Magnetic-Free, Fully Integrated, Compact Microwave Circulator Using Angular-Momentum Biasing

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***Abstract*—Conventional non-reciprocal devices use ferromagnetic materials and an impressed external magnetic bias to break time-reversal symmetry. This solution typically leads to impractically large devices, losses and it is incompatible with integrated circuit technology. We discuss here a different approach to realize non-reciprocal microwave components and materials, based on biasing meta-molecules with the angular-momentum vector. We show that this solution can provide as large non-reciprocity and isolation as magnetically-biased ferrite components, but without their drawbacks. In particular, we present the design and realization of an integrated, magnetic-free, compact microwave circulator realized with conventional circuit components on a dielectric substrate, fully compatible with integrated circuit technology. By using appropriate spatiotemporal modulation of a magnetic-free distributed-element resonating ring, we report over 47 dB isolation and a deeply subwavelength size. We also envision the realization of non-reciprocal metasurfaces and metamaterials based on the same principle.**

I. Introduction

Microwave and optical applications require the use of non-reciprocal components in order to break the time-reversal symmetry in wave propagation. For instance, circulators are frequently used in telecommunication networks, such as RADARs, cellular communications and broadcasting systems, to connect transmitters and receivers to the same antenna, avoiding interference between them [1]. In electromagnetics, non-reciprocity is almost exclusively obtained through Zeeman splitting in magnetically-biased ferromagnetic materials, as represented in Fig. 1(a), which, however, are challenging to integrate into printed circuit boards and lead to bulky devices, due to the need of external magnetic biasing devices [2]. Previous efforts to create magnetic-free non-reciprocity included transistor-loaded ring metamaterials, which support unidirectionally rotating magnetic moments, thus mimicking electron spin precession in ferrites [3]. However, such metamaterials involve significant power consumption in the transistor biasing network and do not cover the practically important area of THz, IR and optical frequencies, where transistors are not available. An alternative method, theoretically introduced in [4], uses azimuthal spatiotemporal modulation to generate an effective biasing angular momentum vector, which can break time-reversal symmetry in a way analogous to magnetic bias, and can subsequently induce non-reciprocity, as envisioned in Fig. 1(b). This approach is in principle applicable to any frequency range and may be achieved using lossless integrated components already available on any circuit board. Here, we provide the first experimental validation of this technique by designing a magnet-less RF circulator with over 47 dB of isolation. The same subwavelength component may be also envisioned as a building block to realize magnet-less one-way mirrors and non-reciprocal metamaterials.

II. Results and Discussion

At the foundation of the proposed technique is an integrated ring resonator spatiotemporally modulated by an appropriate electric signal to sustain an effective azimuthal rotation of the substrate loading the ring [4]. In the device considered here such a component is coupled to three rotationally-symmetric waveguide ports, as shown in Fig. 2(a). The ports' signals of frequency f_s are mixed with modulation signals of frequency f_m, applied to all three ports with the same amplitude and a 120° phase difference, in order to create an effective azimuthal rotation that lifts the degeneracy between the counter-rotating ring modes and produces non-reciprocity. By using coupled-mode theory [5] and the analysis in [4], the conditions for ideal circulation may be derived as

$$Q\kappa_{\mathrm{m}} = 1, \quad f_m = f_s\kappa_{\mathrm{m}}\big/\sqrt{3}, \tag{1}$$

where Q is the quality factor of the ring resonator and κ_{m} is the coupling coefficient between the ring's counter-rotating states induced by the applied spatiotemporal modulation, which is proportional to the modulation amplitude.

The ring in the design presented here consists of three identical unit cells, made of lumped elements, as shown in Fig. 2(b). At the RF frequency f_s, each unit cell is a lumped element equivalent of a transmission-line segment with a varactor used in place of the shunt capacitance in order to obtain the spatiotemporal permittivity modulation required to induce an effective angular momentum bias. Then, coupled-mode analysis ensures that $\kappa_{\mathrm{m}}=\Delta C_{\mathrm{m}}/(2C_2)$, where C_2 and ΔC_{m} are the static and modulated capacitances of the varactor. To maximize the effect, the ring should also resonate at the modulation frequency f_m, which is achieved by adding series capacitances and shunt inductances to the unit cells. The coupling networks of the ring to the ports are also L-C parallel combinations and are necessary for tuning the ring's Q-factor at both frequencies.

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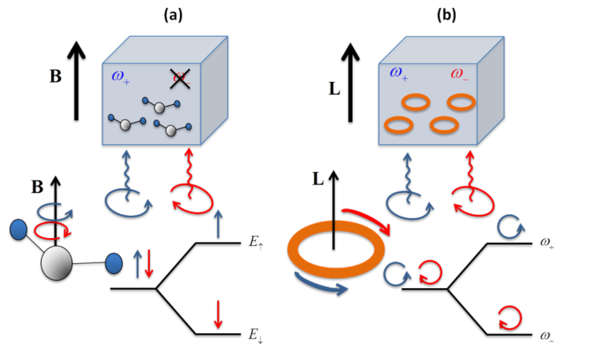

Fig 1. Non-reciprocal response based on (a) ferromagnetic media, and (b) angular-momentum-biased metamaterials. In ferromagnetic media, an external static magnetic bias (***B***) splits degenerate atomic states with opposite spin. Similarly, an externally applied angular-momentum vector splits counter-rotating degenerate modes of an azimuthally-symmetric ring, enabling non-reciprocity [4].

The circulator described in Fig. 2 was designed and fabricated to operate at a carrier frequency of approximately $f_s \approx 190$ MHz. Based on the design constraints in (1), the distributed elements were selected to respond to a modulation frequency $f_m \approx 15$ MHz. The coupling network was also designed to meet the isolation-factor requirements in (1). The final fabricated design is shown in the inset of Fig. 3: the phases of the modulation signals were manipulated prior to the resonator board and combined with the RF signals. Full-wave simulations reveal a resonance at 207 MHz, with a FWHM bandwidth of 15 MHz, in good agreement with the analytical predictions and experimental results. The measured prototype resonates around 170 MHz, due to differences between real components and the ideal ones used in the simulations. Without modulation, the transmission coefficient is evenly split between the two output ports around 170 MHz [see Fig. 3], as expected for a reciprocal three-port symmetrical junction. Conversely, when the modulation signal is applied, the two degenerate modes are split, resulting in destructive interference at one of the output ports and a subsequent transmission null. As shown in Fig. 3, the realized magnetic-free non-reciprocal device yields over 47 dB isolation.

III. Conclusions

A magnetic-free three-port circulator operating at 170 MHz with more than 47 dB isolation was designed, realized and successfully characterized, based on the recently proposed concept of angular-momentum bias to replace magnetic biasing and ferrite components. The presented results do not only open important pathways towards the realization of fully-integrated non-reciprocal antenna systems without magnetic bias, but may be translated also to higher frequency ranges, such as THz, near-IR and nanophotonic components. In addition, the basic component realized here may be envisioned in microstrip configuration to realize a fully integrated printed circulator. This component may be also used as a meta-molecule at the basis of non-reciprocal metasurfaces and metamaterials without magnetic bias: arrays of these elements may be able to induce one-way propagation and isolation in free-space for a variety of electromagnetic and antenna applications.

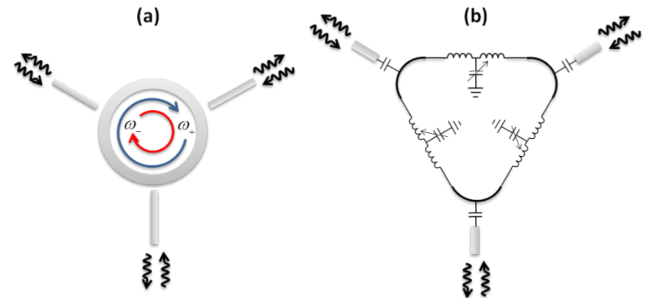

Fig 2. Geometry of the proposed three-port magnetic-free non-reciprocal component. (a) A conventional multiport resonant structure is reciprocal, with two counter-rotating degenerate modes. By removing this degeneracy through appropriate external biasing we create a circulator based on the constructive and destructive interference at the through and isolated ports. (b) Lumped element implementation of the ring resonator: each unit cell is a lumped element equivalent to a transmission line section. The shunt capacitance is implemented as a variable capacitor for achieving the necessary spatiotemporal modulation.

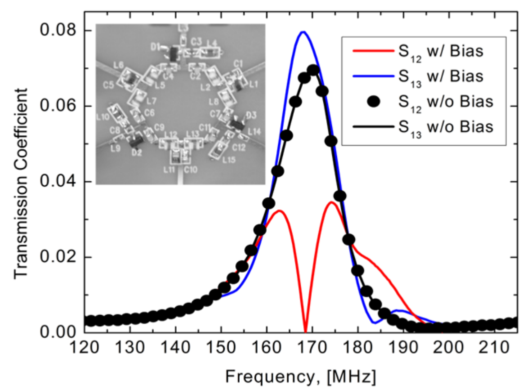

Fig 3. Experimental results for the realized magnet-less circulator with and without modulation. Without the modulation signal (black lines), the transmission is evenly coupled to both output ports. With modulation, the coupling becomes non-reciprocal, providing over 47 dB of isolation at approximately 170 MHz.

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