Magnetless Non-Reciprocal Components based on Spatio-Temporal Conductivity-Modulation

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***Abstract*—Non-reciprocal components, such isolators and circulators, have a wide range of applications at radio frequencies and millimeter-waves in wireless communications and radar systems, to name a few. We demonstrate that by modulating the conductivity around a delay medium, non-magnetic, low-loss, compact and broadband non-reciprocity can be achieved. CMOS circulators at 750 MHz and 28 GHz validate our claims.**

I. Introduction

It is well known that any linear, time-invariant medium or circuit comprised of a material with symmetric permittivity and permeability tensors is reciprocal. Non-reciprocal components, however, are critical to radio-frequency and millimeter-wave wireless systems. For example, the circulator is a vital component in wireless systems which share a single antenna between the transmitter and the receiver at the same frequency, such as monostatic radars and full-duplex wireless. Isolators are required to protect transmitters from back reflections at the antenna. Reciprocity can be broken by violating any one of the conditions required by the Lorentz reciprocity. The most common approach to break reciprocity is by biasing Faraday-active magnetic materials (ferrites) in a constant magnetic field. However, due to the need for permanent magnets and the fact that ferrite materials are incompatible with integrated circuit fabrication processes, these solutions are limited in their cost, size, and weight. CMOS-compatible, active non-reciprocal components have been proposed using the inherent non-reciprocity of an active device. However, active techniques are limited due to their poor linearity and noise performance.

Achieving non-reciprocity using time-variance has gained significant research attention in the recent years. Permittivity has been commonly used as the variable parameter, and is modulated in RF circuits using varactors. The approach in [1] uses varactors in a traveling-wave architecture to achieve non-reciprocity. However, in general, permittivity modulation is very weak – varactors in CMOS have a small modulation contrast of 2 – 4 - due to which these structures tend to have a large form factor to achieve strong non-reciprocity. An approach based on angular momentum biasing of resonant rings was proposed and implemented at microwave frequencies using lumped LC sections with a very small form factor [2]. However, the use of such LC resonances results in small operational bandwidths [2].

On the other hand, conductivity in semiconductors exhibits a very large modulation contrast – CMOS transistors exhibit ON/OFF conductance ratios of $10^3 – 10^5$. Using this insight, we have demonstrated loss-free, compact, broadband non-reciprocity by modulating conductivity around a delay medium. Here, we review the concept of spatio-temporal conductivity-modulation [3-7], and present the performance of circulator prototypes at RF (750 MHz) and millimeter-waves (25 GHz).

II. Spatio-Temporal Conductivity-Modulation

Our switch-based conductivity-modulation concept consists of a delay medium that is sandwiched between two sets of transistors. The passive transistor switches are toggled between ON and OFF states to modulate the conductivity around the delay medium. By choosing an appropriate delay in the medium and synchronization between the modulating clocks, lossless phase non-reciprocity (gyration) is achieved. The gyrator can then be used to realize non-reciprocal 3-port circulators.

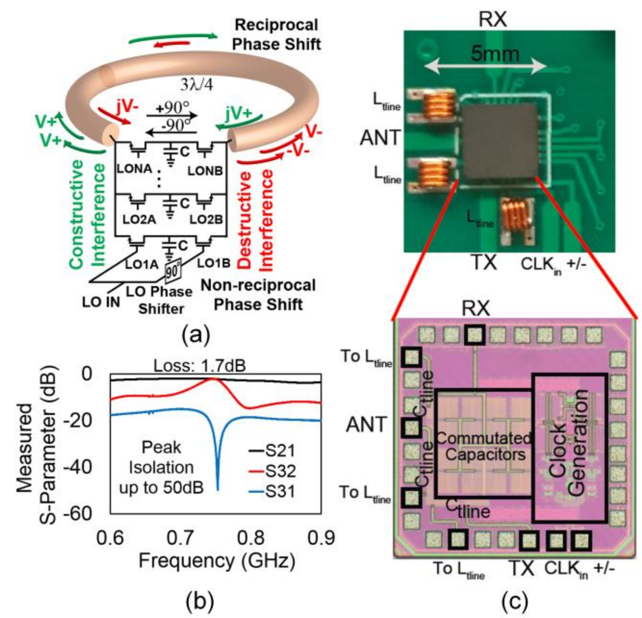

Fig. 1. (a) A 3λ/4 line is wrapped around the N-path-filter-based gyrator to support non-reciprocal wave propagation. (b) Measured S-parameters of the 750MHz 65nm CMOS circulator built using the N-path-filter-based gyrator. (c) 750MHz 65nm CMOS circulator chip photo.

At low RF frequencies, N-path filters have recently become very popular due to their ability to realize tunable high-quality-factor bandpass filters without the use of inductors. N-path filters are linear periodically-time-varying (LPTV) circuits that consist of switches that periodically commutate the signal across a bank of capacitors. We found that a two-port N-path filter with a phase shift between the input and output modulation clocks achieves phase non-reciprocity in addition to the tunable bandpass filtering [3]. The use of a 90º phase shift between the input and output clocks results in low-loss reciprocal forward and reverse transmission magnitude but with a non-reciprocal +/- 90º phase shift, realizing essentially an ultra-compact inductor-free LPTV gyrator.

Circulation can be realized by wrapping a transmission line of length 3λ/4 around the gyrator (Fig. 1(a)). In the clockwise direction, the -270º phase shift from the 3λ/4 transmission line combines with the -90º phase shift from the gyrator to support wave propagation. In the counter-clockwise direction, the -270º phase shift from the line combines with +90º from the gyrator to prohibit wave propagation. A circulator can be realized by introducing three ports, TX, ANT and RX, on the line while maintaining λ/4 distance between them. The TX power handling of the circulator can be increased significantly by placing the RX port next to the gyrator. Due to the circulator's isolation, the RX port, and hence the nodes of the gyrator, are quiet for TX excitations, enhancing linearity and power handling. A 65nm CMOS circulator was implemented based on these concepts (Fig. 1(c)), and achieves a measured insertion loss of 1.7dB and strong TX-to-RX isolation [4].

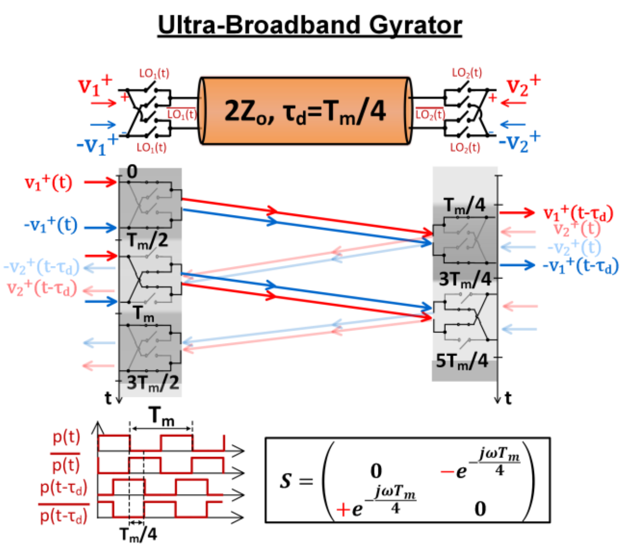

Fig. 2. Ultra-broadband gyrator based on generalized switch-based spatio-temporal conductivity modulation.

A drawback of N-path filters is their inherently narrow bandwidth due to the filtering response that is created. N-path filters are also not readily scalable to millimeter-waves due to their stringent clocking requirements. To this end, we devised a new generalized spatio-temporal conductivity modulation concept, shown in Fig. 2. A differential transmission line is sandwiched between two Gilbert-quad switch sets. The delay between the modulation clocks is equal to one quarter of the modulation period, which is also equal to the delay provided by the transmission line. As a result, a signal travelling from left to right will experience no sign inversion and two sign inversions in the first and second half periods respectively, as shown in Fig. 2. On the other hand, a signal travelling from right to left experiences one sign inversion in both half periods. Consequently, the structure has no loss but a perfectly broadband non-reciprocal phase response of 180º, making it a lossless gyrator over theoretically infinite bandwidth. The modulation clock can also be substantially lower than the operating frequency, enabling the scaling of this structure to millimeter-waves.

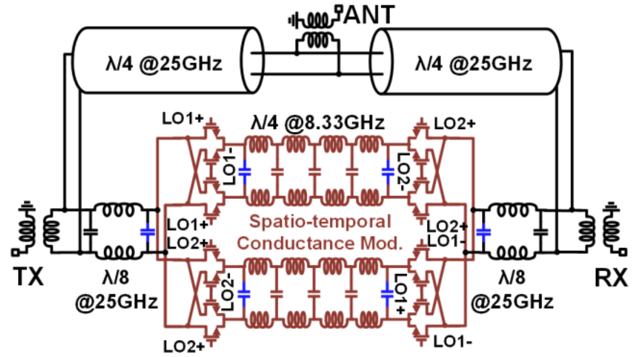

Fig. 3. Circuit diagram of a 25GHz circulator in 45nm SOI CMOS based on the ultra-broadband gyrator.

Based on this concept, a 25GHz circulator was implemented in 45nm SOI CMOS, with the modulation clock operating at 8.33GHz [5,6]. The circuit diagram is shown in Fig. 3. The circulator achieved measured insertion losses of 3.2-3.3dB and near-20dB isolation (limited by the measurement setup) over the 1-dB insertion loss bandwidth of 4.6GHz.

CONCLUSION

This paper reviewed the first CMOS non-magnetic passive circulators reported. Topics for future research include techniques to push the TX power handling towards 1W and beyond, and the incorporation of antenna tuning within the circulator to maintain isolation across varying VSWR.

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