An Integrated Filter-Antenna-Array with High Selectivity and Harmonics Suppression

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***Abstract*— In this paper, a new design of antenna array with filtering performance and harmonics suppression is proposed. By employing a novel four-way out-of-phase filtering power divider proposed in this paper, the traditional power dividers and 50 Ω interfaces of the feeding network can be removed, leading to a highly integrated design with compact size and high performance. To prove the concept, a 2×2 antenna array with filtering performance is designed. The radiating elements are fed by a four-way out-of-phase power divider, which is composed of different types of resonators. The integration of filter, power divider and antenna array not only removes the separate filter, power dividers, 50 Ω interfaces and matching networks from feed networks of traditional array antenna, but also improves the performance of bandwidth and frequency selectivity of the antenna system. First, a novel four-way out-of-phase power divider is studied and then integrated with the radiating patches. The harmonics is inherently suppressed since different types of resonators are adopted in the integrated design. A prototype is developed and the simulated and measured results agree well. Compared with traditional array antenna, the advantages of this integrated filtering array antenna include broad bandwidth, high frequency selectivity, harmonics suppression, flat antenna gain and high cross polarization discrimination. The concept can be extended to large-size arrays such as 4×4 or 16×16 arrays.**

***Index Terms*— Filter-antenna-array (FAA), array, antenna, harmonics suppression, integrated design, resonator.**

I. INTRODUCTION

Currently, the development of wireless system such as mobile communication, wireless local area networks and satellite communications require the system and components to be compact, light weight and highly integrated. Traditionally, the I/O ports of a band pass filter are designed for 50 Ω terminals and cascaded with antenna element with 50 Ω transmission line. However, the input impedance of antenna and filter are usually not perfectly matched since their bandwidths are usually different. This will degrade the frequency response, especially at the band edges. Besides, higher order harmonic may introduce signal interference, which may degrade the quality of the system. Harmonic suppression is a great challenge in band-pass filter design, because of the distribution characteristics of microwave components.

Microstrip antenna array has been widely used in wireless communications, especially in base-stations and satellites for its low profile, light weight and low cost [1]. Usually, a large array requires a large, complicated feed network and an N-way power divider is used to divide the input power into N ways output signals with the same magnitude and phase to feed each antenna element. In the design of RF power divider, quarter wavelength transmission lines are commonly used for impedance matching, which limits the applications. Also, the performance of impedance matching will degrade when the power divider operates in a broadband system.

An integrated design of filter, power divider and antenna array is a flexible solution to the problems aforementioned. The feeding networks are always a combination of transmission lines, power dividers, which can be realized using coupled resonators. Due to the resonators' intrinsic characteristics of frequency selectivity, an embedded filtering function can be achieved. Therefore, separated filters and RF power dividers can be removed so as to reduce the volume and complexity of the RF front- end. In addition, the resonant antenna element itself can be regarded as the last resonator of the filter network in the integrated design [2] [3], which contributes to the improved frequency selectivity and bandwidth. The integrated design of filtering, power divider and antenna array can not only reduce the size and complexity of the front-end circuit, but also improve the frequency selectivity, bandwidth of the front-end system.

The integration of filter and antenna has attracted significant research interests in the past several years for its compact size, increased bandwidth, higher frequency selectivity, harmonic suppression and flatter antenna gain [2]-[14]. In [2], a microstrip filtering antenna array was proposed by integrating filter, power divider and antenna to reduce the complexity of the system. Coupled resonators were used to design the feeding networks with filtering performance. The resonators and the antenna elements are placed on same layer, which causes interference between the antenna elements and resonators. The intrinsic radiation characteristics of the resonator degraded the performance of the cross polarization discrimination (XPD) of the antenna array.

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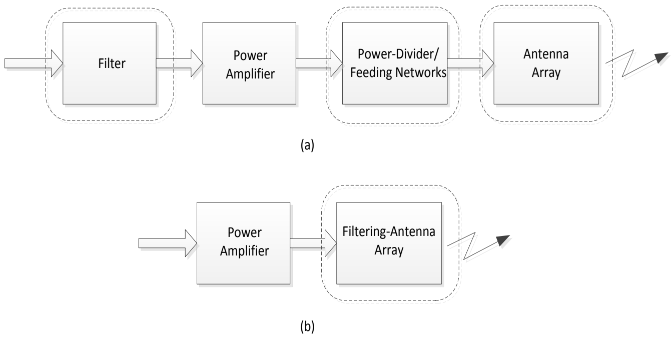


Fig.1 The front-end system with an antenna array: (a) traditional structure, (b) integrated structure

In this paper, a novel design of integrated filtering array is proposed, and a 2×2 antenna array with filtering performance is designed. The antenna array (top layer) and feeding network (bottom layer) share the same ground in the middle layer. The antenna elements are fed by resonators without extended transmission line. A novel four four-way out-of-phase filtering power divider is proposed and the design method of the filtering array is explained. The feeding network is composed of two types of resonators, which has the function of filtering and power dividing. Besides, spurious suppression can be easily realized due to the fact that three types resonators with different harmonic modes are adopted to design the feeding network. Simulated and measured results agree well with each other. It shows that the proposed filtering antenna array has good performance in terms of impedance bandwidth, frequency selectivity, harmonics suppression, antenna gain, in addition to a compact size and integrated design.

This paper is organized as follows. Section II, describes a simplified front-end system block diagram to guide the design. Section III, presents a 4-way out-of-phase power divider. Section IV, details the filtering antenna array design and the method of spurious suppression. Section V, presents the measured results followed by conclusion in Section VI.

II. SYSTEM STRUCTURE EVOLUTION

Fig. 1 (a) shows the front-end system structure of a traditional wireless communication, which is consists of filter, power amplifier, power divider and antenna/antenna array. Each component is designed separately with the assumption of ideal 50 Ω interfaces between each component. However, this assumption is not always accurate, especially at the edges of the operating frequency band, which will lead to impedance mismatching at the interfaces. Deterioration at the edges of the band is a common phenomenon, which can degrade the efficiency of the system and bring about unwanted interference.

To reduce the size of RF front end and remove the losses due to inter-mediate impedance matching networks between each component, components such as filter, power-divider/feeding networks and antenna/antenna array are integrated and designed as a whole, as shown in Fig. 1 (b). In the integrated structure, the functions of filtering and powering dividing can be realized in the design of feeding network.

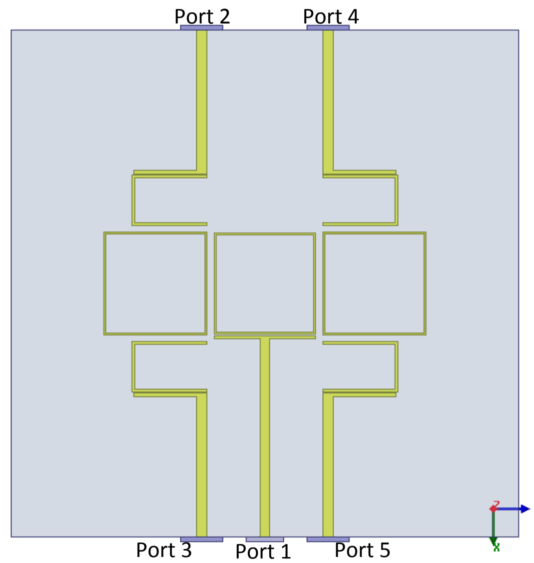


Fig. 2 The layout of the four-way out-of-phase filtering power-divider

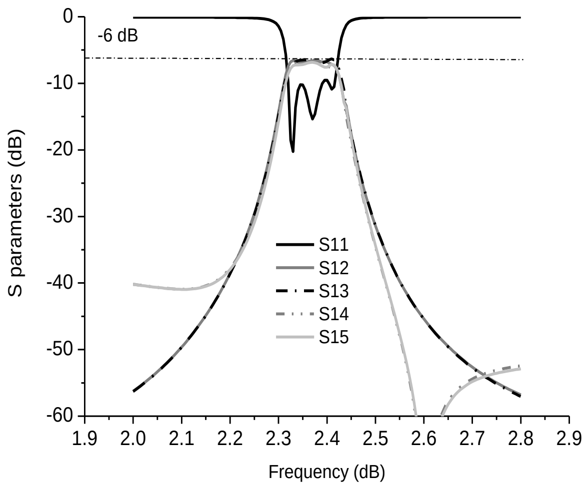
Also, the antenna element can introduce another resonant mode in the integrated design, which can be used to broaden the bandwidth. Besides, the traditional 50 Ω interfaces between the filter, antenna and other passive components are removed, which improves the frequency response of the filter and antenna/antenna array. Compared with traditional front-end system, the integrated design is simplified, compact with improved performance.

III. FILTERING POWER-DIVIDER

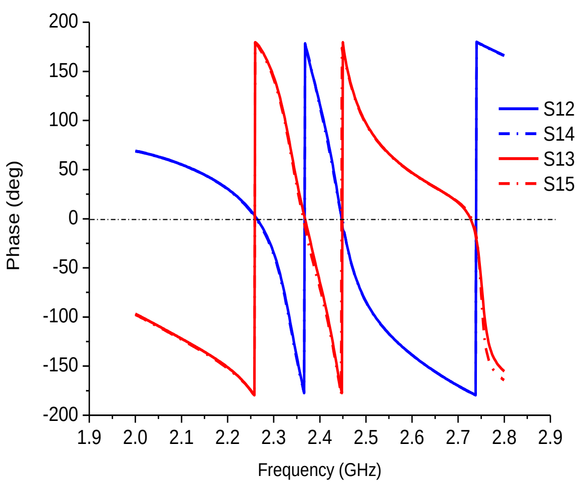
A. 4-way Out-of-Phase Filtering Power-Divider

In the integrated antenna array design, it is necessary to design a feeding network with characteristics of both power dividing and filtering. The input power is divided into N-way evenly by a power divider to feed each antenna element. In the traditional power divider design, 50 Ω transmission line and quarter- wavelength transformers are commonly used [3]. To improve the antenna efficiency and reduce the interferences, high polarization purity is usually required antenna array designs. An out-of-phase feeding is beneficial in improving XPD of the antenna array. The 1800 phase difference is usually realized by half wavelength transmission line which occupies additional space in the feed network and also leads to narrow bandwidth.

In this section, a novel four-way out-of-phase power divider is studied for feeding the antenna array. Fig. 2 shows the layout of the four-way power divider, which consists of two types of resonators, ring strip resonators and hairpin resonators. The ring strip resonator is one-wavelength long in circumference, whereas the hairpin resonator is half-wavelength long. The input signal is coupled to the ring strip resonator and then coupled to two other ring strip resonators on both sides. Each of these two ring strip resonator is then coupled to two hairpin resonators before output at port 2, 3, 4 and 5 respectively. It should be noticed that the power-divider network is symmetric by X- and Y-axis, so the power input



(a)



(b)

Fig. 3 The magnitude and phase response of the filtering power-divider

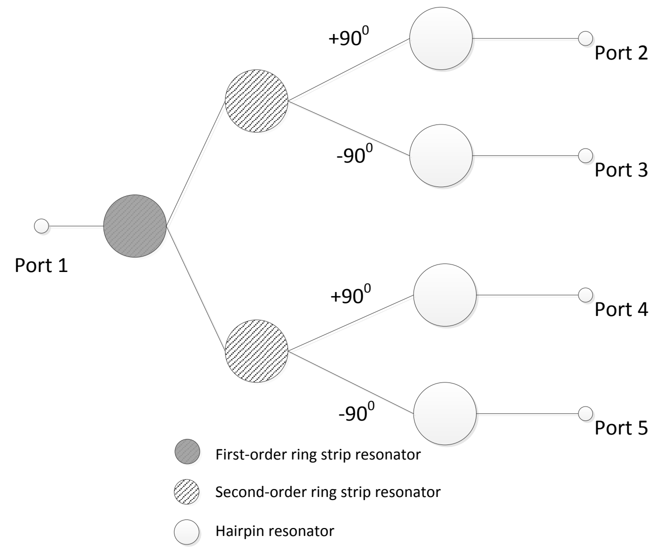


Fig. 4 The topology diagram of the filtering power-divider

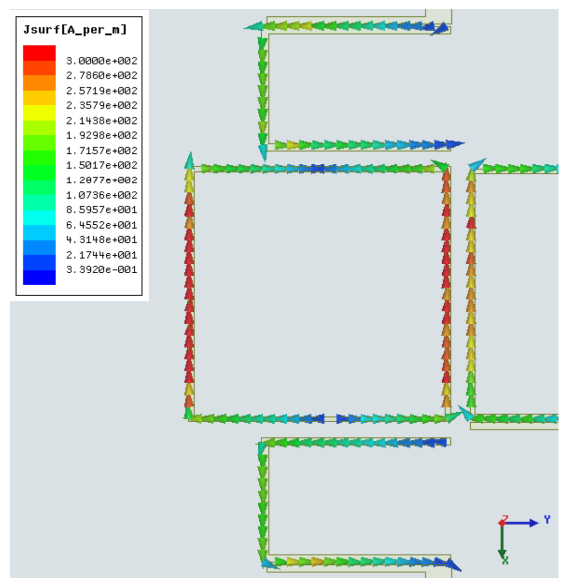


Fig. 5 The simulated current distribution at 2.4 GHz

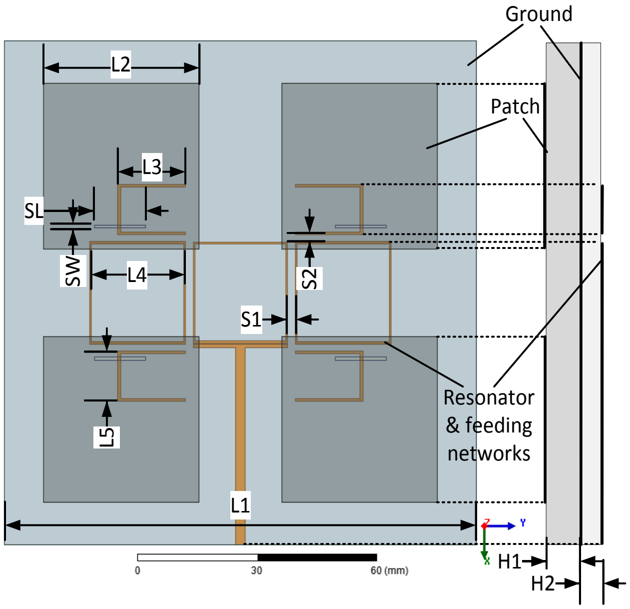
from port 1 can be divided evenly. Since the power divider is composed of resonators, a filtering characteristics is also achieved.

Fig. 3 shows the simulated magnitude and phase responses of the four-way filtering power divider. It is observed that the magnitude of S11 is below -10 dB from 2.31 to 2.42 GHz with three poles in it. These two resonant modes are introduced by the resonators and coupling between them, which contribute to rapid roll-off at the both edges. The four outputs have a flat frequency response of around -6.5 dB in-band. A power divider with flat frequency response is good for the performance of antenna array and front-end system [8]. Fig. 3 (b) shows the phase response of four-way filtering power divider. It can be seen that port 2 and port 4, port 3 and port 5 have a same frequency response, whereas port 2 and port 3 have an 180o phase differences. The mechanism of the four-way out-of-phase filtering power divider will be studied using topology diagram and simulated current distribution in the following part.

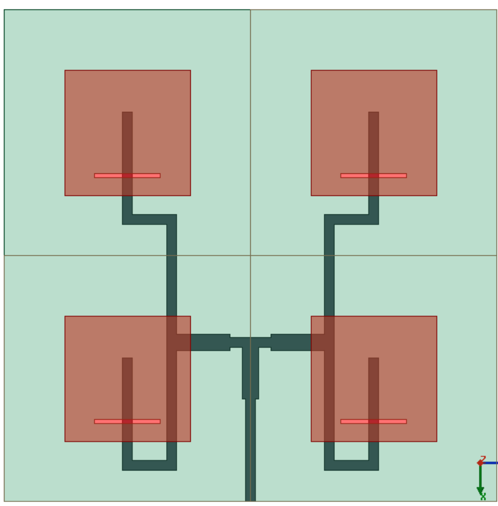
B. Topology Structure Analysis

The topology diagram of the proposed filtering power divider is studied and shown in Fig. 4. The ring strip resonators consist the first- and second-order resonator, while the hairpin resonators is the third-order resonator. These resonators have a same resonant frequency. The coupling between them can be regarded as parallel coupling strip line with a 90 phase delay [2]. It should be noted that the phase increases by 90 before the power in the second ring strip resonator is coupled to hairpin resonator at port 2, whereas the phase decreases by 90 before the power is coupled to the hairpin resonator at port 3. This phase difference is attributed to the half-wavelength electrical length between the two coupling locations.

Fig. 5 shows the current distribution in the resonators at 2.4 GHz. It is observed that the current on the second ring strip resonators reversed at the opposite sides, which result in out-



(a)



(b)

Fig. 6 The configuration of filtering antenna array: (a) proposed filtering antenna array, (b) traditional antenna array

Table 1: Parameters of the filtering antenna: (MM)

L1	L2	L3	L4	L5	SL
120	31.5	17.5	24.6	12	11.6
SW	S1	S2	H1	H2	
0.9	1.7	1.6	1.6	0.787	

of-phase output between port 2 and port 3. The simulated current distribution also demonstrates the validity of the topology diagram in Fig. 4.

IV. FILTERING ANTENNA ARRAY DESIGN

A. Configuration of filtering antenna array

An integrated design of antenna array with filtering performance is proposed in this paper based on the filtering power divider. Fig. 6 (a) shows the top view and side view of the filtering antenna array. This antenna consists of two stacked substrates with a shared ground plane in the middle. The feeding networks is printed on the bottom-layer of a

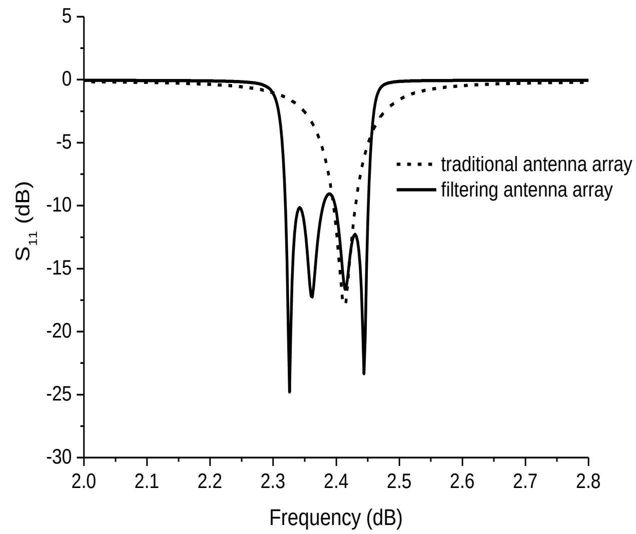


Fig. 7 The simulated S_{11} of the filtering antenna array and a traditional antenna array

Rogers 5880 substrate with a dielectric constant of 2.2 and a thickness of 0.8 mm. The antenna elements are printed on the top-layer substrate of a Rogers 4003 substrate with dielectric constant of 3.55 and a thickness of 1.6 mm. The elements on the top-layer are fed by the hairpin resonators through the slits in the ground plane. The coupling strength between the resonators and the antenna elements are tuned by the lengths and widths of the slits. In this designing, the antenna elements are regarded as the last resonators of the band pass filter with a same resonant frequency f_0 as the traditional transmission line is removed [10]. Besides, the traditional power divider is replaced by the feeding network composed of resonators. The bandwidths of the feeding network and antenna itself, as well as frequency selectivity, have been improved in the integrated designed. Fig. 6 (b) shows a traditional antenna array for comparison. The radiating elements are fed by microstrip line directly and the T-shaped power divider is adopted in the design. The design and simulation were performed using High Frequency Simulation Software (HFSS 15) and the optimized parameters are presented in Table 1.

Fig. 7 compares the simulated S_{11} of the filtering antenna array and the traditional patch antenna. It is observed that the traditional patch has only one resonant mode and the fractional bandwidth is only about 1.6% since the high Q value of the patch antenna. For the filtering antenna, there are four resonant modes in the band, which are produced by the two ring strip resonators, a hairpin resonator and antenna elements. These modes can be controlled by tuning these resonators and couplings between them. Accordingly, the bandwidth of the filtering antenna array can be adjusted according to the requirement. In this design, the fractional bandwidth is above 5.6%, above three times of that of traditional patch antenna. Considering the length of this paper, the process of parameter study and bandwidth controllability is not presented here. Besides, the frequency selectivity of the filtering antenna is

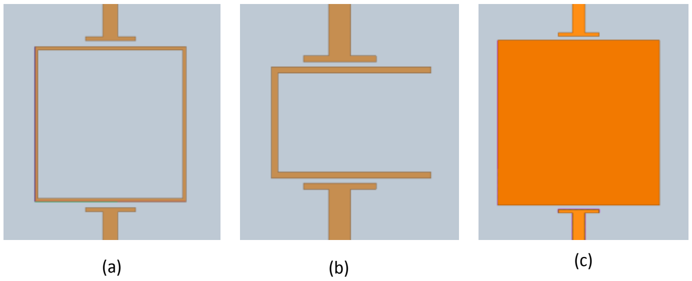


Fig. 8 Configuration of three resonators with weak coupling: (a) ring strip, (b) hairpin and (c) square patch

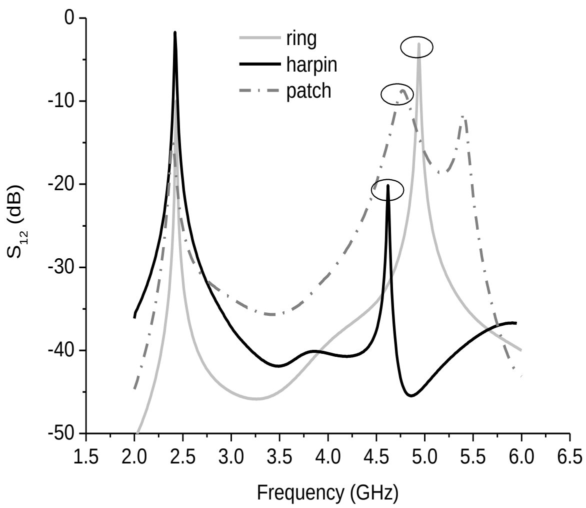


Fig. 9 The S parameter of the three resonators

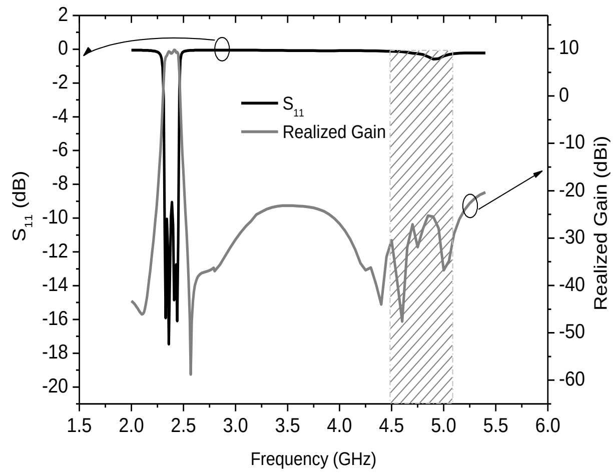
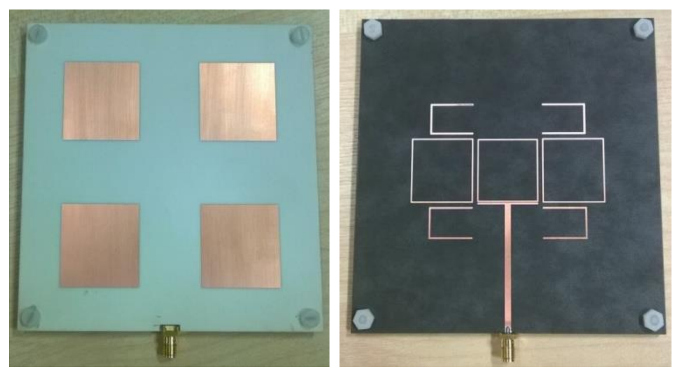


Fig. 10 The simulated S_{11} and antenna gain of the filtering antenna array



(a) (b)

Fig. 11 The photograph of 2×2 filtering antenna array: (a) front view, (b) back view

significantly improved when compared with the traditional antenna.

B. *Harmonics suppression*

It is known that the distributed microwave components such as filters and antennas, can trigger some unwanted higher order harmonics. These harmonics may produce spurious bands, which cause channel interference and deteriorate the quality of the communication system. Usually, the problem of spurious suppression is not an issue to be concerned in antenna design, but which is a challenge in band-pass filter design. In band-pass filter design, the same type of resonator is usually adopted. So the higher harmonics of the resonators are also located at the same frequency, which will result in unwanted bands in the higher frequency. In resonant antenna design, higher modes are also commonly observed since antenna itself can also be regarded as a resonator. The spurious bands of the filter and antenna have an adverse influence on the performance of the whole communication system.

Fig. 8 shows the three types of resonators used in this design: (a) ring strip resonator, (b) hairpin resonator and (c) square patch resonator. A relative weak coupling is applied to study the modes distribution of the three resonators. It is well known that the hairpin resonator and square patch resonator are half wavelength, while the ring strip resonator is one wavelength. The simulated S_{12} is shown in Fig. 9. It is observed that they have an identical basic resonant mode at 2.4 GHz. However, the harmonics are different from each other. As a result, these harmonics detune each other and can not generate a spurious band in the higher frequency.

Fig. 10 shows the simulated S_{11} and realized gains of the proposed filtering antenna array over a wide frequency range. The antenna array has an operating band at 2.4 GHz with a sharp roll-off at both edges of the band. In band, a flat antenna gain response of about 10 dBi is achieved. At the first harmonic, between 4.5 to 5 GHz, the S11 approaches 0 dB and the realized antenna gain reduces to below -20 dBi, as shown in the shadow area. This frequency response demonstrates that the proposed filtering-antenna array has an excellent frequency selectivity and harmonic suppression, which is attributed to the diverse resonators with different harmonics are adopted.

V. RESULTS AND DISCUSSIONS

Fig. 11 shows the photograph of the 2×2 filtering antenna array. The antenna is measured using ZVL vector network analyzer. The measured S11 and the antenna gain are shown in Fig. 12. The simulated S11 is also added for comparison. It is

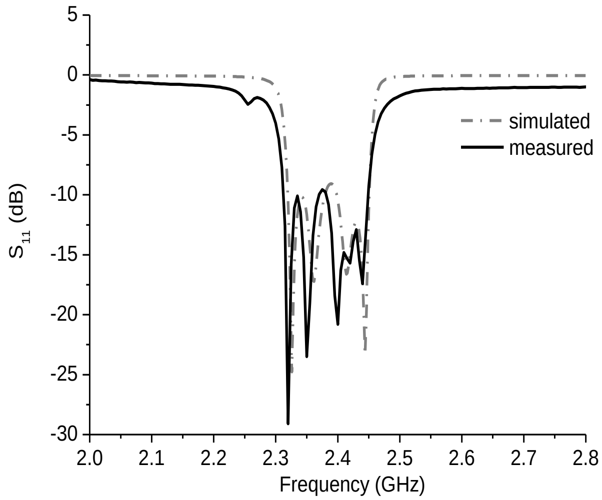
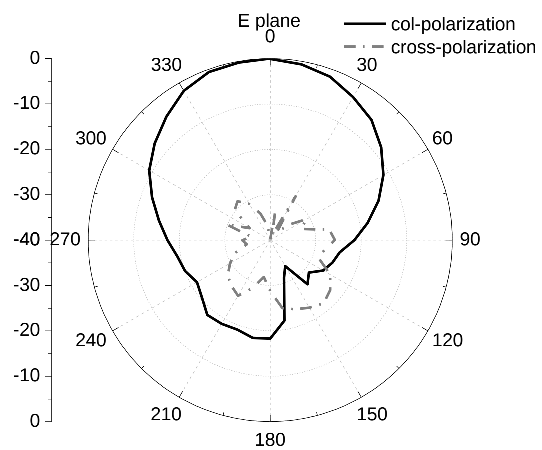
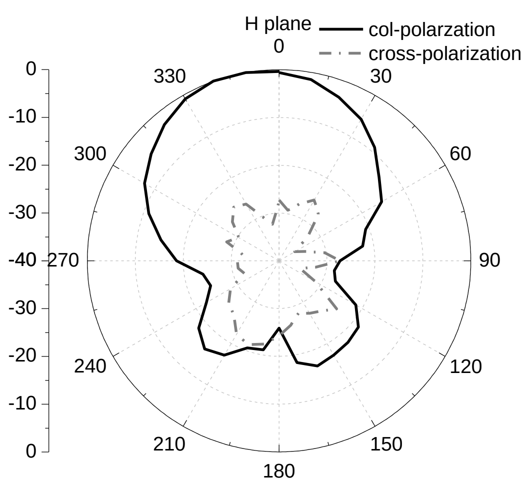


Fig. 12 The simulated and measured S_{11} of filtering antenna array



(a)



(b)

Fig. 13 The normalized measured co- and cross-polarization radiation patterns at 2.4 GHz: (a) E plane, (b) H plane

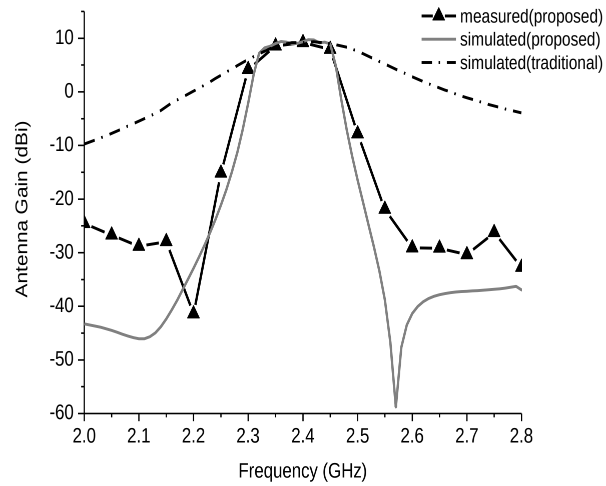


Fig. 14 The measured gain of the filtering antenna array

observed that the measured result agrees well with the simulated one with an impedance bandwidth from 2.31 GHz to 2.46 GHz, namely the fractional bandwidth is 6%.

Fig. 13 shows the normalized measured co- and cross-polarization radiation patterns of the filtering antenna array at 2.4 GHz in E and H plane, respectively. The measured results exhibit a good radiation performance with maximum antenna gain in broadside direction. The slits coupling and out-of-phase feeding adopted in this design result in an excellent XPD of 36 dB and 28 dB in E plane and H plane, respectively. Compared with that in [2], where the XPD is mainly caused by the radiation of feeding networks, the XPD is greatly improved. Besides, the feeding network on the top-layer is not perfect in integration. In this design, these problems are overcome at the cost of one more substrate.

Fig. 14 shows the measured and simulated realized antenna gains of the filtering antenna array. Besides, the simulated realized gains of the traditional antenna array are also added for comparison. It is observed that the simulated and measured results agree well, showing the filtering antenna array has a stable antenna gain response about 9 dBi from 2.3 to 2.45 GHz and it sharply reduce to below -20 dBi in the beyond the operating band. For the traditional antenna array, the maximum antenna gain is at 2.4 GHz, but it slowly decreases along the both sides of the center frequency, which demonstrates the good frequency selectivity of the filtering antenna array proposed.

VI. CONCLUSION

In this paper, a 2×2 filter-antenna-array has been proposed. Different from traditional antenna array design, this antenna has filtering characteristics, because the feeding network is composed of ring strip and hairpin resonators. The bandwidth and frequency selectivity are also improved. To illustrate the designing method, a four-way out-of-phase power divider has also been studied. Harmonics of the antenna can be suppressed by utilizing the difference of harmonics of diverse types of resonators in this design. The measured results agree well with the simulated ones, showing that the proposed filtering antenna array has excellent performance in terms of frequency selectivity, bandwidth, radiation characteristics and antenna gain.

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