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Filtering Antennas: Design Methods and Recent Developments

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I. Introduction

With wireless communication technologies continually and rapidly developing, radio frequency (RF) frontend systems are experiencing a profound evolution toward the goal of highly integrated and miniaturized RF frontends with improved performance. Traditionally, passive components in the RF frontend, such as filters, antennas, and duplexers, have been designed individually and cascaded through a 50 Ω interface. This inevitably leads to bulky physical dimensions and complex circuits, high insertion loss, and signal distortion, especially at the band edges. In multi-band or multi-standard communication systems, multiple operating bands of the base-station antenna are normally achieved using several separate subarrays operating at different frequencies, which can cause serious interference between different bands for different services due to the limited space on the antenna platform. Highly integrated multifunctional RF frontends would provide a high-efficiency solution to those advanced and miniaturized wireless systems. As the key components in any RF frontend system, the integration of filters and antennas can significantly improve the frequency selectivity, bandwidth, stability of in-band gain, out-of-band rejection, and system efficiency, and therefore, they have received much research interest and opened up a broad avenue for antenna research and development in recent years.

An integrated filtering antenna is a new type of component that simultaneously combines filtering and radiation functionalities. One of the most important properties of the filtering antenna is that the filter and the antenna can no longer be clearly distinguished (i.e., the antenna and filter serve as parts of each other). A filtering antenna can replace the cascading connection between the filter and antenna, avoid additional insertion loss from their interface, and achieve a more compact size. Due to its good out-of-band radiation suppression properties, filtering antennas can also be used in multi-band aperture-shared base station array antenna design to tackle the serious mutual coupling problem, leading to a much improved isolation between different services without increasing the total size of the antenna. In millimeter-wave RF chip systems, a high Q and low loss filter is often required to ensure a high frequency selectivity, which is very challenging at millimeter-wave frequencies. A feasible solution is to use an integrated filtering antenna where the antenna itself performs filtering and radiation simultaneously, namely an integrated filtering antenna.

Filtering antennas have attracted a great deal of research interest over the past few years and a wide range of filtering antennas with improved performance have been reported. There are three typical approaches to designing filtering antennas: cascaded filter-antennas [1]-[3], the synthesis method based on a bandpass filter [4]-[8], and the fusion method [9]-[12]. Based on these approaches, different types of filtering antennas have been designed. The most popular type of filtering antenna is based on a microstrip antenna (i.e., the filtering microstrip antenna or FMA) [13]-[29]. Other types of filtering antennas include filtering waveguide-slot antennas [30]-[35], filtering slot antennas [36]-[37], filtering dielectric resonator antennas (DRA) [38]-[41], and filtering dipole antennas [42]-[46]. The idea of filtering antennas has also been used in periodic structures design, such as metamaterial antennas and frequency selective surfaces (FSS) [47]-[49]. Filtering antennas working in the millimeter-wave frequency have also been investigated [50]-[52].

In addition to improving antennas' frequency selectivity performance, the approaches developed in filtering antenna design can also be used in other areas. For example, low-profile circularly polarized (CP) antennas with improved bandwidth have been achieved by employing the 90° phase delay between coupled resonators [25]-[29]. In [53]-[60], duplexing filtering antennas with improved isolation were developed for facilitating different wireless services in different frequency bands.

II. Filtering Antenna Design Methods

In this section, three typical approaches to designing filtering antennas are illustrated. The advantages and disadvantages of each approach are discussed and compared.

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A. Cascaded Filter and Antenna

As a traditional solution, filter and antenna are usually cascaded via a 50 Ω interface to select the desired signal and suppress the undesirable interference out of the band, as in the schematic shown in Fig. 1(a). This cascaded method is straightforward and convenient since the antenna and filter can be individually designed and tuned. To ensure proper system function, a narrowband bandpass filter (BPF) and a broadband antenna are usually incorporated, and the performance of the entire filter-antenna system is primarily determined by the BPF, as illustrated in Fig. 1(b). Thus, the frequency response of the system can be controlled solely by adjusting the BPF, making it suitable for reconfigurable antennas [1]-[3]. However, there are many serious problems with this cascaded architecture. First, a wideband antenna (wider than the BPF) is required to guarantee the system function, which is very challenging for some antennas with a relatively high Q (e.g., microstrip patch antennas). In addition, the RF frontend system is inevitably bulky and complicated due to the separated assembly and extra transmission lines and interfaces. This cascaded system may also suffer from extra insertion loss due to the imperfect connection between the filter and the antenna, especially at the band edges, which may lead to signal distortion.

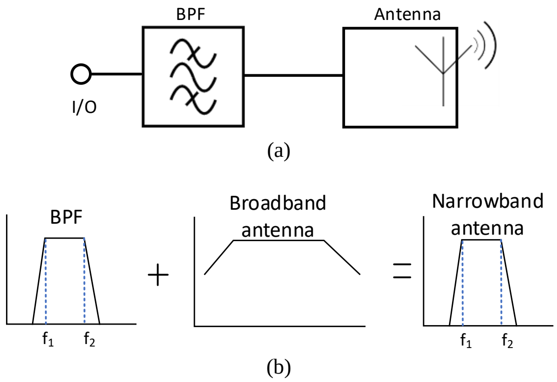


Fig. 1. (a) Schematic of a cascaded filter and antenna, (b) corresponding spectrum demonstration

B. Synthesis Method Based on Coupled-Resonator Filter Theory

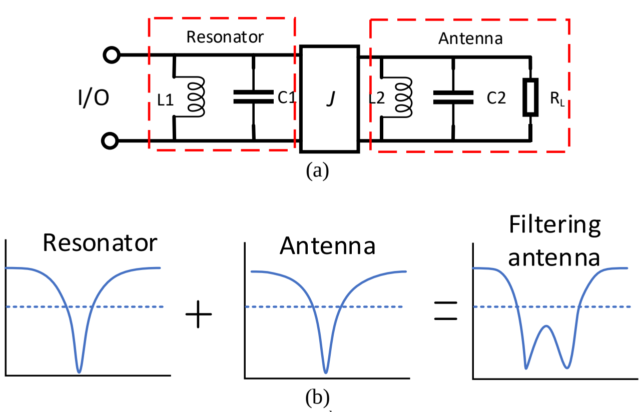


Fig. 2. (a) Equivalent circuit of a 2nd-order in-series co-design filtering antenna, (b) corresponding S-parameter response.

To overcome the disadvantages of the cascaded filter-antenna, different co-design methods have been investigated to achieve a seamless integration between filter and antenna. The synthesis method based on a bandpass filter is one of the most popular approaches, where the antenna serves as the radiating element and the last resonator of a bandpass filter. The design process can be summarized in coupling matrix terms as follows [61]. As illustrated in Fig. 2, the radiating element serves as the last resonator of the BPF, which can be modeled as a shunt *RLC* resonator with *R* representing the radiation resistance. The other resonator is modeled by a shunt *LC* resonator and the coupling between them by a *J*-inverter. The evolution of the frequency response is illustrated in Fig. 2(b). Usually, a resonant antenna has limited bandwidth, which restricts the impedance bandwidth. When the antenna is integrated with a filter (i.e., a filtering antenna), second-order filtering responses with two resonant points can be achieved, which can significantly enhance the bandwidth and the frequency selectivity of the antenna. Compared with the cascaded method, this co-design method has many advantages. First, the volume and complexity of the RF frontend system can be noticeably reduced due to the removal of the 50 Ω interfaces, resulting in an improved efficiency. In addition, and very importantly, the requirement of the antenna's bandwidth can be relaxed, making it more flexible in the design. Moreover, by using this co-designed method, the bandwidth and the higher order harmonics suppression can be improved.

C. Fusion Method

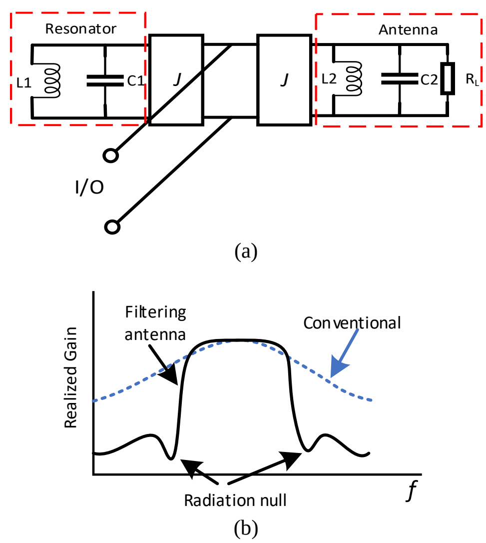


Fig. 3. (a) Equivalent circuit of the parallel co-designed filtering antenna, (b) comparison of the gain response between a conventional antenna and a parallel co-designed filtering antenna.

Recently, a novel approach of designing a filtering antenna without introducing an extra filtering circuit has been proposed. This is the so-called fusion method [9]. This type of filtering antenna can be modeled using a parallel equivalent circuit, as shown in Fig. 3(a). Unlike the previous synthesis methods, the idea behind the fusion method is to integrate resonant structures in parallel with the antenna to generate band-stop functions at both sides of the passband. As a result, a bandpass-like gain response can be formed, as depicted in Fig. 3(b). Because the parallel resonant structures are designed to resonate outside the passband, they have little effect on the in-band antenna performance. In addition, cross-coupling or source-load coupling can be easily introduced due to the parallel architecture, resulting in radiation nulls close to the band edges. These radiation nulls can be purposely designed to control the bandwidth and frequency selectivity of the antenna. The main design challenge is to generate and control radiation nulls. The key advantages of this fusion method in filtering antenna design are low insertion loss and high efficiency.

III. Literature Review of Filtering Antennas

In this section, a variety of recently published filtering antennas based on the methods mentioned above will be summarized and discussed. They are the filtering microstrip antenna (FMA), dipole antenna, waveguide slot antenna, dielectric resonator antenna (DRA), millimeter-wave antenna, and duplexing filtering antenna.

A. Filtering Microstrip Antennas

1) Dual-Band Dual-Polarized FMA

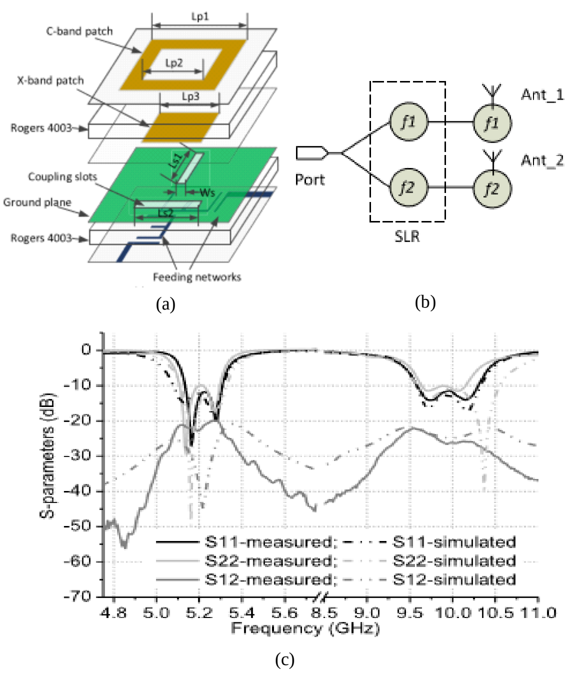


Fig. 4. Dual-band dual-polarized filtering antenna reprinted from [19]: (a) configuration, (b) resonator-based topology, (c), S-parameter responses.

Dual-band dual-polarized antennas with shared apertures have been widely used in satellite and base station applications. To design the dual polarization, a symmetrical radiating element is required. Fig. 4 presents the configuration, resonator-based topology, and frequency responses of a C-/X-band dual-polarized filtering microstrip antenna. The antenna is composed of a ring patch and a square patch nested together as the C- and X-band radiating elements and two stub-loaded resonators (SLR). In this work, the two frequency bands for each polarization can be excited simultaneously by utilizing a dual-mode resonator as the feed. In this way, two operating bands over a wide frequency ratio can be readily excited. In addition, the coupled resonator and the patch form the second-order resonant structure, which can improve the bandwidth and frequency selectivity at both bands.

2) Wideband Circularly Polarized FMA

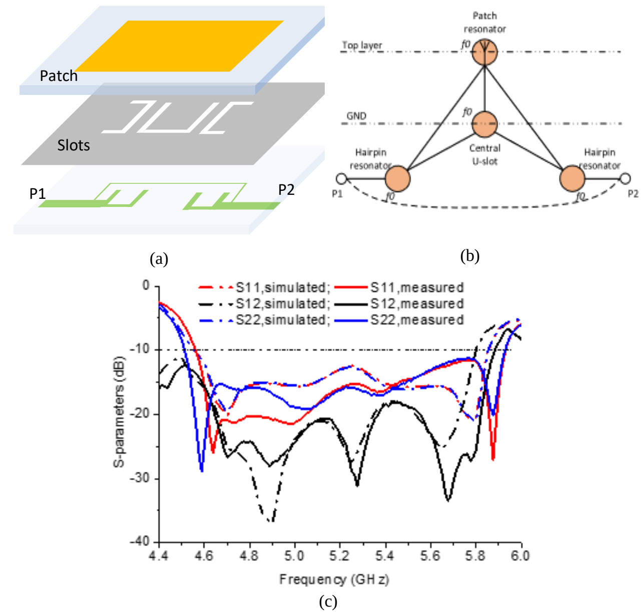


Fig. 5. LH/RH CP filtering antenna reprinted from [28]: (a) configuration, (b) resonator-based topology, (c), S-parameters responses.

The concept of co-design also provides a new way to design wideband low-profile circularly polarized (CP) microstrip antennas by utilizing the inherent 90° phase delay generated between two coupled resonators [25]-[29]. Fig. 5 presents the geometry and topology of the dual-CP microstrip antenna reported in [28], and its S-parameters. The F-shaped microstrip serves as the first-order resonator, which is simultaneously coupled to the patch via the slots on the sides and the slots in the center. The center U-slot has the same resonance as the patch, serving as the second-order resonator, where the side slots are non-resonant. This creates two signal paths which bring about a 90° phase delay to realize the CP radiation. Using this approach, the patch can be excited by two groups of resonators with a 90° phase delay, and therefore, both impedance bandwidth and axial ratio bandwidth can be significantly improved without increasing the thickness of the antenna.

B. Filtering Dipole Antennas

The dipole is one of the simplest and most widely used types of antennas. However, even this ubiquitous antenna can be enhanced by introducing filtering antenna design methods, achieving improved bandwidth, frequency selectivity, and out-of-band rejection performance.

1) Printed Filtering Dipole Antenna

Fig. 6 shows the configuration, equivalent circuit, and frequency responses of the filtering dipole antenna reported in [46]. The antenna is composed of a printed dipole on the upper layer as the radiator and a shorted strip with embedded slots on the lower layer as the feed. The shorted and the opened ends can be equivalent to inductance and capacitance, respectively, forming a shunt resonator, which is then coupled to the dipole antenna, generating a second-order filtering antenna with an improved bandwidth (triple the original result). The embedded slots function as a band-stop filter in the higher band

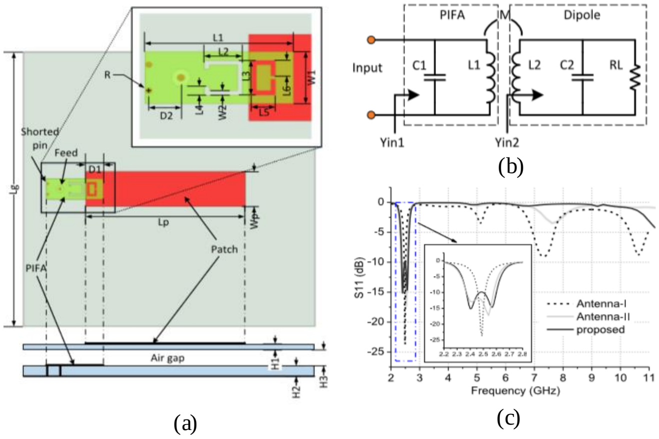


Fig. 6. Filtering dipole antenna reprinted from [46]: (a) configuration, (b) equivalent circuit, (c), S-parameter responses.

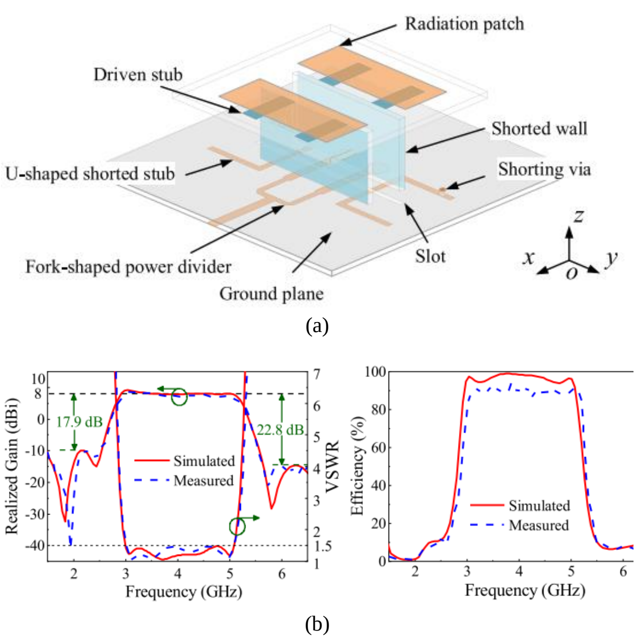


Fig. 7. Filtering magnetoelectric dipole antenna reprinted from [42]: (a) configuration, and (b) frequency responses.

to eliminate undesired harmonics/interference. Thus, by using filtering antenna methods, the bandwidth and out-of-band rejection performance can be significantly improved.

2) Filtering Magnetoelectric Dipole Antenna

In contrast to traditional dipoles, a magnetoelectric dipole has innate broadband and stable radiation properties, and therefore, has been increasingly used in base station antenna design. The filtering magnetoelectric dipole antenna design focuses on improving the frequency selectivity. Fig. 7 presents a filtering magnetoelectric antenna and its frequency responses [42]. The antenna is composed of a radiating patch, a driven stub, a fork-shaped feed, and two shorted stubs. The radiation nulls are introduced by the stacked driven stubs and the shunt shorted stubs, which can be regarded as quarter-wavelength resonators. Thus, the position of the radiation nulls can be controlled by adjusting the dimensions of the driven strips and the shorted stubs.

C. Filtering Waveguide Slot Antennas

Waveguide slot antennas, including traditional all-metal waveguide antennas and substrate integrated waveguide (SIW) antennas, have the merits of low loss, robust structure, and excellent heat dissipation. In this section, both types of waveguide antennas with integrated filtering functions are discussed.

1) All-Metal Filtering Waveguide Slot Antenna

Fig. 8 shows the configuration, prototype, and frequency response of a filtering antenna array based on all-metal waveguide reported in [34]. The antenna is designed based on a coupled-resonator filtering/power-splitting network with its last order of resonators slit to radiate energy. Using the synthesis method for the bandpass filter, the incident power can be distributed to the slotted waveguides uniformly or non-uniformly. In this way, the side-lobe of the antenna can be

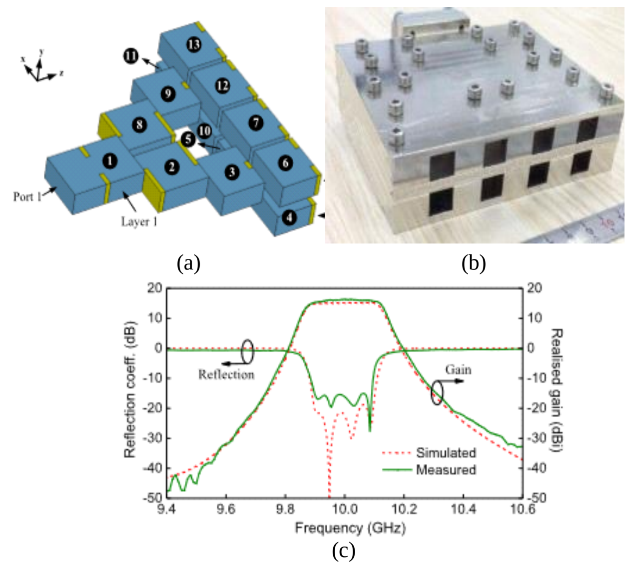
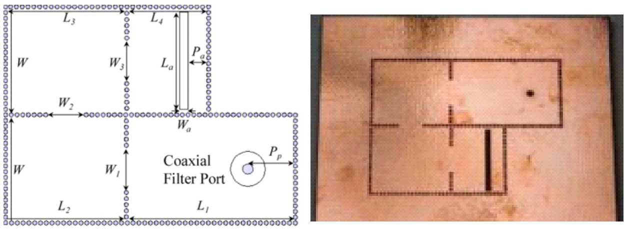


Fig. 8. All-metal filtering waveguide slot antenna array reprinted from [34]: (a) configuration and prototype, (b) frequency responses.

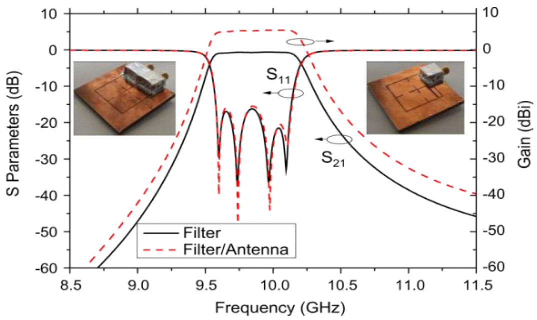
suppressed. Even though no radiation null is introduced in this work, the antenna shows excellent fourth-order filtering performance, which is attributed to a high-order resonant circuit. Thanks to the low-loss property of the waveguide resonator, the filtering antenna demonstrates a high efficiency of over 90%.

2) Filtering SIW Antenna

Fig. 9 presents the configuration and frequency responses of the filtering SIW antenna proposed in [30]. The SIW filtering antenna is achieved by employing four coupled SIW cavities with a slot etched in the last cavity as a radiator, resulting in a fourth-order resonant structure. It should be noted the fourth cavity is smaller than the other cavities, which is due to the loading effects of the slot. All SIW cavities were conceived in one dielectric substrate, allowing for a low profile and ease of fabrication. As can be seen in Fig. 9(b), the filtering antenna exhibits the fourth-order filtering response with four observed reflection zeros, demonstrating excellent frequency selectivity. In the band of interest, the antenna shows a filter-like flat gain response.



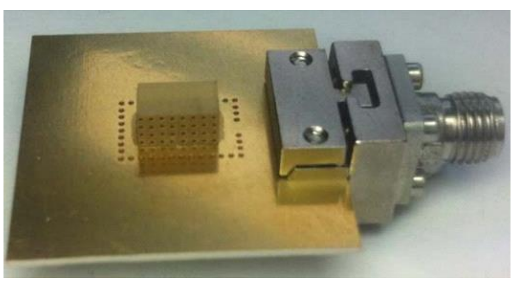
(a)



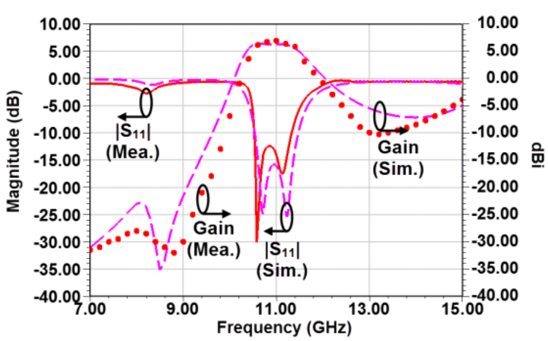
(b)

Fig. 9. filtering SIW antenna reprinted from [30]: (a) configuration and prototype, (b) frequency responses of the antenna.

D. Filtering Dielectric Resonator Antennas



(a)

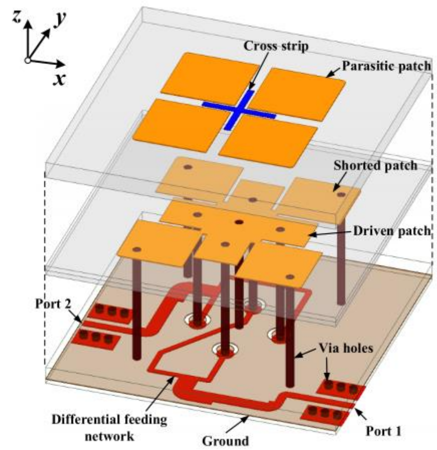


(b)

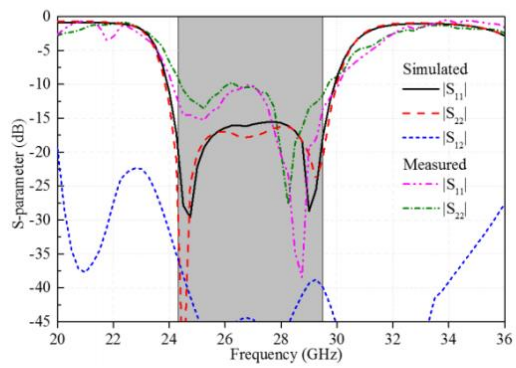
Fig. 10. Filtering DRA reprinted from [38], (a) prototype, (b) frequency responses.

The filtering dielectric resonator antenna (DRA) has also attracted considerable attention due to its low cost, high efficiency, and ease of excitation. Filtering DRAs can be achieved by co-design of a DRA with a resonator using bandpass filter synthesis methods. Fig. 10 shows the configuration and frequency responses of the filtering DRA proposed in [38]. The antenna was designed following the synthesis method of a filter discussed Section II. A method of altering the external quality factor is investigated by introducing air holes in the dielectric material. In this way, the filtering DRA can meet different bandwidth requirements.

E. Millimeter-Wave Filtering Antennas



(a)



(b)

Fig. 11. Mm-wave filtering patch antenna reprinted from [50]: (a) configuration, (b) frequency responses.

The millimeter-wave (mm-wave) filtering antenna has attracted increased interest as mm-wave antennas become one of the key components in 5G wireless networks. Mm-wave filtering antennas not only reduce the volume and complexity of a system but also significantly reduce the cost of the RF frontend system.

Fig. 11 presents a dual-polarized mm-wave patch antenna with bandpass filtering response [50]. It consists of a differential-fed cross-shaped driven patch and four stacked parasitic patches. The combination of the stacked patches and the driven patch can be equivalent to a bandstop filtering circuit for generating a radiation null at the upper band edge. Then, four additional shorted patches were placed beside the cross-shaped driven patch to introduce another radiation null at the lower band edge. Moreover, by embedding a cross-shaped strip between these four stacked patches, the third radiation null is generated to further suppress the upper stopband. As a result, a quasi-elliptic bandpass response is realized without requiring extra filtering circuits.

F. Duplexing/Multiplexing Filtering Antennas

In wireless communication, the transmit (Tx) and receive (Rx) modules usually occupy different frequency bands to reduce the channel interference. A filtering duplexing antenna with multiple ports can work at different bands while exhibiting good isolation. Fig. 14 shows the configuration and its frequency responses of the linearly polarized duplexing antenna proposed in [55]. The antenna is composed of a square patch as the radiator for both bands, a common resonator (between the two channels) coupled to the patch via a slot, and two resonator-based frequency selective paths. The operating principle can be explained by a topology presented in Fig. 12(b). It should be noted that cross-couplings between resonators are introduced to improve the frequency selectivity and isolation between the two ports. The duplexing circuit and the patch antenna were co-designed using coupling matrix methods and a very compact size is achieved. The two ports of the duplexing antenna are designed to operate at 4.7 and 6.0 GHz, respectively, with a channel isolation of over 30 dB. In each band, the antenna exhibits very good frequency selectivity with a third-order filtering response achieved.

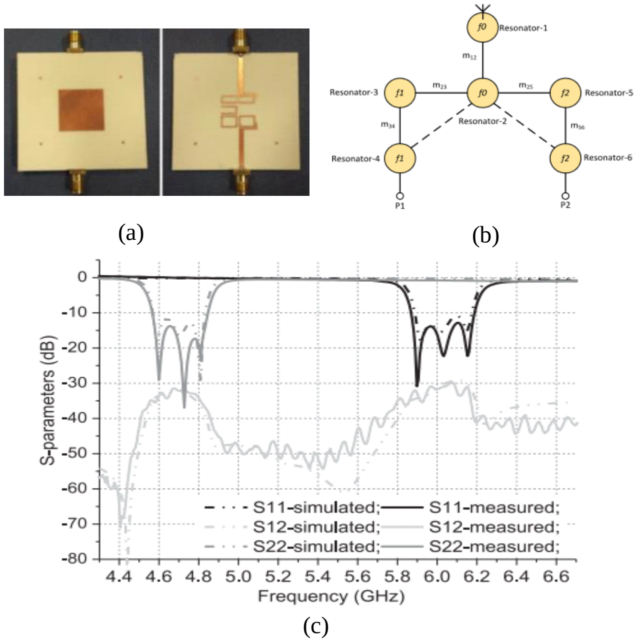


Fig. 12. Compact duplexing filtering antenna reprinted from [55]: (a) prototype, (b) resonator-based topology, (c) frequency response.

IV. Filtering Antenna Applications

Thanks to the many advantages and the new features introduced by co-designed filtering antennas, this relatively new antenna paradigm has found many applications in both the commercial and the military sectors. Fig. 13 shows the prototype and the frequency responses of a dual-band dual-polarized filtering base station antenna proposed in [62]. The target bands for the low-band and the high-band operations are 790-862 MHz and 880-960 MHz. These are achieved by four dipoles and the stacked patches, respectively. Because of the adjacent operating bands and the nested configuration of the two antennas, the high mutual coupling needs to be mitigated. To tackle this design challenge, filtering functions are introduced in both antennas to improve the inter-band rejection. By purposely introducing radiation nulls at the lower and higher band edges, the isolation between the two antennas can be enhanced from 5 dB to 15 dB. Such a reduced mutual coupling ensures that the two antennas work properly in proximity.

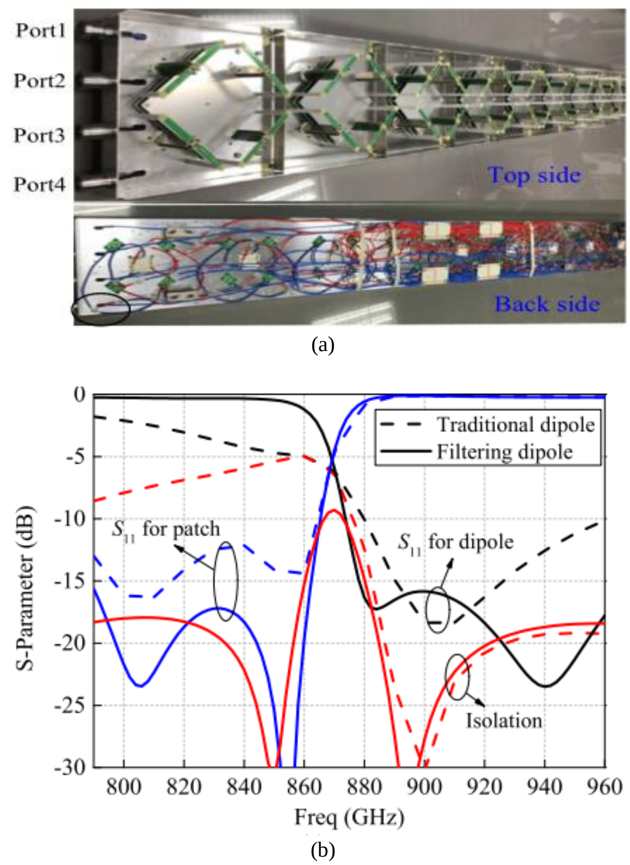


Fig. 13. Dual-band dual-polarized filtering base station antenna reprinted from [62]: (a) prototype of the array, (b) S-parameters.

V. Conclusion

This paper introduces co-designed filtering antennas based on different methods and structures. Compared with conventional antennas, filtering antennas can exhibit improved frequency selectivity, bandwidth, in-band gain response, out-of-band rejection, and system efficiency. First, the design methods were illustrated, including cascaded filter-antennas, the synthesis method, and the fusion method. Advantages and disadvantages of each method were discussed. Next, a literature review of recently developed filtering antennas was presented, covering microstrip antennas, dipole antennas, waveguide-slot antennas, DRAs, mm-wave antennas, and duplexing antennas. The principles behind the implementation of each filtering antenna were explained. Finally, two examples of how filtering antennas are used in base stations were presented.

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