Magnetic-free Circulator Based On Spatio-Temporal Modulation Implemented via Switched Capacitors For Full Duplex Communication

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***Abstract*—Conventional microwave circulators rely on ferromagentic materials to break the time-reversal symmetry, and thus realizing a non-reciprocal passive device. In terms of system design, the use of ferromagentic materials renders the circulator integration with other transceiver blocks difficult, because they are still incompatible with CMOS fabrication processes. Recently, the concept of spatio-temporal modulation has been introduced to break the time-reversal symmetry, alleviating the need of ferromagnetic materials. In this paper, we present the design of a magnetic-less linear passive circulator based on spatio-temporal modulation of lumped first order LC resonators connected in a Y topology. Unlike other approaches, in this work the spatio-temporal modulation is implemented using switched capacitors, which yield a much simple circuit and has the advantage of high linearity. As a proof of concept, we designed a circulator at 1 GHz that shows an isolation of 44 dB with an insertion loss of 2.9 dB.**

I. Introduction

Same frequency full duplex communication doubles the channel capacity, since one could *simultaneously* transmit and receive over the same frequency channel. This feature makes it an attractive candidate for the upcoming 5G mobile standard, where high data rates are required to support for example high quality video streaming. In a typical full duplex architecture, a circulator is needed to route the transmitted/received signals as well as to isolate the transmitter from the receiver. In conventional circulator design, a ferromagnetic material is used to break the time-reversal symmetry leading to a non-reciprocal device. This resulted in a bulky device and made the circulator difficult to integrated with other CMOS based circuits. For that reason, using full duplex communication became practically unappealing, and thus realizing a magnetic-free and CMOS compatible circulators is the bottleneck to implementing full duplex communication in modern transceivers.[1]

To avoid the use of ferromagnetic materials, the concept of angular momentum biasing has been introduced to break the time-reversal symmetry [2]. When ferromagnetic materials are subjected to an external magnetic field, the electrons are forced to *rotate* in a certain direction as shown in Fig.1(a), and as a result non-reciprocity is achieved. In analogy, time-reversal symmetry can be broken by directly biasing the medium with an angular momentum vector (Ω). It was illustrated in [3] that

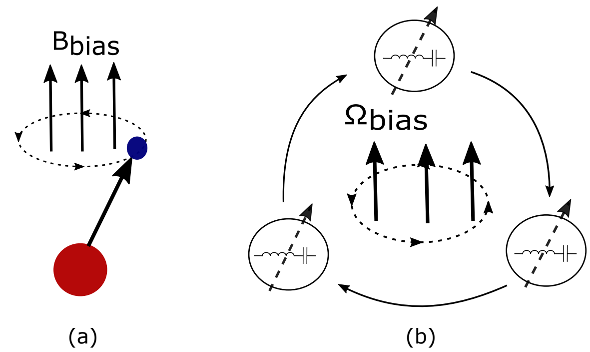

Fig. 1. Achieving non-reciprocity: (a) external mangetic field biasing ferromagnetic materials and (b) angular momentum biasing resonant tanks .

angular momentum biasing can be achieved by modulating the resonance frequency of three resonant circuits with continuous periodic signals that are phase shifted from one another, hence the name *spatio-temporal modulation* as shown in Fig.1(b). So far to practically realize the modulation, varactors have been used to modulate the resonance frequency[3]. However, the non-linearity of the varactors affects the circulator linearity as well as its power handling. In addition, filters are needed to isolate the RF frequency (f_{rf}) from the modulation frequency (f_{fm}), which complicates the circulator design. In this paper, we tackle this problem by designing, as a proof of concept, a circulator at 1 GHz based on switched capacitors. The simulated S-parameters of the circulator shows an isolation of 44 dB, insertion loss of 2.9 dB, and return loss of 11 dB.

II. Results and Discussion

The investigated topology is comprised of three series LC tanks (first order band-pass filters) that are connected in a Y topology as shown in Fig.2. First, the value of the inductor (L1) and the capacitor (C1) are chosen to resonate around 1 GHz. The frequency of operation has been chosen as we plan to integrate the circulator with a full duplex transceiver designed to operate at 1 GHz. Furthermore, a switch in series with a capacitor (Cm) is connected in shunt with the main capacitor (C1). The switch is a Single Pole Single Throw (SPST) switch that is controlled by a square pulse with one-third duty cycle i.e. the pulse width is one-third the period (1/T_m). To realize the spatio-temporal modulation, the control signals are delayed with respect to each other by one-third the period (0, $T_m/3$ and $2*T_m/3$). A current excited at any port propagating with frequency f_{RF} can be decomposed into three propagating modes; a common mode, a mode that rotates in a clockwise direction (right-handed rotation), and a mode that rotates in an anti-clockwise direction (left-handed rotation). Without modulation, these modes are degenerate (exists at the same frequency) and the power gets split equally. However, the application of spatio-temporal modulation lifts the degeneracy by favoring one direction of rotation, which is the direction of phase increase) leading to an un-even power split. The performance of the circulator can be optimized by varying the modulation frequency (f_m) and the switched capacitor value (C_m). After extensive numerical optimization, Fig.3 shows the circulator optimized S-parameters for modulation frequency of f_m=160 MHz and switched capacitor of C_m=0.74 pF. At 1 GHz, the circulator shows an isolation ($|S_{21}-S_{31}|$) of 44 dB, insertion loss of 2.9 dB, and return loss of 11 dB. Finally, it is worth mentioning that the proposed switched-capacitor approach simplifies the circuit, since no filters are needed to isolate the RF frequency from the modulation frequency.

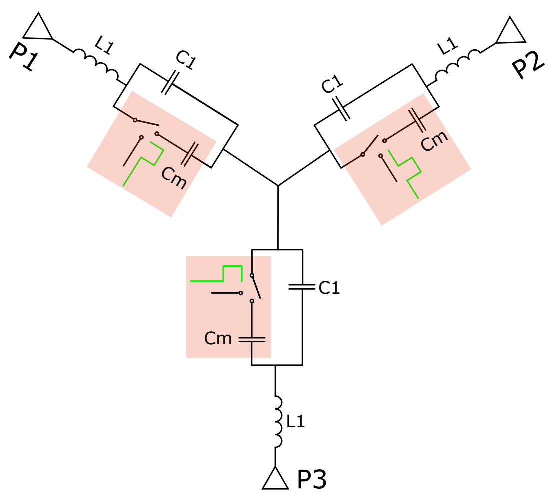

Fig. 2. Realizing spatio-temporal modulation using switched capacitors. The control signals are square pulses with one-third duty cycle and are delayed with respect to each other by one-third a period $(0, T_m/3$ and $2*T_m/3)$

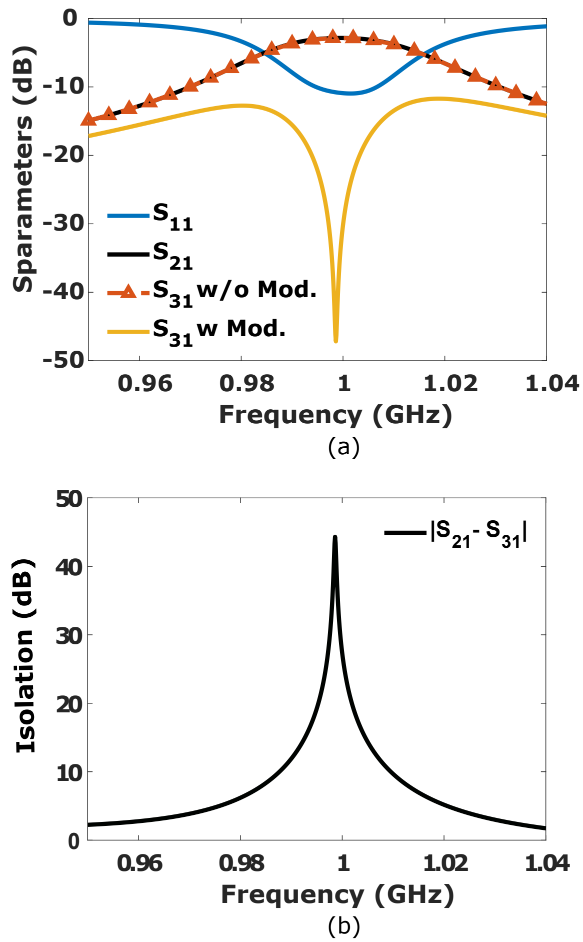

Fig. 3. Simulated Circulator: (a) Sparameters and (b) Isolation.

III. Conclusions

In this paper, we discussed the concept of breaking the time-reversal symmetry, and hence achieving non-reciprocity, using angular momentum biasing. Furthermore, we investigated the use of switched capacitors to realize angular momentum biasing through the spatio-temporal modulation of three LC series tanks connected in a Y topology. The proposed approach resulted in an isolation of 44 dB with an insertion loss of 2.9 dB. This result is promising as designing a circulator without ferromagnetic materials can open the door into implementing a cost-effective full duplex system in CMOS technology for upcoming 5G mobile applications.

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