1.95GHz Circulator based on a Time-Modulated Electro-Acoustic Gyrator

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Recent research has demonstrated spatiotemporal conductance modulation as an effective means of achieving magnetic-free non-reciprocity. The first of these works utilized staggered commutation of switches around a low-pass filter to accomplish a non-reciprocal 90° phase shift (*Nat. Commun.* **7,** 11217, 2016), which the authors then exploited to realize a low-loss, high-linearity circulator. Since the circuit operates on the principle of down- and up-converting signals around a low-pass filter, it requires modulation frequencies on the order of the center frequency of operation, which leads to high power consumption and challenges at higher frequencies. This was addressed by replacing the low-pass filter with delay lines in a doubly-balanced gyrator structure (*Nat. Commun.* **8,** 795, 2017). In this approach, the center frequency of operation is an integer multiple of the modulation frequency, determined by the delay line. This is a potentially powerful aspect, since large delays can significantly reduce modulation frequencies and thus power consumption. This also leads to the potential of implementing non-reciprocal elements in semiconductor platforms in which high-quality switches are unavailable, such as GaN and GaAs. However, due to fundamental delay-bandwidth-size trade-offs, the achievable delay in the electromagnetic domain is limited. In this paper, we combine staggered-conductance modulation with the large delays available in acoustic devices to realize an electro-acoustic gyrator. We also demonstrate the implementation of a microwave circulator based on this device.
The electro-acoustic gyrator is a balanced structure in which acoustic delay lines are placed between commutating switches. When the delay of the acoustic device is a one-fourth of the period of the modulation frequency, signals entering the network in the forward direction experience no loss with a 0° phase shift. However, in the reverse direction, the signals experience a sign flip. The S-parameters of the resulting network can be written as in Eq. (1) inside the bandwidth of the acoustic delay lines, where ω_{in} is the frequency of the signal entering the network and ω_m is the modulation frequency.

$$S = \begin{pmatrix} 0 & -e^{-j\frac{\pi\omega_{in}}{2\omega_m}} \\ e^{-j\frac{\pi\omega_{in}}{\omega_m}} & 0 \end{pmatrix} \tag{1}$$

When ω_m is chosen so that $\omega_{in}= (2n+1)\ \omega_m$, the S-parameters collapse to those of an ideal gyrator. Since acoustic delay lines are inherently band-limited, ω_m must be less than half the bandwidth of the delay line. Furthermore, the unavoidable presence of dispersion in low-loss acoustic devices presents a further limitation on ω_m and it must be accounted to avoid further loss and undesired effects. These considerations are explored further in the design and PCB implementation of a 1.95GHz circulator with a 50 MHz modulation frequency. At 1.95GHz, the resulting device has measured insertion losses of -3.63dB, -3.28dB, and -8.86dB for S_{21}, S_{32}, and S_{12} respectively. The isolation levels for reverse transmission are -10.7dB, -11.42dB, and -41.92dB for S_{12}, S_{23}, and S_{31} respectively. These results place the electro-acoustic gyrator as a highly effective method of implementing non-reciprocal components with very low modulation frequencies.