Wideband Self-Decoupling Dielectric Patch Filtennas With Stable Filtering Response

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ABSTRACT Wideband self-decoupling of bandwidth-enhanced dielectric patch (DP) filtennas with stable filtering response are proposed in this letter. The TM{101} and TE{121} modes of the DP are combined to design a wideband antenna while its high-order TM{111} mode is used to introduce an intrinsic upper radiation null, leading to a good filtering response. Sequentially, 1 × 2 DP filtennas have been taken as an example to verify that improving the isolation can keep the filtering performance of the filtenna array basically consistent with the original filtenna element, which is a design concept proposed for the first time in this paper. To maintain almost the same filtering response when the antenna elements are spaced closely, the wideband self-decoupling between the antenna elements is obtained by properly choosing the parameters (i.e. dielectric constants of the DP and substrate), without adding extra decoupling structures. For validation, 1 × 2 closely-spaced filtennas are fabricated and tested. The measured results denote that the prototype has impedance bandwidth (|S{11}| < −10 dB) of about 21.2% from 4.47 GHz to 5.53 GHz and in-band isolation is over 20 dB. Benefiting from the self-decoupling scheme, the difference of the in-band gain and stopband suppression between the element and 1 × 2 DP filtennas is reduced significantly, showing stable filtering response of the filtennas.

INDEX TERMS Self-decoupling, dielectric patch (DP) filtenna, wideband, stable filtering response.

I. INTRODUCTION Multiple antennas are widely applied in modern wireless communication system. Generally, the antennas/arrays operating at the same or different frequency bands are equipped in a limited space of base station for saving cost and size as depicted in Fig. 1(a). However, there is strong mutual coupling that always degrades the system performance, including impedance matching, efficiency, and radiation pattern. Thus, it has become a challenging work that needs to be addressed urgently to decouple among these antennas.

On the one hand, for the antenna elements operating at the same frequency, many approaches have been developed to improve the isolation between them by adding extra structures, such as neutralization line [1], [2], metasurface [3], [4], electromagnetic band gap [5], [6], [7], [8], [9], decoupling feeding network [10], [11] and metal decoupling structure [12]. Subsequently, numerous self-decoupling antennas have attracted much attention in terms of compactness and simplicity without additional structures. For example, a weak field near the antenna element is skillfully created in [13] so that a terrific isolation can be achieved when another element is allocated in this weak field. In [14], the TE{113} mode of the dielectric resonator (DR) antenna (DRA) is excited to improve the isolation by simply increasing the height of the DRA element. In [15], the isolation can be improved greatly by appropriately selecting structural parameters of the dielectric patch (DP) antenna (DPA). Although [13], [14], [15] all...
behave with good self-decoupling performance, the narrow impedance bandwidth would limit their practical application.

On the other hand, for the antenna elements operating at different frequencies, filtennas that select signals in the required band and reject the undesired signals have been developed to effectively suppress the mutual coupling between them. The designs in [16], [17], [18], [19], [20], [21], and [22] are mainly achieved by structural transformation of the antenna. Also, substrate integrated waveguide (SIW) technology has been widely employed in the designing of filtennas in [23], [24], [25], and [26], but they are suffering from limited bandwidth. Therefore, wideband filtenna with a simple structure needs more attention.

Nowadays, multiple antenna elements are usually adopted in an array for higher gain as shown in Fig. 1(a). In this case, the arrays operating at different frequencies may interfere with each other inevitably due to the mutual coupling. The problem can be overcome if each array is designed with good filtering response, called filtenna array, as sketched in Fig. 1(b). Traditionally, filtering power dividers or matching networks [27], [28], [29], [30] are exploited to design the filtenna arrays. However, they can only achieve port-to-port isolation between different arrays. Furthermore, if multiple filtenna elements are combined to endow the array with filtering response instead of optimizing the overall filtering performance of the filtenna array, its design efficiency can be increased significantly. Nevertheless, the study about this has only received little attention. In [31], decoupling and filtering functions are realized simultaneously in the filtenna array by T-networks. But the periodic structures are complicated and need time-consuming optimization. In [32], the cascaded structure comprised of several different stubs can both generate two radiation nulls and act as an efficient decoupling isolator. However, the problematic issue of narrow impedance bandwidth in [31] and [32] still exists. More importantly, the effect of isolation on the filtering response of the closely-spaced filtennas has not been mentioned. In this paper, wideband self-decoupling DP filtennas with stable filtering response are investigated. The main novelties and merits are as follows:

(1) The dominant TM$_{101}$ mode and high-order TE$_{121}$ mode of the DP are used to design bandwidth-enhanced DP filtennas, meanwhile, the high-order TM$_{111}$ mode is utilized for generating upper stopband radiation null (achieving filtering response). Finally, wideband self-decoupling is easily realized by selecting appropriate dielectric constant of the DP and substrate without any structure.

(2) More importantly, the antennas operating at the same frequency and different frequencies are discussed at the same time. We have studied the case when filtenna elements are applied to an array for MIMO system. For this reason, 1 $\times$ 2 DP filtennas have been taken as an example to study. It is found that the mutual coupling will deteriorate the filtering performance of the original filtenna element. Therefore, we demonstrate that improving the isolation can keep the filtering performance of the filtenna array basically consistent with the original filtenna element (with stable filtering performance), which is a design concept proposed for the first time in this paper. This discussion provides a significant guideline for designing filtenna array and simplifies the design method of filtenna array (from filtenna element to filtenna array).

To the end, 1 $\times$ 2 closely-spaced filtennas are manufactured and measured. An acceptable agreement between the simulated and measured results is shown.

II. WIDEBAND DP FILTENNA ELEMENT

Fig. 2 exhibits the configuration of the wideband DP filtenna element fed by the feeding microstrip line. The driven DP (Ceramic, $\varepsilon_r=69$, tan $\delta=8.5 \times 10^{-4}$, $h_1=0.93$ mm) with the size of $a \times b$ is on the top of Substrate 1. Substrate 1 is Rogers RO3003(tm) with $\varepsilon_r=3$, tan $\delta=1.3 \times 10^{-3}$ and height of $h_2=1.524$ mm. Substrate 2 is Rogers RO4003(tm) with $\varepsilon_r=3.55$, tan $\delta=2.7 \times 10^{-3}$ and thickness of $h_3=0.813$ mm. A 50 $\Omega$ feeding microstrip line is printed on the bottom of Substrate 2. A slot is etched from the ground plane for coupling energy into the antenna. All of the simulations are carried out in ANSYS HFSS software.

As shown in Fig. 3, the $E$-field distributions of the dominant TM$_{101}$ mode, high-order TE$_{121}$ mode, and TM$_{111}$ mode of the DP are found by the eigenmode simulation (the Solution Type in HFSS is selected as “Eigenmode”, and the eigenmode of DPA can be obtained by choosing different frequencies). TM$_{101}$ and TE$_{121}$ modes are the operating modes of the proposed antenna. Consequently, the equivalent effective dielectric constants ($\varepsilon_{eff}$) and the equivalent thickness ($h_{eff}$) can be obtained from [33] and [34]. In addition, for the TM$_{101}$ mode, there is

$$k_x = \frac{\pi}{a}, \quad k_y = 0, \quad k_z = \frac{2 \arctan(\varepsilon_{eff} \alpha_c/k_z)}{h_{eff}}$$

For the TE$_{121}$ mode, there is

$$k_x = \frac{\pi}{a}, \quad k_y = \frac{2\pi}{b}$$
FIGURE 2. The configuration of the proposed bandwidth-enhanced DP filtenna element. (a) Top view. (b) Side view. (Design parameters: $\varepsilon_r^1 = 69$, $\varepsilon_r^2 = 3.0$, $\varepsilon_r^3 = 3.55$, $s_l = 60$ mm ($\lambda_0$), $s_w = 55$ mm (0.92$\lambda_0$), $h_1 = 0.93$ mm, $h_2 = 1.524$ mm, $h_3 = 0.813$ mm, $a = 28$ mm, $b = 32$ mm, $c = 2.8$ mm, $d = 7.1$ mm, $l = 10$ mm, $f = 0.9$ mm, $L = 5.3$ mm.) ($\lambda_0$ is the corresponding wavelength in free space).

For both modes, the resonant frequencies can be obtained by

$$f = \frac{c}{2\pi\sqrt{\varepsilon_{\text{eff}}}} \sqrt{k_x^2 + k_y^2 + k_z^2}$$

where $k_x$, $k_y$, and $k_z$ denote the wavenumbers along the x-, y-, and z-axis, respectively. $\alpha_1$ and $\alpha_2$ are the wave numbers of the dissipation mode in the air and substrate along the z-axis, respectively. Finally, the length ($a$) of the antenna can be calculated as 29.7 mm (the optimal value is 28 mm). The length ($b$) can be calculated as 30.7 mm (the optimal value is 32 mm).

The TE$_{121}$ mode is made to be close to the dominant TM$_{101}$ mode by adjusting the aspect ratio of the DP, thus expanding the impedance bandwidth. At the same time, the TM$_{111}$ mode which is regarded as a non-excitation and non-radiation mode introduces an intrinsic upper band-edge radiation null [35]. The slot is etched from the ground plane and its size determines the impedance matching. Therefore, the dimension of the slot is set as 2.8 mm $\times$ 7.1 mm through parameter scanning analysis for good impedance matching.

Furthermore, key parameters ($b$ and $L$) are investigated with the other parameters unchanged as shown in Fig. 4. For the different results with $b$ as shown in Fig. 4(a), as $b$ increases from 24 mm to 35 mm, the TE$_{121}$ mode moves downward from 5.67 GHz to 5.35 GHz while the TM$_{101}$ mode is fixed. Similarly, the upper radiation null also shifts downward from 6.04 GHz to 5.71 GHz with the variation of $b$ while the lower edge suppression level remains unchanged. For the different results with $L$ as shown in Fig. 4(b), with the increase of $L$, the stopband suppression at the upper band is enhanced. At the same time, when $L$ increases from 4.3 mm to 5.3 mm, the impedance matching improves, but when $L$ continues to increase to 6.3 mm, the bandwidth decreases. Thus, it can be concluded that the impedance bandwidth as well as the radiation null can be controlled simultaneously by $b$ and $L$ with optimal values of 32 mm and 5.3 mm, respectively. Finally, a wideband DP filtenna element (4.63 GHz-5.57 GHz) is achieved under a simple structure.

III. WIDEBAND SELF-DECOUPLING 1 $\times$ 2 DP FILTENNAS

In order to study the case when filtenna elements are applied to the array for MIMO system, 1 $\times$ 2 DP filtennas have been taken as an example to investigate. Herein, two wideband DP filtenna elements designed above are placed back to back along the y-axis. The configuration of the closely-spaced DP filtennas is outlined in Fig. 5. In this section, the stability of...
the filtering response of $1 \times 2$ DP filtennas is studied from the perspective of isolation.

In the following simulation, port 1 is excited while port 2 is terminated by a 50 Ω load. To offer a clear insight into the decoupling mechanism, three sets of $1 \times 2$ DP filtennas with different parameters (i.e. $\varepsilon_{r_1}$ and $\varepsilon_{r_2}$) evolved from Antennas I to III are investigated. For easy comparison, the center frequency is fixed at around 5 GHz. The length ($a$) of the DP and spacing $S$ are fixed at 28 mm and 30 mm, respectively. For better illustration, two new indices are introduced to measure the fluctuation level of the filtering response between the filtenna element and $1 \times 2$ DP filtennas. Hence, the smaller the PGD (in-band peak gain difference) and AAD (average absolute difference of suppression level) values, the more stable the filtering response of $1 \times 2$ DP filtennas.

In the following analysis, when the two specified parameters are varied, the other parameters remain unchanged. Detailed information is tabulated in Table 1.

In our recent work [15], combining the EM field equations, the attenuation constant ($\alpha$) in Region 1 (Fig. 5) can be expressed as $\alpha^2 = k_1^2 + k_2^2 + \varepsilon_{r_0}k_0^2$. It can be found that the mutual coupling between the two DPAs is mainly affected by $\varepsilon$ (which can be influenced by the dielectric constants of the DP and substrate). Fig. 6 plots the $E$ field vector diagrams of Antennas I and III at (a) TM$_{101}$ and (b) TE$_{121}$ modes.

The $S$-parameters of the three antennas are plotted in Fig. 7(a). In reference Antenna I, the $|S_{11}|$ of $1 \times 2$ DP filtennas moves obviously towards the upper band compared with its element and it has the worst in-band minimum isolation of 15.09 dB ($|S_{21}| < -15.09$ dB). In reference Antenna II, as $\varepsilon_{r_1}$ increases to 60 while $\varepsilon_{r_2}$ decreases to 5, the $|S_{11}|$ of $1 \times 2$ DP filtennas still has a little offset compared with its element while its $|S_{21}|$ improves to $-17.69$ dB in the passband. Remarkably in Antenna III, when $\varepsilon_{r_1}$ and $\varepsilon_{r_2}$ reach 69 and 3 respectively, it can be clearly seen that the simulated $|S_{11}|$ of the element and $1 \times 2$ DP filtennas are almost identical and overlapped in the entire operating band (4.62 – 5.56 GHz). Furthermore, the in-band minimum isolation has obviously improved to better than 20 dB. As discussed above, the simulated $|S_{21}|$ of $1 \times 2$ DP filtennas is especially sensitive to the variation of $\varepsilon_{r_1}$ and $\varepsilon_{r_2}$. It can be concluded that the larger the ratio of $\varepsilon_{r_1}/\varepsilon_{r_2}$, the higher the wideband isolation between the filtenna elements can be achieved.

To visually demonstrate the impact of different isolation on the filtering performance of $1 \times 2$ DP filtennas, Antennas I and III are selected from Table 1 to compare filtering response with their corresponding elements, as given in Fig. 7(b). In reference Antenna I, the isolation is only 15.09 dB, and then the PGD between the element and $1 \times 2$ DP filtennas reaches 1.88 dB and the AAD between them at the upper stopband is 9.26 dB. This means that the in-band peak gain of $1 \times 2$ DP filtennas deviates greatly from its element, and the upper skirt selectivity degrades a lot. Impressively, in Antenna III, the PGD (0.26 dB) and AAD (2.86 dB) are reduced significantly. That is to say, as the wideband isolation improves, the filtering response of $1 \times 2$ DP filtennas can...
maintain stable (almost the same with the element). Based on the above analysis, the parameters of Antenna III are set as the optimal ones. The bandwidth, isolation, PGD, and AAD of all the antennas are listed in Table 1.

The wideband self-decoupling between the elements has been achieved by choosing the proper dielectric constants, ensuring a stable filtering response of $1 \times 2$ DP filtennas. In other words, under the premise of high wideband isolation, the filtenna element is designed first and then combined into $1 \times 2$ DP filtennas without optimizing them, thereby the design efficiency is greatly improved.

IV. EXPERIMENT VERIFICATION AND DISCUSSION

For demonstration, $1 \times 2$ wideband self-decoupling DP filtennas are designed and measured. The detailed dimensions are given in Fig. 2 and 5 captions. In fabrication, DPs are processed separately and then installed together with other parts (manufactured by PCB technology) by adhesive. The adhesive has little effect on the performance of the antenna. Fig. 8 shows the photograph of the prototype and the measurement environment is shown in Fig. 9. The measurement process consists of three parts:

1. $S$-parameters measurement (network analyzer Agilent): Calibrate, and connect antenna for $S$-parameters.

2. Gain measurement: The signal is generated by the Agilent E8257D for the standard horn antenna. Then the power received by the prototype is recorded by the Agilent E4447A [34].

3. Radiation pattern measurement: The prototype which is set at a particular frequency rotates 360 degrees to measure the gain at all angles for the radiation pattern.

As shown in Fig. 10, the realized gain curves between the measurement and simulation show reasonable agreement. In this design, the operating bandwidth is defined as the one with $|S_{11}| < -10 \text{ dB}$ and $|S_{21}| < -20 \text{ dB}$. The measured and simulated bandwidths are about 21.2% (4.47 to 5.53 GHz) and 18.46% (4.62 to 5.56 GHz). The measured in-band isolation is $>20.67 \text{ dB}$, and the simulated one is $>20.02 \text{ dB}$. The relatively-large difference of $|S_{21}|$ between the simulation and measurement is from 4.37 GHz-5.42 GHz, and the experiment $|S_{21}|$ is better than the simulation one, which can be mainly attributed to two factors, i.e. misalignment of the DPs and the extra losses introduced by the SMA connectors. Since the isolation is more than 20 dB, meaning little energy transmission from port 1 to port 2, the errors in experiment can lead to a relatively-large fluctuation of $|S_{21}|$. 

FIGURE 11. Simulated and measured normalized radiation patterns of the prototype at (a) 4.78 GHz. (b) 5.48 GHz.

Fortunately, the in-band $|S_{21}|$ is better than $-20$ dB in simulation and experiment, which is acceptable in application [37]. In Fig. 11, the simulated and measured radiation patterns of the prototype are compared at 4.78 GHz and 5.48 GHz, showing good agreement. The tilt of the $E$-plane radiation patterns can be attributed to inadequate wideband isolation and the off-central location of one of the DPs on the ground plane in simulating and measuring radiation patterns. The radiation efficiency of this antenna is shown in Fig. 12. As we can see, the in-band radiation efficiency in measurement is greater than 85.45%, and the peak efficiency is 97.88% at 5.42 GHz, showing good agreement with the simulation.

Table 2 shows the summary of the comprehensive comparison between the proposed work and the previous designs. For the DRA in [14], the isolation at the single mode (TE$_{113}$ mode) is greatly improved by increasing the height of the DRA element. Our design belongs to a DPA. Although its profile is slightly higher than microstrip patch (MP) antenna (MPA), it lower than DRA [14] and features wide bandwidth due to multi-mode characteristic [33], [38], large design freedom [15] and so on. For the same DPA in [15], the isolation can be improved by appropriately selecting structural parameters of the DPA. Both of them belong to the self-decoupling technique, which is attractive due to low design complexity. However, in addition to their narrow bandwidths (6.08% and 7.2%, respectively), their designs of them are not applicable for coexistence with antennas operating at different frequencies due to the lack of filtering response. For metal patch antennas [31], [32], they have realized both the decoupling and filtering performance simultaneously. In [31], although the filtering and decoupling networks have been simplified as much as possible by sharing parts of the networks, extra T-shaped multi-section transformers are needed to make up for the mismatching induced by the filtering and decoupling, resulting in high design complexity. In [32], two structures are added to a typical metallic patch, leading to a relatively complicated design procedure. In addition to narrow bandwidth and complicated design [31], [32], the effect of mutual coupling on filtering performance is not mentioned. Differently, the effect of the mutual coupling between the filtenna elements on the filtering performance filtenna array is discussed here for the first time. As a new kind of DRA, the DPA have several attractive advantages such as low loss and high radiation efficiency, as compared with metal antennas. In this design, a wideband self-decoupling technique for bandwidth-enhanced DP filtennas is realized in a simple way. The proposed $1 \times 2$ DP filtennas have a much wider bandwidth of 18.46% than those in [14], [15], [31], and [32]. It is found that the stable filtering response of the array (same as the filtenna element) is achieved when the isolation is improved. Obviously, this discussion is vital for offering an easy way from the filtenna element to closely-spaced filtennas.

### V. CONCLUSION
A wideband self-decoupling technique for bandwidth-enhanced DP filtennas has been presented for the first
time. After the design of a bandwidth-enhanced DP filtenna element, it can be found that good wideband isolation can be obtained by selecting the proper dielectric constant. More importantly, 1 × 2 DP filtennas can maintain almost the same stable filtering response as the filtenna element due to the improvement of wideband isolation. Remarkably, the proposed wideband self-decoupling method would be attractive and applicable for large-scale filtenna arrays where antennas/arrays operate at the same band or different bands.

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