Nonreciprocal devices based on angular-momentum biasing

Dimitrios L. Sounas

Department of Electrical and Computer Engineering
Wayne State University
Onsager conditions of nonreciprocity

\[ B: \text{bias quantity, odd symmetric under time reversal} \]

\[ t \rightarrow -t \quad B \rightarrow -B \]

\[ S_{21}(B) = S_{12}(-B) \]

Angular-moment.-biased acoustic circulator


\[ v = 0.5 \, \text{m/s} \ll 340 \, \text{m/s} \]
How it works...

Magnetic nonreciprocity

Zero bias

\[ \mu: \text{scalar} \]

\[ \omega_+ = \omega_- \]

Nonzero bias

\[ \tilde{\mu}: \text{tensor} \]

\[ \omega_+ \neq \omega_- \]
How it works...

Static ring

\[ \omega_+ = \omega_- \]

Spinning ring

\[ \omega_+ \neq \omega_- \]

Fresnel-Fizeau effect (optics)
Doppler effect (acoustics)

Bias velocity \( v/c \)

Mode frequency (Hz)
Acoustic circulator scattering parameters

\[ v = 0 \text{ m/s} \]

\[ v = 0.5 \text{ m/s} \]

\[ v = \frac{c}{2Q\sqrt{3}} \]
Effective spinning with ST modulation

$$\varepsilon + \Delta \varepsilon(\varphi, t)$$

$$\Delta \varepsilon(\varphi, t) = \Delta \varepsilon_m \cos(\omega_m t - l_m \varphi)$$

Acoustic waves  \( c = 340 \text{ m/s} \)  \( v = 0.5 \text{ m/s} \)

EM waves  \( c = 3 \times 10^8 \text{ m/s} \)  \( v = 440 \text{ km/s} \)

Experimental demonstration

Towards more systematic designs

Specify operation frequency $\omega_0$

Select $L$ and $C$ according to $LC = \frac{1}{\omega_0^2}$

Select $V_m$ and $\omega_m$ from design charts

Acceptable response

Yes

1st round design

No

Design charts of the delta topology

Kord, Sounas, A. Alù, IEEE TMTT, vol. 66, pp. 911-926, 2018
Measured response of the delta topology

Differential circulators

STM circulators generate intermodulation products at \( f \pm n f_m \)

These products can be minimized by using a differential topology

Differential circulators

Delta

Theory

Wye

Experiment

Experimental results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{RF}$</td>
<td>1 GHz</td>
</tr>
<tr>
<td>$f_m$</td>
<td>0.1 GHz</td>
</tr>
<tr>
<td>IL</td>
<td>&lt; 2 dB</td>
</tr>
<tr>
<td>RL</td>
<td>&lt; 23 dB</td>
</tr>
<tr>
<td>BW (20 dB IX)</td>
<td>23 MHz</td>
</tr>
<tr>
<td>P1dB</td>
<td>28 dBm</td>
</tr>
<tr>
<td>IIP3</td>
<td>31 dBm</td>
</tr>
<tr>
<td>$V_m$</td>
<td>2.3 V</td>
</tr>
</tbody>
</table>

The problem with generation of modulation signals is that they are generated externally, leading to complicated networks with multiple filters and phase shifters.
Locally generated modulation

Modulation signals are generated at the location of each modulated element through phase locked local oscillators.

Common-differential topology

RF signal: common mode
Modulation signal: differential mode

Natural isolation between the RF and modulation paths

Equivalent circuit for the RF signal

Equivalent circuit for the modulation signal
Demonstration with a delta circulator

The oscillators generating the modulation signals are implemented on the same board as the circuit.
Oscillator design

The varactors are being shared between the circulator and the oscillator.

Cross-coupled pair

Transmission line to next stage

Connection in a ring

Transmission line from previous stage

Connection in a ring

Modes with 120 deg phase difference
Oscillator signals in the time domain

Oscillator 1

- Positive terminal
- Negative terminal
Scattering parameters

With oscillators off

\[ f_m = 365 \text{ MHz} \]
\[ V_{osc} = 15 \text{ V} \]
\[ V_{var} = 8 \text{ V} \]

With oscillators on

\[ I_X = >30 \text{ dB} \]
\[ I_L = \sim 5 \text{ dB} \]
\[ R_L = \sim 8 \text{ dB} \]
Tuning w.r.t. to oscillator DC bias

- Osc. DC Bias8 V
- Osc. DC Bias10 V
- Osc. DC Bias12 V
- Osc. DC Bias14 V
- Osc. DC Bias16 V
IM Products and Linearity
Power consumption in STM circulators

Manley-Rowe relations for general modulated network

\[ \sum_{i=1}^{N} \frac{P_{i,DC}}{I_{i,DC}} \frac{\partial I_{i,DC}}{\partial \omega_m} + \sum_{m=-\infty}^{\infty} \sum_{n=1}^{\infty} \frac{nP(m\omega + n\omega_m)}{m\omega + n\omega_m} = 0 \]

\[ P(\omega_m) = -\sum_{n=2}^{N} P(n\omega_m) - \sum_{n=1}^{\infty} n \left[ \frac{P(\omega + n\omega_m)}{\omega + n\omega_m} - \frac{P(\omega - n\omega_m)}{\omega - n\omega_m} \right] \]

Exchanged power \( P_{exc} \)

Power exchange is identically zero for the differential circulator, for which there are no intermodulation products at the ports.

Power consumption in STM circulators

Angular momentum biasing in optics

$$\Delta \varepsilon_m = 10^{-4} \varepsilon$$

$$Q \Delta \varepsilon_m \approx 1$$

D. L. Sounas, A. Alù, *ACS Photonics* 1, 198 (2014)
Angular momentum biasing in optics

Photonic crystal implementation

A. Mock, D. Sounas, and A. Alù, *ACS Photon.*, vol. 6, pp. 2056-2066, 2019
Conclusions

➢ Angular momentum biasing is a promising approach for the design of low-loss symmetric magnetless circulators

➢ Main challenge: CMOS implementation

➢ Future direction: extension to metasurfaces in combination with the local modulation technique

Thank You!