Breaking Reciprocity: Techniques and Applications

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Outline

- What is reciprocity and how to break it?

- Applications of nonreciprocity and state-of-the-art

- New family of inductorless infinitesimal nonreciprocal components

- Summary and future opportunities
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(Non)Reciprocal Wave Propagation

Reciprocal

Antennas

Radiation pattern = Receiving pattern

Passive Components

Power splitter = Power combiner

Nonreciprocal

- Circulators
- Isolators
- Active Circuits: LNAs, PAs, Active Mixers, …
- Unilateral Parametric Amplifiers
Breaking Reciprocity

Magnetic materials (ferrites)

Non-linear systems

Active devices

Time-variant systems

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

[Ref: RF-Cl, Inc.]

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

[Ref: Fan, Science 2012]

[Ref: Reiskarimian, Nat. Comm. 2016]

[Ref: Estep, Nat. Physics 2014]
Non-Reciprocity Through Active Devices

Cascaded Transistors

Transistor-Based Metamaterials

Approaches based on active devices are limited in their application due to poor noise and linearity performance.

[Ref: Tanaka, Proc. of IEEE, 1965]
[Ref: Kodera, IEEE TMTT, 2013]
Nonlinearity-Based Non-Reciprocity

Single-mode waveguide

Kerr nonlinearity

Weak transmission in the forward direction

High transmission in the forward direction

Low transmission in the backward direction

Kerr nonlinearity

Single-mode waveguide

\[
P \simeq \varepsilon_0 \left( \chi^{(1)} + 3 \chi^{(3)} |E_0|^2 \right) E_\omega \cos(\omega t)
\]

Non-reciprocity based on nonlinear structures is limited to the range of signal powers.

[Ref: Shi, Nat. Photonics, 2015.]
Source: Prof. Fan slides
Spatio-Temporal Modulation

### Permittivity

\[ (2m+1)\frac{\lambda}{4} @ f_s \]
\[ n\frac{\lambda}{2} @ f_p \]

\[ \omega_p = (2m+2n+1)\omega_s \]

\[ \epsilon(t) \]
\[ \epsilon(t-T_{mod}/3) \]

[Ref: Kamal, Proc. of IRE, 1960]

\[ \epsilon(t) \cos(\omega_p t) \]

\[ \epsilon(t-T_{mod}/3) \cos(\omega_p t-90^\circ) \]

### Conductivity

\[ \sigma(t) \]

\[ \Delta z \]

\[ V_g(t) \]

\[ R_{\text{switch}} \]

\[ \begin{align*}
\sigma_{\text{max}} &= \frac{R_{\text{off}}}{R_{\text{on}}} \\
\sigma_{\text{min}} &= 10^5
\end{align*} \]

[Ref: Estep, Nat. Phys, 2014]


### Permeability

[Ref: Kamal, Proc. of IRE, 1960]

Nonlinear Inductor
Non-Reciprocity Using Time-Variance

Permittivity Modulation

Permittivity modulation in silicon has limited modulation index \( \frac{C_{\text{max}}}{C_{\text{min}}} \sim 2-4 \).
Revival of Commutated Networks

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

[Ref: Ghaffari, IEEE TCAS-I, 2010]
Passive Phase Non-Reciprocity

Phase-shifts applied to signals near $f_{LO}$ traveling in opposite directions have opposite signs.
Non-Reciprocal Wave Propagation

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

Preventing Back-Reflections in Base Stations


Isolator/Circulator

Base Station Types

Source: Qorvo

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Output Power (W)</th>
<th>Cell Radius (km)</th>
<th>Users</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femtocell</td>
<td>0.001 to 0.25</td>
<td>0.010 to 0.1</td>
<td>1 to 30</td>
<td>Indoor</td>
</tr>
<tr>
<td>Pico Cell</td>
<td>0.25 to 1</td>
<td>0.1 to 0.2</td>
<td>30 to 100</td>
<td>Indoor/Outdoor</td>
</tr>
<tr>
<td>Micro Cell</td>
<td>1 to 10</td>
<td>0.2 to 2.0</td>
<td>100 to 2000</td>
<td>Indoor/Outdoor</td>
</tr>
<tr>
<td>Macro Cell</td>
<td>10 to &gt;50</td>
<td>8 to 30</td>
<td>&gt;2000</td>
<td>Outdoor</td>
</tr>
</tbody>
</table>
Nonreciprocal Components in Base Stations

Base Station Types

- Suburban
- Urban
- In-Building
- Pico Cell
- Micro Cell
- Macro Cell

Source: Qorvo

Macrocells

- Ferrites

Center Frequency: 0.7-1GHz
Size: 1400mm² (~x²/100)
Price: ~$10-$100

Microcells

- GaN-Based

[Ref: Biedka, IEEE IMS 2019]
[Ref: Bahamonde, IEEE IMS 2020]

Compact, Cheap

Picocells

- PCB-Based

[Ref: Bahamonde, IEEE USNC-URSI, 2018]

Compact, Cheap
Applications of Nonreciprocal Devices

Simultaneous Transmit and Receive (STAR) continuous-wave radar systems

Automotive Application

Active Reciprocal Quasi-Circulator

Center Frequency: 77GHz band
TX-ANT loss: 6.5dB

[Ref: Porranzl, IEEE IMS 2016]

Spatio-Temporal Conductivity-Based Circulator

Center Frequency: 60GHz
TX-ANT Loss: ~3.5dB

[Ref: Nagulu, IEEE ISSCC 2019]

Picture courtesy of: http://www.radartutorial.eu/
Applications of Nonreciprocal Devices

Simultaneous Transmit and Receive (STAR) continuous-wave radar systems

Vital-Signs Detection Application

Active Reciprocal Quasi-Circulator

[Ref: Kuo, IEEE T-MTT 2016]

Spatio-Temporal Conductivity-Based Circulator?

[Ref: Reiskarimian, IEEE RFIC 2020]

Active area: 0.167mm²
Applications of Nonreciprocal Devices

Superconducting Quantum Systems

Spatio-Temporal Conductivity-Based Circulator

Center Frequency: 6.5GHz
Core Power: ~2mW (at 4K)

[Ref: Ruffino, IEEE JSSC, 2020]
Applications of Nonreciprocal Devices

**Full-Duplex Wireless**

- Same frequency
- Same time

**Antenna Pair**

**Reciprocal Balanced Duplexer**

- Form factor
- Insertion loss

**Integrated Magnetic-Free Passive Circulator**

- Integrated
- Low loss
- High linearity
- High isolation

[Ref: van Liempd, ISSCC 2015.]

[Ref: Nagulu, RFIC 2018.]
Applications of Nonreciprocal Devices

Full-Duplex Phased Array

Signal levels and radiation pattern for nominal beamforming weights
Signal levels and radiation pattern after sacrificing DoFs
Signal levels for nominal single-antenna case

Full-Duplex MIMO

[Ref: Baraani Dastjerdi, Reiskarimian, et al, RFIC 2018.]

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Survey of Nonreciprocal Devices

Ferrites

Center Frequency 0.7-1GHz
Size: 1400mm² (~λ²/100)

Conductivity Modulation

Center Frequency ~1GHz
Size: 16.5mm² (~λ²/6000)
Includes 13 inductors + 3 off-chip baluns

Angular Momentum Biasing

Center Frequency 1GHz
Size: 36mm² (~λ²/2400)

[Kord, TMTT 2019]

Electro-Acoustic

Center Frequency 0.9GHz
Size: 36mm² (~λ²/3000)

Switched-Delay

Frequency Range 0.1-1GHz
Size: 18.5mm² (~λ²/5000)
Includes 2 transmission lines

Regardless of the approach, nonreciprocal devices are bulky especially at RF frequencies.
Conventional Notch Filter Structures

[Differential Notch Filter Diagram]

[Single-Ended Notch Filter Diagram]

[S21 Magnitude vs Frequency Graph]

[Diagram of Differential and Single-Ended Notch Filters]

[Ghaffari, JSSC 2013]
New Multi-Phase Notch Filter Structure

Enables a programmable notch depth by changing $\Delta \Phi$.

[Khorshidian, Reiskarimian, et al, ISSCC 2020]
New Multi-Phase Notch Filter Structure

$\Delta \Phi = 7\pi/4$

[Khorshidian, Reiskarimian, et al, ISSCC 2020]
Negative Transresistance in Switched Capacitor Circuits

\[
V_{\text{in}} \quad \Phi_0 \\
| \quad \Phi_1 \quad \Phi_2 \quad \Phi_3 \quad \Phi_4 \quad \Phi_5 \quad \Phi_6 \quad \Phi_7 \\
V_{\text{out}} \\
\]

\[
\begin{array}{c|cccc}
\Phi & 0 & 315 & 90 & 135 \\
\Phi & 45 & 180 & 225 & 270 \\
\Phi & \\
\end{array}
\]

\[
C_G \\
C_G \\
C_G \\
C_G \\
\]

<table>
<thead>
<tr>
<th>Transresistance in the</th>
<th>$0 \leq \Delta \Phi &lt; \pi/2$</th>
<th>$\pi/2 \leq \Delta \Phi &lt; \pi$</th>
<th>$\pi \leq \Delta \Phi &lt; 3\pi/2$</th>
<th>$3\pi/2 \leq \Delta \Phi &lt; 2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>forward direction, $\text{Re}(-Y_{21})$</td>
<td>Always $+$</td>
<td>$+$</td>
<td>Always $-$</td>
<td>$+$</td>
</tr>
<tr>
<td>reverse direction, $\text{Re}(-Y_{12})$</td>
<td>$+$</td>
<td>$-$</td>
<td>Always $-$</td>
<td>$+$</td>
</tr>
</tbody>
</table>

†: Depends on the capacitor value and $\Delta \Phi$

[Khorshidian, Reiskarimian, et al, ISSCC 2020]
Adding Nonreciprocal Transresistance

Low loss and high rejection is achieved in the opposite direction by using a nonreciprocal transresistance.

\[ \Delta \Phi = \frac{7\pi}{4} \]

\[ R_{21} \approx \infty \quad R_{12} \approx R_{\text{small}} \]

[Reducing \( R_p \) creates a low-loss passband]

[Khorshidian, Reiskarimian, et al, ISSCC 2020]
Measurement Results

- Widely Tunable (0.2-1GHz)
- Low loss (1.1-2dB across the tuning range)
- Size: 0.25mm$^2$ ($\sim \lambda^2/1,440,000$)

[Khorshidian, Reiskarimian, et al, ISSCC 2020]
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This is the first demonstration of integrated tunable infinitesimal nonreciprocal components on silicon.
Acknowledgement

This work has been done in collaboration with Prof. Harish Krishnaswamy’s group at Columbia University.

Thank You!

Any Questions?

Check out our recent publication featured in this talk:


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