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Non-Magnetic Non-Reciprocal Microwave Components—State of the Art and Future Directions

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ABSTRACT Non-reciprocal components such as circulators, isolators and gyrators find utility in numerous microwave wireless applications, including high-power transmitters, simultaneous transmit-and-receive communication and radar systems, and emerging cryogenic quantum computing implementations. Today, such components are implemented using ferrite materials, which lose their reciprocity under the application of an external magnetic field. However, ferrite materials are incompatible with semiconductor integrated-circuit fabrication processes, and therefore ferrite non-reciprocal components are difficult to miniaturize to chip scales, rendering them bulky and expensive. This has motivated significant research into non-magnetic non-reciprocal components over the past 50 years. In recent years, this research has been invigorated by breakthroughs in time-modulated non-reciprocal components, and their integration into silicon integrated circuits. This paper reviews the history of non-reciprocal electronics, surveys recent research results in the area, and describes outstanding directions for future research.

INDEX TERMS Circulators, CMOS RF design, isolators, microwave passive circuits (hybrid), nonreciprocal microwave devices.

I. INTRODUCTION

The principle of reciprocity as an underlying symmetry underpins many different physical domains, including electromagnetics, acoustics, elastodynamics, and thermodynamics. The study of reciprocity in these different fields dates back to the works of Green, Rayleigh, Helmholtz, Lorentz, Carson, Onsager and Casimir [1]–[7]. In the field of electromagnetics, loosely speaking, the principle of reciprocity implies that in most scenarios, waves travel in the same manner in forward and reverse directions. More formally, reciprocity essentially implies that wave propagation remains unchanged if the source point and observation point are interchanged.

The implications of reciprocity in microwave engineering are ubiquitous - it is reciprocity that ensures that antenna transmits in the same manner as which it receivers. It is also reciprocity that ensures that a power combiner that combines two signals in one direction acts as a power splitter in the reverse direction.

The Lorentz Reciprocity theorem states that any linear time-invariant medium with symmetric permittivity and permeability tensors must be reciprocal. For such a linear network with a finite number of ports, reciprocity implies that its scattering matrix S must satisfy the symmetry condition $S^T = S$. Perhaps the most fundamental non-reciprocal component is the gyrator, whose S-parameters are given by

$$S_{GYRATOR} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \quad (1)$$

representing a component that is matched at both ports and features lossless transmission in both directions, but with 180° phase difference between forward and reverse directions. The significance of the gyrator is that, as proposed by Tellegen in 1948 [8], it is the fifth fundamental circuit element beyond the (reciprocal) resistor, inductor, capacitor and transformer. With these five fundamental circuit elements, any non-reciprocal circuit can be synthesized. Two such non-reciprocal circuits or components are the circulator and the isolator, whose S parameters are given by

$$S_{CIRC} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, S_{ISO} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}. \quad (2)$$

The isolator is a two-port device that transmits the signal in one direction without loss, but completely absorbs the signal in the other direction. Such a device finds application in high-power microwave transmitters to protect power amplifiers from back-reflections from the antenna. The antenna impedance can change significantly due to changes in the electromagnetic environment, and these changes can cause larger-than-typical voltage swings at the power amplifier output, potentially damaging the power devices. The use of an isolator makes the power amplifier immune to antenna impedance variations. A circulator is a three-port non-reciprocal component where the signal incident at any port "circulates" to the next port in the clockwise or counter-clockwise direction, while remaining isolated from the third port. Circulators are used in simultaneous-transmit-and-receive communication transceivers and radars [9]–[13] with the three ports connected to the transmitter, antenna and receiver. The signal generated by the transmitter circulates to the antenna, while a signal incident at the antenna circulates to the receiver. Circulators are also used ubiquitously in cryogenic quantum computing applications to excite and readout qubits [14].

Traditionally, non-reciprocal components have been implemented using ferrite materials, which lose their reciprocity under the application of an external biasing magnetic field. Commercial ferrite circulators and isolators today achieve extremely low loss (<1 dB in many cases) and very high power handling (tens to hundreds of watts) [15], [16]. However, ferrite materials require complex post-processing steps, and are very challenging to integrate into semiconductor manufacturing processes, despite significant efforts [17], [18]. Electromagnetic coupling in gyromagnetic materials tends to be weak, causing the ferrite films to be tens to hundred-times thicker than the back-end-of-the-line (BEOL) in semiconductor processes. Ferrite film growth requires extremely high temperatures and oxidizing atmospheres, which are incompatible with semiconductor manufacturing. Finally, the coefficient of thermal expansion varies significantly between ferrites and typical semiconductors, producing stress at the ferrite-semiconductor interface during the wafer cooling process. Consequently, ferrite circulators and isolators tend to be bulky and expensive devices that are currently not suitable for low-cost, small-form-factor applications. Recently, low temperature (70 °C) fabrication of a ferrite circulator on a PCB was explored. However, this approach leads to high insertion loss and low isolation [19].

As a result, there has been significant research over the past several decades focused on non-magnetic non-reciprocal components that can be integrated into chip-scale semiconductor ICs. Approaches can be classified into three categories - (i) based on the use of active transistors, (ii) based on the use of non-linearity, and (iii) based on the use of time modulation. This paper will focus on historic and recent research on non-magnetic non-reciprocal components based on these approaches [20]–[22], and will conclude with an outlook on future research directions.

II. NON-RECIPROCITY BASED ON ACTIVE TRANSISTORS AND NONLINEARITY

Transistors that are biased with a DC current or a DC voltage are inherently non-reciprocal due to their unilateral gain. For instance, an active-biased transistor with a forward gain $|S_{21}| > 1$ can act as as an isolator with non-reciprocal signal transmission $|S_{21}| > |S_{12}|$. Initial efforts to realize magnetless non-reciprocal components were based on active transistors. A wide range of non-reciprocal components ranging from gyrators [23] and isolators to circulators [24]–[28] have been demonstrated. Three port active circulators can be categorized into two groups: (i) symmetric circulators that have identical transmission between their ports [24]–[26], and (ii) quasi-circulators (QC) in which the transmission happens only between two pairs of ports [27], [28]. Fig. 1(a) depicts one of the first realizations of the symmetric three-way circulator where 3 transistors are connected in a circular loop. Monolithic realizations of this symmetric architecture were demonstrated in [29], [30]. Due to the rotational symmetry, three-way active circulators should be realized with some loss in the circulator loop to maintain stability [28].

Active QCs, on the other hand, do not have symmetric transmission between all three ports, and can provide active gain in their two transmission paths. Generally, they are of interest in wireless systems such as full-duplex transceivers and simultaneous-transmit-and-receive radars, where low-loss transmitter-to-antenna and low-noise antenna-to-receiver transmissions are necessary while fully isolating the receiver from the transmitter. One of the common architectures includes QCs based on passive cancellation where a passive device is used to isolate the TX and the RX [28], [31], [32]. Other approaches include unilateral active divider/combiners where the signal from the TX port is split into two parts and summed in-phase and out-of-phase at the ANT and RX ports respectively [27]. More recent implementations of QCs at mm-wave frequencies can be found in [33], [34].

Non-reciprocal properties of active transistors have also been explored to realize non-reciprocal metamaterials [35], [37]. As shown in Fig. 1(b), active biased transistors can be embedded within ring resonator loops to create unidirectional signal propogation within the rings, similar to magnetic-biased ferrites.

Active approaches are readily compatible with IC fabrication and can be realized within a compact form-factor. However, active-biased transistors add noise and nonlinear distortion [28], which has historically prevented active non-reciprocal components from being widely deployed. Power handling can be enhanced at the expense of added noise and power consumption through linearity enhancement techniques

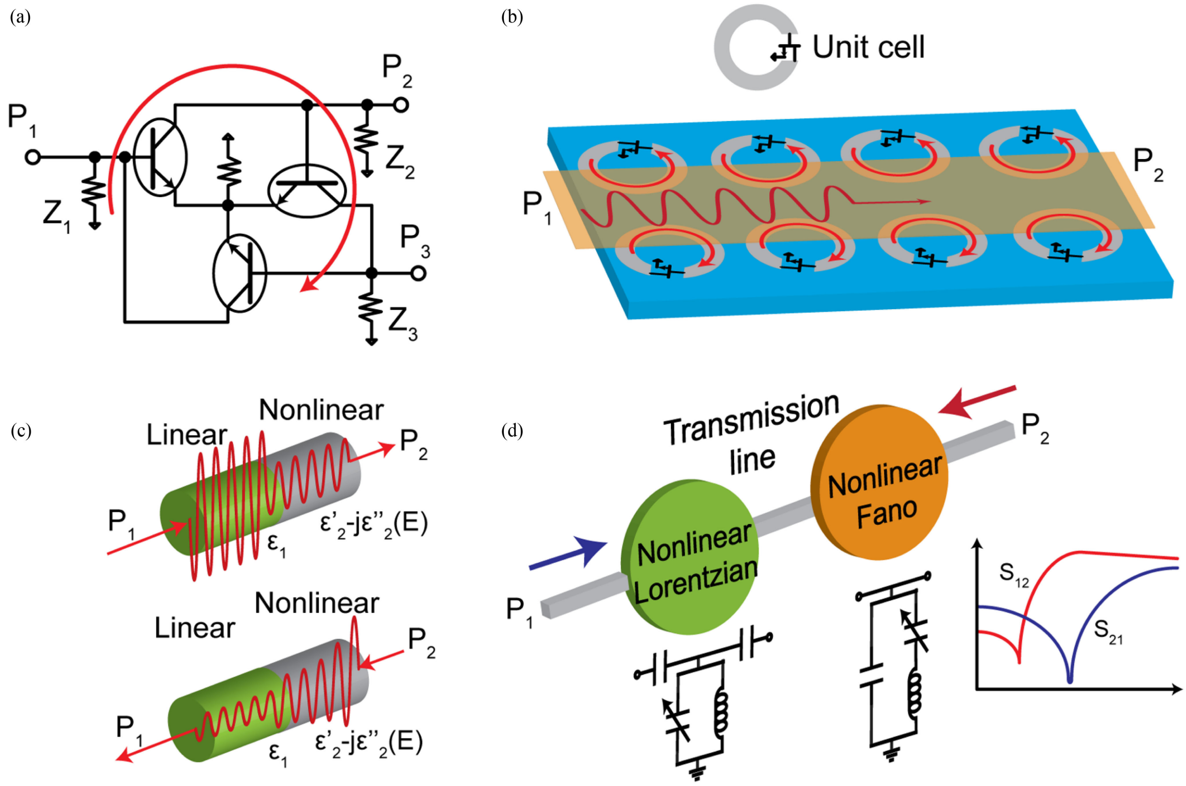

FIGURE 1. (a) A non-magnetic non-reciprocal circulator based on a circular connection of active-biased transistors [24]. (b) Metamaterial supporting non-reciprocal wave propagation based on embedded active transistors [35]. (c) Principle of operation of nonlinear isolators within a cascade of a linear and a non-linear media. (d) A nonlinear isolator based on a cascade of a nonlinear Lorentzian resonator and a nonlinear Fano resonator [36].

such as transistor source degeneration. Additionally, III-V/III-N compound semiconductor technologies (such as GaAs and GaN) exhibit superior Johnson Limit (speed-breakdown voltage trade-off) to silicon-based technologies, and can lead to better power handling for active circulator implementations.

Non-linearity in conjunction with spatial asymmetry can also be leveraged to break reciprocity. Such approaches have been widely explored at optical frequencies exploiting the rich body of research on nonlinear photonics [38], [39]. The operation of such nonlinear isolators generally relies on the fact that the response of a nonlinear medium depends on the amplitude of the signal propagating through it. Generally, nonlinearity in media, devices and circuits tends to be compressive, implying that more powerful signals undergo more severe attenuation. The spatial asymmetry implies that signals incident from one side enter the nonlinear region with greater amplitude, undergoing more attenuation, while signals entering from the other side enter the nonlinear region with lesser amplitude, and suffer less attenuation (Fig. 1(c)). However, the fundamental challenge with such approaches is that non-reciprocity is only exhibited over a limited range of signal power levels and there is a trade-off between the forward transmission loss and the range of signal powers over which non-reciprocity can be achieved. Fig. 1(d) depicts an interesting recent effort towards relaxing this trade-off [36] by employing a cascade of two nonlinear resonators (one Lorentzian and one Fano). It has also been suggested that the cascading of additional suitably designed resonators can successively relax the loss-bandwidth and power-range trade-off. Nevertheless, this limitation, as well as the distortion induced by nonlinearity, precludes the use of such non-reciprocal components in most electronic applications with high linearity requirements such as wireless communication. Nonlinear isolators are also limited by a dynamic reciprocity mechanism [40] – in the presence of a strong incident signal, the response to a second weak signal is reciprocal across the two ports. In general, nonlinear isolators operate well when excited from a single port, and their functionality becomes complicated when excited at both ports simultaneously [41].

III. NON-RECIPROCITY BASED ON TIME VARIANCE

Time variance can also be used to realize non-reciprocity. Over the past few decades, there has been a strong interest in breaking reciprocity and building magnetic-free circulators by exploiting temporal modulation [14], [20]–[22]. In principle, time variance can be applied to achieve non-reciprocity with no added noise while maintaining linearity. In practice, the variable material parameter that is modulated is typically associated with some loss, and the phase noise of the modulation signal has to be considered. Techniques to achieve non-reciprocity through time variance can be classified into three categories: (i) permittivity modulation using varactor/refractive index modulation, (ii) permeability modulation, mainly used in cryogenic applications through

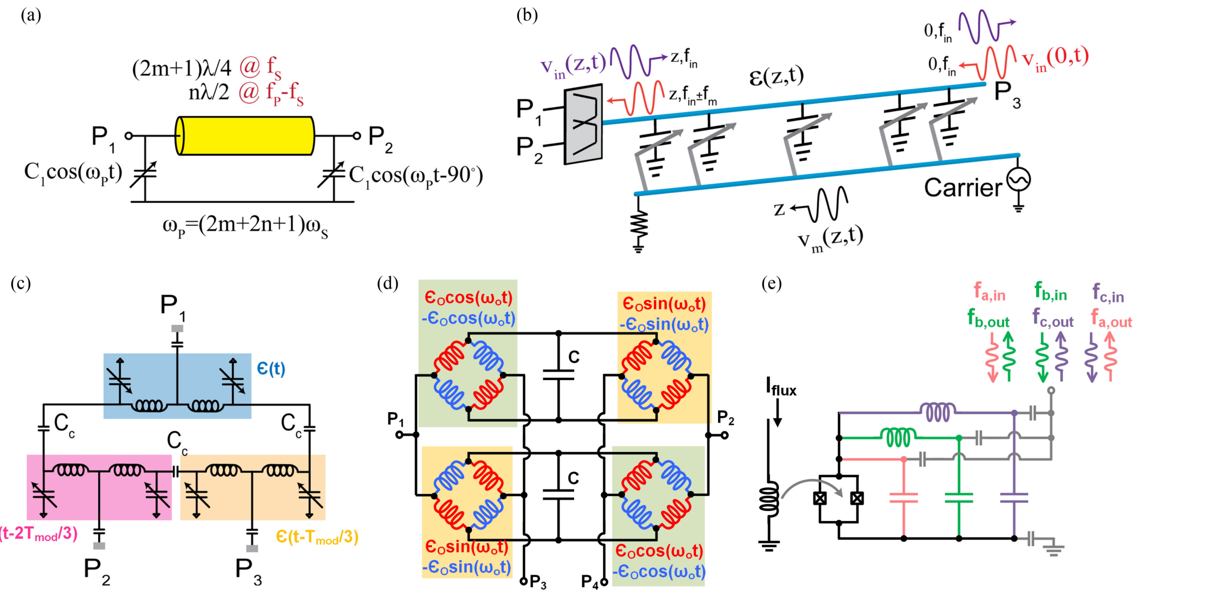

FIGURE 2. **(a) Parametric non-reciprocal device based on temporal modulation of semiconductor-diode capacitances across a transmission-line delay [45]. (b) Non-reciprocal wave propagation accompanied by frequency conversion through traveling-wave permittivity modulation along a transmission line [46]. (c) Angular momentum biasing through permittivity modulation in coupled resonant rings [48]. (d) Superconducting, widely tunable microwave on-chip circulator based on DC SQUIDs [58]. (e) A superconducting, unidirectional frequency converter exploiting non-reciprocity in frequency space [59].**

Josephson junctions (JJ) [42], [43] and superconducting quantum interference devices (SQUIDs), and (iii) conductivity modulation with the use of transistor switches.

A. PERMITTIVITY MODULATION

Parametric amplification through reactance modulation is considered one of the early forms of low-noise amplification [44]. The capacitance of a semiconductor diode is modulated using a pump signal to impart gain to the design signal. Later, these approaches were applied to realize non-magnetic non-reciprocal components. In [45], the frequency-conversion characteristics of two semiconductor-diode parametric circuits with phase-shifted pump signals and separated by a quarter-wave transmission line was exploited to realize passive temporally-modulated gyrators and circulators (see Fig. 2(a)). This architecture is a precursor to the approaches being pursued recently in the microwave and photonic domains. More recently, it was shown that parametric modulation in a quasi-distributed transmission lines can achieve non-reciprocity through direction-dependent frequency conversion [46]. In this architecture, traveling wave modulation is imparted to varactors distributed along a quasi-distributed transmission line. As shown in Fig. 2(b), a signal wave traveling in the same direction as the modulation is converted in frequency to intermodulation frequencies, while the signal traveling in the opposite direction remains unaffected. In such approaches in general, the length of the transmission line is inversely proportional to the modulation contrast (C_{max}/C_{min}). Since modulation ratios offered by varactors typically range from 2 to 4, this approach results in form-factors that are comparable to the wavelength.

In another body of work, inspired by Faraday rotation, traveling-wave modulation has been exploited in ring structures to impart angular-momentum biasing and realize circulators. The first effort in this body of work exploited the rotary motion of air in a ring cavity to realize a non-magnetic acoustic circulator [47]. Indeed, all time-modulation-based approaches take inspiration from the fact that wave propagation in moving media is inherently non-reciprocal.[1] Later, in [48], such a rotary motion was imitated in an electronic circuit by employing traveling-wave modulation to varactors in a three-resonator loop to realize a circulator at microwave frequencies as shown in Fig. 2(c). The use of resonators based on lumped inductors and capacitors miniaturizes the size of the ring significantly while boosting the varactor modulation effect, resulting in a stronger non-reciprocal response in subwavelength dimensions. The three resonator loop can be implemented in various configurations to such as delta or wye topologies to realize circulators with varied performance [49], [50]. Recently, such an approach has been exploited in CMOS to realise an isolator and a circulator at millimeter-wave frequencies [51]. Extreme miniaturization is also possible through the use of MEMS and FBAR resonators in conjunction with varactors in hybrid electronic-acoustic approaches [52]–[54].

While these permittivity modulation approaches are very promising, the high-Q resonances lead to lower bandwidths when compared with non-resonant structures. Additionally,

[1]The approach described in the previous paragraph based on traveling-wave modulation in a linear transmission line [46] imparts linear momentum biasing and mimics the linear motion of a medium

varactors suffer from low quality factor and poor linearity, especially as operating frequencies are increased towards millimeter-waves, resulting in high insertion loss and poor large signal performance. Therefore, additional research is needed to enhance bandwidth and improve performance at higher frequencies.

B. PERMEABILITY MODULATION

Similar to capacitance modulation, parametric effects based on inductance modulation in a ferromagnetic medium have also been explored in the past [55], [56]. However, with the advancement of integrated semiconductor platforms, this approach took a back seat as inductance modulation is very challenging in typical integrated circuits. Nevertheless, these approaches have continued to evolve in the quantum-computing community due to the availability of tunable, nonlinear inductive elements such as JJs and SQUIDs in cryogenic superconducting platforms. Circulators and isolators play a prominent role in the readout of qubits in superconducting quantum computing applications. However, ferrite circulators occupy substantial space in the dilution refrigerator, limiting the maximum number of qubits that can be operated simultaneously [14]. Recognition of the need for compact, non-magnetic circulators has inspired cryogenic non-reciprocal circulators and isolators based on parametric frequency-conversion and synthetic rotation principles, using JJs and SQUIDs as the modulated element. JJs and SQUIDs offer higher modulation ratios of $10-50$ when compared to room-temperature varactors [57].

In [60], a transmission line is embedded between two JJ-based mixers to realize a gyrator, an approach very similar to the switched-transmission-line gyrator discussed in the later sections of this paper. This gyrator can then be incorporated within a Mach-Zehnder interferometer employing two 90° hybrids to realize a multi-port circulator. In [58], it has been shown that a differential gyrator realized using the mixer-delay-mixer configuration can also act as a 4-port circulator when excited using 4 individual ports, hence eliminating the need for 90° microwave hybrids and enabling a circulator within a compact footprint (Fig. 2(d)). Approaches where non-reciprocity is coupled with frequency translation have also been explored - in [59], a 3-way frequency-translating circulator is proposed by modulating a SQUID using 3 microwave drives, resulting in a uni-directional three-way frequency-conversion process (Fig. 2(e)).

C. CONDUCTIVITY MODULATION

Transistor switches, on the other hand, can be modulated with much larger modulation ratios when compared to varactors and JJs, with $\frac{R_{OFF}}{R_{ON}}$ varying between 10^3-10^5 [61]. As a result, there has been a significant interest in realizing non-reciprocal components using hard-switching offered by transistor switches. Switching circuits date back to the 1950 s with the introduction of the N-path filter, where the signal is commutated across a bank of capacitors through mechanical brushes to realize high-Q comb filters at the commutation frequency [62]. Recently, the N-path filter has been extensively re-investigated and re-invigorated in CMOS implementations by replacing the mechanical brushes with transistor switches to realize compact, inductor-less, high-Q, linear tunable bandpass/bandstop filters at RF frequencies [63]. While the traditional two-port N-path filter is reciprocal, it was recently demonstrated that by phase-shifting the commutation of the input and output switches in a 2-port N-path filter, phase non-reciprocity can be achieved [64]. In this work, the clock signals of a 2-port N-path filter were phase-shifted by 90° to realize a compact CMOS integrated gyrator with a non-reciprocal phase of 180°. Further, a $3\lambda/4$ line is wrapped around the gyrator to implement the first CMOS integrated circulator as shown in Fig. 3(a). It was also shown that by placing the gyrator right next to one of the ports (say port 3, connected to a sensitive receiver), the voltage swing associated with an excitation at port 1 (connected to a high-power transmitter) can be greatly suppressed across the gyrator switches due the isolation of the circulator, thereby enhancing the power handling of the circulator for excitations at port 1. Later, the embedding of the phase shifted N-path filter into a hybrid-coupler to enhance the bandwidth was also explored [65].

The non-reciprocity achieved by the N-path filter is inherently narrowband due to the bandpass filtering response created by the N-path filter. Furthermore, the N-path filter is not readily scalable to mmWave frequencies due to its stringent clocking requirements. Switched transmission line techniques have consequently been explored to achieve broadband non-reciprocity [66], [69]. In this technique, commutation is performed across a bank of transmission lines instead of capacitors, leading to broadband responses. This technique also allows the lowering of the modulation frequency of the switches compared to the operating frequency by appropriately increasing the length of the transmission line, and was exploited to realize a millimeter-wave 25 GHz fully-integrated magnetic-free passive circulator [70] (Fig. 3(b)) modulated at 8 GHz. The ability to lower the modulation frequency can also be used to enhance the power handling at RF frequencies through the use of high-voltage transistors. Along these lines, highly-linear RF circulators with watt-level power handling and in-built antenna tuning have been realized at 1GHz [71], [72]. This technique has also been adapted to switching across bandpass filters (as opposed to transmission lines) to further enhance the operating frequency deeper into the millimeter-wave regime and realize a CMOS circulator at 60GHz [73]. Similar ideas were also explored for cryogenic applications by cooling a circulator based on switched all-pass-filters to ≈4K [74]. Similar structures have also been used to implement the first extremely-wideband circulators operating from DC to RF frequencies [67] (Fig. 3(c)). In an effort to reduce the modulation frequency and its associated power consumption dramatically, the transmission lines between the switches were replaced with surface-acoustic wave filters as they provide large group delays within an extremely-small footprint when compared with on-chip electromagnetic

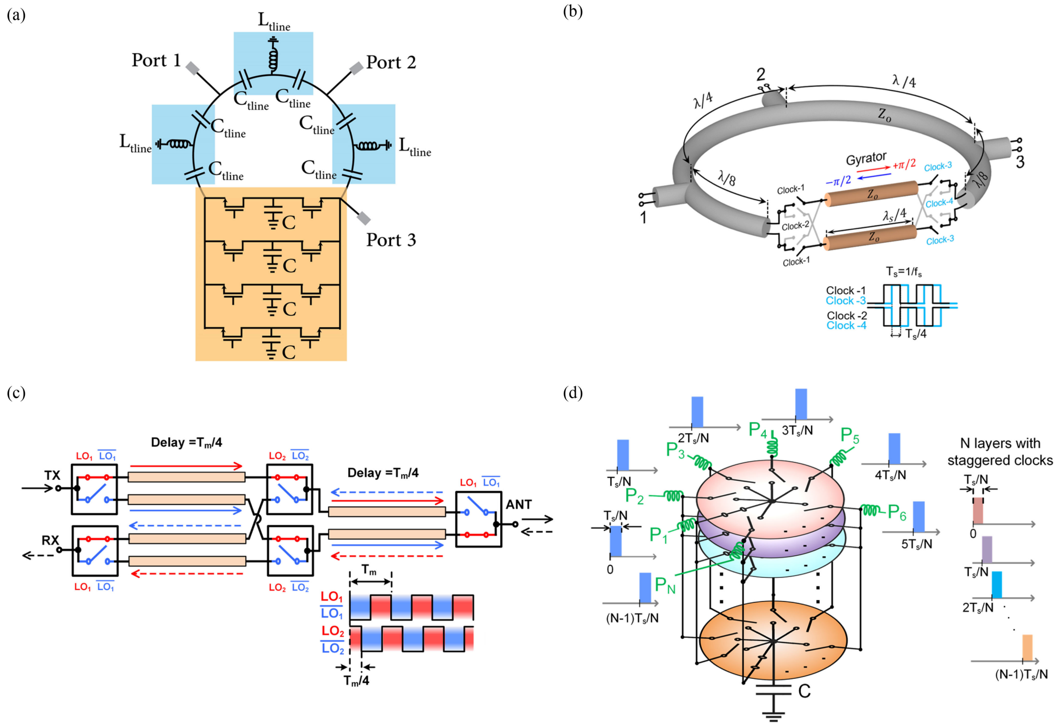

FIGURE 3. **(a) CMOS circulator based on an N-path filter gyrator employing commutation across a bank of capacitors [64]. (b) CMOS circulator based on switched transmission line gyrator employing staggered commutation across delay lines [66]. (c) An ultra-wideband circulator based on sequentially-switched delay lines [67]. (d) CMOS based N-Way circulator realized using N-port switched capacitor layers [68].**

passive structures [75]. While these implementations have paved the way towards integrated non-reciprocal components with performance metrics that are beginning to be relevant for practical applications [76], the use of conventional reciprocal elements such as transmission lines and couplers within these non-reciprocal structures still imposes limits on size, bandwidth and insertion loss. In a different context, N-path, commutated, switched-capacitor networks have been shown to exhibit extremely-broadband slow-wave propagation beyond the conventional delay-bandwidth limit, enabling the realization of a low-loss, ultra-broadband, reconfigurable, reciprocal/non-reciprocal delay element [77]. Due to the usage of just switches and capacitors, such a delay element can be implemented in an extremely-compact form factor. More recently, the concept of angular momentum biasing was combined with N-path-commutated broadband delays, effectively synthesizing a helicoidal motion of an electrostatic medium to realize an ultra-compact, ultra-broadband, N-port circulator with non-reciprocal response ranging from DC to GHz frequencies [68].

The enhanced linearity of passive-transistor-switch circuits over active-transistor-based circuits arises from the fact that passive transistor-based switches are typically modulated with square-wave signals that hard-switch between the ground and supply rails. Hence, to produce non-linearity, the input signal levels should become comparable to the supply voltage as opposed to being comparable the bias levels in active circuits. Additionally, the performance of transistor switches improves with technology scaling due to reduced switch parasitics. Voltage swing across the gate-source/drain (V_{GS}) and source-drain (V_{DS}) terminals are the two main sources of switch non-linearity. In a well-designed switching circuit, the switch resistance tends to be much lower than the port impedance, thus greatly suppressing the drain-source voltage (V_{DS}) and its associated non-linearity. Additionally, circuit techniques such as gate bootstrapping and clock boosting can be employed to enhance the linearity of the transistor switches. This enhanced linearity offered by switches is also the reason why a passive switching mixer is typically preferred over an active mixer or a parametric mixer in modern-day frequency-conversion circuits. One drawback of a passive transistor switch is that it cannot impart power gain, unlike active transistors or parametric devices employing reactance modulation.

IV. FIGURES OF MERIT: THE SIZE-BANDWIDTH TRADE-OFF AND ANTENNA INTERFACE EFFICIENCY

An ideal antenna interface should exhibit no loss, no added noise, large power handling, large bandwidth, no additional power consumption and infinitesimal size. However, these metrics trade off with each other in practical implementations. For instance, passive reciprocal hybrids or electrical balance duplexers (EBDs) [78], [79] represent reciprocal alternatives to circulators for single-antenna full-duplex operation. They exhibit high linearity but suffer from a fundamental 3 dB loss. Magnetic circulators exhibit low loss and extremely high power handling but typically suffer from large form factor.

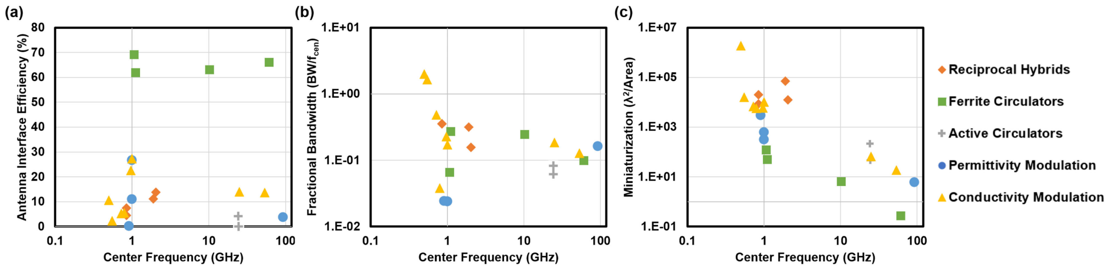

FIGURE 4. **Performance comparison between various techniques: (a) antenna interface efficiency versus center frequency, (b) fractional bandwidth versus center frequency and (c) area miniaturization versus center frequency.**

Recent time-modulated circulators have demonstrated watt-level handling and near 2 dB loss [72] but their bandwidths are limited to a fraction of the center frequency, while other architectures have demonstrated extremely wide bandwidths and infinitesimal form factor at lower power handling [68]. Hence to enable a fair comparison between these architectures, we discuss three figures of merit for antenna interfaces: (i) antenna interface efficiency (η_{ANT}) which calculates the efficiency of the device by taking into account power handling, insertion loss, noise figure and DC power consumption [80], (ii) fractional bandwidth, namely the ratio of the bandwidth to the center frequency, and (iii) miniaturization factor, which is the ratio of the square of the free-space wavelength at the center frequency to the area occupied by the device.

A. ANTENNA INTERFACE EFFICIENCY (η_{ANT})

Antenna interface efficiency (η_{ANT}), evaluates the degradation in the system efficiency due to the presence of the antenna interface enabling simultaneous-transmit-and-receive operation. Consider a full-duplex wireless link with a power amplifier generating $P_{out,PA}$ with a drain efficiency of η_{PA}, and an antenna interface with a TX-ANT loss of S_{21}, ANT-RX noise figure of NF and DC power consumption of $P_{DC,interface}$. The effective transmitted power and power consumption of the link relative to an ideal antenna interface can be expressed as $P_{out,link} = P_{out,PA} \times S_{21}/NF$ and $P_{DC,link} = P_{out,PA}/\eta_{PA} + P_{DC,interface}$. The efficiency of this FD link can be expressed as $\eta_{link} = P_{out,link}/P_{DC,link}$. Additionally, the link efficiency can also be expressed as efficiency of the power amplifier η_{PA} multiplied by efficiency of the antenna interface η_{ANT}. Therefore, the antenna interface efficiency can be expressed as

$$\eta_{ANT} = \frac{P_{out,PA} \times S_{21}/NF}{P_{out,PA}/\eta_{PA} + P_{DC,interface}} \times \frac{1}{\eta_{PA}} \times 100\%. \quad (3)$$

In a practical system, the maximum value of $P_{out,PA}$ will be limited by the power handling of the antenna interface which will be the minimum of one of the following metrics: (i) the TX power at which the TX-ANT transmission compresses by 1 dB, i.e., the TX-ANT $P_{1\,dB}$, (ii) the TX power at which the ANT-RX path compresses by 1 dB, i.e., the TX-induced ANT-RX $P_{1\,dB}$, and (iii) the TX power at which the transmit power reaches the spectral regrowth limit. Fig. 4(a) depicts the antenna interface efficiencies across operating frequency of circulators demonstrated using various techniques for $\eta_{PA} = 45\%$ and the power handling of the antenna interface is limited by TX-ANT $P_{1\,dB}$. It can be seen that non-magnetic circulators based on time modulation, particularly those based on conductivity modulation, have recently started to exceed reciprocal hybrids and EBDs in antenna interface efficiency, particularly because of their ability to achieve lower loss, but still lag ferrite circulators by roughly a factor of 2.

B. BANDWIDTH-SIZE TRADE-OFF

The bandwidth-size trade-off is a fundamental trade-off that spans across various fields such as acoustics, optics, and electronics. For instance, miniaturizing a transmission line using lumped inductors and capacitors leads to lower cut-off frequency due to the Bragg limit. In Figs. 4(b) and (c), we depict a comparison of various circulator implementations in terms of the fractional bandwidth and miniaturization factor versus center frequency. It can be seen that non-magnetic circulators achieve significantly superior miniaturization when compared with ferrite circulators, with recent conductivity modulation architectures achieving extreme miniaturization [68]. Recent conductivity modulation architectures [67], [68], [81] have also started to achieve superior fractional bandwidth when compared with reciprocal hybrids, EBDs and ferrite circulators.

V. OUTLOOK

While non-magnetic circulators and isolators based on time-variance have gained significant interest, and current implementations show promise, with the best implementations reaching near 2 dB insertion loss and multi-watt power handling [72] ($\eta_{ANT} \approx 30\%$), nevertheless, they still require a leap forward in insertion loss, power handling and noise to replace their magnetic counterparts. The main bottlenecks for insertion losses and power handling in CMOS implementations are the poor quality-factor of on-chip passives and low breakdown voltage of CMOS transistor switches. The usage of high-quality off-chip passives such as gold-plated/glass-integrated passive devices (IPDs) would greatly improve the performance of CMOS circulators and isolators. For instance, in [82] a low loss microstrip line exhibiting 0.075 dB/mm was demonstrated, representing up to 10× lower resistive losses when compared to conventional CMOS transmission lines with losses of 0.5–0.7 dB/mm. Hence, co-integrating these high-Q passives

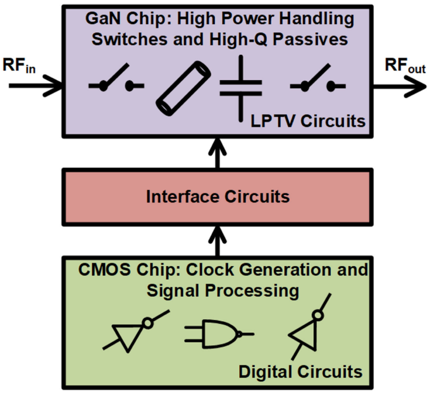

FIGURE 5. Heterogenous integration of LPTV ciruits in GaN-CMOS leveraging the advantages from both the technologies.

with integrated non-reciprocal components represents a promising route to improving insertion loss levels. On the other hand, III-V/III-N compound semiconductor technologies (such as GaAs and GaN) exhibit superior Johnson Limit (speed-breakdown voltage trade-off) to CMOS, and also integrate high-quality passives due to the insulating nature of the substrate and the use of gold metallization, but lack the high transistor density and yield offered by CMOS. Hence, heterogeneous integration of GaAs/GaN with CMOS, where the signal path comprising the switches and the passive components are integrated in GaAs/GaN, and CMOS technology is used for the generation of the complex modulation signals, as shown in Fig. 5, represents a promising direction [83].

A dimension in which non-magnetic integrated circulators and isolators can shine when compared with their ferrite counterparts is in their co-design with the rest of the system. As briefly described earlier, CMOS circulators that incorporate antenna tuning functionality have been demonstrated [71], [72]. The insertion loss of such circulators must be compared with loss of a ferrite circulator summed with that of the antenna tuner. In [84], the authors describe an N-path-filter-based circulator-receiver,where the N-path switches are repurposed to serve as a down-conversion mixer, thereby realizing the combination of a circulator and a receiver in a single circuit. This concept has been further scaled to array implementations for full-duplex multi-antenna systems, including phased-array circulator-receiver arrays [85] and multi-input multi-output (MIMO) arrays [86]. Isolating bandpass filters, combining the functionalities of isolators and bandpass filters have also been investigated in [87]–[89]. Non-reciprocal radiating structures have been also been investigated, combining non-reciprocal component functionality with antenna functionality. In particular, in [90], a time-modulated leaky-wave antenna system effectively merging an antenna, a circulator, and a mixer was proposed, allowing the device to operate as a complete transceiver.

Other important issue that requires further attention is the effect of clock phase noise. Due to reciprocal mixing between the strong excitation (TX signal) and the clock phase noise, the noise figure of the circulator (ANT to RX) can degrade in the presence of the strong TX signal [71]. A detailed analysis of this reciprocal mixing effect is critical and has not been addressed before. Initial studies indicate that uncorrelated phase noise between the various phase-shifted clock signals degrades performance, while correlated noise cancels out and has minimum effect. Therefore, techniques that ensure noise correlation between the various phase-shifted clocks, such as the retiming of the clocks with the input square-wave clock [91], are expected to reduce the effect of reciprocal mixing without a significant impact on clock path power consumption.

VI. CONCLUSION

In summary, non-reciprocal components based on ferrite materials are an integral part of the current-day electrical, optical and quantum systems, but have limited application in portable, low-cost systems due to their large form-factor and implementation cost. As an alternative, integrated non-magnetic non-reciprocal components, specifically those based on time-variance, have gained significant attention in the recent years and their performance is rapidly improving, making them relevant to real-world applications such as full-duplex wireless communication, radar and quantum computing. We hope that this review will illuminate new directions for research and spur further progress in this exciting field.

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