Enabling Fully-Integrated Magnetic-Free Non-Reciprocal Antenna Interfaces by Breaking Lorentz Reciprocity

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***Abstract*— The next generation of wireless communication systems brings the promise of a ubiquitous communication system among billions of connected devices. Advances in antenna (ANT) interface design are an important aspect of enabling such systems. The aim of this brief is to report our recent developments in fully-integrated magnetic-free non-reciprocal ANT interfaces for emerging wireless communication paradigms, as well as novel receiver front-end design techniques which benefit from the nonreciprocal behavior of these ANT interfaces.**

***Index Terms*— Circulator, Non-reciprocity, Magnetic-free, Simultaneous transmit and receive, STAR, Full-duplex, FD, 5G.**

I. Introduction

THE next generation of wireless communication systems is envisioned to deliver 100-1000 times higher data rate and connected devices, which requires a combination of new circuits and systems concepts to enhance spectrum efficiency and energy efficiency and ensure scalability and compatibility with various technology candidates of 5G, such as massive MIMO and Full-Duplex (FD) wireless [1]. In this report we focus our attention on the design and implementation of nonreciprocal antenna interfaces for such systems.

In applications where antenna pairs cannot be afforded, integrated shared-antenna interfaces with low-loss, high transmitter-to-receiver isolation and high linearity are highly desirable. Among the various shared-antenna interfaces existing today, almost none can simultaneously provide all the conditions mentioned above. Recently, we have introduced a new family of nonreciprocal components by breaking Lorentz reciprocity which have paved the way towards the integration of low-loss shared-antenna interfaces with high isolation and promising linearity for the first time on silicon platform.

II. Magnetic-Free Nonreciprocal Antenna Interfaces

Lorentz reciprocity is a fundamental characteristic of the vast majority of electronic materials, circuits and components. However, non-reciprocal components, such as circulators and isolators, are critical for various RF applications, including communications, radar, imaging and sensing. Reciprocity can be broken by breaking one of three necessary conditions such as (i) time-invariance, (ii) linearity or (iii) by using magnetic material. In recent years, in the fundamental physics community, there has been progress on breaking reciprocity through time-variance, specifically spatiotemporal modulation of material permittivity [2], [3].

Linear periodically time-varying (LPTV) circuits have been quite the hot topic over the last several years in integrated circuit community, primarily due to their ability to realize tunable radio-frequency high-quality-factor filters (the so-called N-path filters) in CMOS for the first time. However, we have discovered that LPTV circuits have a rich set of unique properties that go far beyond high-Q filtering.

Our switch-based circuits may be understood as performing spatiotemporal conductance modulation, and leverage the fact that conductivity is a variable material property that is unique to semiconductors. Conductivity in semiconductors can be modulated over a wide range relative to permittivity. The fundamental physical principles from our recent work [4] is described here, as well as showcasing three generations of CMOS circulator-based wireless systems [5-7] targeting emerging FD applications.

N-path filters are a class of LPTV networks where the signal is periodically commutated through a bank of capacitors. We have found that applying a relative phase shift to the non-overlapping clocks driving the input and output switch sets of a two-port N-path filter, imparts a nonreciprocal phase-shift to the signals traveling in the forward and reverse directions since they see a different ordering of the phase-shifted switches. The magnitude response remains reciprocal and low-loss, similar to traditional N-path filters. To convert phase non-reciprocity to non-reciprocal wave propagation, an N-path-filter with +/-90º phase-shift is placed inside a transmission line loop with a length of 3λ/4. The combination of the nonreciprocal phase shift of the N-path filter with the reciprocal phase-shift of the transmission line results in supporting a unidirectional wave propagation (-270-90=-360º), because the boundary condition for wave propagation in the reverse direction cannot be satisfied (-270+90=-180º). Additionally, a three-port circulator can be realized by placing ports anywhere along the loop as long as they maintain a λ/4 circumferential distance between them. Interestingly, maximum linearity with respect to the TX port is achieved if the RX port is placed adjacent to the N-path filter, since the inherent TX-RX isolation suppresses the voltage swing on either side of the N-path filter, enhancing its linearity [4], [5].

A 610-850MHz FD receiver IC prototype incorporating the non-magnetic N-path-filter-based passive circulator described above and additional analog baseband (BB) SI cancellation (Fig. 1(a)) was designed and fabricated in the 65nm CMOS process [5]. 42dB of SI suppression is achieved across the circulator and analog BB SIC through a joint optimization

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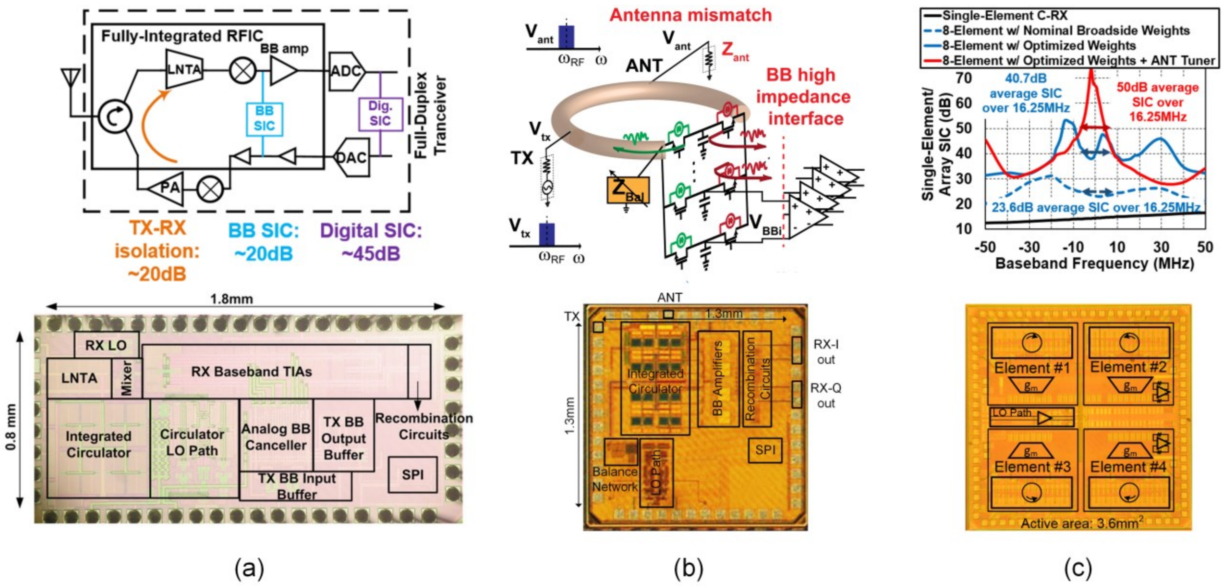

Fig. 1. Three generations of CMOS circulator-based wireless systems [5-7]. (a) Demonstration of multi-domain self-interference cancellation (SIC) across ANT, analog and digital domains. (b) Circulator-receiver architecture with embedded balancing impedance to recover TX-RX isolation in the face of antenna mismatch. (c) Full-duplex circulator-receiver phased-array by repurposing spatial degrees of freedom.

over a BW of 12MHz. An overall SI suppression of 85dB for the FD receiver is achieved in conjunction with digital SIC.

While form factor, cost and compatibility with CMOS are all important metrics in designing the ANT interface, further benefits can be achieved by integration of the ANT interface on the same platform as the rest of the transceiver. In such a scenario, the ANT interface can be treated as a part of joint design procedure for the radio front-end, unlike traditional ANT interfaces which are designed separately to interact with a 50Ω impedance at the transmitter and receiver ports to obtain best performance and to provide ANT matching. In [6] we have reported a new FD architecture called circulator-receiver. Our structure benefits from a simplified design merging the ANT interface, down-converter and ANT impedance tuning capability into a single block.

A 610-975MHz prototype circulator-receiver was designed and fabricated in 65nm CMOS technology as shown in Fig. 1(b). The average small-signal TX-BB isolation (referred to the ANT port) at best is about 25dB. Engaging and optimizing the balance network dramatically improves the average small-signal and large-signal isolation to 40dB over 20MHz BW at +8dBm of TX average output power.

More recently we have demonstrated how wideband SIC can be achieved by using phased-array beamforming with no additional power consumption while minimizing link budget (transmitter and receiver array gain) penalty by repurposing spatial degrees of freedom (Fig. 1(c)). This work is going to be published in RFIC conference in June 2018 [7].

III. Conclusion and Future Work

This report presented recent research efforts on magnetic-free nonreciprocal ANT interfaces and circulator-based front-ends. Topics for future research includes improving the power handling of integrated circulators as well as integrated ANT tuning schemes which can cover wider VSWR circles. Furthermore, demonstration of nonreciprocal shared ANT interfaces in MIMO systems is of interest.

IV. Career Plan

Upon graduation I wish to begin a career as a faculty member at a tier one research university. I would like to combine my passion for research with the opportunity to teach and mentor students. I believe that the MTT-S Graduate Fellowship has boosted my career, improved the quality of my research and has enabled me to expand my professional network through participation in the IEEE IMS/RFIC 2017 conference. I am grateful to the IEEE MTT-S society for this award and I look forward to be more involved in the MTT-S efforts to promote the advances in microwave engineering.

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