Non-Reciprocity Based on Synthetic Momentum Bias

Ahmed Kord
Department of Electrical and Computer Engineering
The University of Texas at Austin
Austin, TX, USA
ahmed.kord@gmail.com

Dimitrios Sounas
Department of Electrical and Computer Engineering
Wayne State University
Detroit, MI, USA
dsounas@wayne.edu

Andrea Alù
Photonics Initiative
Advanced Science Research Center
New York, NY 10031, USA
aalu@gc.cuny.edu

***Abstract*— In this contribution, we discuss our recent progress in the context of devices and metamaterials that break reciprocity through the synthesis of momentum bias induced by suitably designed spatio-temporal variations. After reviewing our progress and latest metrics to realize magnet-free isolators, circulators and antennas based on time-varying circuits, we discuss their signal transport properties in arrays of these elements, and their potential in realizing integrated full-duplex communication systems, which have been gaining significant interest recently in anticipation of future high-throughput applications that require simultaneous transmission and reception on the same frequency.**

I. Introduction

Time-reversal symmetry is a fundamental property of several 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 and circulators, with several electromagnetic applications. For instance, isolators are necessary in optical systems to protect laser sources from reflections. Circulators are crucial to enable full-duplex communications [1]-[9], which has been gaining interest in anticipation of future high-throughput applications that require simultaneous transmission and reception on the same frequency channel at the same time. Traditionally, non-reciprocity has been achieved through magnetic biasing of ferrite materials, leading to bulky and expensive devices devices which are incompatible with conventional integrated circuit (IC) technologies. In order to overcome this problem, magnetless implementations of non-reciprocal components have been pursued over the past few decades, based on self-biased hexaferrites and ferromagnetic nanowires [10]-[15], transistors [16]-[20], or parametrically modulated networks [21]-[33]. Among these different approaches, linear time-varying circuits have shown the utmost promise to satisfy all the necessary requirements of practical systems. In this context, several new techniques have been proposed based on spatiotemporal modulation angular momentum (STM-AM) biasing [21]-[29], *N*-path filtering [30], [31], and transmission line (TL) switching [32]. In particular, [21] showed that a cyclic-symmetric magnet-free circulator can be realized by coupling three resonators and modulating their oscillation frequencies with 120 deg phase-shifted periodic signals. [23] refined this concept further and derived the necessary conditions to achieve optimal performance, which resulted in the first Watt-level magnetless circulator. Furthermore, [24] developed a differential STM-AM circulator that dramatically enhanced the performance of many metrics, particularly insertion loss and noise figure which were reduced to 0.8 dB and 2.5 dB, respectively, the lowest among all magnetless circulators reported to-date. Also, [25] presented a broadband circulator with a 20 dB isolation bandwidth (BW) of 140 MHz and derived a theoretical bound on such metric. These works have been gaining a lot interest in the academic and industrial communities and, therefore, were accompanied by numerous advances using similar concepts at different frequency ranges and even in various physical domains [30]-[31]. In particular, [30] relied on staggered commutation of *N*-path filters to realize a highly miniaturized gyrator, which when embedded in a loop of reciprocal phase shifters can yield the operation of a circulator. [32] has shown that the gyrator can also be built using switched TLs instead, which increases the BW and reduces the modulation frequency by a factor of three compared to the *N*-path filter implementation. Similarly, [34], [35] relied on switched TLs to realize an ultra-wideband quasi-circulator.

Despite the significant improvements introduced in the above works, the maximum power handling of all magnetless circulators presented to-date is still limited to about 1 Watt. Furthermore, the inherent time varying characteristics of these circuits result in finite spurs due to mixing between the modulation signals and the inputs coming from the TX or the ANT ports. These spurs not only pose an interference problem to adjacent channels but they also effectively degrade the performance of the circulator itself. Specifically, they increase the insertion loss because of the power lost in generating them and they impose a restriction on the lowest possible modulation frequency to avoid aliasing from the image signals around the intermodulation (IM) products. [24] presented a partial solution to this problem based on connecting two single-ended (SE) circulators differentially. Nevertheless, the IM products were still limited to –30 dBc in practice because of finite non-linearities of the used varactors.

In this talk, we describe our efforts to address these challenges by exploring arrays of magnet-less circulators, showing how these circuits can improve the overall power handling, reduce insertion loss and broaden the bandwidth of operation of these devices. We will also provide physical insights into the operation of these devices, envision a path towards system integration and analyze wave propagation in metamaterials based on these elements.

REFERENCES

[1] D. Korpi, J. Tamminen, M. Turunen, T. Huusari, Y. S. Choi, L. Anttila, S. Talwar, and M. Valkama, "Full-duplex mobile device: pushing the limits," *IEEE Commun. Mag.*, vol. 54, no. 9, pp. 80–87, September 2016.

[2] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-Band Full-Duplex Wireless: Challenges and Opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sept 2014.

[3] B. Debaillie *et al.,* "Analog/RF Solutions Enabling Compact Full-Duplex Radios," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1662–1673, Sept 2014.

[4] D. Bharadia *et al.,* "Full duplex radios," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 375-386, Sept. 2013.

[5] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296-4307, Dec. 2012.

[6] M. Jain *et al., "*Practical, real-time, full duplex wireless," in *Proc. 17th Annu. Int. conf. Mobile Comput. Netw. ACM*, Las Vegas, NV, USA, Sept. 2011, pp. 301-312.

[7] J. I. Choi *et al., "*Achieving single channel, full duplex wireless communication," in *Proc. 16th Annu. Int. Conf. Mobile Comput. Netw. ACM,* Chicago, IL, USA, Sept. 2010, pp. 1-12.

[8] J. Zhou *et al.,* "Integrated full duplex radios," *IEEE Commun. Mag.*, vol. 55, no. 4, pp. 142–151, Apr. 2017.

[9] A. Kord, D. L. Sounas, and A. Alù, "Achieving Full-Duplex Communication: Magnetless Parametric Circulators for Full-Duplex Communication Systems," *IEEE Microw. Mag.*, vol. 19, no. 1, pp. 84-90, Jan. 2018.

[10] B. K. O'Neil and J. L. Young, "Experimental investigation of a self-biased microstrip circulator," *IEEE Trans. Microw. Theory Techn.,* vol. 57, no. 7, pp. 1669-1674, 2009.

[11] J. A. Weiss, N. G. Watson, and G. F. Dionne, "New uniaxial-ferrite millimeter-wave junction circulators," in *Proc. Int. Symp. IEEE MTT-S Microw.*, Long Beach, CA, USA, 1989, vol. 1, pp. 145–148.

[12] A. Saib, M. Darques, L. Piraux, D. Vanhoenacker-Janvier, and I. Huynen, "Unbiased microwave circulator based on ferromagnetic nanowires arrays of tunable magnetization state," *J. Phys. D, Appl. Phys.*, vol. 38, no. 16, pp. 2759–2763, Aug. 2005.

[13] L. P. Carignan, A. Yelon, D. Menard, and C. Caloz, "Ferromagnetic nanowire metamaterials: Theory and applications," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 10, pp. 2568–2586, Oct. 2011.

[14] S. A. Oliver *et al., "*Integrated self-biased hexaferrite microstrip circulators for millimeter-wavelength applications," *IEEE Trans. Microw. Theory Techn.,* vol. 49, no. 2, pp. 385-387, 2001.

[15] J. Wang *et al., "*Self-biased Y-junction circulator at Ku band," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 6, pp. 292-294, 2011.

[16] T. Kodera *et al.*, "Magnetless nonreciprocal metamaterial (MNM) technology: application to microwave components," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 3, pp. 1030–1042, Mar. 2013.

[17] T. Kodera, D. L. Sounas, and C. Caloz, "Artificial Faraday rotation using a ring metamaterial structure without static magnetic field," *Appl. Phys. Lett.*, vol. 99, Jul. 2011, Art. no. 03114.

[18] S. Wang, C. H. Lee, and Y. B. Wu, "Fully Integrated 10-GHz Active Circulator and Quasi-Circulator Using Bridged-T Networks in Standard CMOS," *IEEE Trans. Very Large Scale Integr. (VLSI) Sys.*, vol. 24, no. 10, pp. 3184–3192, Oct. 2016.

[19] C.-H. Chang, Y.-T. Lo, and J.-F. Kiang, "A 30 GHz active quasicirculator with current-reuse technique in 0.18 µm CMOS technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 12, pp. 693–695, Dec. 2010.

[20] G. Carchon and B. Nanwelaers, "Power and noise limitations of active circulators," *IEEE Trans. Microw. Theory Techn.*, vol. 48, no. 2, pp. 316–319, Feb. 2000.

[21] N. A. Estep *et al., "*Magnetic-free non-reciprocity and isolation based on parametrically modulated coupled-resonator loops," *Nat. Phys.*, vol. 10, no. 12, pp. 923-927, Nov. 2014.

[22] N. A. Estep, D. L. Sounas, and Andrea Alù, "Magnetless Microwave Circulators Based on Spatiotemporally Modulated Rings of Coupled Resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 2, pp. 502-518, Feb. 2016.

[23] A. Kord, D. L. Sounas, and A. Alù, "Magnetless Circulators Based on Spatio-Temporal Modulation of Bandstop Filters in a Delta Topology," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 2, pp. 911-926, Feb. 2018.

[24] A. Kord, D. L. Sounas, and A. Alù, "Pseudo-Linear Time-Invariant Magnetless Circulators Based on Differential Spatio-Temporal Modulation of Resonant Junctions," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 2731-2745, Jun. 2018.

[25] A. Kord, D. L. Sounas, Z. Xiao, and A. Alù, "Broadband Cyclic-Symmetric Magnet-less Circulators and Theoretical Bounds on their Bandwidth," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 12, Dec. 2018, pp. 5472-5481.

[26] A. Kord, M. Tymchenko, D. L. Sounas, H. Krishnaswamy, and A. Alù, "CMOS Integrated Magnetless Circulators Based on Cyclic-Symmetric Angular-Momentum Biasing," *IEEE Trans. Microw. Theory Techn.*, under review.

[27] D. L. Sounas, N. A. Estep, A. Kord, and A. Alù, "Angular-Momentum Biased Circulators and Their Power Consumption," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 11, Nov. 2018, pp. 1963-1967.

[28] A. Kord, D. L. Sounas, and A. Alù, "Differential Magnetless Circulator Using Modulated Bandstop Filters," in *Proc. IEEE MTT-S Int. Microw. Symp. (IMS) Dig*, Honolulu, HI, USA, Jun. 2017.

[29] A. Kord, D. L. Sounas, and A. Alù, "Low-Loss Broadband Magnetless Circulators for Full-Duplex Radios," in *Proc. IEEE MTT-S Int. Mircow. Symp. (IMS)*, Philadelphia, Pennsylvania, USA, Jun. 2018.

[30] N. Reiskarimian and H. Krishnaswamy, "Magnetic-free non-reciprocity based on staggered commutation," *Nat. Commun.*, vol. 7, Apr. 2016.

[31] N. Reiskarimian, J. Zhou, and H. Krishnaswamy, "A CMOS Passive LPTV Non-Magnetic Circulator and Its Application in a Full-Duplex Receiver," *IEEE J. Solid-State Circuits*, vol. 52, no. 5, pp. 1358-1372, May 2017.

[32] T. Dinc *et al.*, "Synchronized conductivity modulation to realize broadband lossless magnetic-free non-reciprocity," *Nat. Commun.*, vol. 8, no. 1, p. 795, Oct. 2017.

[33] A. Nagulu, A. Alù, and H. Krishnaswamy, "Fully-Integrated Non-Magnetic 180nm SOI Circulator with >1W P1dB, >+50dBm IIP3 and High Isolation Across 1.85 VSWR," in *IEEE Radio Freq. Integ. Circuits Symp. (RFIC)*, Philadelphia, PA, USA, Jun. 2018,

[34] M. M. Biedka *et al., "*Ultra-Wide Band Non-reciprocity through Sequentially-Switched Delay Lines," *Scientific Reports*, vol. 7, Jan. 2017.

[35] M. M. Biedka *et al.*, "Integrated time-varying electromagnetic devices for ultra-wide band nonreciprocity," in *IEEE Radio Wireless Symp. (RWS)*, Anaheim, CA, USA, Jan. 2018, pp. 80–83.