Magnetless Circulators Based on Synthetic Angular-Momentum Bias: Recent Advances and Applications

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Abstract— In this paper, we discuss recent progress in magnet-free non-reciprocal structures based on a synthetic form of angular momentum bias imparted via spatiotemporal modulation. We discuss how such components can support metrics of performance comparable with traditional magnetic-biased ferrite devices, while at the same time offering distinct advantages in terms of reduced size, weight, and cost due to the elimination of magnetic bias. We further provide an outlook on potential applications and future directions based on these components, ranging from wireless full-duplex communications to metasurfaces and topological insulators.

Index Terms— Angular-momentum, non-reciprocity, magnet-free, spatiotemporal modulation, metamaterials.

I. INTRODUCTION

THE demand for multimedia-rich applications and services has been dramatically increasing over the last few decades. As a result, the sub-6 GHz electromagnetic spectrum, where most of deployed communication systems operate, has become saturated with unprecedented data traffic leaving no more bandwidth for further growth in the transmission rate. In order to overcome this problem, full-duplex radios have been proposed. In such systems, data streams are transmitted in the uplink and downlink simultaneously on the same carrier frequency [1]-[9], which doubles the spectral efficiency compared to half-duplex time- and frequency-division systems. The key challenge in full-duplexing, however, is that it requires considerably large self-interference cancellation (SIC) between the transmitter (Tx) and receiver (Rx) of every communication node in order to prevent the strong Tx signal from saturating the Rx frontend modules. For instance, WiFi signals are transmitted at an average power of +20 dBm and the noise floor is around -90 dBm, hence SIC is required to be as high as +110 dB. For many years, this level of SIC was impossible to attain, therefore full-duplex radios were presumed irrelevant in practice. Recently, several works challenged this long-held assumption and demonstrated that full-duplexing can, in fact, be achieved by using a combination of radio-frequency (RF) [3]-[5], analog [6]-[7], and digital techniques [8]-[9]. The basic idea in digital and analog approaches is to generate a weighted version of the Tx signal that mimics its echo into the receiver and subtract it from the Rx signal before and after the analog-to-digital converter. Since the strength contrast between the Tx and Rx signals can be billions in magnitude, the subtraction must be performed extremely accurately, otherwise it may end up adding more interference. But the presence of non-idealities such as noise, non-linearity, and dynamic variation of the antenna input impedance, make this process a non-trivial task. Therefore, analog and digital SIC approaches must be preceded by another layer of isolation at the RF frontend in order to relax their design requirements and mitigate their sensitivity to inevitable errors. Fortunately, circulators can play this role [10]-[64]. Not only can they achieve low insertion loss, thus overcoming the fundamental limit of electrical-balance duplexers, but they also allow the Tx and Rx nodes to share a single antenna thus making full-duplexing more attractive compared to multi-input multi-output (MIMO) radios.

For decades, circulators have been built almost exclusively through magnetic biasing of rare-earth ferrites [10]-[19]. These magnetic devices can achieve excellent performance in terms of isolation, power handling, bandwidth of operation, and insertion loss, yet they typically result in bulky, non-integrable, and expensive devices that may not be suited for various commercial systems. In order to overcome these problems, magnet-free implementations of circulators based on active solid-state devices or nonlinear materials with geometric asymmetries have been pursued [20]-[29]. Despite significant research efforts over many years, these alternative solutions continued to suffer from a fundamentally poor noise figure and limited power handling, hence the appeal of a fully passive material that can provide non-reciprocity kept favoring magnetic approaches. Recently, however, it was shown that parametric circuits can overcome these limitations and achieve excellent performance together with low-cost and small-size. For example, [31] introduced the concept of spatiotemporal modulation angular-momentum (STM-AM) biasing to synthesize cyclic-symmetric magnetless circulators. This was then followed by numerous works extending these concepts to
realize various magnet-free components, including circulators, gyrators, and isolators [31]-[55]. In particular, [33]-[36] refined the STM-AM concept by finding the necessary conditions to ideally mimic magnetic biased cavities, thus enabling the development of many new circuits with unprecedented performance. In this article, we review recent advances in STM-AM devices and provide an outlook on their possible impact on technology and future research directions. We also discuss the unusual properties of two-dimensional metasurfaces consisting of arrays of such elements, which may be engineered to behave as magnetized ferrites or topological insulators [66]-[85].

II. OPERATION PRINCIPLES OF MAGNETIC CIRCULATORS

The S-matrix of an ideal circulator can in general be written in the following form

$$\begin{bmatrix}
0 & 0 & 1 \\
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix},$$

(1)

Equation (1) shows that an input signal at, say, port 1 is exclusively routed to port 2 without any reflections or leakage to port 3. Similarly, an input signal at port 2 or 3 is routed to port 3 and 1, respectively. In other words, an ideal circulator is cyclic-symmetric and exhibits zero insertion loss, perfect matching, and infinite isolation. In reality, however, not only the S-matrix is limited by the inevitable dissipation in the constituent materials of the circulator, but it is also frequency dispersive and maintains non-reciprocity over a finite bandwidth (BW). Despite such practical imperfections, the harmonic response of a linear non-dispersive cyclic-symmetric circulator can still give us an invaluable insight into the physical principles of breaking reciprocity. For example, an excitation at one port of an ideal circulator, say port 1, can be decomposed using superposition into three sub-circuits, as shown in Fig. 1(a)-(c). In Fig. 1(a), the applied voltage sources are identical in both magnitude and phase while in Fig. 1(b) and Fig. 1(c), the sources have different phases, which increase by 120 deg either in the clockwise or counter-clockwise direction. Because of such distinctive phase pattern, we refer to such excitations as the in-phase (0), clockwise (+), and counter clockwise (−) modes, respectively. In general, each of these modal excitations generates a current component at the output ports and their linear combination gives the solution to the original excitation at port 1. If the circuit is symmetric and has only three terminals (no internal connections to ground), then a non-zero in-phase current violates Kirchhoff’s current law, hence it cannot be excited. Furthermore, if a preferred sense of precession is provided to the counter-rotating currents, then they will be excited with an equal amplitude, say $I_n$, and opposite phase, say $\pm \alpha$. Consequently, the total current at the n-th port becomes

$$I_n = 2I_0 \cos\left(\frac{(n-1) 2\pi}{3} + \alpha\right),$$

(2)

where $n$ is the port index. For $\alpha = 30$ deg, Equation (2) results in $I_3 = 0$ and $I_1 = -I_2 = \sqrt{3}I_0$. In other words, the impinging signal at port 1 is exclusively routed to port 2 and isolated from port 3. This implies that it is possible to implement an ideal circulator by imparting a preferred sense of precession to a pair of counter-rotating modes in a symmetric three-port network.

This principle indeed governs the way in which magnetic circulators operate: consider a ferrite cavity connected symmetrically to three ports at 120 deg intervals as depicted in Fig. 2. If a strong magnetic bias is applied orthogonally to the cavity in order to align the spinning electron dipole moments along a particular direction, the spin imparts a form of angular-momentum bias at the microscopic level, which in turn translates into a preferred sense of precession for the rotating modes of the cavity. As a result, if these modes are excited by an impinging signal at one port, say port 1, they accumulate different phases as they appear the other two ports. For a particular strength of the bias, these modes can sum up in phase at one of the output ports, say port 2, and destructively interfere at the other, i.e., port 3. If power dissipation inside the cavity is

![Fig. 2. Stripline Y-junction magnetic circulator [10].](image-url)
negligible, then this means that the incident power is exclusively routed from port 1 to 2. Due to the geometrical three-fold symmetry of the circulator, excitation at ports 2 or 3, will similarly be routed to ports 3 and 1, respectively, which yields the S-matrix of (1).

III. LIMITATIONS OF ACTIVE CIRCULATORS

Despite the fact that magnetic-circulators can achieve excellent S-parameters, power handling and noise performance with negligible power consumption, they suffer from large size and high cost due to the fact that they require an external bulky magnet and rare-earth ferrite materials. These critical problems prohibited an ubiquitous use of such devices in wireless communication systems and played an important role in consolidating the false assumption that full-duplex radios are impossible to realize in practice. For this reason, an interest in investigating magnet-free approaches to design circulators has emerged since the advent of solid-state transistors. When a BJT transistor, for instance, is biased with a dc current, it operates as a trans-conductance amplifier which converts ac voltages applied at its base terminal into large currents flowing from its emitter to collector terminals. A reverse voltage applied at either of the output terminals, however, is isolated from the base. In other words, a current-biased transistor operates as an isolator with forward gain. By combining three of such active isolators in a loop as shown in Fig. 3(a), an active magnet-free circulator can be constructed as explained in [20]. Variants of this circuits at different frequency ranges were also investigated over the years. For example, a robust low-frequency implementation using operational amplifiers (op-amps) was also presented in [21]. More recently, a synthetic active metamaterial consisting of an array of transistor-loaded microstrip ring resonators was also proposed in [22] as an artificial medium to replace magnetic-biased ferrites. In such materials, the transistors simply kill one of the rotating modes supported by the ring, thus allowing to realize active circulators as depicted in Fig. 3(b).

It is also worth mentioning that nonlinear materials have also been explored as an alternative medium to realize magnet-free circulators, especially at optical frequencies where transistors do not exist [27]-[29]. However, the resulting devices were only able to work when only one port is excited at a time. When two or more ports are concurrently excited, the S-parameters suffer from hysteresis and strongly depend on the relative phase between the input signals. Therefore, this approach is less useful than its active transistor-based counterpart which can support simultaneous excitation from different ports and at the same time offers distinct advantages in terms of weight, size, cost, and scalability compared to magnetic-biased ferrite devices. Unfortunately, however, active circulators still suffer from low power handling and poor noise figure. A comprehensive analysis of these fundamental limitations was presented in [26] leading to the conclusion that active circulators are not suitable for use as frontend modules in the vast majority of microwave applications where Tx power is either high or Rx sensitivity is critical.

IV. PARAMETRIC STM-AM CIRCULATORS

In recent years, time-varying circuits were presented as a promising solution to realize circulators that could handle much higher power, exhibit better linearity, and achieve lower noise figure than active implementations, while at the same time eliminating the necessity for bulky magnets and expensive materials needed in ferrite devices. Table I summarizes these advantages in comparison to traditional magnetic and active technologies presented in previous sections. Among all recent

![Diagram](image)

Fig. 3. (a) Active circulator consisting of three common-emitter amplifiers in a loop, each acting as an isolator [20]. (b) Active circulator consisting of three coupled transistor-loaded ring resonators forming an artificial metamaterial nonreciprocal core [22].

| Approach | Magnetic | Active | Parametric |
|----------|----------|--------|------------|
| Magnet   | Required | Not required | Not required |
| Size     | Large    | Small   | Medium     |
| Cost     | High     | Low     | Low        |
| Insertion loss | Low | Low (or gain) | Medium |
| Isolation | Medium | Medium | High |
| Bandwidth | Wide | Average | Average |
| Power handling | High | Low | Medium |
| Noise figure | Low | High | Medium |
| Power dissipation | Low | High | Medium |
works on parametric circulators, STM-AM circuits, which is the main focus of this article, have shown significant promise in satisfying the challenging requirements of practical systems at different portions of the electromagnetic spectrum. In particular, our group presented in [56] a circulator for airborne sound by synthesizing an effective angular momentum bias, in the form of mechanical rotation of air, inside a circularly symmetric resonant acoustic cavity. Such bias imparted a macroscopic sense of precession to the degenerate modes of opposite handedness supported by the cavity, which translates into non-reciprocity and isolation as explained in Sec. II. Using similar principles, one could imagine spinning a circuit board sufficiently fast to break reciprocity for the electromagnetic signals traveling across a resonant device, but arguably this mechanical spin would be even less practical than magnetic approaches to non-reciprocity. However, spatiotemporal modulation can impart a form of synthetic angular momentum bias, enabling the implementation of compact STM-AM circulators as described in the following.

A. Single-Ended Topologies

Consider a symmetric resonant three-port network consisting of three series or parallel $LC$ tanks connected in a loop or to a central node, resulting in four possible combinations as shown in Fig. 4. Let us further assume that the instantaneous oscillation frequencies of the tanks are spatiotemporally modulated as follows

$$f_e = f_0 + \Delta f \cos \left(2\pi f_{m} t + (n-1)\frac{2\pi}{3}\right), \quad (3)$$

where $f_0 = \frac{1}{2\pi\sqrt{L_0C_0}}$ is the natural oscillation frequency of the tanks, $\Delta f$ is the modulation depth, and $f_m = \omega_m/2\pi$ is the modulation frequency. In practice, (3) is implemented using varactors, switched capacitors or Josephson junctions, depending on the target application. In the case of varactors, for instance, $\Delta f$ can be written as $\Delta f = kV_m$, where $k$ is the slope of the C-V curve. The modulation scheme of (3) synthesizes an effective angular momentum bias in the clockwise direction since the phases of the modulation signals increase by 120 deg in that direction thus lifting the degeneracy of the rotating modes and allowing them to oscillate at different frequencies, say $\omega_{\pm}$. Between these two frequencies, the skirts of the resonances do allow transmission, whether the original resonance was bandpass or bandstop, and they exhibit opposite phases. Therefore, if an input signal is incident at one port in the middle of these two frequencies, i.e., $\omega_0$, it will excite the two resonances with equal magnitude and opposite phases $\pm \alpha$, which is consistent with the generic description of the previous section based on providing a preferred sense of precession. It is also worth mentioning that the amount of splitting $\omega_+ - \omega_-$ depends on the modulation parameters $f_m$ and $V_m$, thus allowing to control the value of $\alpha$. As explained earlier, for $\alpha = 30$ deg, ideal circulation can be achieved at $\omega_0$. In light of this discussion, this condition will correspond to a certain combination of $f_m$ and $V_m$.

As an example, the bandstop/delta topology of Fig. 4(c) was built and tested in [33]. The measured insertion loss (IL), return loss (RL), and isolation (IX) at the center frequency of 1 GHz were 3.3 dB, 10.8 dB, 55 dB, respectively, and the measured BW was 2.4% (24 MHz). This circuit can also be reconfigured for operation at different channels over a frequency range of 60 MHz by simply changing the DC bias of the varactors. The measured 1- and 20-dB compression points of IL and IX, respectively, were both +29 dBm. Also, the measured IIP3 was +33.8, which are reasonable nonlinearity metrics meeting the specifications for a range of applications. It is important to stress that these metrics stem from the properties of the employed circuit components, not from a fundamental limit in the approach to non-reciprocity. It can also be proven that STM-AM circulators are inherently passive linear circuits [42], hence we expect that the overall noise figure (NF) is approximately equal to the IL but slightly larger due to noise folding from the intermodulation products (IMPs) and phase noise in the modulation signals. Indeed, the measured NF was 4.5 dB at 1 GHz and less than 4.7 dB over the BW. These results

![Fig. 4. Single-ended topologies of STM-AM circulators [35]. (a) Bandpass/wye. (b) Bandstop/wye. (c) Bandstop/delta. (d) Bandpass/delta.](image)

![Fig. 5. Differential configurations of STM-AM circulators [34]. (a) Current-mode.(b) Voltage-mode.](image)
are summarized in Table II and the interested reader is referred to [33] for further technical details.

B. Differential Configurations

As illustrated in previous section, single-ended STM-AM circulators can achieve good performance in terms of several metrics, particularly in terms of power handling and noise figure. Nevertheless, these circuits suffer from large intermodulation products (IMPs) in close proximity to the desired BW, resulting from parametric mixing induced by the temporal modulation and from the inevitable non-linearities associated with its circuit components. These IMPs draw power from the input signal, which limits IL to about 2 dB in practice. They are also considerably large, i.e., only 10 dB below the fundamental harmonic, and they equally appear at all ports for excitation at a single port. Therefore, the IMPs resulting at the Rx port from the Tx excitation could saturate the Rx front-end regardless of how much isolation is achieved at the fundamental frequency. Similarly, the IMPs resulting from the Rx signal at the Tx port can cause instability issues to the power amplifier (PA) because of load-pull effects. More importantly, the IMPs at the antenna (ANT) port, either due to the Tx or the Rx signal, pose a serious interference problem to adjacent channels and would prohibit compliance with the spectral mask regulations of most commercial systems. Therefore, it is crucial to reject these products. This problem was overcome in [34] by combining two single-ended circuits similar to those presented in the previous section in a differential voltage- or current-mode architecture, as shown in Fig. 5 and maintaining a constant 180 deg phase difference between their modulation signals, i.e.,

$$f_{m,n} = f_0 + \Delta f \cos \left( 2\pi f_{d,i} + (n-1) \frac{2\pi}{N} \right)$$

(4)

where $f_{m,n}$ and $f_{u,n}$ are the modulation signals of the two constituent single-ended circuits. As an example, in [34], the voltage-mode configuration of Fig. 5(b) was built and tested using two of the single-ended bandstop/delta circuits depicted in Fig. 4(c). The measured IL, RL, and IX after de-embedding the baluns were 0.78 dB, 23 dB, and 24 dB, respectively, and the fractional BW was 2.3% (23 MHz). Table II also summarizes these results along with other metrics and the interested reader is referred to [34] for further details.

C. N-Way Architectures

While the differential STM-AM circulators presented in previous section dramatically improved the performance over many metrics compared to the single-ended implementations, their spurious emission can remain strong when non-idealities in the circuit are considered. In order to address this problem, we can extend the differential configuration to an N-way architecture, consisting of N unit cells connected in parallel or in series as shown in Fig. 6 [35]. The modulation scheme in this case becomes

$$f_{m,n} = f_0 + \Delta f \cos \left( 2\pi f_{d,i} + (n-1) \frac{2\pi}{N} \right)$$

(5)

where $i = 1; N$ is the unit index and $n = 1; 3$ is the tank index in the $i$-th unit. Equation (5) reduces to (4) for $N = 2$, and this generalization is more effective at eliminating the IMPs that are not multiples of $N f_{m,n}$ in the presence of nonidealities, such as non-linearities, phase synchronization errors and random mismatches between the constituent elements. As a by-product, N-way circulators provide better power handling, enhanced by a factor of $N$ since the input power is split amongst $N$ units. Nonetheless, the benefits of the N-way architectures come at the expense of an overall increased size and power consumption. As before, Table II summarizes the results and the interested reader is referred to [35] for further technical details.

D. Bandwidth Extension

The instantaneous BW of all circuits presented thus far is limited by the modulation frequency $f_{m}$, the loaded quality factor $Q_i$ of the resonant junction, and the order of the
constituent resonators. For example, first-order resonators, i.e., series or parallel $LC$ tanks, with 10–20% modulation frequency and 50 Ohm termination led to a BW of about 3–4% at best. One solution to improve this further is to increase $f_m$, but this approach increases power consumption, prohibits the use of thick-oxide low-speed technologies that could handle high power, and complicates scaling the center frequency to the mm-wave bands. Alternatively, one may think of replacing the LC tanks with high-order LC filters but this would increase the circuit complexity and size dramatically. In order to approach such a bound, the order of the matching filters must be very large. In practice, however, the maximum order is limited by the additional losses exhibited by the filters themselves which increase the circulator’s overall IL.. In order to experimentally validate this technique, [36] relied on a 2nd-order filter and a current-mode bandpass/wye STM-AM circuit resulting in a three-fold increase in the BW from 4% (40 MHz) to 14% (140 MHz). The measured results of all other metrics are again summarized in Table II and the interested reader is referred to [36] for further details.

E. Integrated Implementations

The results presented in the previous sections were all based on printed circuit board (PCB) prototypes which, despite outperforming previous works in many metrics, were still limited in size. To overcome this problem and to achieve significant miniaturization, an IC implementation is highly desirable. Towards this goal, [37] modified the bandpass/wye

![Photographs of the first CMOS STM-AM circulator][37]. (a) Chip. (b) Board.

Fig. 8. Photographs of the first CMOS STM-AM circulator [37]. (a) Chip. (b) Board.

![Photographs of the first MEMS STM-AM circulator][41]. (a) Chip. (b) Board.

Fig. 9. Photographs of the first MEMS STM-AM circulator [41]. (a) Chip. (b) Board.

| Reference | [33] | [34] | [35]† | [36] | [37] | [41] |
|-----------|------|------|------|------|------|------|
| Architecture | Single-ended Bandstop/Delta | Differential Bandstop/Delta | Parallel N-way Bandstop/Delta | Broadband Current-mode Bandpass/Wye | Current-mode Bandpass/Wye |
| Technology | PCB | PCB | N/A | PCB | CMOS 180-nm | MEMS/PCB |
| Cent. frequency (GHz) | 1 | 1 | 1 | 1 | 0.91 | 2500 |
| Mod. frequency (%) | 19 | 10 | 10 | 11 | 11.6 | 1.6 |
| 20 dB IX BW (%) | 2.4 | 2.3 | 3 | 14 | 2.4 | 0.72 |
| Max IX (dB) | 55 | 24 | 25 | 31 | 65 | 30 |
| Min IL (dB) | 3.3 | 0.8 † | 2.2 | 4.2 | 4.8 | 4 |
| Max RL (dB) | 11 | 23 | 24 | 16.7 | 11 | 15 |
| P1dB (dBm) | +29 | +29 | +39 | +23 | N/A | +28 |
| IX20dB (dBm) | +29 | +28 | +41 | N/A | N/A | N/A |
| IIP3 (dBm) | +33 | +32 | +43 | N/A | +46 | +40 |
| Min NF (dB) | 4.5 | 2.5 | 2.2 | N/A | 5.2 | N/A |
| Max. IMP (dBc) | @ $f_0 + f_m$ | @ $f_0 + f_m$ | @ $f_0 + 2f_m$ | @ $f_0 + f_m$ | @ $f_0 + f_m$ | @ $f_0 + f_m$ |
| Power diss. (mWatt) | N/A | N/A | N/A | N/A | 64 | 0.15 |
| Size (mm$^2$) | 143 | 286 | N/A | 480 | 36 | 225 † |

N/A: Not available. † Simulation results. ‡ Baluns are de-embedded. * MEMS die area = 0.25 mm$^2$. |
As an example, the non-reciprocal polarization rotation imparted by such surfaces can reach 1,000s of degrees per wavelength, a very impressive metric considering that these surfaces can be implemented in standard CMOS technology without need of an applied magnetic bias. Beyond electro-optical modulation of these arrays, similar phenomena can be achieved using all-optical modulation via nonlinearities. By parametrically pumping a nonlinear etalon with two circularly polarized waves at detuned frequencies, it is possible to impart an effective angular momentum bias that replaces the modulation schemes discussed in the previous sections [65].

Opportunities arise also to impart non-reciprocal responses to surface waves propagating along an array of STM-AM biased devices. Arguably a striking example of this type is the opportunity to mimic the response of a topological insulator (TI) for electromagnetic waves. A TI is a material that acts as an insulator in the bulk and as a conductor on its edge or boundary, independent of the way in which the boundary is deformed or changed [66]-[69]. What is unique about such materials is that its edge conduction states are symmetry-protected by the topology of their conduction bands delimiting the bandgap, hence they allow unusually robust conduction properties at the foundations of the quantum Hall effect, among many other unusual phenomena. Translating these concepts from electronics to electromagnetics, a photonic TI enables unidirectional reflection-free propagation on the edges of the (meta)-material within a photonic bandgap, immune against a
Fig. 11. (a) Hexagonal lattice consisting of electronic STM-AM circulators based on the bandpass wye topology of Fig. 2(a) [85]. An artificial boundary is created at the middle of two domains inside the lattice, each with an opposite direction of STM-AM bias. Schematic and energy density of a single meta-atom near the artificial interface are shown in the insets. (b) Band diagram with four conduction bands (blue) and a topologically protected edge state (purple) at the artificial interface.

While TIs were originally envisioned and discovered in condensed-matter physics, their extension to classical photonic [69]-[78], acoustics [79]-[83], and circuits [83]-[85] has been driving a lot of excitement. In such a case, symmetry breaking at a degeneracy point in momentum space is typically sufficient to induce topological order and enable edge states. Breaking time-reversal symmetry is a particularly effective way to realize electromagnetic TIs, since it supports robust, broadband non-reciprocal propagation and guarantees the absence of reflected modes regardless of the nature of the possible disorder in the system.

Here, we consider an array of STM-AM elements that realize an electromagnetic TI with non-reciprocal edge propagation. Since the edge states in this case emerge from periodic temporal variations, the resulting system is referred to as a Floquet TI. An example is shown in Fig. 10(a) [81]: the unit cell of the corresponding hexagonal lattice is depicted in Fig. 10(b) and it consists of two waveguide STM-AM circulators in which the time modulation synthesizes a rotation, similar to what described in the previous sections, to impart an effective angular momentum bias. The STM-AM waveguide circulator is consistent with the bandpass/delta topology of Fig. 4(d), and the modulation can be achieved by modulating the volume of each cavity using piezoelectric actuators, or in other similar schemes as described in the previous sections. Fig. 10(c) shows a comparison between the band diagrams of such a photonic crystal with and without modulation. Without modulation (blue curves), four propagating bands are found around 22 kHz, two of which appear to be slow in nature corresponding to static modes, while the other two correspond to fast Dirac bands with degeneracy at both G and K points. On the other hand, when the modulation is turned on (orange curves), the band diagram folds with periodicity equal to the modulation frequency, as would be expected from the Floquet-Bloch theorem. More importantly, since the modulation breaks the temporal symmetry, the degeneracy at both G and K points is lifted and a bandgap opens. Ref. [81] theoretically predicted the existence of a unidirectional edge state in such a gap by calculating the topological invariant of the first Chern class for the four conduction bands. Such a prediction was then validated through full-wave simulations of a truncated lattice confirming the theoretical analysis.

In [85], an electronic STM-AM TI was also presented. Similar to the TI of Fig. 10, the lattice was also hexagonal but the meta-atom was based on a bandpass/wye STM-AM circulator, as in Fig. 4(a). Without modulation, the lattice exhibits a continuous energy spectrum with six Dirac points. When the STM-AM biasing is applied to each meta-atom, the degeneracy of the Dirac points is lifted and a bandgap opens in the bulk. Furthermore, in order to test the presence of an edge mode, the lattice can be divided into two regions, one with a clockwise STM-AM bias and the other with a counter clockwise bias. Such a division results in a domain wall between the two regions that can support an edge state and is easier to calculate numerically. Fig. 11(a) shows the spatial distribution of the energy density of such a mode when excited at the middle of the bulk. As depicted in the left inset, the energy is localized around the artificial boundary and decays sharply in the bulk. Fig. 11(b) shows the band diagram for such a scenario, which indeed manifests an edge mode that can carry energy only in the +x direction. An experimental demonstration for elastic waves has also been recently reported using arrays of piezo-electric elements [82], also showing dynamic reconfigurability and opportunities for multiplexing. 

STM-AM Floquet TIs do not require fast modulation speeds nor phase uniformity between different unit cells, which eases their implementation and makes them relevant for practical applications, for instance for multiplexing. The channels can be dynamically reconfigured thanks to the possibility of creating artificial domain walls by simply controlling the direction of the STM-AM bias, which is of significant importance in today’s programmable systems. This, in turn, opens the door to new venues and possibilities in future research directions.

VI. CONCLUSIONS

In this paper, we reviewed the concept and recent progress on magnet-free STM-AM devices. We outlined the underlying physical principles and presented its basic topologies and advanced architectures, with a focus on the single device element to realize circulators. For completeness, the results of all fabricated prototypes are summarized in Table II. We also provided an outlook on the potential impact STM-AM circulators may have on future technologies such as wireless full-duplex communications and in the field of metamaterials such as Floquet topological insulators. The antennas and propagation community can play a pivotal role in pushing forward the application research on these systems, in which many outstanding challenges remain, both from the modeling and theoretical perspective, for instance in the efficient calculation of time-modulated systems, and from the practical
and efficient implementation of these devices for various applications.

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