Magnet-Free Circulators Based on Linear Time-Varying Circuits

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Abstract— **In this project report, we summarize the results on magnet-free circulators based on spatiotemporal modulation of three-port resonant junctions. Optimal single-ended implementations based on series or parallel *LC* tanks connected in a wye or a delta topology, respectively, are developed. Also differential implementations based on combining two single-ended circuits in either a voltage- or a current-mode architecture, resulting in pseudo-linear time-invariant devices with enhanced performance, are presented. Moreover, CMOS integrated and MEMS implementations, suitable for low-cost and large-scale production, are presented. Also, broadband implementations based on combining a narrowband junction with conventional bandpass filters are developed. The proposed circuits are all validated with theoretical, simulated and measured results, with unprecedented performance nearly in all metrics in comparison to the current state of the art.**

I. Introduction

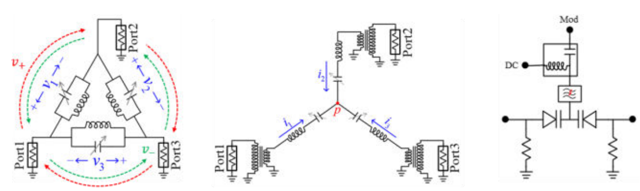
Time-reversal symmetry is a fundamental property of many physical and engineering systems which implies that the laws governing such systems are invariant if the evolution of time is reversed. Breaking this symmetry is essential to realize non-reciprocal components such as isolators, gyrators, and circulators, which have many applications at different parts of the electromagnetic (EM) spectrum. For instance, isolators are necessary in optical systems to protect laser sources from reflections. Also, gyrators permit the realization of passive networks that cannot be built by using only the conventional *RLC* elements and transformers such as high-*Q* frontend filters. More importantly, circulators are crucial to enable full-duplex communication, which has been gaining a lot of interest recently in anticipation of future high-throughput applications that require simultaneous transmission and reception on the same frequency.

Traditionally, non-reciprocity has been achieved through magnetic biasing of rare-earth ferrite materials leading to bulky and expensive devices which are incompatible with conventional integrated-circuit (IC) technologies. In order to overcome this problem, magnetless implementations of such components have been pursued over the past few decades, based on self-biased hexaferrites, transistors, or parametrically modulated networks. Among these different approaches, linear time-varying circuits have shown the utmost promise to satisfy all the necessary requirements of practical systems, including low-loss, low-noise, high-power, low-cost, and small size. In this context, we present in this report the so-called spatiotemporally modulated angular-momentum (STM-AM) biased circulators. In Section II, we explain how these magnet-free non-reciprocal circuits work and present optimal implementations using discrete, CMOS, and MEMS technologies. In Section III, we summarize the measured results of all designs and highlight their remarkable performance in comparison to the current state of the art. Finally, we draw our conclusions in Section IV.

II. STM-AM Magnetless Circulators

Magnetic circulators consist of a ferrite cavity symmetrically attached to three ports at 120 deg intervals and biased with a magnetic field that aligns the electrons' dipole moments in the same direction. This, in turn, provides a preferred sense of precession for the two counter-rotating modes excited in the cavity by an impinging wave on an input port and allows them to destructively interfere at one output port and sum up at the other, in a cyclic-rotating fashion. Interestingly, the same effect can be achieved without magnetic fields by spatiotemporally modulating the oscillation frequencies of three coupled resonators forming a three-port junction with signals having the same frequency and amplitude but their phases increase by 120 deg in a particular direction.

Fig. 1 shows the optimal single-ended implementations (S.E.) of STM-AM circulators, which consist of three parallel or series *LC* tanks connected in either a delta or a wye topology, respectively, and the natural oscillation frequencies of the tanks are modulated through a pair of common cathode varactors. While these circuits can indeed achieve large isolation at the fundamental harmonic (see Table I), they still suffer from two problems: (i) strong intermodulation (IM) products due to mixing between the RF and modulation signals and (ii) narrow bandwidth. The first problem can be solved by using a differential architecture, which combines two single-ended



(a) (b) (c)

Fig. 1. Single-ended STM circulators: (a) Delta topology. (b) Wye topology. (c) Variable capacitor implementation.

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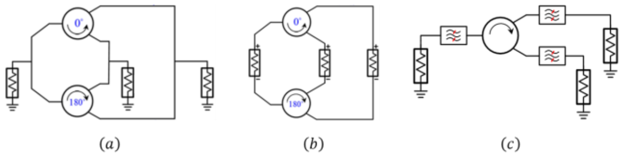

Fig. 2. Differential STM circulators: (a) Voltage-mode. (b) Current-mode. (c) Broadband implementation.

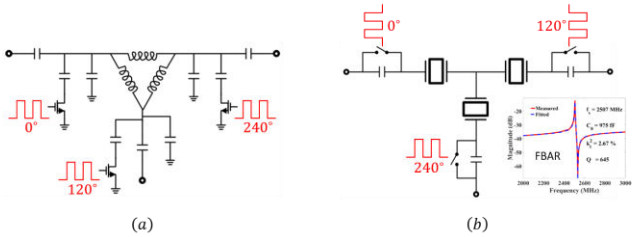

Fig. 3. Chip-scale STM-AM circulators: (a) CMOS implementation. (b) MEMS implementation.

delta or wye circuits with a constant 180 deg phase difference between their modulation signals in voltage- or current-mode architecture, as shown in Fig. 2(a) and Fig. 2(b), respectively. The cancellation of the IM products enhances the performance of all metrics (see Table I) and makes these circuits act as a pseudo-linear time-invariant system which, in turn, permits cascading them with identical bandpass filters as shown in Fig. 2(c) to reshape their non-reciprocal frequency response and increase the 20 dB IX BW three-fold (see Table I).

The magnetless circulators circuits presented so far can indeed achieve remarkable performance in all metrics (see Table I), yet they are based on PCB technology and off-the-shelf discrete components, which limits their size and cost efficiency and prohibits large-scale production. In order to overcome this problem, an IC implementation is highly desirable. Fig. 3 shows a proposed chip-scale implementation wherein the varactors are replaced by switched capacitors allowing their integration using a standard 180 nm CMOS process, thus reducing the form factor to only 36 um2.

The form factor of CMOS STM-AM circulators is limited by the fact that they require high-Q inductors (>50) which cannot be integrated on chip. In order to overcome this problem, an inductorless MEMS implementation which replaces the *LC* tanks by compact thin-Film Bulk Acoustic Resonators (FBARs) is proposed in Fig. 3(b). Interestingly, the high-Q (>1000) of the FBARs also drastically reduces the modulation frequency to 0.24% of the circulator's center frequency, the lowest among all magnetless circulators reported to-date.

III. Conclusions

I am planning to pursue an academic career in the United States focusing on RF and microwave engineering for a variety of applications including wireless communications and bioelectronics. The MTT-S Graduate Fellowship has been a great recognition to which I am deeply grateful and it shall help me outstand in a very competitive community to achieve my career goals. I am also thankful I had the opportunity to attend the IMS 2018 and interact with excellent researchers from top-tier universities and companies.

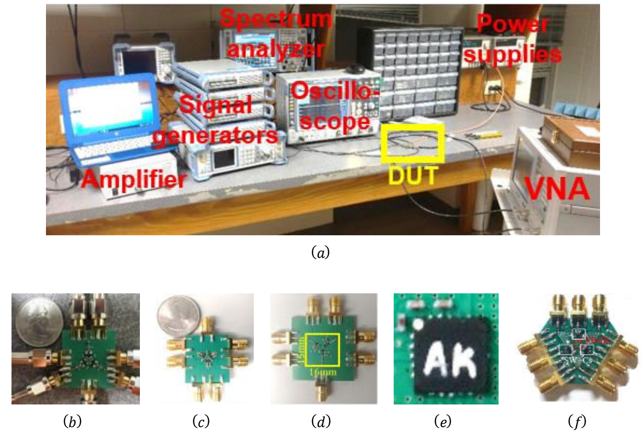

Fig. 4. Photographs of (a) experimental setup and (b)-(f) prototypes. (b) Single-ended. (c) Differential. (d) Broadband. (e) CMOS. (f) MEMS.

TABLE I
Summary of The Measured Results

Metric\Circ.	[2]	[3]	[4]	[5]	[7]
RF Freq. (MHz)	1000	1000	1000	915	2506
Mod Freq. (%)	19	10	11	12	0.24
BW (%)	2.4	2.3	14	4.3	0.72
IX (dB)	>20	>20	>20	>20	>20
IL (dB)	<3.4	<2	<5.8	<5	<5
RL (dB)	>9	>20	>12.6	>9	>15
Phase (deg)	Linear	Linear	Linear	Linear	Linear
P1dB (dBm)	>+29	>+28	>+23	N/A	>+28
IX20dB (dBm)	>+29	>+28	>+23	N/A	N/A
IIP3 (dBm)	>+33	>+32	>+35	+6.1	>+40
NF (dB)	<4.5	<2.7	N/A	<5.4	N/A
IM (dBc)	<-11	<-30	N/A	<-19	<-20
Size (mm2)	143	286	480	36	100

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