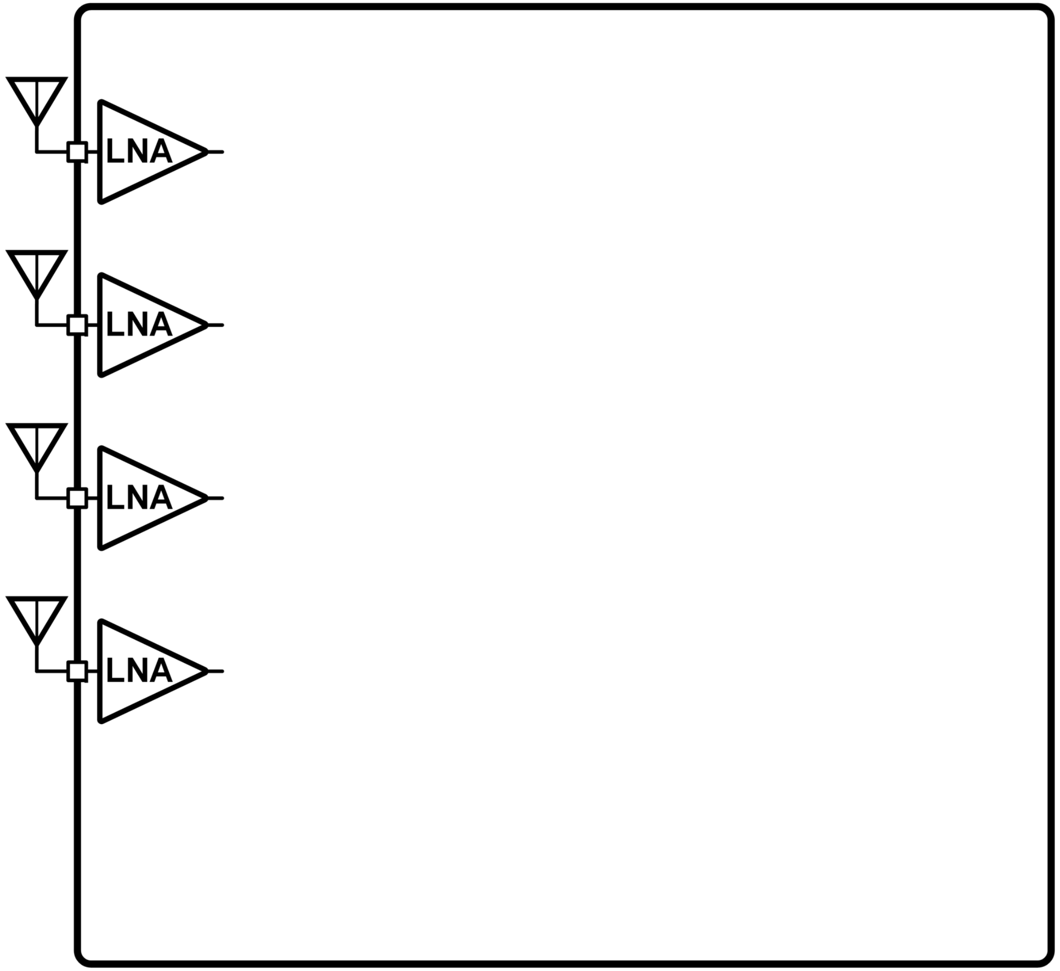
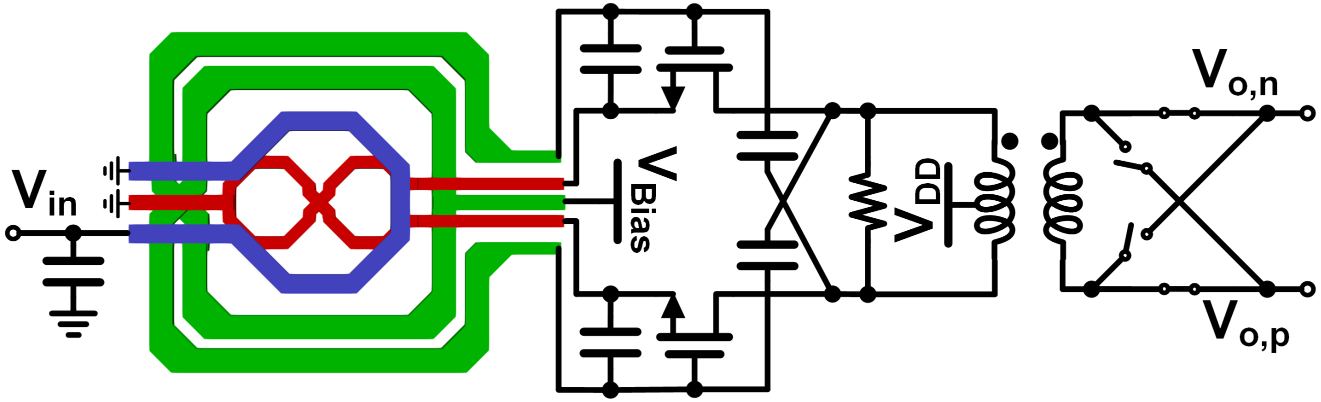
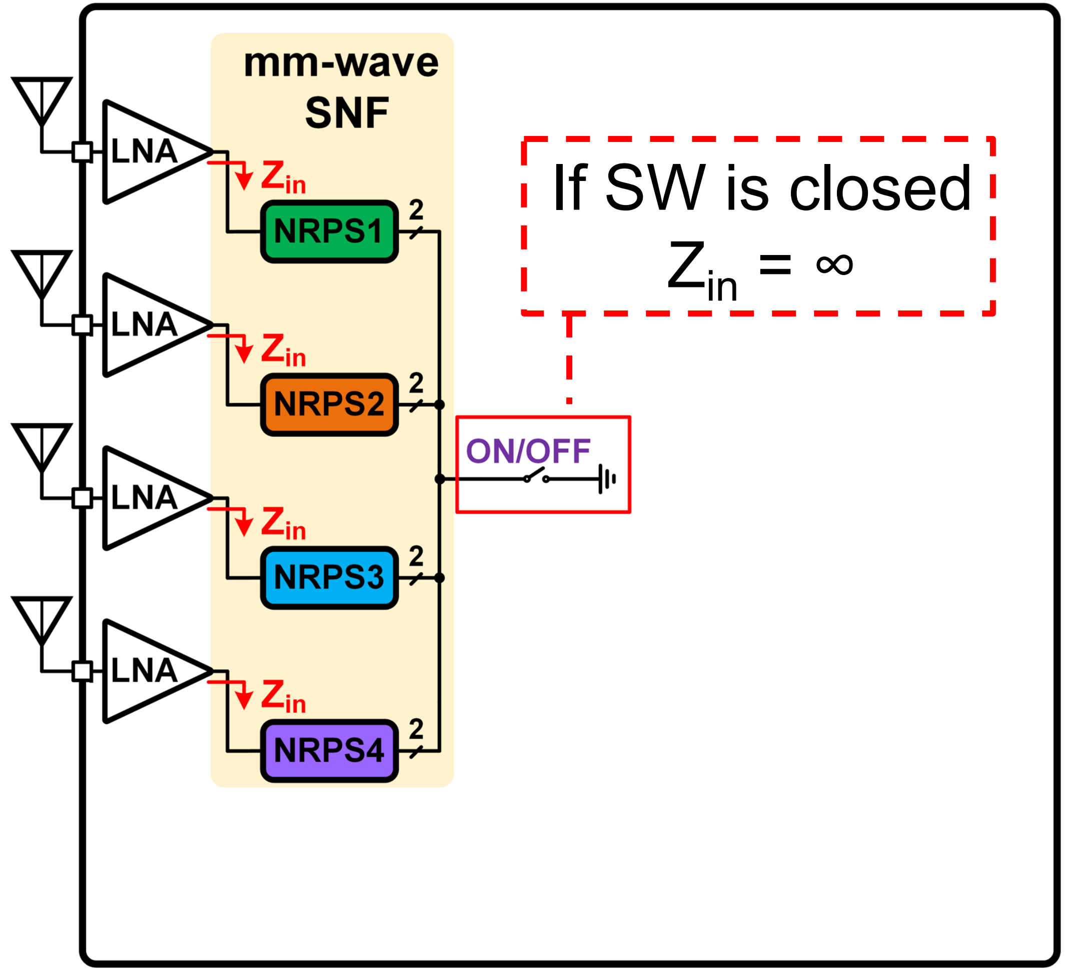
System Block Diagram



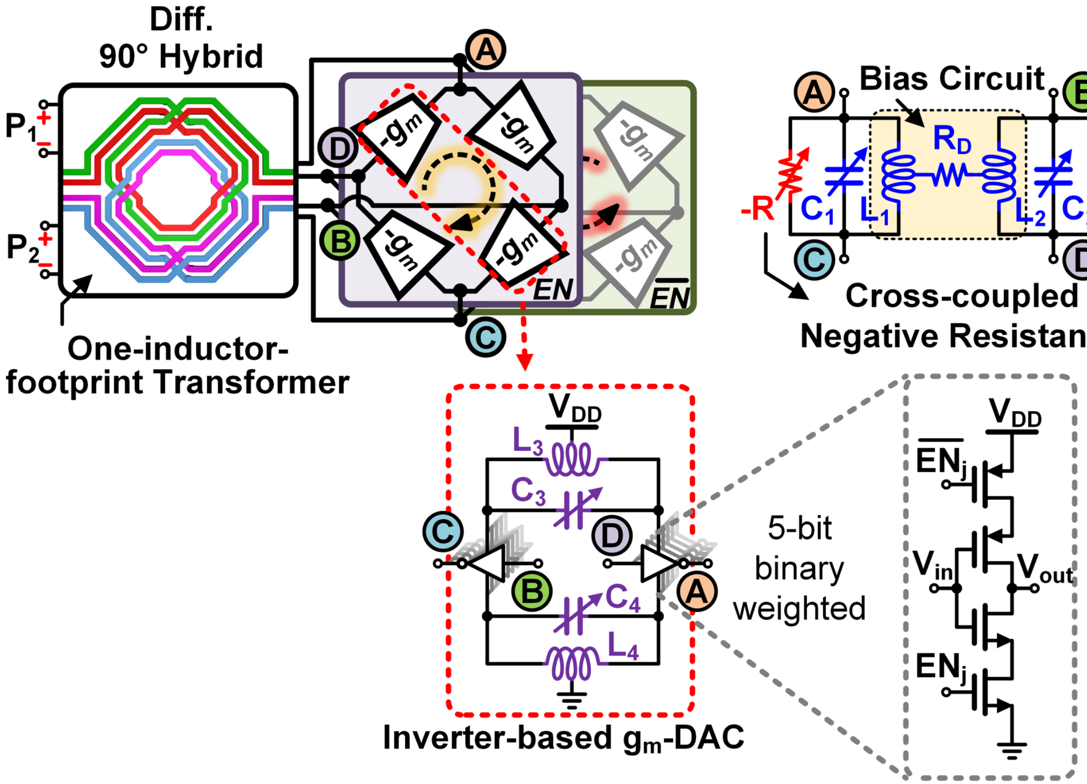
- LNA
  - Single-stage LNA
  - High linearity performance
  - Changing the polarity to cover 360°



System Block Diagram



- NRPS
  - Cover 360°



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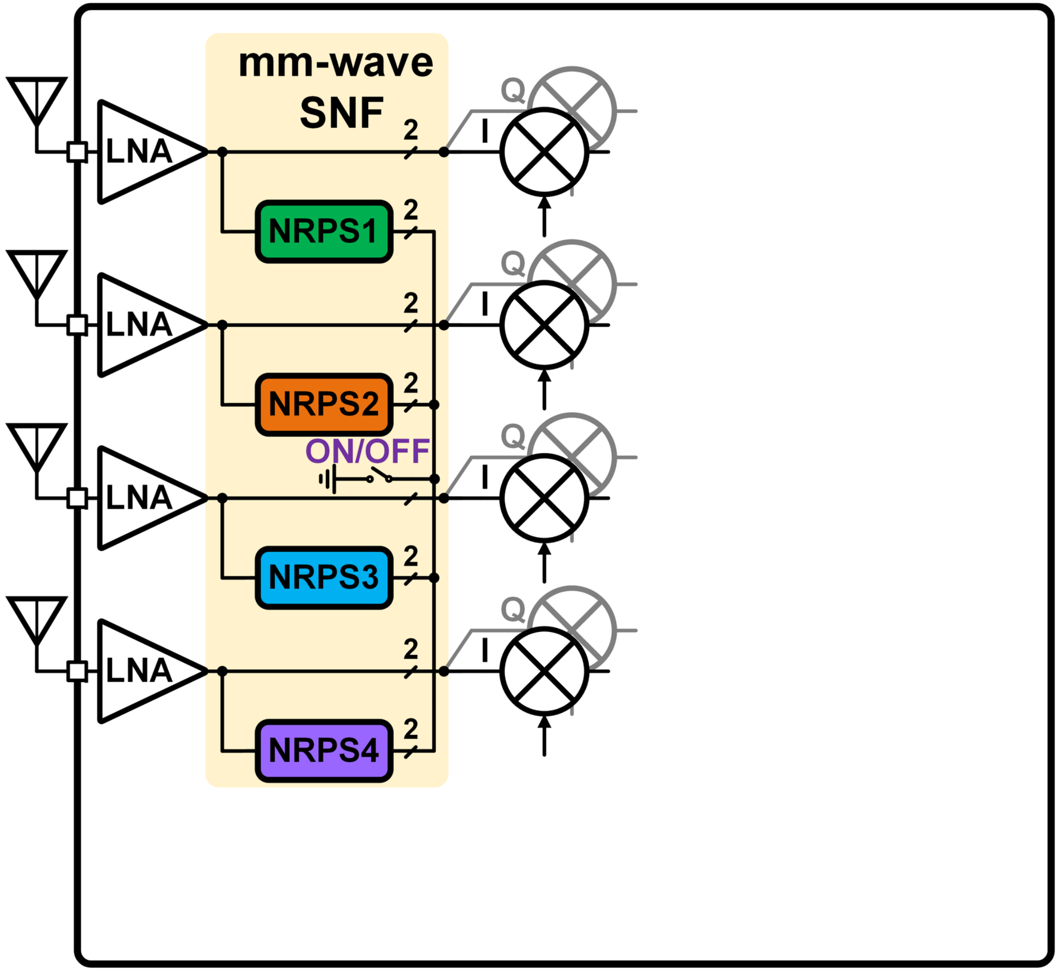
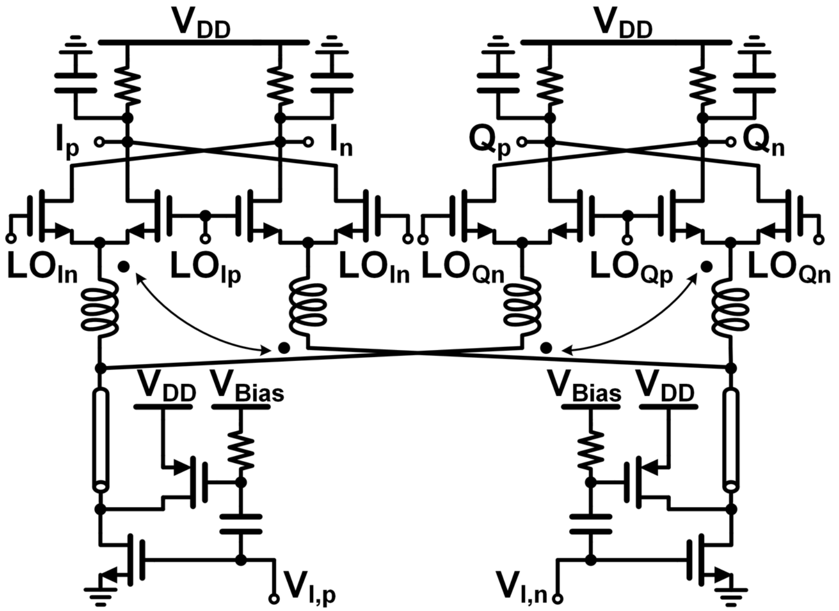
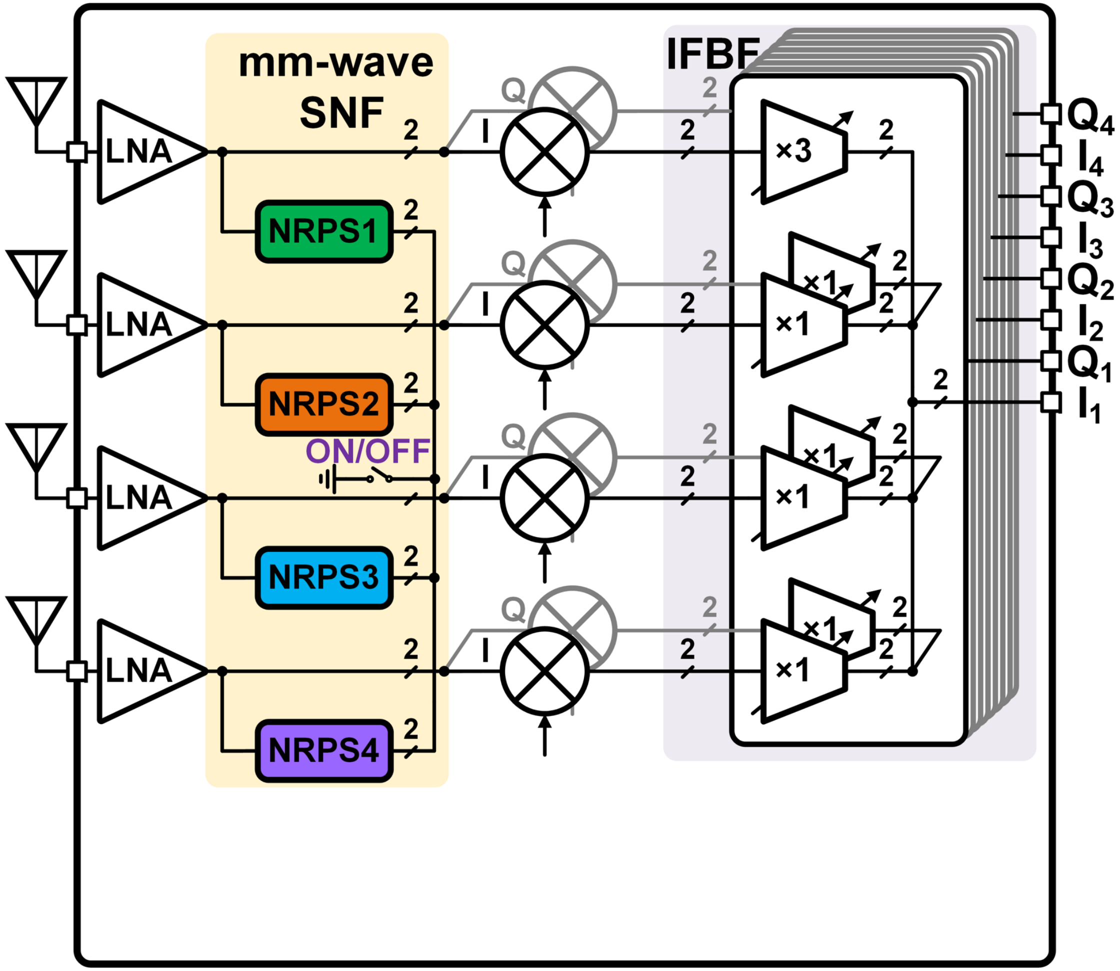


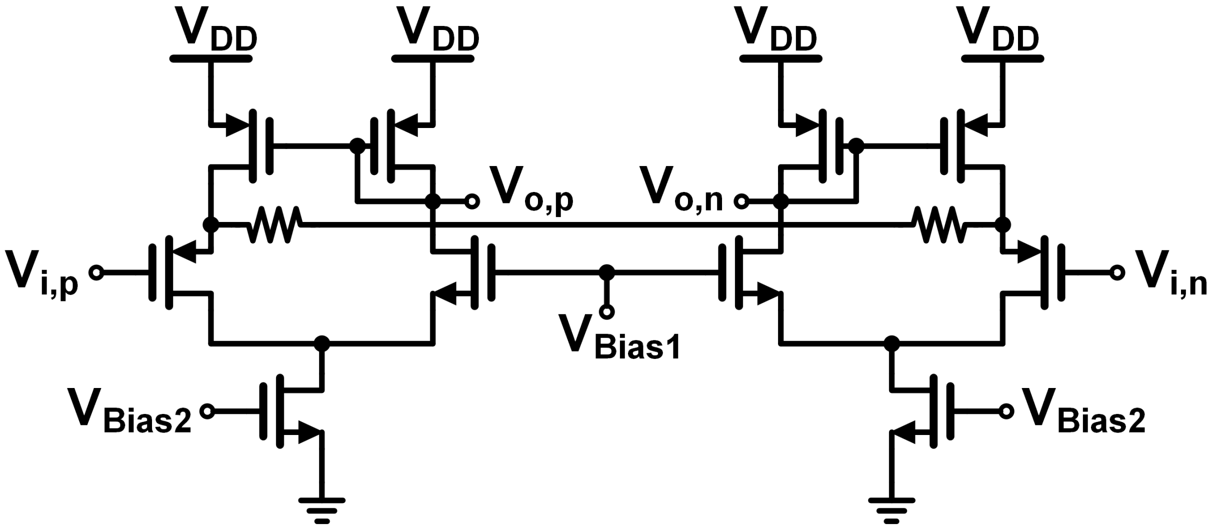
- Active Quadrature Mixer
  - g_m-boosting
  - Inter-stage peaking network with transmission line



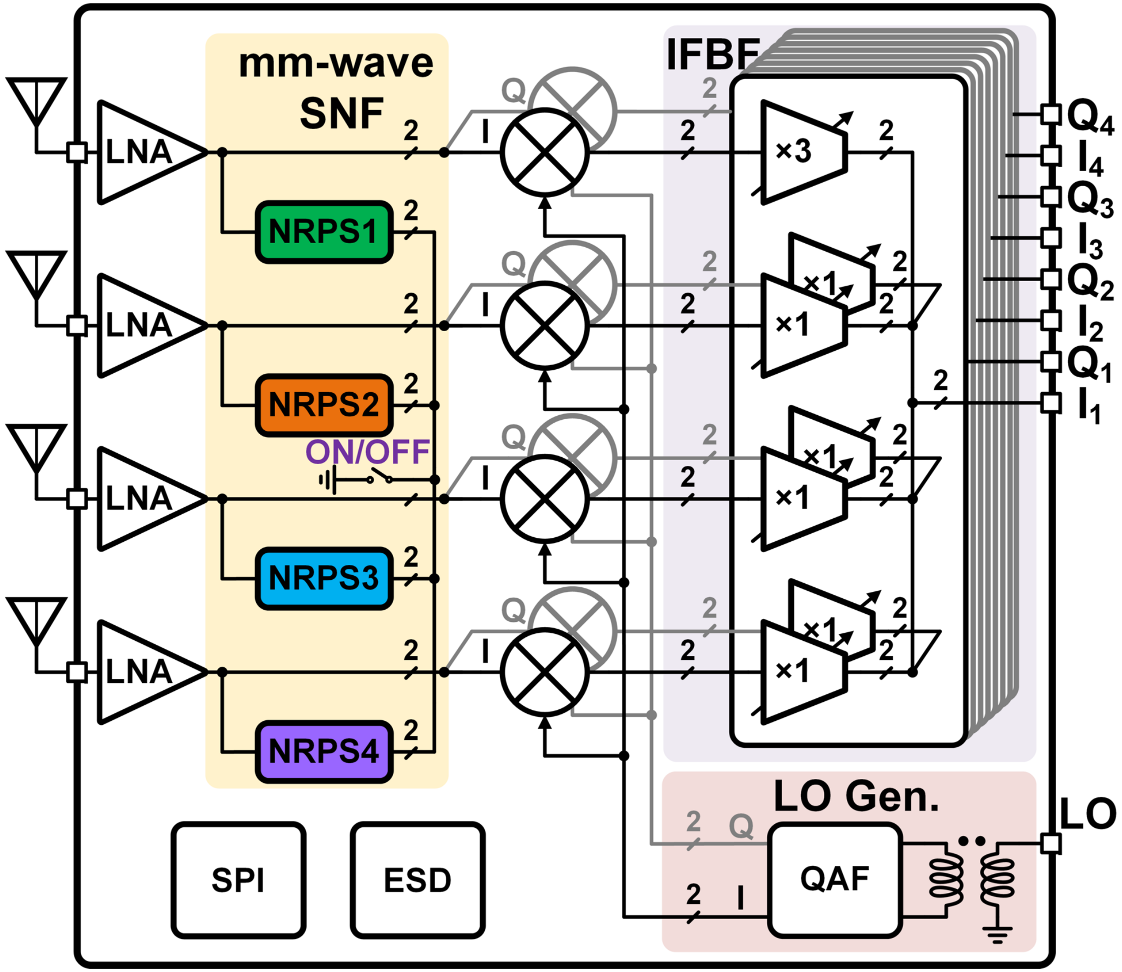
System Block Diagram



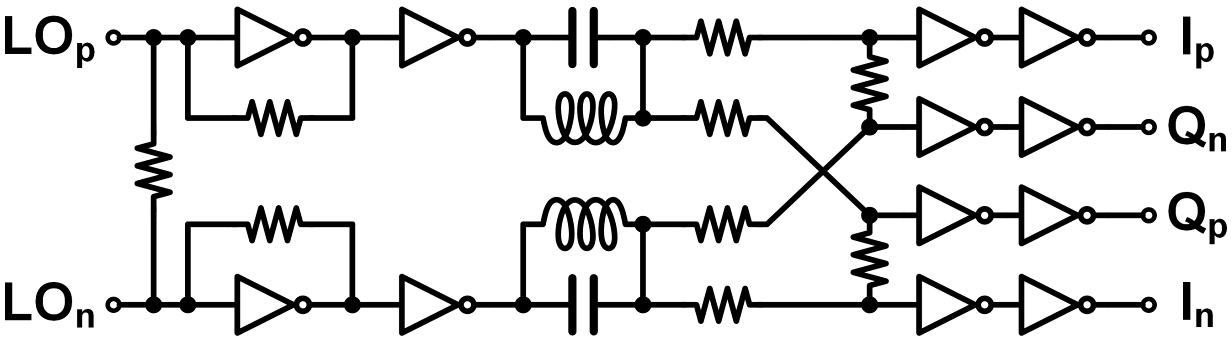
- IF beamformer
  - High linearity due to the feedback loop



System Block Diagram

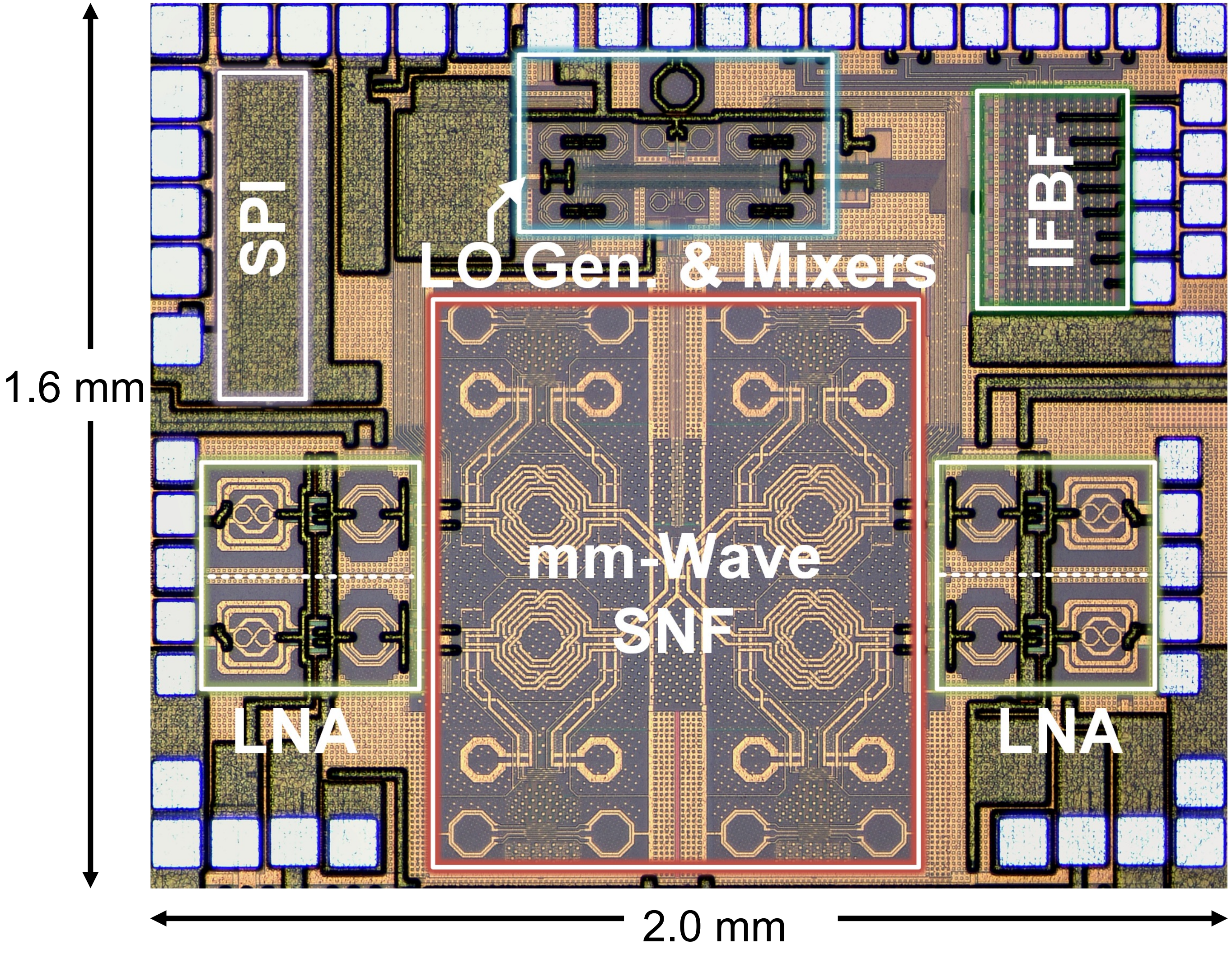


- LO Generation
  - Quadrature All-pass Filter (QAF)



Die Micrograph

- Technology
  - 45nm SOI GlobalFoundries
- Silicon Area
  - 3.2 mm^2
- Power Supply
  - 0.9V for LNA
  - 1.2V for others



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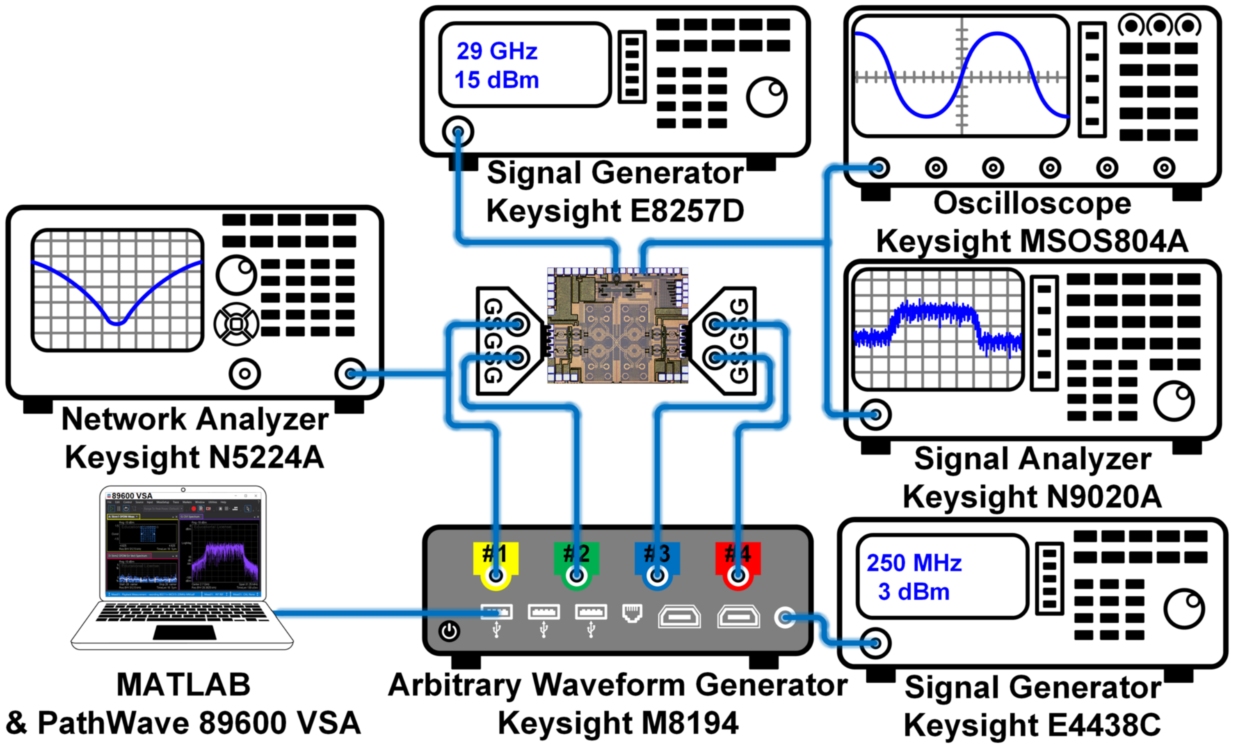
Gain, NF, and S_{11}



Signal Generator Keysight E8257D

Oscilloscope Keysight MSOS804A

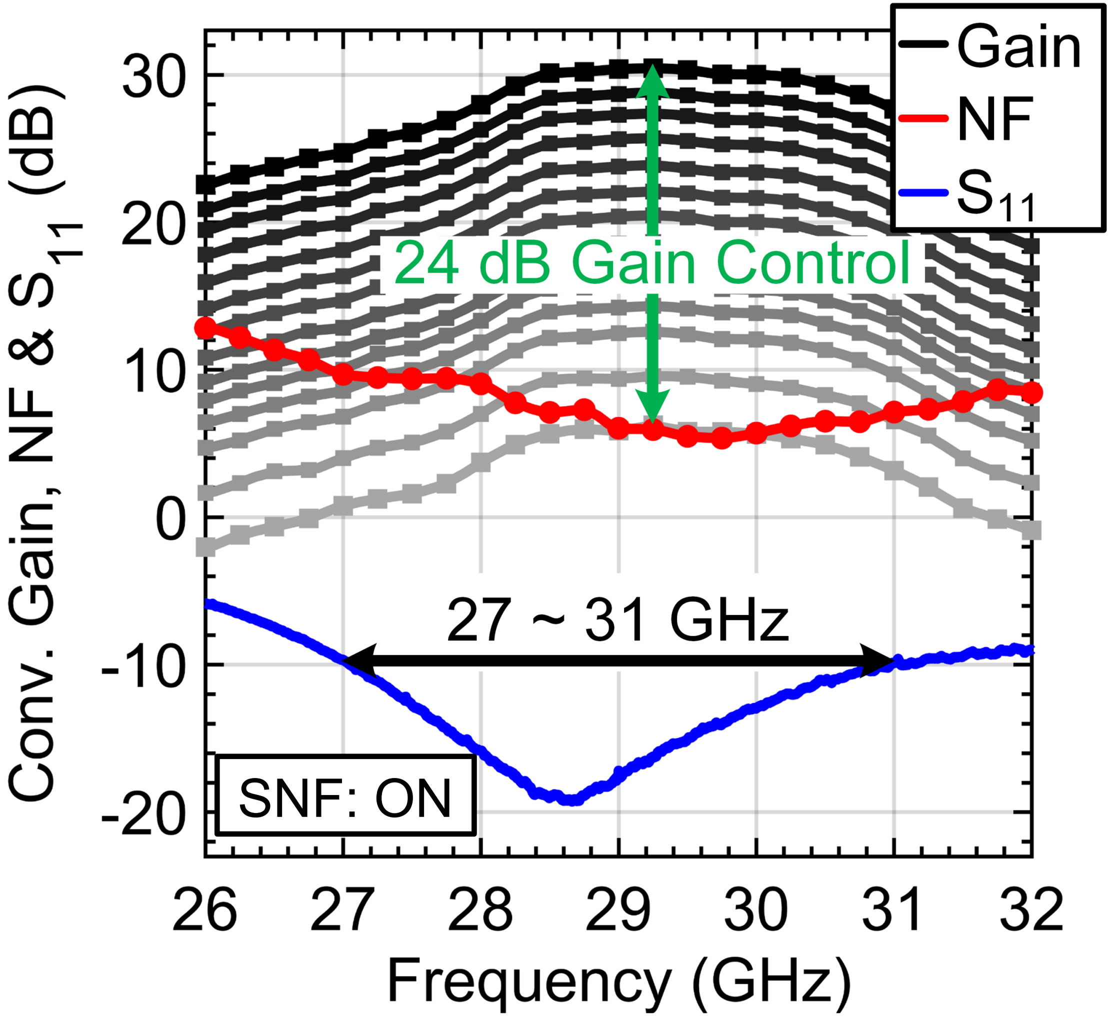
Network Analyzer Keysight N5224A

Signal Analyzer Keysight N9020A

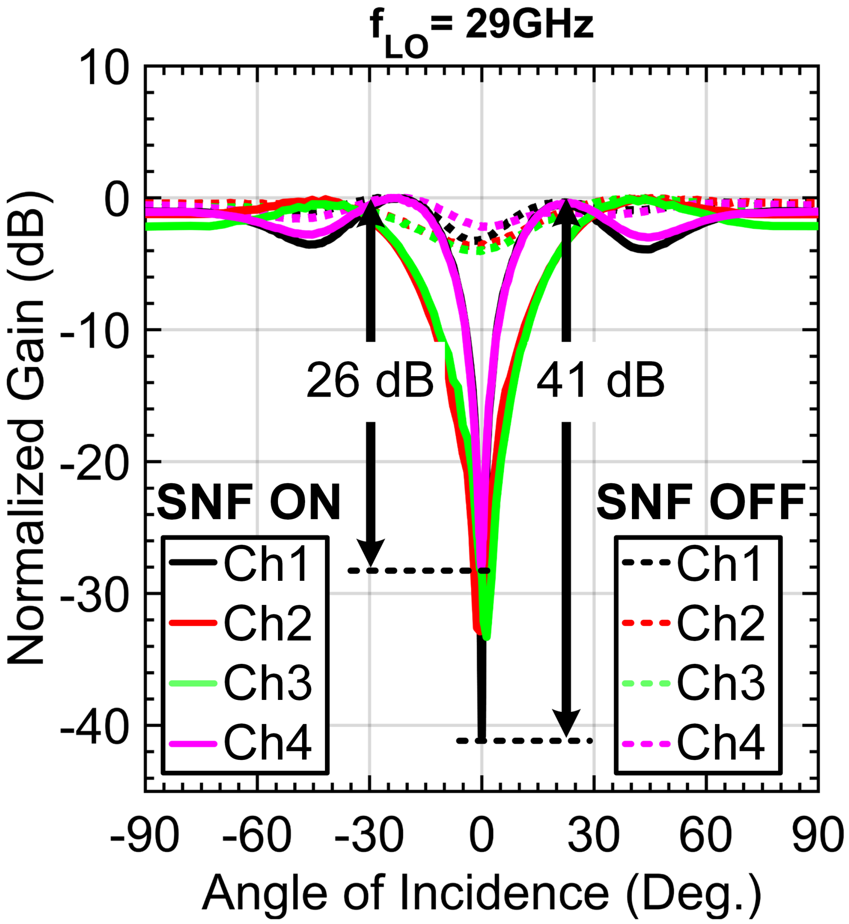
MATLAB & PathWave 89600 VSA

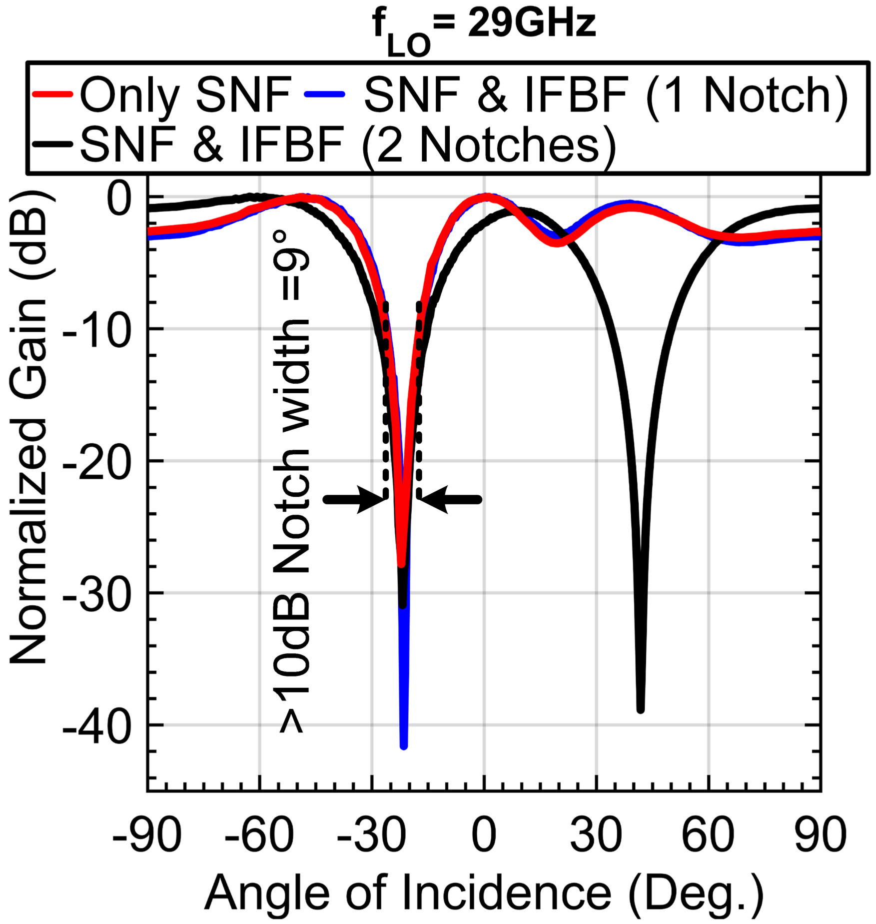
Arbitrary Waveform Generator Keysight M8194

Signal Generator Keysight E4438C



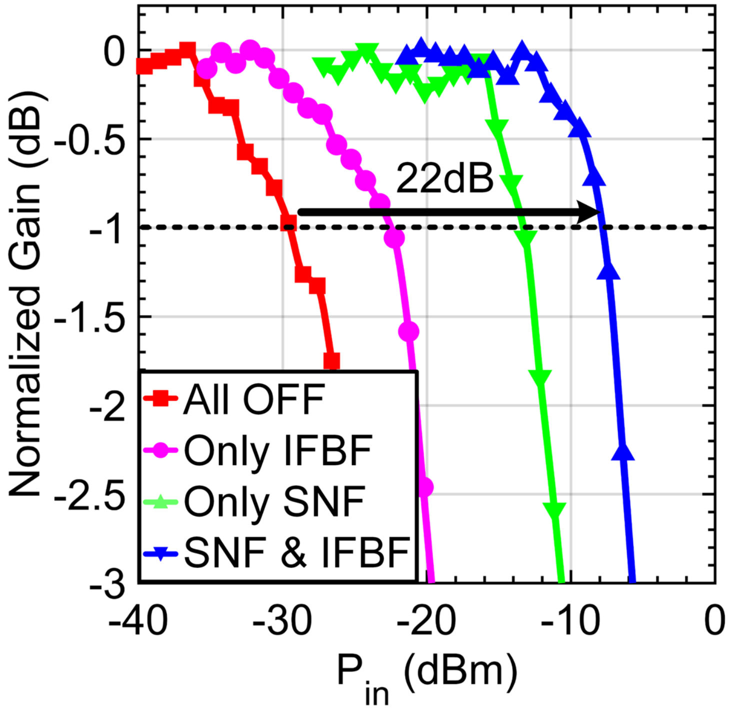
Notch Depth





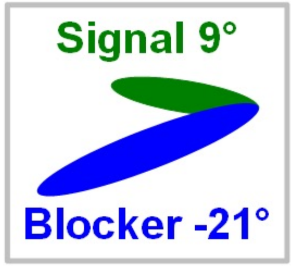
Up to two spatial notches can be created by independently tuning SNF and IFBF.

Linearity Test

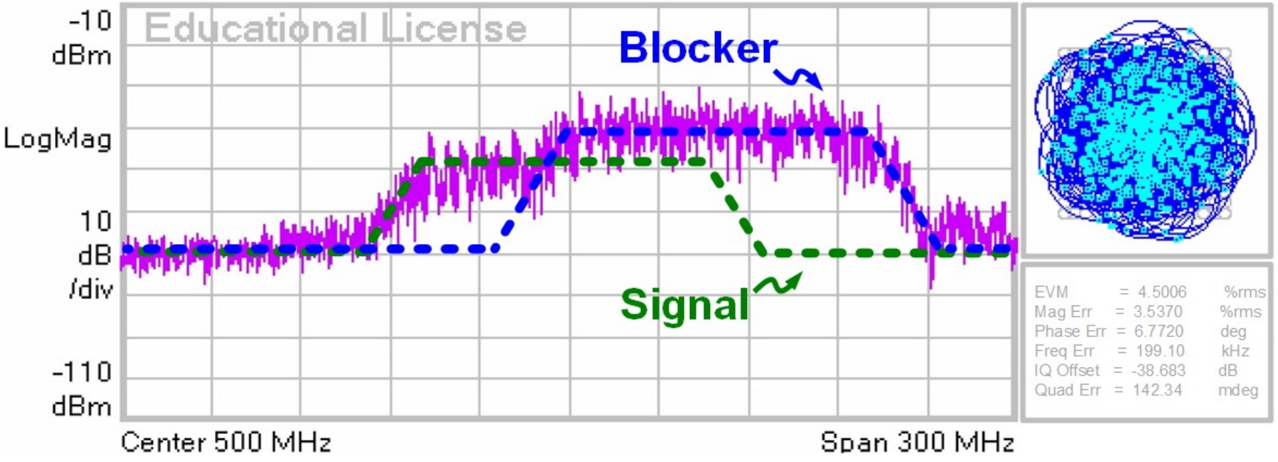


SNF & IFBF off:	-30 dBm
IFBF on:	-22 dBm
SNF on:	-13 dBm
SNF & IFBF on:	-7.8 dBm

100 MS/s 256 QAM
Signal: 29.00 GHz
Blocker: 29.05 GHz
SINR: -8 dB

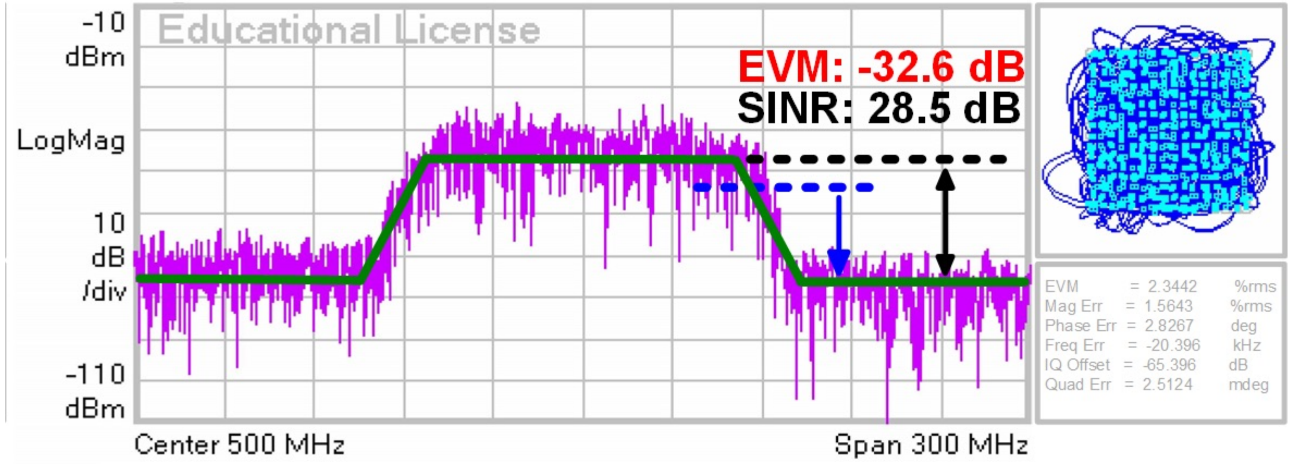


SNF: OFF



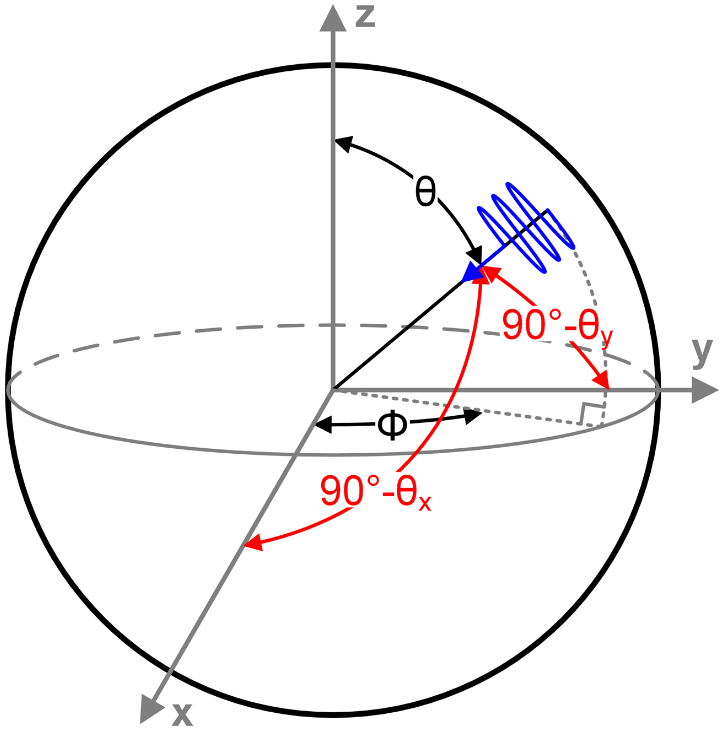
```
EVM          =  4.5006     %rms
Mag Err      =  3.5370     %rms
Phase Err    =  6.7720     deg
Freq Err     =  199.10     kHz
IQ Offset    =  -38.683    dB
Quad Err     =  142.34     mdeg
```

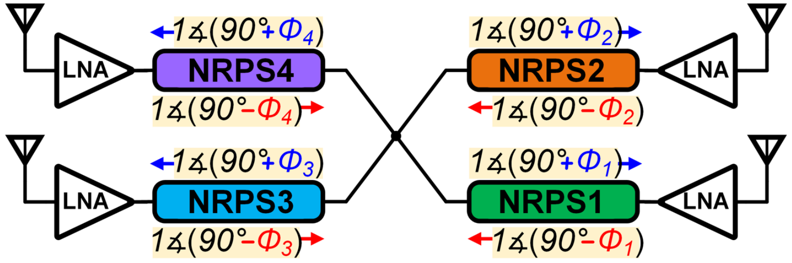
SNF: ON



```
EVM          =  2.3442     %rms
Mag Err      =  1.5643     %rms
Phase Err    =  2.8267     deg
Freq Err     =  -20.396    kHz
IQ Offset    =  -65.396    dB
Quad Err     =  2.5124     mdeg
```

2-D SNF

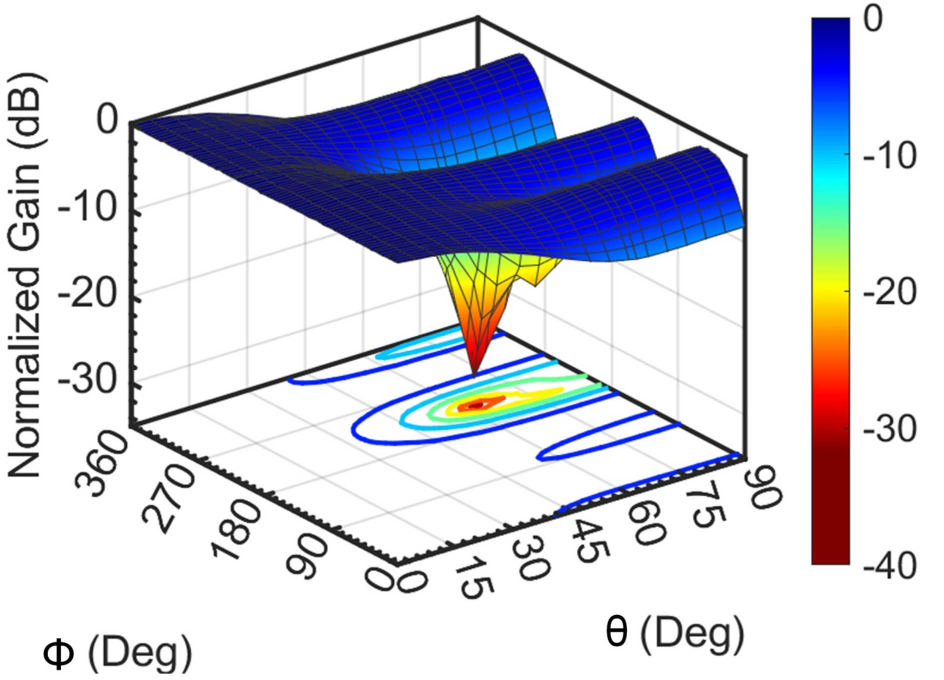




NRPS settings

Φ_1	$\frac{1}{2}(+\theta_x+\theta_y)$	Φ_3	$\frac{1}{2}(+\theta_x-\theta_y)$
Φ_2	$\frac{1}{2}(-\theta_x+\theta_y)$	Φ_4	$\frac{1}{2}(-\theta_x-\theta_y)$

$\sin\theta_x = \sin\theta\cos\Phi$
$\sin\theta_y = \sin\theta\ \sin\Phi$



This receiver structure can support 2-D MIMO.

Comparison Table

	M. Huang, TMTT19 [2]	M. Huang, JSSC19 [3]	R. Garg, ISSCC20	L. Zhang, ISSCC22 [4]	T. Huang, TMTT23	This Work
Technology	130nm SiGe	45nm SOI	65nm	40nm	45nm SOI	**45nm SOI**
Frequency Range [GHz]	23-30	27-41	28	23-29	23-37	**27-31**
Spatial Blocker Suppression Dimension	1-D	1-D	1-D	1-D	2-D	**1-D and 2-D**
$NF_{DSB,eq}$ [dB]	4.2-6.3	4.3-6.3	6.0-7.8	4.8-7.1	4.8-5.9	**5.4-9.7**
In-Notch IP1dB [dBm]	N/A	-19[1]	N/A	-14	-20[1]	**-7.8**
Out-of-Notch/In-Notch OIP3 [dBm]	N/A	9/27	N/A	N/A	N/A	**14.1/30.1**
Max RF/IF Notch Depth [dB]	41	62	37	40	43.6	**41**
Min >10dB Cancellation Spatial Notch width [°]	48-58[1]	27-32[1]	~11 (CH1&4)[1] ~22 (CH2&3)[1]	8.5-14 (CH1&4) 22-24 (CH2&3)	28-51[2]	**8.7-13 (CH1&4)** **23-25 (CH2&3)**
Power Cons./RX element [mW]	70	70-85	112.4	56.1	132.2-200.3	**62.8-71.4**
Modulation	100 MS/s 256 QAM	100 MS/s 256 QAM	100 MS/s 16 QAM	100 MS/s 64 QAM	100 MS/s 64 QAM	**100 MS/s** **256 QAM**
Desired Signal EVM after Blocker Suppression [dB] (Input SINR [dB])	-32.6 (-10)	-32.8 (-8)	-20.3[3] (0)	-27.9 (-15)	-26.3[1] (-3[1])	**-32.6** **(-8)**
Area [mm^2]	21.6	23.4	10.6	2.8	18.4	**3.2**

[1] Estimated from figures. [2] Calculated the real angles from figures. [3] Over-the-air (OTA) measurement results.

4x higher spatial blocker tolerance than fully-integrated prior work ([Zhang, ISSCC'22])

Outline

- Motivation and Introduction
- Proposed RX Architecture with Spatial Notch Filter
- Proposed Non-Reciprocal Phase-Shifter
- Implementation
- Measurement Results
- Conclusion

Conclusion

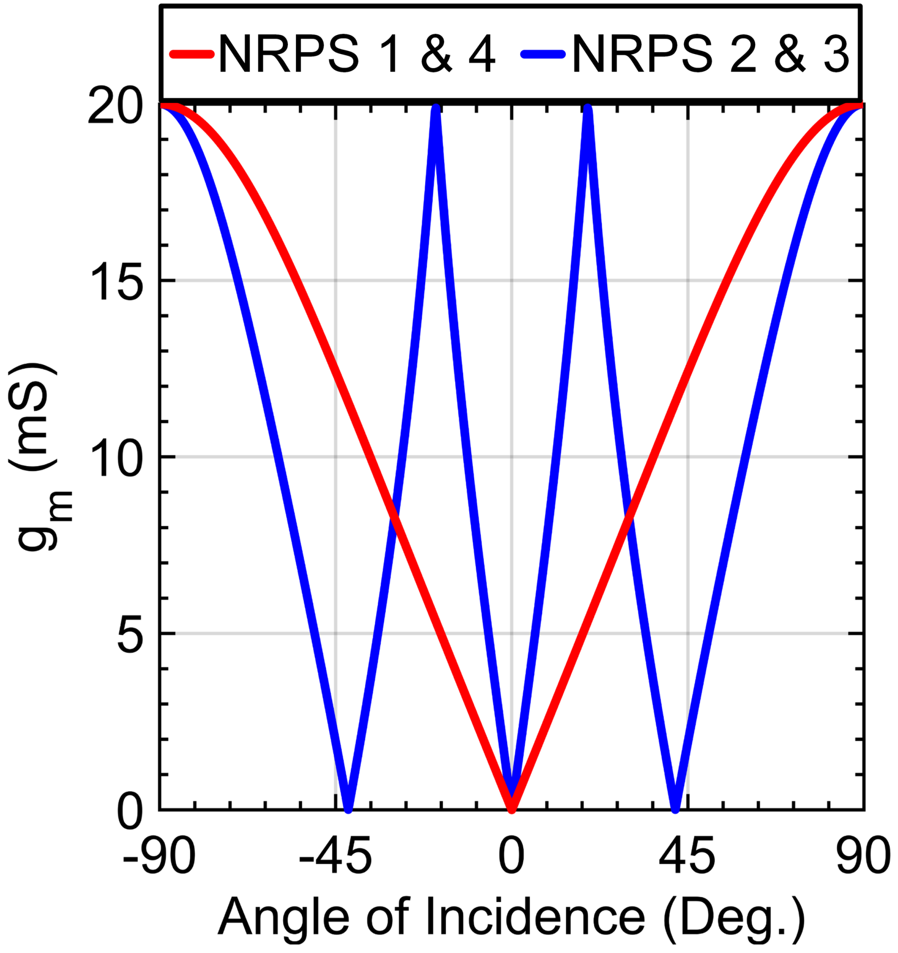
- A novel non-reciprocal low-loss and compact phase-shifter is proposed.
- By taking advantage of non-reciprocity, spatial notch filtering is achieved at the LNAs' outputs.
- Non-reciprocal phase-shifters can be disabled in the absence of blockers.
- Compared to prior fully-integrated mm-wave receivers, this work achieves the highest in-notch input P_{1dB}.

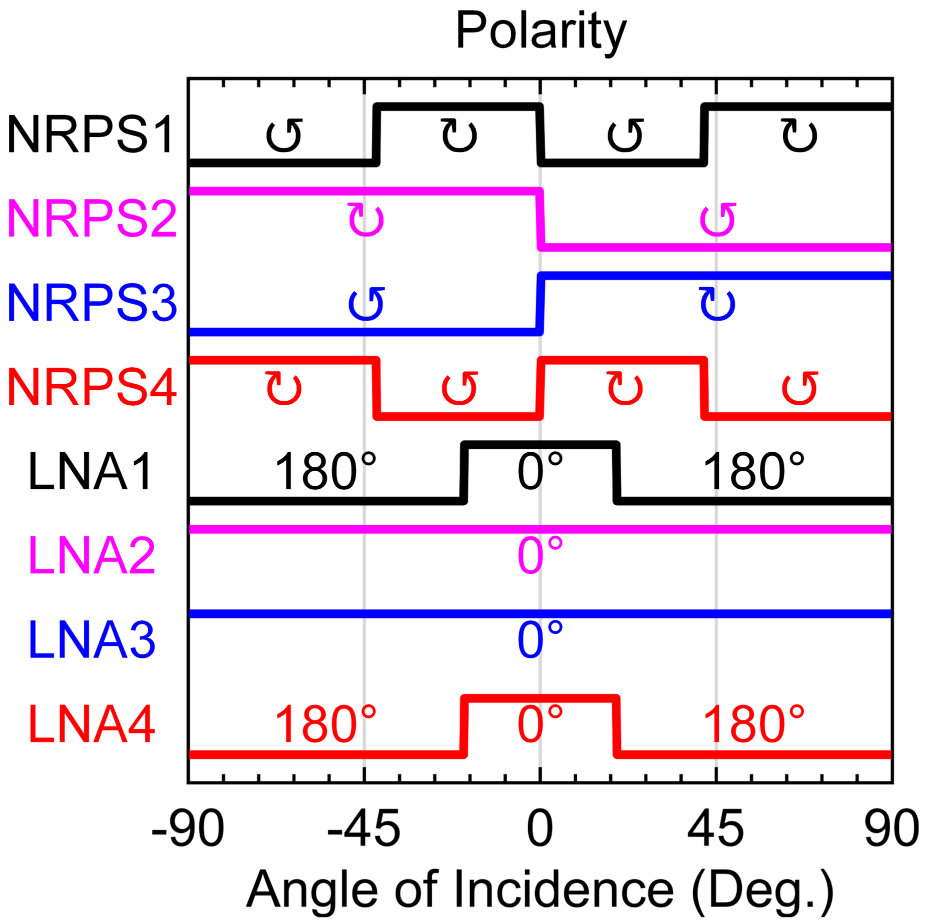
Acknowledgments

- The authors thank Dr. Qingyun Xie, Eunseok Lee, Jessica Kedziora and Yidong Fang for their assistance during measurements and the MIT MTL faculty for equipment assistance.
- The chip fabrication was financially supported by MIT Center for Integrated Circuits and Systems (CICS).

Thank you for your attention.

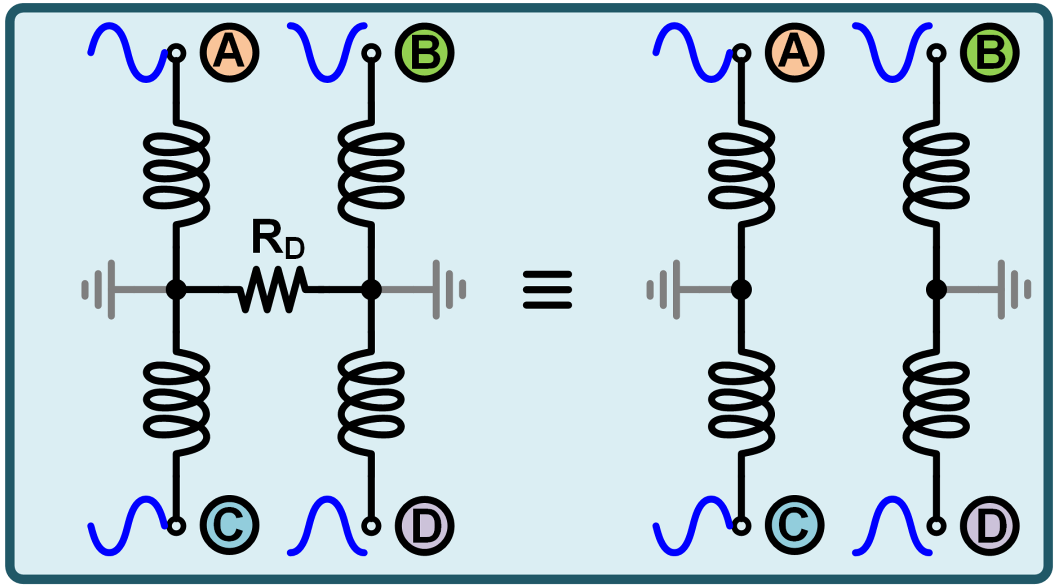
NRPS Setting





Bias Circuit

Phase-shifter Mode



Oscillation Mode