A Wideband Magnetic-Free Circulator Using Spatio-Temporal Modulation of 2-pole Bandpass Filters

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***Abstract*— Spatio-temporal modulation (STM) has been recently introduced to efficiently implement angular momentum biasing, which is a biasing technique that breaks the time reversal symmetry yielding a non-reciprocal response. In literature, several circulators have been designed using STM of triple first-order series or shunt resonators connected in Y or Δ topology. Utilizing first-order resonators leads to a narrow band response in terms of isolation and return loss. In this paper, we tackle this problem by using a 2-pole series bandpass resonators. As a proof-of-concept, the circulator is designed at 500 MHz, and demonstrates a 15-dB isolation fractional bandwidth of 8.5%, insertion loss of 3.9 dB, and return loss of better than 13 dB.**

***Index Terms*— Magnetic-free Circulator, Spatio-Temporal Modulation, Higher-Order Filters, Y Topology.**

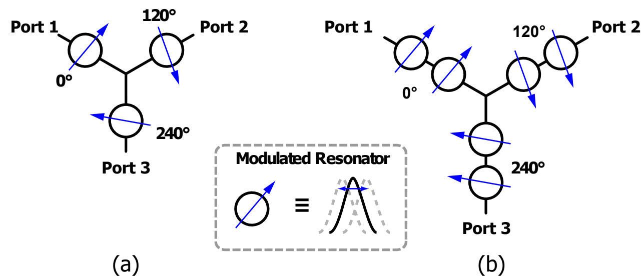

Fig. 1. Magnetic-free circulator based on STM of (a) resonator and (b) 2-pole bandpass filter.

I. Introduction

Conventionally, non-reciprocity in the RF and microwave frequency ranges is achieved using ferromagnetic materials exposed to an external magnetic field. This approach results in devices, such as isolators and circulators, that are bulky, expensive, and hard to integrate with other circuitries. Angular momentum biasing was introduced in [1] as an alternative biasing technique that does not require any magnets. The non-reciprocity was achieved by spatio-temporal modulation (STM) of the relative permittivity of a ring resonator along the azimuth direction with a sinusoidal wave of frequency f_m. The modulation creates intermodulation products ($f_{RF} \pm f_m$) with a preferred sense of rotation, i.e. the degeneracy of the resonant modes are shifted by the application of the angular modulation. Conceptually, the modulation is taking place in space (modulating the medium) and by a time-varying signal, hence the name spatio-temporal modulation [2]. The disadvantage with this approach is a relatively weak modulation effect.

A more efficient implementation was illustrated in [2]. Instead of modulating a continuum medium, the ring resonator is broken up into 3 coupled resonators. The resonant frequency of the resonators are modulated to create the angular momentum biasing. To this end, a progressive phase shift of 120° is applied to the modulation signals, as illustrated in Fig. 1(a).

Several STM based circulators have been demonstrated in literature. In [3], three series LC resonators were connected in a Y topology. Although the circulator showed an isolation ($|S_{21}|$ (dB)-$|S_{31}|$ (dB)) better than 50 dB, it suffered from a large insertion loss of 10 dB. The loss was attributed to the generation of a large number of higher order intermodulation (IM) products. In [4], a differential architecture was proposed to reduce the spurious IM products. The proposed architecture is comprised of two single-ended (SE) STM-based circulators with opposite rotation direction, i.e. there is a 180 ° phase difference between the modulation signals applied to each SE circulator. When compared to the single-ended circulators, the differential architecture not only significantly improved the circulator performances in terms of insertion loss, return loss, and isolation, but also relaxed the required modulation frequency and depth.

To date, all reported STM-circulators utilize single resonators, which result in an isolation bandwidth of 2–3%. In [5], an isolation bandwidth of 13.9% was achieved by using a bandpass filter as a matching network, while the circulator core is still first-order.

In this work, we propose an alternative approach to widening the isolation bandwidth by incorporating a 2-pole bandpass resonators as shown in Fig. 1(b). Compared to [5], the proposed approach has the advantage of using less number of components. In addition it adds degrees of freedom since the modulation parameters of each resonator can be set separately.

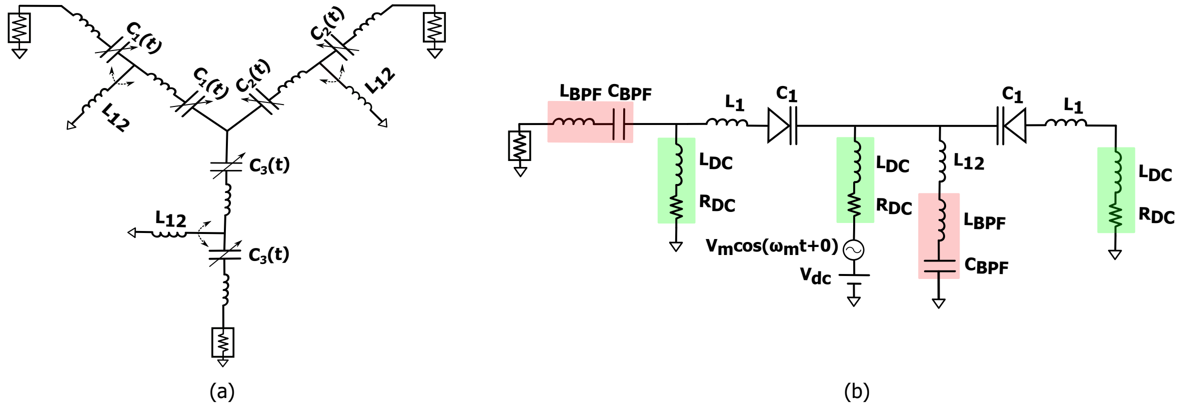

Fig. 2. Proposed circulator architecture: (a) 2-pole bandpass resonators connected in a Y topology and (b) practical implementation of a time-varying capacitor using varactors along with the necessary biasing network and filters.

II. Proposed Circulator Architecture

As shown in Fig. 2(a), the proposed circulator is composed of three 2-pole bandpass (series LC resonators) filter connected in a Y topology. The resonant frequency, viz., the operation frequency of circulator, is chosen to be 500 MHz to ensure the availability of modulation sources and high quality factor passive components . The coupling between each resonator is controlled by a shunt inductor L_{12}.

The STM of the filter center frequency is achieved by modulating the capacitance of each resonator. In practice, this variable capacitor can be implemented with diode varactors. For simplicity, the modulation phase of the two varactors in each filter branch is set to be the same. Similar to Fig. 1, there is a progressive phase shift of 120° between the three filter branches in order to implement angular momentum biasing.

Fig. 2(b) depicts a practical implementation of the STM using diode varactors along with the necessary biasing networks. The overall capacitance of the varactors can be expressed mathematically as

$$C_n(t) = C_0 + \Delta C \cos\left[\omega_m t + \frac{2(n-1)\pi}{3}\right], \quad (1)$$

where $n = 1, 2, 3$. C_0 is the mean capacitance when the varactors are biased with dc voltage V_{dc}, ΔC is the modulation index that relates to V_m, and ω_m is the modulation frequency. Furthermore, a bandpass filter (L_{BPF} and C_{BPF}) with center frequency at f_{RF} is used to eliminate any interference between the input RF frequency (f_{RF}) and the modulation frequency (f_m). Finally, a low pass filter (L_{DC}) in series with a resistor (R_{DC}) are used to provide a path to ground for the dc bias and the modulation frequency.

III. Simulation Results and Discussion

First, we start by investigating the circuit response without applying any modulation (Fig. 3).The non-modulated triple-port circuit behaves as a bandpass filter with low-ripple transmission characteristics between 0.48 GHz to 0.52 GHz. Clearly, because all three ports are connected due to the absence of the STM, imperfect return loss and insertion loss can be clearly observed. We will demonstrate that the proper filter shape is restored when STM is turned on.

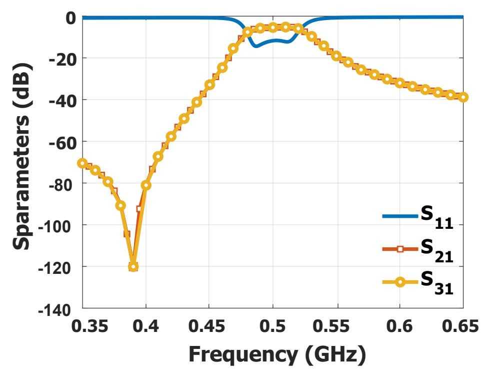

Fig. 3. **Non-modulated** response showing a general 2-pole filter characteristics with a flat passband and two poles in the return loss.

There is a transmission zero at 390 MHz, which is attributed to the shunt coupled branch (L_{12}, L_{BPF} and C_{BPF}) in Fig. 2 (b).

By applying a sinusoidal signal with modulation frequency of 60 MHz and amplitude of 2.2 V, the non-reciprocal response shown in Fig. 4 is obtained. It is worth mentioning that Skyworks SMV1231 varactor has been used in simulation. To highlight the advantage of using 2-pole filters, Fig. 5 shows the S-parameters of the circulator based on first order resonators. It is clear that the 2-pole filter based circulator shows a flatter passband, and a better return loss over a larger bandwidth. More importantly, the port 1-to-3 isolation (S_{31}) is uniformly better than 20 dB across the entire working bandwidth for the 2-pole filter based circulator.

Fig. 6 compares the isolation ($|S_{21}|$(dB)-$|S_{31}|$(dB)) of the single-resonator and 2-pole filter based circulators. Although single-resonator circulators can achieve larger isolation of 35 dB, the corresponding 15-dB isolation bandwidth is very narrow (2.5%). On the other hand, the 2-pole filter based circulator shows two isolation peaks with a maximum isolation of 28 dB and attains a 15-dB isolation fractional bandwidth of 8.5%. Critical parameters used in the simulation are summarized in Table I.

The prototyping of the proposed STM circulator design is currently in progress. The measurement results will be presented at the conference.

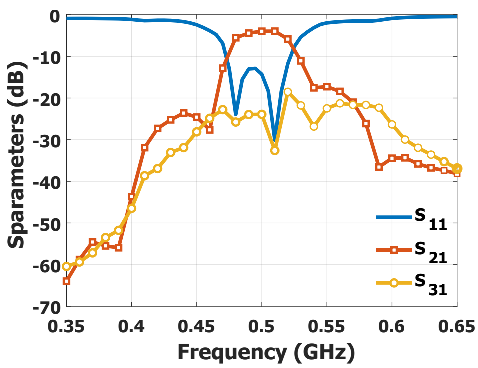

Fig. 4. Simulated S-parameters of the proposed circulator based on STM of 2-pole filters .

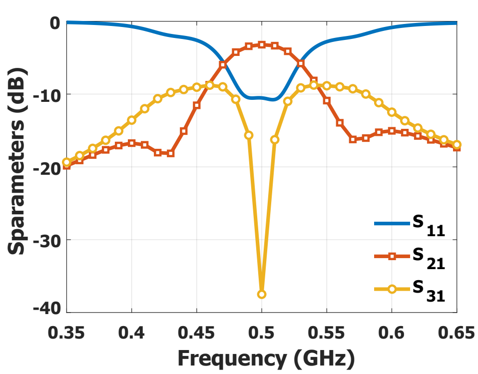

Fig. 5. Simulated S-parameters of the circulator based on STM of single resonators.

IV. Conclusion

In this paper, we present a magnetic-free circulator based on the spatio-temporal modulation of 2-pole bandpass resonators. 2-pole isolation with dual isolation peaks is obtained with flat passband and return loss better than 13 dB, which also has two poles in the passband and behaves as a 2-pole bandpass filter. The proposed circulator with its large isolation bandwidth along with the flat passband responses makes it a suitable candidate for applications such as full duplex wireless communication, frequency division relay systems, and automotive radars.

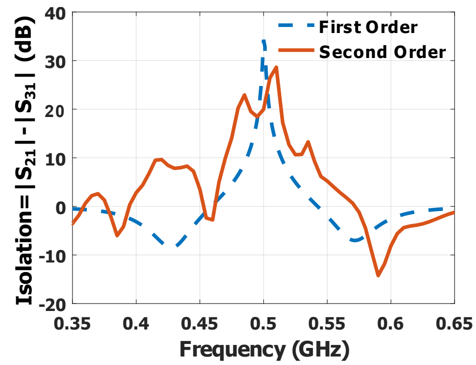

Fig. 6. Simulated isolation performance for circulators with single resonator and 2-pole filters.

TABLE I
List of Critical Simulation Parameters

Parameter		Value
Resonator	$\mathbf{L_0}$	120 nH
	$\mathbf{C_0}$	0.73 pF at 4.4 V
	$\mathbf{\Delta C}$	0.32 pF
Bandpass Filter	$\mathbf{L_{BPF}}$	27 nH
	$\mathbf{C_{BPF}}$	3.9 pF
Coupling	$\mathbf{L_{12}}$	16 nH
Biasing	$\mathbf{R_{DC}}$	0.5 kΩ
	$\mathbf{L_{DC}}$	180 nH
Modulation	$\mathbf{f_m}$	60 MHz
	$\mathbf{V_m}$	2.2 V

References

[1] D. L. Sounas, C. Caloz, and A. Alu, "Giant non-reciprocity at the subwavelength scale using angular momentum-biased metamaterials," Nat. Commun., vol. 4, p. 2407, Sept. 2013.
[2] N. A. Estep, et al. "Magnetic-free non-reciprocity and isolation based on parametrically modulated coupled-resonator loops," Nature Physics, vol. 10, no. 12, pp. 923-927, 2014.
[3] N. A. Estep, D. L. Sounas, and A. Alu, "Magnetless microwave circulators based on spatiotemporally modulated rings of coupled resonators," IEEE Trans. Microw. Theory Techn., vol. 64, no. 2, pp. 502-518, 2016.
[4] Ahmed Kord, Dimitrios L. Sounas, Andrea Alu, "Pseudo-Linear Time-Invariant Magnetless Circulators Based on Differential Spatiotemporal Modulation of Resonant Junctions," IEEE Trans. Microw. Theory Techn., vol. 66, no. 6, pp. 2731-2745, 2018
[5] Ahmed Kord, Dimitrios L. Sounas, Zhicheng Xiao, Andrea Alu, "Broadband Cyclic-Symmetric Magnet-less Circulators and Theoretical Bounds on their Bandwidth," arXiv:1805.0194.