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Seamless Integration Technology for Filtenna Toward 5G/6G Wireless Communications

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ABSTRACT The fifth generation (5G) mobile communication systems employ technologies such as massive MIMO, millimeter-wave (mmWave), and ultra-dense networks to support higher transmission data rate and lower latency, thereby enabling commercial deployment. Furthermore, the forthcoming sixth generation (6G) networks will integrate terrestrial and non-terrestrial networks, aiming to achieve full spectrum, full applications, and global coverage. Whether in the context of 5G or 6G networks, base transceiver stations (BTS) require a substantial number of radio frequency (RF) transceiver chains and antenna array, particularly in mmWave frequency bands. It is known that bandpass RF filters between antenna elements and transceivers are key components for suppressing out-of-band spurs and interference. The single board seamless integration of transceivers and antennas has become a growing trend. It means there is no extra room for a large number of filters at mmWave bands, leading to the emergence of integrated designs that combine filtering circuitry with antennas, known as filtenna or filtering antenna. With illustrated examples, the design methodologies, operational principles, and implementation strategies of filtennas are reviewed in this paper.

INDEX TERMS Filtenna, filtering antenna, 5G communications, 6G communications, radiation null, filtering circuitry, coupled resonator theory, coupling matrix, multipath coupling, cross coupling, open-circuited stub, collaborative type, fusion type.

I. INTRODUCTION

MOBILE communication technology has evolved substantially over the last fifty years, delivering astonishing outcomes. Each generation of mobile communication, from the first to the current fifth, has undergone distinct levels of advancement in channel capacity, bandwidth, data rate, and security. Fig. 1 illustrates multiple access technologies and transceiver chains spanning from 1G to 5G. Specifically, the first-generation (1G) of mobile communication realized the transformation from wire communication to wireless analog communication based on technologies such as AMPS, TCAS, and NMT [1]. With the further development and maturity of technologies such as integrated circuits (ICs), microprocessors, and digital signal processing, digital technology using TDMA is introduced into second-generation mobile systems to substitute analog technology, thus boosting their channel capacity, anti-interference and safety [2]. The 1G and 2G base transceiver stations (BTS) employ a single-input single-output (SISO) system, and their radiation part are typically low-gain antennas to provide a wide coverage. Given the tremendous demand for mobile Internet access, some advanced CDMA technologies, such as WCDMA, TD-SCDMA, and CDMA2000, have been proposed in third-generation (3G) mobile systems to achieve relative high uplink and downlink peak rates [3], [4]. The primary distinction between 3G network technology and the previous two generations of communication networks is that it fully supports a wider range of multimedia technologies.

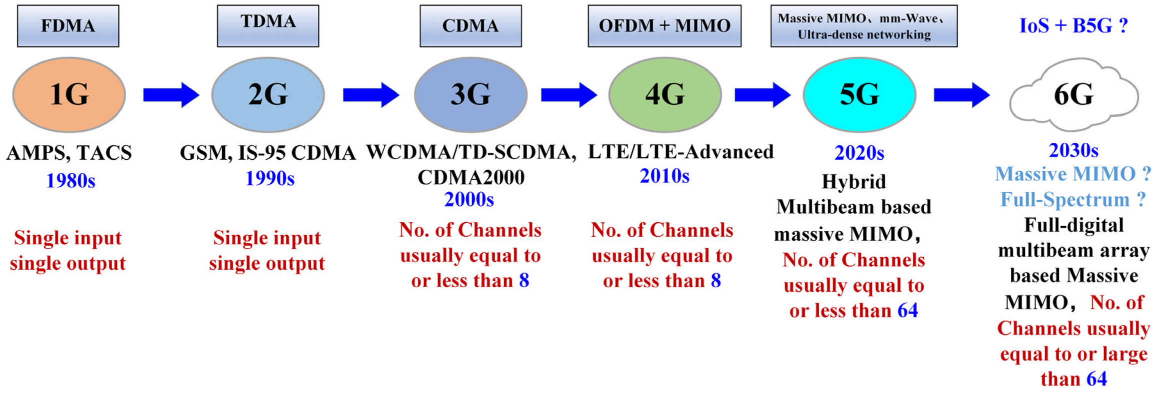

FIGURE 1. Multiple access technologies and transceiver chains spanning from 1G to 5G.

Immediately afterwards, 3GPP proposed LTE and LTE-A as the technical standards of 3.9G and 4G based on MIMO and OFDM technologies, respectively, ushering in greater intelligence in mobile terminals [5], [6], [7]. Diversity gain and spatial multiplexing are implemented to the baseband in 3G and 4G BTS for MIMO architectures, and the number of channels typically equal to or less than 8.

Starting from 2019, 5G has been officially commercialized, employing sub-6GHz (FR1) and millimeter-wave (mmWave) (FR2) bands, with a peak rate of 10 Gbps [8], [9], [10]. The 5G base stations exploit massive MIMO [11], mmWave [12], ultra-dense networking (UDN) technologies [13] to support higher data rate and lower latency. The AAU in commercial 5G BTS recruits a phased-subarray-based hybrid multibeam array, supporting up to 64 or more transceiver chains with even more radiating elements [14]. Although 5G has made considerable advancements over 4G communication systems, it can be tricky to acquire sufficiently superior connections in some application scenarios and services, such as global coverage, ultra-low latency, ultra-high data rate, ultra-high positioning accuracy, and ubiquitous wireless intelligence [15]. Countries and standardization organizations around the world have conducted preliminary research on sixth-generation (6G) to tackle the aforementioned limitations and challenges. Overall, the 6G will integrate terrestrial and non-terrestrial networks, which is expected to be descripted as "Global coverage, all spectrum, full applications, all senses, all digital, and strong security" [16]. In comparison to the terahertz frequency band, the mmWave has undergone full development of the 5G era, the device capability has been vastly enhanced, the industrial chain is fully developed and rich, and it can fulfill most of the application requirements of the 6G system, so it will be the initial option for the 6G network. Among them, the full-digital multibeam based massive MIMO in mmWave band is expected to become one of the key technologies of 6G, which requires the number of transceiver channels to be equal to or greater than 64 [17].

With the growth of semiconductor technology in recent years, chips have evolved in a manner of high integration, low power consumption, low cost, and multifunction, making 5G/6G mmWave massive MIMO array and phased-array systems integrated into single printed-circuit-board (PCB) using innovative multichannel beamforming chips, effectively decreasing the volume, weight, cost, and power consumption of devices [18], [19]. Fig. 2 depicts a typical 5G/6G mmWave massive MIMO system architecture based on phased array technology. As a key component of wireless communication system, the filter is typically resided between the antenna and the RFIC to suppress out-of-band spurs, local oscillator leakage, and image frequency interference to provide excellent radiation performance. However, it invariably brings the following issues: 1) it requires the design of extra matching circuits, which increase the workload and development cycle; 2) it increases the footprint of the RF chain, which is incompatible with the miniaturization and integration design of the RF circuit; and 3) it introduces additional insertion loss and degrades the cascaded noise figure [20]. Furthermore, hundreds or even thousands of filters need to be encompassed into the RF front-end for the emerging 5G/6G mmWave SoB (system on board) architecture, which drastically increases the cost. Added to that, there is no extra room for a large number of filters. As a result, it is critical that the filter be merged into the antenna, and then it results in a new component: Filtenna, which is becoming a key technology for seamless SoB/SoP/SiP integration of antenna, passive elements and integrated circuits of radio systems. The concept of filtenna is stemmed from a Ph. D. dissertation and patent reported in [21] and [22], and its merits as reported in [170] have demonstrated that filtennas are highly suited for miniaturized and low-cost platforms. Filtennas have been thoroughly developed in recent years due to their attractive features, and two distinct design methodologies have gradually emerged: 1) collaborative type; 2) fusion type. This paper reviews the advances in microwave and mmWave filtennas in recent years. Section II illustrates various collaborative-type filtennas. In Section III, the design theory and method of filtennas based on fusion type are summarized and compared. In Section IV, the performance comparison and discussion between various filtenna types, followed by conclusion in Section V.

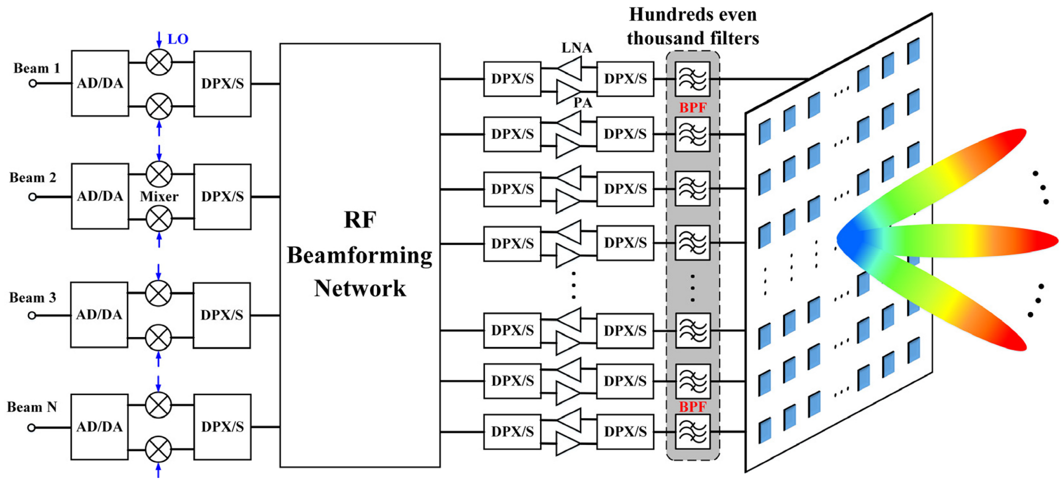

FIGURE 2. Typical system architecture of 5G/6G mm-Wave massive MIMO array based on phased array technology.

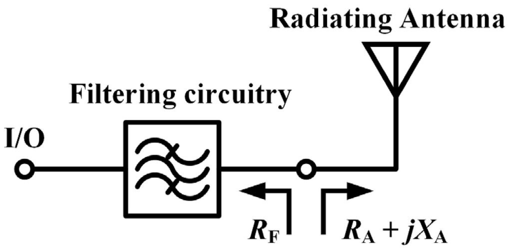

FIGURE 3. Scheme of IBFC-based filtenna.

II. COLLABORATIVE-TYPE FILTENNA

The collaborative-type filtennas involve the integrated design of both the filter and the antenna. This type of filtennas is classified into two design methodologies: 1) implanting the bandpass filtering circuitry (IBFC) into the feeding network of the antenna to filter out spurious signals, and 2) utilizing the radiating element as the final stage resonator of the filtering circuitry and employing coupled-resonator theory (CRT) for the overall design. In the following sections, the basic operation principle, design, and applications of the two design methodologies of filtennas are discussed.

A. IBFC-BASED FILTENNAS

Fig. 3 delineates the scheme of the IBFC-based filtenna. Differing from the scenario involving cascaded filter and antenna, impedance matching at the interface is taken into account in the filtenna design. The filtering characteristics of the first type of filtenna mainly depend on the IBFC-based feed network, including bandwidth, gain selectivity, and out-of-band suppression. Different types of filtering circuits such as resonant cavity [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], microstrip resonator [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45] and reconfigurable resonator are embedded in the feed network to obtain band-limited radiation characteristics. It should be noted that the bandwidth of the filtering circuit is usually narrower than the operating bandwidth of the radiating element to ensure proper system function within the desired frequency band [56].

Metallic or substrate-integrated waveguide resonant cavities exhibit higher Q-factor, resulting in reduced losses and enhanced frequency selectivity. As illustrated in Fig. 4(a), a planar COCO filtenna based on alternately series-fed microstrip antenna was proposed in [32], which achieves high selectivity by implanting a third-order substrate-integrated waveguide (SIW) inductive window bandpass filter. It should be noted that the SIW filter is integrated into the microstrip feed network of the planar COCO antenna, which can obtain a relatively compact footprint. As a result, unwanted out-of-band signals are effectively suppressed, and only the signal passing through the bandpass filter excites the radiating element.

In order to improve the gain of the RF link, a high directional radiation beam and frequency selectivity can be realized simultaneously by constructing a filtering power division network. Typically, as shown in Fig. 4(b), a wide-band 2×2 patch array filtenna based on four-way filtering power divider was proposed in [34] with favorable harmonic suppression. By ingeniously loading multiple short-circuited and open-circuited stubs in the four-way differential power divider, several transmission zeros (TZs) appear on the both sides of the passband, which effectively improves the harmonic suppression. The filtenna, which is based on the power division network and sponsored by the U-slot patch array, possesses a wide bandwidth, high gain, low cross-polarization level, and the harmonic suppression of up to three times the center frequency.

Furthermore, as an important form of filter, the reconfigurable filtering circuit is critical to the scalability of the filtenna. The frequency and bandwidth of the filtering circuit is controlled by loading pin diodes, varactor diodes, and MEMS switches on the resonator to accommodate the requirements of various application scenarios to accomplish multi-functional multiplexing. A frequency-reconfigurable filtenna is proposed in [50] with sharp out-of-band rejection

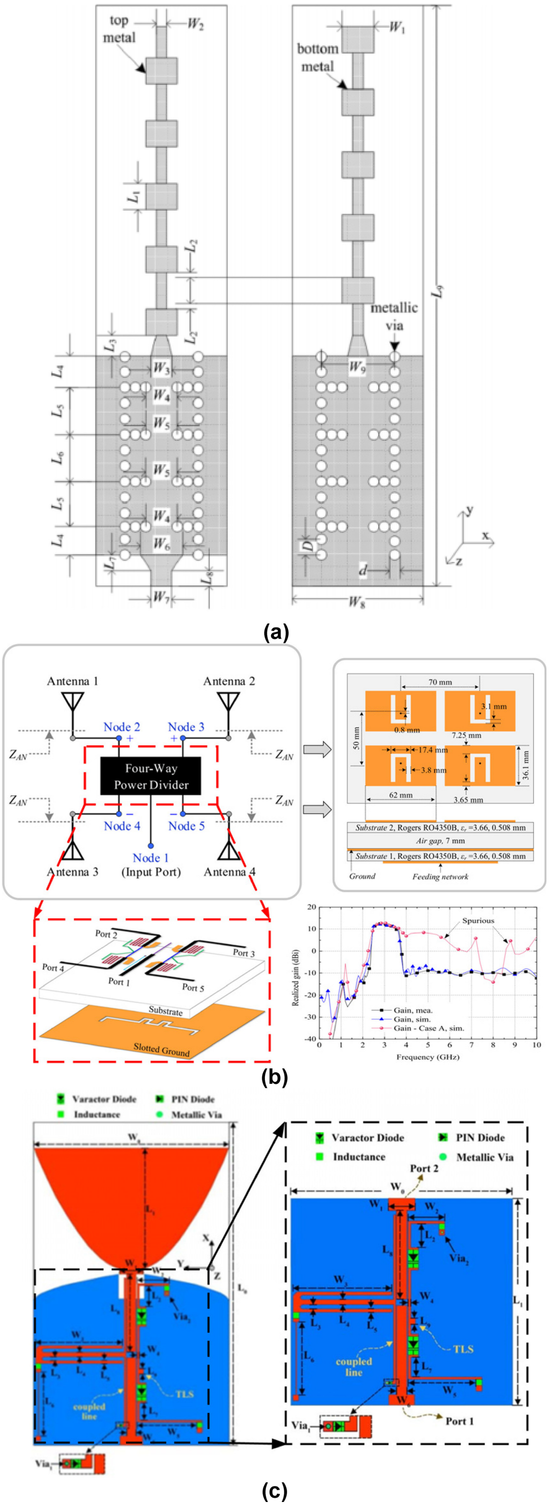

FIGURE 4. (a) Resonant cavity-based filtering circuitry. (reproduced from [32]) (b) Microstrip-type filtering circuitry. (reproduced from [34]) (c) Reconfigurable resonator filtering circuitry. (reproduced from [50]).

in both its wideband and continuously tunable narrowband states, as shown in Fig. 4(c). The filtenna is primarily made up of a funnel-shaped monopole and a reconfigurable filtering circuit. A broadband multi-mode resonator, a narrow-band resonator, and two parallel coupled lines

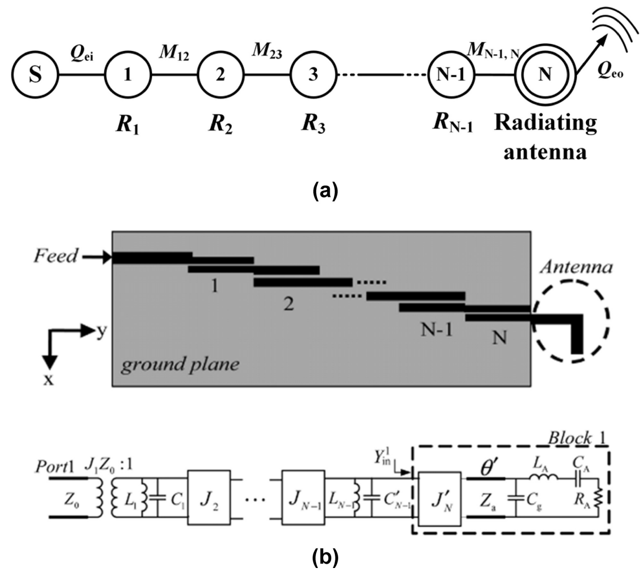

FIGURE 5. (a) Coupling and routing diagram of an Nth-order filtenna. (b) Planar structure of the Nth-order filtenna (reproduced from [58]).

comprise its filtering circuit. By altering the state of the pin diode on the multi-mode resonator, it is possible to switch between the broadband and narrowband modes. The two varactor diodes serve to constantly adjust the operating frequency in the narrowband state.

In broad terms, the filtenna based on IBFC provides superior filtering properties, which are defined by the performance of the inbuilt filtering circuit. However, it invariably results in relatively low radiation efficiency, excessive circuit footprint, degrading the signal-to-noise ratio of the receiver.

B. CRT-BASED FILTENNAS

The CRT-based filtering antenna swaps the last resonator and load impedance of a multi-order bandpass filter with a radiating antenna that presents a series or parallel RLC equivalent circuit, and its design process is generally represented as a coupling matrix [57]. According to coupled resonator theory, the coupling between different resonators, as well as the coupling between a resonator and the last-stage radiating antenna, is typically represented by a J/K inverter [58]. As an outcome of the formation of several resonance points (similar to transmission poles), CRT-based filtennas frequently have an appropriately wide bandwidth in comparison to conventional antennas. It should be noticed that as the order of the CRT-based filtenna increases, the frequency selectivity of the filtenna enhances, as does the spur suppression level, which is consistent with the nature of the filter.

Similar to the conventional filters, the most representative feature in the CRT-based filtenna is the *N*th-order direct-coupled filtering response, with its coupling and routing diagram depicted in Fig. 5(a). A co-design approach for direct-coupled filtenna synthesis based on lumped element model is proposed in [58] and verified with L-shaped radiating antenna and N-1 parallel coupled line resonators, as shown in Fig. 5(b). The design is accomplished by first extracting the circuit model of the antenna, then casting it into the synthesis of a typical parallel coupled line filter. As a proof-of-concept, a filtenna based on a third-order Chebyshev response provides good skirt selectivity and flat in-band gain as a design example. Without restricting the antenna model, coupling coefficients between cascaded resonators and I/O external quality factors (Q_e) in a Nth-order filtenna are retrieved in [57], [59]. To safeguard the primary filtering characteristics, the radiation quality factor of the filtenna (Q_r) needs to coincide with the external quality factor of the filter, and the coupling coefficients between resonators and radiating antenna are calculated by means of customary coupled resonator theory. With merits of low-loss and high-power capability, a large number of resonant-cavity-based filtennas such as SIW [60], [61], [62], [63], [64], [65], [66] and waveguide [67], [68], [69], [70], [71] have been thoroughly reported in the designs of the microwave/mmWave antenna with excellent frequency selectivity. To maintain high frequency selectivity, direct-coupled filtennas typically possess relatively large size, making them challenging to implement for multi-beam applications. To address this issue, the fully shielded eight-mode SIW (FSD-EMSIW) cavity with both high Q factor and compact footprint is proposed in [60] and adopted as resonators in the filtenna array design, as shown in Fig. 6(a). The filtenna with a direct-coupled fourth-order bandpass filtering response integrates the resonator and radiating structure into a multi-layer printed circuit board, including two stacked patch antennas and two FSD-EMSIW resonators. The coupling between the resonant cavity and the stacked patch is achieved through a rectangular aperture. Furthermore, by etching orthogonal rectangular apertures on the M3 layer, the filtenna can be extended to dual-polarization operation. As shown in Fig. 6(b), in order to meet the requirements of 5G mmWave applications, a 4×4-element single-polarized phased array with a 20dB stopband suppression level and ±45° beam-scanning capability has been designed and validated, which can cover the N257 and N258 frequency band (i.e., 24.25 GHz ∼ 29.5 GHz).

The above-mentioned direct-coupled topology is employed in a radiating element design and demonstrates outstanding filtering performance. Nevertheless, for the purpose to form a high-gain filtering response in a two-dimensional array, an all-resonator-based filtenna array is proposed in [59] [72], [73], [74], [75], [76], [77], [78], [79], which offers the flexibility of controllable bandwidth of array antenna as well as the ability to avoid the extra insertion loss and design difficulty caused by the matching circuit in the power division network. As depicted in Fig. 7, an all-resonator-based 8×8-element filtenna array is proposed for the high-efficiency terahertz applications [72]. The coupling diagram encompasses an over-mode cavity, high-order mode ($TE_{8,1,0}$ mode) waveguide transmission lines, and radiating slots. Its ingenuity lies in achieving high-selectivity filtering

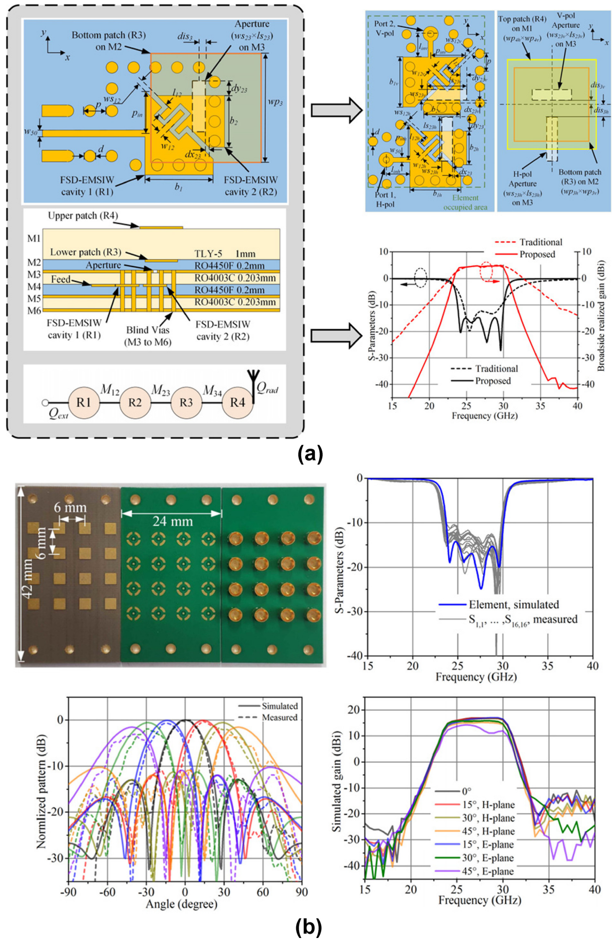

FIGURE 6. **(a) Configurations of FSD-EMSIW cavity-fed filtenna with direct-coupled response. (b) Its measured radiation patterns and frequency response. (reproduced from [60]).**

response by introducing virtual electric walls in the feeding network, while simultaneously significantly enhancing the radiation efficiency. It should be noted that by varying the coupling strength between resonators, the amplitude-tapering feed network required for low sidelobe filtennas can be achieved [74].

In addition to the direct-coupled response, the advanced multi-path coupling methodology [80], [81], [82], [83], [84], [85] has also been introduced into the resonator and antenna designs to create radiation nulls, so as to improve the roll-off rate coefficient and stopband suppression level. The cross coupling is strategically implemented in filtenna design to create radiation nulls at the finite frequencies to boost the selectivity. The typical coupling topology of cascaded trisection (CT) and cascaded quadruplet (CQ) responses are both verified to construct R-probes fed dual-polarized filtering patch antenna [81]. As expected for a CT filtenna, with an assumption that the direct-coupling and cross-coupling paths are out of phase, a single radiation nulls appears above or below the gain passband, the position of which is predicted by the coupling matrix. As a solution to introduce more radiation nulls at finite frequencies, the

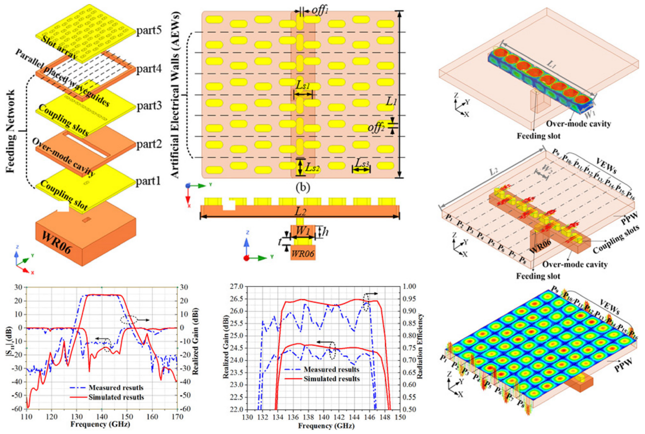

FIGURE 7. Configuration and frequency response of a high efficiency all-resonator-based filtenna array (reproduced from [72]).

CQ topology has four cascaded nodes, each with one cross coupling, so that a pair of radiation nulls can be created near the gain passband. As a kind of multi-path coupling methodology, source-load coupling is introduced in the filtenna design by using a radiating microstrip line to feed the antenna, and generates radiation nulls on either side of the passband, thereby constructing a quasi-elliptic filtering response, which has the merit of reducing the number of resonators and providing radiation efficiency [83]. Furthermore, the concept of multi-mode resonators is also constructed to further introduce more coupling paths and widen the operating bandwidth and reducing the order of the filtenna [86], [87], [88], [89], [90]. The N+2 coupling matrix is a powerful tool to assist in the designs of multi-mode filtenna, which can be obtained by transverse matrix synthesis technique and matrix rotation technique. By judiciously and skillfully designing the signs of input and output couplings from the source and load terminations to resonator nodes in the core matrix (i.e., M_{Si} and M_{Li}), several radiation nulls are obtained outside the gain passband [91].

Operating in multiple independent frequency bands to access different services with multi-mode terminals builds further demands on the multifunctional and highly integrated design for filtenna to accommodate this multiband RF signal reception and transmission into a single RF transceiver. Mixed resonators or multi-mode resonators are routinely exploited to construct such a filtenna [84], [92], [93], [94], [95], [96], [97]. As shown in Fig. 8(a), the fully-shielded quarter-mode SIW (FSD-QMSIW) cavity is proposed to build the three-order dual-band filtenna by using the first two modes, namely TE_{101} and TE_{103} modes. Among them, the TE_{101} mode resonates in the n258 band, while the TE_{103} mode is responsible to the n260 band. The dual band multi-path coupling topology is accomplished by coupling the mmWave signal in FSD-QMSIW to two pairs of ring patches stacked on the M1 and M2 layers. As a result, four radiation nulls appear near the gain passband to improve the stopband attenuation for dual-polarization operation. To

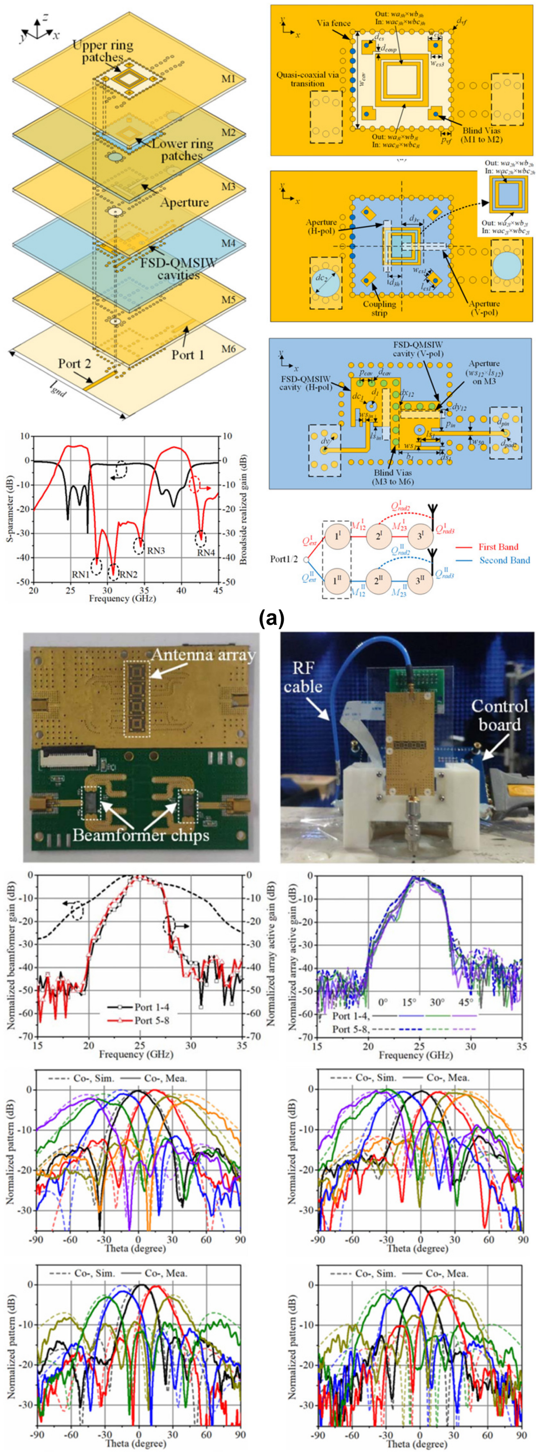

FIGURE 8. (a) Configurations of CRT-based dual-band filtenna with multi-path coupling. (b) Its measured setup, radiation patterns, and frequency response. (reproduced from [97]).

consolidate the validity of the design strategy, the passive and active 1×4-element filtenna array is fabricated to verify beam scanning capability and filtering performance, as shown in Fig. 8(b). The scanning angles of the filtenna array are up to ±45° at 26 GHz and ±30° at 39 GHz, respectively.

The gains drop between two bands is greater than 20dB for dual-polarization state. In addition, the development of multiplexing filtenna is also particularly essential to the multi-standard communication systems, as it can not only drastically minimize interference between different antennas for various services, but also reduce the footprint of the antenna.

Since the CRT-based filtennas employ the radiating antenna as the last order resonator of the filter, their bandwidths are frequently wider than the IBFC-based filtennas. Likewise, as compared to the IBFC-based filtennas, it can minimize the footprint of the filtenna even further. Naturally, whether the filtenna is based on CRT or IBFC, a portion of filtering circuit is retained, resulting in the drawbacks of a large footprint and relative low efficiency. As the CRT-based filtenna still involves a trade-off between overall size and frequency selectivity, it additionally promotes the growth of filtenna research.

III. FUSION-TYPE FILTENNAS

In recent years, starting from solving the issue of excessive footprint and seeking to better integrate the designs of the antenna and filter, a fusion design strategy that does not call for extra or fewer filtering circuits has been presented and deeply embraced with filtenna design. This fusion-type filtenna integrates resonant components in parallel with a radiating antenna based on the radiation reshaping method, establishes a filtering response by creating radiation nulls near the gain passband. Such a bandstop function preforms efficiently in the antenna design to choke off signal transmission over its stopband, while maintaining a perfect radiation for the operating frequency band. This particular category of filtennas can be delineated into the following quintessential domains based on the mechanisms underlying the generation of radiation nulls: 1) evolved radiator; 2) defected ground structure (DGS) on the ground plane of the antenna; 3) parasitic structures near the radiator; 4) evolved feeding topologies. To generate multiple radiation nulls for improving the selectivity of the passband, various permutations and combinations of the aforementioned aspects are typically employed.

A. EVOLVED RADIATOR

The adaptation of the radiator involves employing sophisticated techniques such as etching slot on the radiating element [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], incorporating an array of short-circuited metallic vias [110], [111], [112], [113], [114], [115], introducing open stubs connected to radiating structure [116], [117], [118], [119], [120], [121], exciting radiator with intrinsic radiation nulls [122], [123], [124], and parallelizing multiple resonating elements [125], [126], [127], all orchestrated to cancel the broadside radiation to attain a refined filtering response.

In retrospect of slot-loading technique, it is found that they hold pervasive utility in bandwidth enhancement strategies,

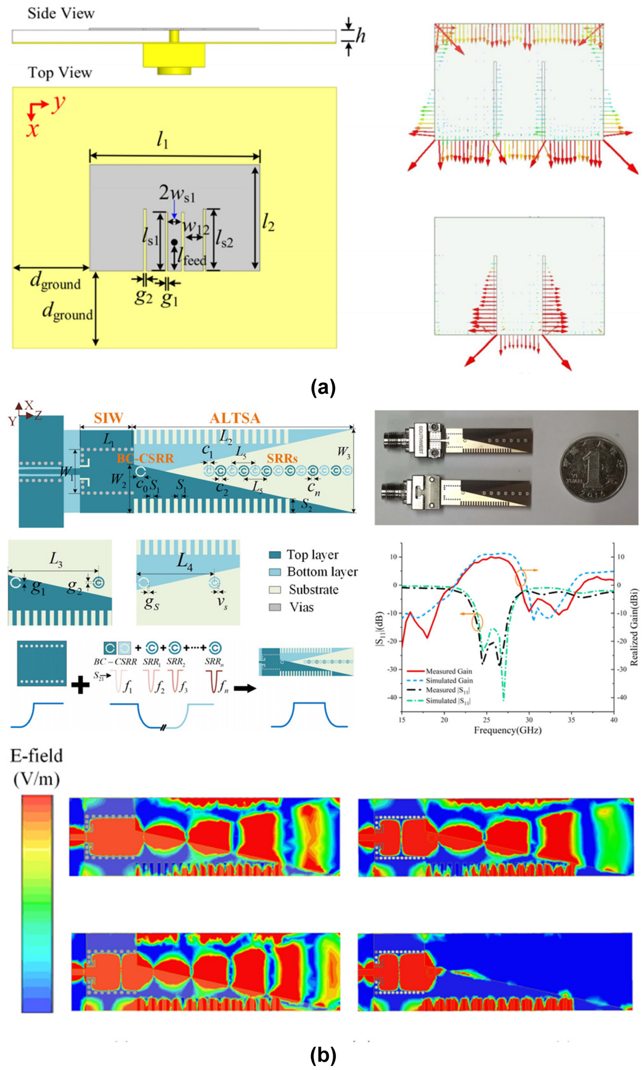

FIGURE 9. Fusion-type filtenna with slot-loading technique based on (a) radiating patch (reproduced from [100]) and (b) ALTSA (reproduced from [101]).

exemplified by structures like E-shaped and U-shaped slots. Subsequently, by ingeniously and judiciously devising slot-loading techniques, it becomes possible to manipulate the electric field distribution of radiators and introduce multiple coupling paths between radiators, thus engendering the tailored filtering responses. This technique typically embodies two salient attributes: firstly, its radiation behavior within the operating frequency range aligns with that of conventional, unloaded radiator; secondly, it orchestrates the generation of radiation nulls at the margins of the antenna efficiency curve, thereby yielding a gain response characterized by a gradual attenuation, commonly referred to as the roll-off phenomenon [128]. Concretely, taking the patch antenna as a prime illustration, individual slot or multiple pairs of slots are introduced into the radiator design, as shown in Fig. 9(a). These slots are predominantly positioned in a symmetrical manner on either side of the feeding point [100]. As anticipated, it retains the integrity of the current distribution of the fundamental TM_{10} mode. Even more remarkably, it bestows radiation nulls at specific frequencies, owing to the mutual cancellation of circumferential currents induced by the excitation of distinctive slot modes. It is worth noting that the incorporation of multiple pairs of slots with varying lengths can lead to the excitation of multiple slot modes, thus further enhancing the frequency selectivity. Furthermore, in dielectric resonator antenna design, the incorporation of etched slot may give rise to a combination of slot mode and cavity mode, subsequently introducing multiple radiation nulls at the passband edges [106]. Similarly, analogous slot-loading techniques are also applicable to traveling-wave filtenna design. As illustrated in Fig. 9(b), the introduction of broad-coupled complementary split ring resonator (BC-CSRR) within the overlapping area of two flaring plates in ALTSA can suppress unwanted signals by introducing strong resonances [101]. Consequently, in contrast to the low-frequency radiation nulls generated due to the high-pass characteristics of SIW, BC-CSRR induces radiation nulls in the higher frequency bands. The electric field distribution at 30.6 GHz reveals that BC-CSRR obstructs the forward propagation of radio frequency signals. Within composite structures featuring multiple radiators, the incorporation of etched slots could potentially introduce augmented coupling paths, leading to the occurrence of cross-coupling or mixed electric and magnetic couplings [130].

Due to their inherent shunt inductive characteristics, shorting pins often induce alterations in the original electric field distribution and electrical dimensions of the radiating antenna. Nevertheless, with skillful arrangement, they can also broaden bandwidth [113], ameliorate impedance matching [114], and induce radiation nulls at the edges of the passband. As illustrated in Fig. 10(a), for the stacked patch configuration, the introduction of several shorting pins to the driven patch layer has altered the current distribution in the lower frequency range [131]. It leads to an opposing current distribution between the shorting pins and the feeding probe, thereby creating radiation nulls in the upper stopband. In the realm of slot-loaded patch configurations, shorting pins also play a role in enhancing impedance matching and generating radiation nulls at specific frequencies [132], as exemplified in Fig. 10(b). It is evident that the electric field at the radiating edge weakens upon the loading of shorting pins. This phenomenon arises from the parallel-series resonance established by the equivalent capacitance of the slot and the equivalent inductance of the shorting pins, thus inhibiting broadside radiation. It is vital to emphasize that the location of radiation nulls is determined by the resonant frequency of the parallel-series resonant circuit.

Open stubs, serving as resonant components, have been utilized in microstrip bandstop filter [128]. In recent years, owing to their capacity to introduce controllable radiation nulls through their interaction with the radiating structure, they have exerted a substantial impact on the landscape of filtenna design. When a single stub is loaded onto the radiating element, radiation nulls occur at a stub length of approximately one-quarter wavelength, thereby efficiently shorting this point to ground plane. As depicted in Fig. 11, four additional stubs are incorporated along the short sides of octagonal slot to introduce supplementary radiation null and resonant point, thereby enhancing both bandwidth and frequency selectivity [133]. At the newly created resonant

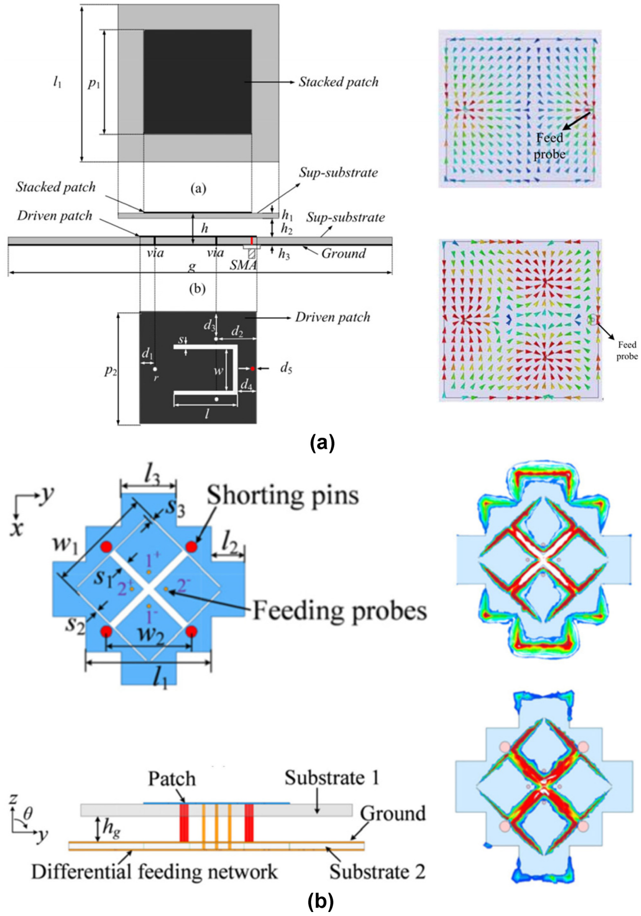

FIGURE 10. Fusion-type filtenna with multiple metallic via holes for (a) stacked patch (reproduced from [131]) and (b) slot-loaded patch configurations (reproduced from [132]).

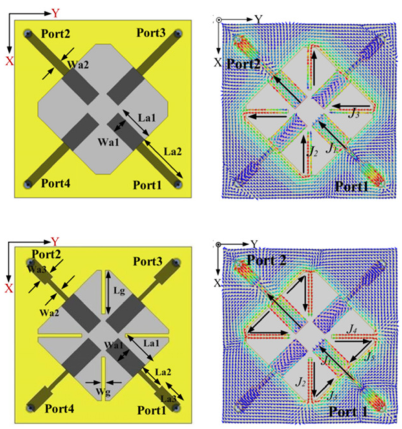

FIGURE 11. Fusion-type filtenna with open stubs and without open stubs. (reproduced from [133]).

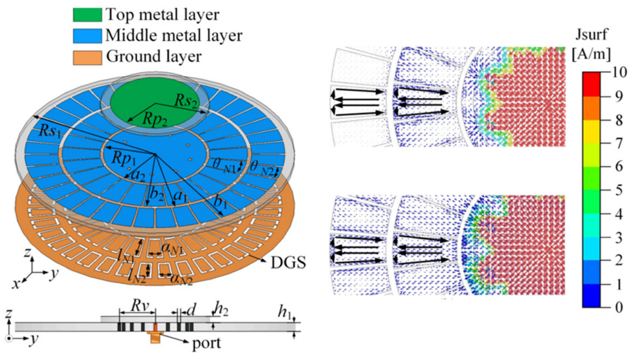

FIGURE 12. Fusion-type filtenna with DGS on the ground plane. (reproduced from [140]).

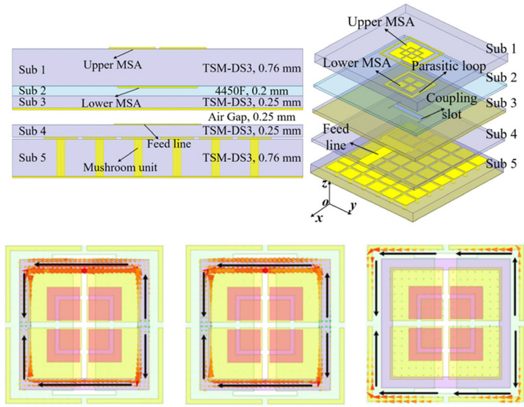

FIGURE 13. Configuration and electric field distribution of the RGW-fed filtenna with parasitic loop. (reproduced from [146]).

point, the vector sum of the surface currents on the open stubs, synergistically contributing to gain superposition and bandwidth enhancement. On the other hand, at the radiation null point, the vector sum of the surface currents on the stubs opposes and cancels out those on the feed line, giving rise to the generation of radiation null. Moving beyond the confines of the single stub loading configuration, several techniques such as Y-shaped [116] and inverted-F [119] stubs have also been innovatively explored and developed to establish multiple radiation nulls.

Owing to high-order mode radiation and equivalent transmission line models, several radiators inherently possess radiation nulls, example of which include dielectric resonator antenna [122], cavity-backed antenna [123], and magneto-electric dipole antenna [124]. Furthermore, parallelizing multiple resonating elements not only effectively broadens the bandwidth but also facilitates the creation of radiation nulls through multi-path coupling [125], [126], [127]. It is worth noting that the locations of these radiation nulls are determined by the feeding arrangement.

B. DGS ON THE GROUND PLANE

Given its capacity to effectively incorporate inductive and capacitive components [134], [135], DGS is frequently employed in the design of low-pass filters. The resonant frequency of DGS is governed by a parallel L-C circuit. As a result, from a practical standpoint, the DGS section can serve as a viable alternative to parallel L-C resonator in numerous scenarios, such as filtenna design [136], [137], [138], [139], [140], [141], [142], [143], [144], [145]. The DGS are typically etched beneath the radiator to change current distribution for achieving robust backward radiation, consequently leading to the broadside null. As shown in Fig. 12, two circles of C-shaped DGS are etched onto the ground plane of a multi-mode monopolar circular patch antenna to facilitate the generation of two radiation nulls in the lower stopband. It is observable that due to the perturbation of DGS, opposite currents are induced along the inner and out arc-shaped patches. The surface current on the outer patch remains relatively weak at lower radiation null frequency, yet exhibits significant enhancement at higher radiation null frequency. This observation signifies that these two radiation nulls are attributed to the inner and outer DGS, respectively.

C. PARASITIC STRUCTURES NEAR THE RADIATOR

In the fusion-type filtenna design, an efficacious approach for incorporating radiation nulls involves the parasitic structure near the radiating aperture. These parasitic configurations can be categorized into coplanar and non-coplanar structures based on their spatial relationship with the radiating element. Typically, these parasitic structures impart a marginal increment in circuitry or a slight elevation in profile height.

Typically, coplanar parasitic structures introduce supplementary circuitry into the array, encompassing elements such as loops [146], [147], [148], [149], [150], [151], [152], [153], patches [154], [155], [156], and strips [157], [158], [159], [160], [161], [162], [163]. Taking the loop structure as an illustration, as depicted in Fig. 13, the metasurface antenna fed by printed ridge gap waveguide (PRGW) technology is established as elucidated in [146], wherein the parasitic loop is employed atop the driving patch layer and encircles it. By incorporating parasitic loop, two radiation nulls are introduced in the lower stopband, concurrently inducing in-band resonance to further widen the bandwidth (i.e., new resonant point). To delve into the mechanism of radiation null generation, simulations were conducted on the surface current of the metasurface antenna [See Fig. 13]. As observed, at the two radiating null frequencies, most of the energy is concentrated in the parasitic loop and very little energy is coupled to the radiating antenna. Therefore, a superior radiation suppression level is achieved in lower frequency band. At the new resonant frequency, the upper metasurface antenna is effectively excited, and its current distribution is nearly in phase, resulting in enhanced broadside radiation.

Non-coplanar parasitic structures are commonly employed by superimposing an additional metallic surface above the radiating aperture, encompassing configurations such as stacked patches [164], [165], [166], [167], [168], [169], resonant structure [170], [171], [172], [173], metamaterial [174], near-field parasitic antenna [175], [176], vias [177], and the

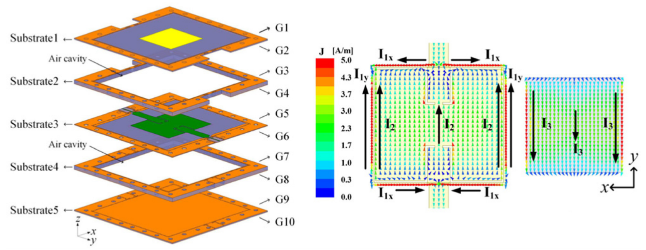

FIGURE 14. Geometry and electric field distribution of stacked patch based on SISL platform. (reproduced from [150]).

like. The stacked patch technique facilitates the attainment of favorable electrical performance across wide bandwidths, consequently rendering it extensively applicable in bandwidth enhancement. By adroitly exploiting the coupling between the driven patch and the stacked patch, this technique introduces supplementary radiation nulls and resonant points in the filtenna design. As illustrated in Fig. 14, the differential-fed stacked patch antennas, as expounded upon in [150], serves to elucidate the mechanism underlying the generation of radiation nulls. Insight from the current distribution at radiation null frequency reveals a distinct concentration of current along the perimeter of the rectangular loop. These currents cancel each other in the x-direction, while in the y-direction, their flow aligns with that of the driven patch. Despite the heightened strength of the currents on either side of the stacked patch, their orientation stands in opposition to that of the rectangular loop. As a result, far-field radiation along the boresight direction mutually cancelling, leading to the emergence of radiation nulls.

Resonant structures typically positioned above the radiating aperture, such as frequency selective surfaces (FSS), split ring resonator (SRR) arrays, and polarizers, confer radiating antenna with substantial filtering responses. The locations of radiation nulls intricately tied to the characteristics of these resonant structures. As shown in Fig. 15, a filtenna is properly constructed in [170] by covering FSS at horn aperture. The high-Q substrate integrated waveguide cavity FSS (SIWC-FSS) furnishes a radiating null in the upper stopband to enhance frequency selectivity. The transmission responses under both normal and oblique incidence effectively corroborate the merits of the filtenna in terms of filtering response, anti-interference, radar cross section (RCS) reduction.

D. MODIFIED FEEDING TOPOLOGIES

By enhancing traditional feeding topologies and fully exploiting their transmission characteristics, it is possible to generate radiation nulls within the desired frequency bands. From a global perspective, the evolved methods for feeding topology in accordance with this typically fall into four distinct categories: 1) loading open-circuited/short-circuited stubs; 2) Integrating filtering structures; 3) feeding structures possessing inherent filtering properties; 4) hybrid feeding topologies. To gain a better understanding of the

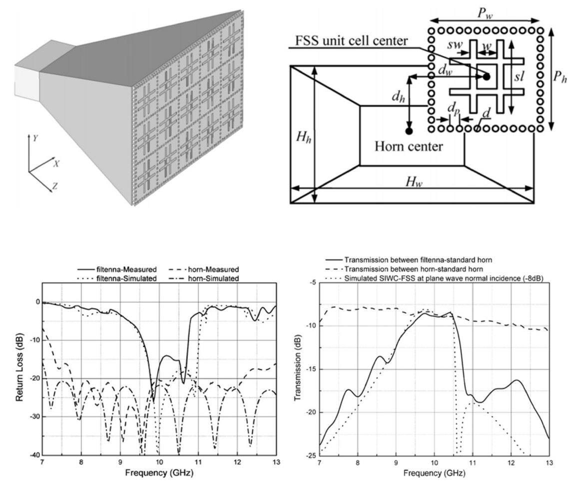

FIGURE 15. Fusion-type filtenna consisting of horn antenna and SIWC-FSS. (reproduced from [170]).

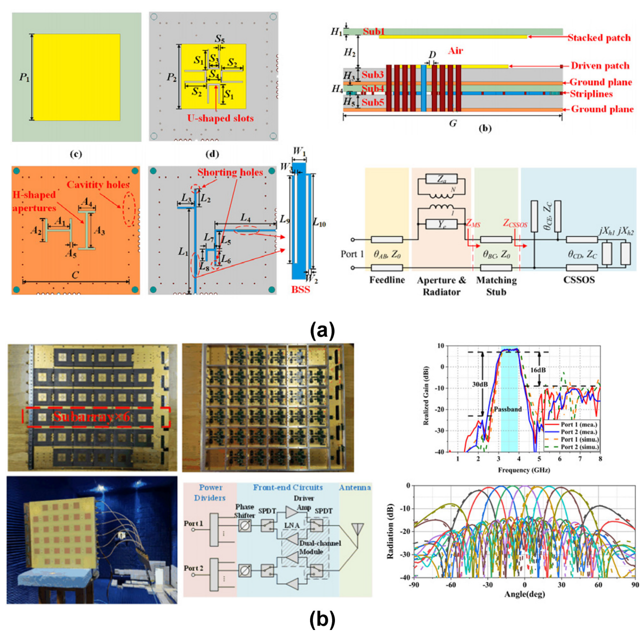

FIGURE 16. Fusion-type filtenna with hybrid multiple stubs loading in feed topology. (reproduced from [192]).

aforementioned methods, each of these approaches will be analyzed and elucidated in the following sections.

According to transmission line theory, a segment of terminated open-circuit or short-circuit transmission line, the input impedance approaches infinity or zero at specific frequencies [20]. This characteristic is applicable to the generation of radiation nulls, and as such, it is captured in the design of feeding topologies for filtenna [178], [179], [180], [181], [182], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193], [194], [195], [196], [197], [198], [199], [200], [201]. In the case of hybrid multiple stubs loading configurations, the locations of radiation nulls can be predicted using a multi-port network [192]. As depicted in Fig. 16(a), the complementary pair of a short-circuited stub and an open-circuited stub (CSSOS) is developed in the aperture-coupled stacked patch antenna to generate two extra radiation nulls, thereby suppressing the undesired 1^{st} harmonic and enhancing the lower stopband suppression level. In this design, the equivalent circuit of the antenna is derived, and the complementary relationship between open-circuited stub and short-circuited stub is obtained by setting the transmission response $S_{21} = 0$ for the two-port network. Consequently, by judiciously adjusting the characteristic impedance of the feed line and the electrical lengths of CSSOS, the location of the radiation nulls can be controlled within the desired frequency band. Benefitting from its compact dual-polarization design, this radiating element can be extended to active phased-array applications. T/R circuits are integrated on the backside of the filtenna and interconnected through metallized hole. Experimental validation has confirmed the ±40° beam-scanning capability and stopband rejection level exceeding 30dB for the 32-element active phased array, as delineated in Fig. 16(b).

Additional filtering structures are presented in the feeding topology in the forms of parallel-coupled resonators [143], [202], [203], [204], [205], [207], [209], resonant cavities [206], and slot resonator [208], among others. This aligns seamlessly with the design of microstrip bandstop filters. What sets it apart from collaborative-type filtennas is that the integration of filtering structures in the feeding topology is geared towards generating radiation nulls and enhancing selectivity, without introducing excessive circuit footprint. Typically, it involves only a single resonator.

Another significant methodology for generating radiation nulls in the feeding topologies involves feeding structures with inherent filtering properties. By adjusting the parameters of these feed networks, the location of the radiation nulls can be flexibly controlled. In this regard, the foremost consideration pertains to transmission lines endowed with filtering characteristics, such as SIW and rectangular waveguide [210], [216], among others. Taking SIW as an illustrative example, owing to its high-pass filtering attributes, antenna designed with SIW as the guiding-wave structure inherently exhibit steep selectivity and higher suppression levels in the lower stopband [222]. Furthermore, the series feed network is comprehensively analyzed for its in-band and out-of-band response to demonstrate its inherent filtering properties [211], [212], [215]. Within the operating frequency range, the induced currents on the radiating element are in phase, resulting in high boresight gain. At the out-of-band frequencies, the radiating elements are either not excited or the induced currents on them are out of phase, leading to radiation suppression. Although series feed networks can achieve excellent filtering characteristics by creating fixed radiation nulls, their operating bandwidth is often constrained by the array scale. Additionally, specific feeding configuration [213], [214], due to the formation of a resonant structure, are capable of generating radiation nulls.

Distinguished from the collaborative-type filtennas, the fusion-type filtennas stand apart by obviating the need for the incorporation of resonator structures. It achieves

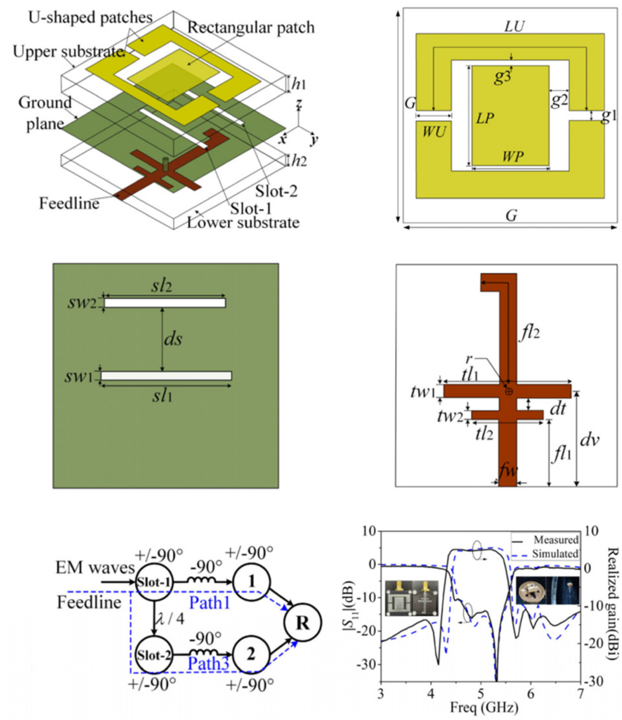

FIGURE 17. Fusion-type filtenna based on multiple coupling slots. (reproduced from [219])

cross-coupling or hybrid electric and magnetic coupling solely through the introduction of multiple feeding nodes, thereby circumventing an augmentation of the footprint of the antenna. Taking the patch antenna as an illustrative example, the introduction of multiple coupling slots [217], [218], [219] and the incorporation of additional strips [220] and feeding probes [221] along the transmission path give rise to the induction of radiation nulls and resonant points. Two parallel coupling slots are etched between the feed lines and rectangular patch enclosed by U-shaped parasitic patches [219], as depicted in Fig. 17, to furnish extra coupling paths. Slot-2 is positioned at a quarter-wavelength distance from Slot-1 and assumes responsibility for the coupling pathway from the feeding port to free space. Due to the quarter-wavelength separation between Slot-1 and Slot-2, a 90° phase delay is inherent in the nascently engendered coupling pathway. Consequently, a 180° phase difference between Paths 1 and 3 ensues, thereby giving rise to a radiation null at the upper edge of the passband.

The fusion-type filtenna, without introducing conspicuous filtering circuits, achieves its dual capability of in-band radiation and the suppression of extraneous out-of-band interference by seamlessly integrating the filter and antenna in its design. This innovative approach addresses the issue of oversized dimensions in collaborative-type filtennas, ultimately enabling compact, highly integrated, and multi-functional designs.

IV. COMPARISON AND DISCUSSION

Table 1 provides a comprehensive performance comparison for various filtenna types. Collaborative-type filtennas

TABLE 1. Performance comparison for various filtenna types.

IBFC-based collaborative-type filtenna	Bulky size	Low	Not flexible	Not flexible	Difficult
CRT-based collaborative-type filtenna	Moderate size	moderate	Not flexible	Not flexible	Not easy
Fusion-type filtenna	Compact size	High	Flexible	Flexible	Easy

commonly employ a cascading arrangement of multiple resonators, resulting in a substantial physical footprint and comparatively high insertion losses. Furthermore, the additional losses introduced by supplementary filtering circuits can potentially compromise the radiation efficiency of collaborative-type filtennas. In contrast to collaborative-type filtenna, fusion-type strategy does not call for extra or fewer filtering circuits, thus showcasing relatively compact footprint. Fusion-type filtennas frequently employ parallel resonant structures to generate stopband characteristics, minimizing their impact on in-band performance. Consequently, they offer flexibility in bandwidth and frequency selectivity control by adjusting the geometric dimensions of the antenna without altering its fundamental structure. It is noteworthy that, owing to the diminishing element spacing in phased array configuration and constraints imposed by commercial multi-layer PCB processes, fusion-type filtennas, characterized by their compact nature and simple stacked structures, facilitate seamless integration with silicon-based multi-channel RF chips, thereby enabling beam scanning capabilities. In the case of CRT-based filtennas, the incorporation of resonators with wide bandwidth, miniaturized area, and desirable stopband suppression characteristics, coupled with a simple stacked structure, renders them compatible with the integration paradigm expounded in this paper.

V. CONCLUSION

In essence, this paper conducts a comprehensive review of filtennas or filtering antennas and categorizes them into two distinct integrated design methodologies, namely, collaborative and fusion-type approaches. Exemplifications are provided to elucidate the operational principles, design methodologies, and implementation strategies for these two different types. It is worth noting that, in comparison to the previous four generations of mobile communication, the 5G and 6G networks require the integration of a greater number of RF transceiver chains, higher frequency bands, and enhanced flexibility, all while maintaining a significantly superior electrical performance. We believe that seamless integration technology for filtenna will play an even more pivotal role in future commercial telecommunications infrastructure than ever before.

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