

Millimeter Wave SIW Cavity-Fed Filtenna Arrays for 5G Wireless Applications

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SUMMARY In this paper, millimeter wave (mmWave) filtenna arrays for 5G applications are proposed. Two kinds of 2-element subarrays are designed for horizontal and vertical polarizations. Each subarray consists of three substrate integrated waveguide (SIW) cavities and two sets of stacked patches. Fully-shielded combined eighth-mode SIW (FSD-CEMSIW) cavities are used in the filtenna design. This cavity not only works as the first-stage resonator but also as the power divider for the subarray. As a result, a four-order bandpass filtering response is achieved. Filtenna arrays were fabricated and measured for demonstration. The impedance bandwidths of these subarrays cover 24–30 GHz, including the 5G mmWave bands (n257, n258, and n261) with measured average gains of 8.2 dBi and more than 22 dB out-of-band suppression. The proposed antennas can be good candidates for 5G mmWave communication to reduce the system complexity and potential cost of the mmWave front-ends.

key words: filtenna, mmWave, 5G, array antenna, substrate integrated waveguide

1. Introduction

With the 5G communication development, millimeter wave bands have drawn intensive research interests due to their broad spectrum bandwidth, which supports higher wireless transmission speed and low latency [1]–[3]. Filters are critical components in mmWave transceivers to provide the out-of-band suppression for the signal-to-noise ratio improvement [4]–[6]. To realize the compact and low loss connection, it is desirable to effectively fuse the functionality of the filters and antennas, and realize the so-called filtenna (filtering antenna) [7]–[9]. Moreover, massive MIMO antenna arrays are investigated to overcome the path loss and realize flexible beam-scanning in mmWave bands [10]–[12]. This technique not only places a significant limitation on the antenna element distance but also makes growing demand on the scale of the antenna arrays. Implementing the mmWave front-ends of the large antenna array may be complicated and expensive when the antenna array is excessively large. Thus, in order to meet the requirements of equivalent isotropic radiated power (EIRP) and reduce the system complexity, antenna elements can be combined to form a subarray [13], [14], as shown in Fig. 1.

Several filtenna elements and subarrays for 5G mmWave applications have been proposed in recent years

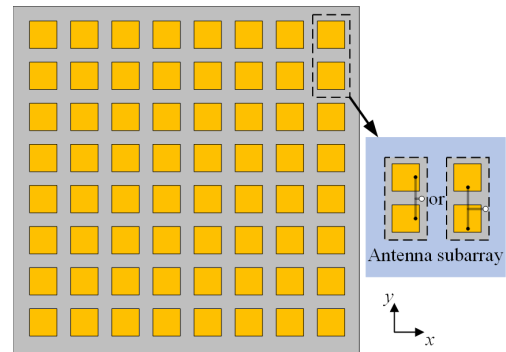


Fig. 1 Configuration of the antenna subarray in the massive MIMO antenna array.

[15]–[19]. Filtenna elements based on stacked radiating patches have been reported in [15], [16], which realize the compact antenna element with filtering functions. Filtenna element, 1×2 and 1×4 subarrays are reported in [17], consisting of microstrip resonators, U-shaped slots, and patches. Filtenna subarrays in [18], [19] are based on substrate integrated waveguide (SIW) cavities to eliminate the radiation loss in the microstrip lines. However, the bulky size of the SIW cavity and low gain of the slot antenna limit their application.

Fully-shielded eighth-mode SIW (FSD-EMSIW) cavity proposed in [16] can be a good candidate for mmWave filtenna design due to its compact size, high quality factor, and flexibility in controlling the electrical properties. Nevertheless, power dividers need to be added to excite each radiating element in the subarray, which may cause additional loss. In this paper, two FSD-EMSIW cavities are mirror placed to realize one fully-shielded combined eighth-mode SIW (FSD-CEMSIW) cavity. Two kinds of mmWave 2-element filtenna arrays for two orthogonal polarization based on the FSD-CEMSIW cavity are proposed. There are three cavities and two sets of stacked patches in each subarray, and the FSD-CEMSIW cavity works as both the first resonator and power divider. The filtenna subarrays realize the four-order bandpass filtering response covering the 5G mmWave bands (n257, n258, and n261). Due to its 1×2 array configuration, the beam-scanning coverage ability is not affected in the horizontal plane, and limited beam-scanning about $\pm 15^\circ$ can be achieved in the vertical plane, which is suit for the 5G base station application.

The paper is structured as follows. Section 2 introduces the characteristics of the FSD-CEMSIW cavity. Section 3

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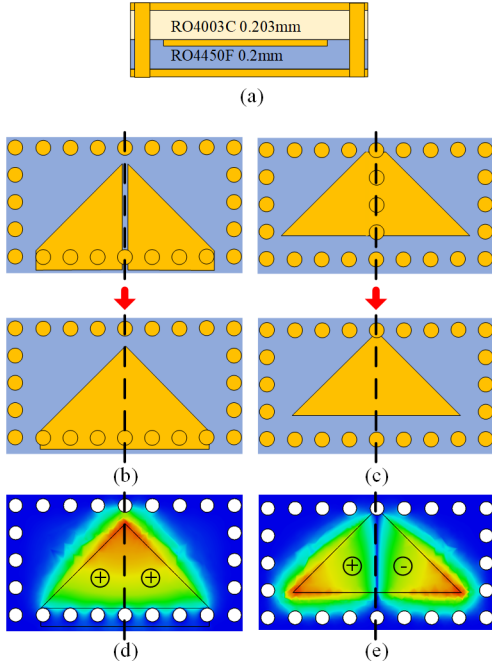


Fig. 2 Configuration of the proposed FSD-CEMSIW cavity. (a) Side view, (b) evolution from the FSD-EMSIW cavities to FSD-CEMSIW cavity with 0° phase difference by combining the patches, (c) evolution from the FSD-EMSIW cavities to FSD-CEMSIW cavity with 180° phase difference by removing vias. (d) E-field of the FSD-CEMSIW cavity with 0° phase difference, (e) E-field of the FSD-CEMSIW cavity with 180° phase difference.

presents the design guideline and extracted parameters of the resonators. Section 4 gives the measured results and demonstrates the proposed filtenna in array applications. Finally, the conclusion is given in Sect. 5.

2. High Q Resonator Design

The configuration of the proposed two kinds of fully-shielded combined eighth-mode SIW (FSD-CEMSIW) cavities for two polarizations are given in Fig. 2, which are the fusion of two FSD-EMSIW cavities in [16], and the triangle patches are connected to the ground by some vias. Both high Q resonators consist of three copper layers ($t = 35 \mu\text{m}$), one dielectric layer ($\epsilon_{r1} = 3.55$, $\tan \delta = 0.0027$, and $h = 0.203 \text{ mm}$) and one prepreg layer ($\epsilon_{r2} = 3.52$, $\tan \delta = 0.004$, and $h_b = 0.2 \text{ mm}$). Due to the surrounding vias and metal layers, the electric field (E-field) is restricted inside the resonator, as shown in Fig. 2(d)–(e). Comparing with the FSD-EMSIW cavity, the proposed FSD-CEMSIW cavities can be viewed as two FSD-EMSIW cavities placed side by side. Thus, the E-field in two sides of the symmetrical line has the same magnitude with 0° or 180° phase difference, which can be used to excite two antenna elements. In other words, these structures can work as both resonators and power dividers in the filtenna design. Such configuration is beneficial to reduce the sizes and complexity of the subarray feeding network.

The overall size and simulated quality factor of the

Table 1 Comparison of unloaded quality factors and size of the proposed cavity and other resonators.

	Proposed	FSD-EMSIW	SIW
Q_u	180	183	203
Size*	$0.42 \times 0.21 \lambda_0^2$	$0.21 \times 0.21 \lambda_0^2$	$0.4 \times 0.4 \lambda_0^2$

* λ_0 denotes the wavelength at the resonant frequency.

proposed FSD-CEMSIW cavity comparing with the FSD-EMSIW cavity and SIW cavity have been listed in Table 1. The radiation loss is eliminated in these high Q resonators due to their fully shield structures, which is attractive in filtenna design. Because of the flexibility in dividing energy and compact size, the proposed fully-shielded cavities are adopted in the filtenna subarray design.

3. Antenna Design

Figure 3 shows the configuration of the two-element subarrays for two polarizations. The antenna arrays for horizontal and vertical polarization are named Array-H and Array-V in this paper. Each antenna consists of three dielectric layers, two bonding layers, and six copper layers. TLY-5 ($\epsilon_r = 2.2$ and $\tan \delta = 0.0009$), RO4003C, and RO4450F are used in the design. Each subarray consists of an SMPM connector, a quasi-coaxial transition, three high Q resonators, and two sets of stacked patches. The antenna feeding network is placed between M3 and M6, while the two sets of stacked patches are realized on M1 and M2. The ground planes (on M3, M5, and M6) are connected by the blind vias (M3 to M6). In each filtenna, the first resonator (R1) FSD-CEMSIW cavity is excited by the input stripline. The energy is equally divided into the two FSD-EMSIW cavities (R2' and R2''), as illustrated in Fig. 4. And then, the energy is coupled to the two lower patches (R3' and R3'') through the coupling aperture on M3, and radiated from the two upper patches (R4' and R4''). The distance between the top patches is 6 mm ($0.54 \lambda_0$ at 27 GHz). Therefore, a four-order bandpass filtering response is achieved, and the corresponding coupling topology is shown in Fig. 5.

The design guideline of the filtenna subarrays will be discussed in the following sections.

3.1 Antenna Design Procedure

In order to cover the 5G mmWave bands (n257, n258, and n261) and consider the inevitable manufacturing errors, the design specifications of the filtenna subarrays are given as follows:

$$f_0 = 27 \text{ GHz}, \text{ BW} = 6 \text{ GHz},$$

$$FBW = \text{BW}/f_0 = 22.22\%, \text{ Order} = 4$$

$$\text{Element number} = 2, \text{ Element distance} = 6 \text{ mm}$$

The corresponding normalized coupling matrix $[m]$ of the equivalent filter with in-band return loss better than 15 dB can be derived as [20]:

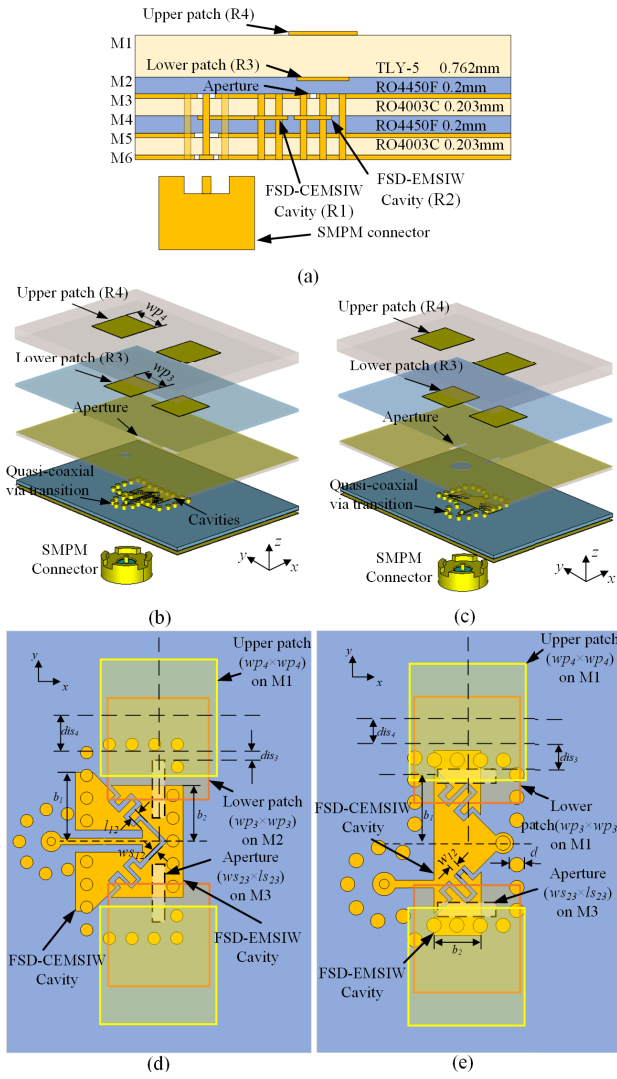


Fig. 3 (a) Lamination stack-up of the antenna array. (b) Configuration of the Array-H. (c) Configuration of the Array-V. (d) Top view of the Array-H. (e) Top view of the Array-V. $b_1 = 1.64$, $b_2 = 1.3$, $d = 0.3$, $dis_3 = 0.32$, $dis_4 = 0.75$, $l_{12} = 0.63$, $ls_{23} = 1.36$, $w_{12} = 0.15$, $wp_3 = 2.5$, $wp_4 = 2.8$, $ws_{12} = 0.1$, $ws_{23} = 0.3$ (unit: mm). (e) Top view of the Array-V, $b_1 = 1.69$, $b_2 = 1.13$, $d = 0.3$, $dis_3 = 0.5$, $dis_4 = 0.71$, $l_{12} = 0.3$, $ls_{23} = 1.4$, $w_{12} = 0.15$, $wp_3 = 2.6$, $wp_4 = 2.85$, $ws_{12} = 0.11$, $ws_{23} = 0.3$ (unit: mm).

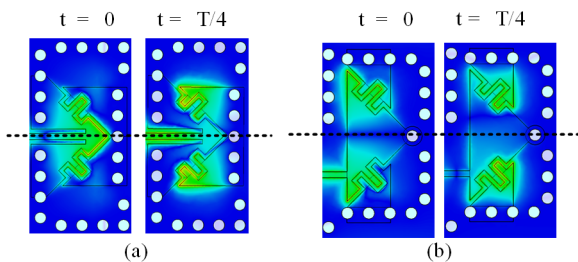


Fig. 4 E-field in (a) Array-H, (b) Array-V.

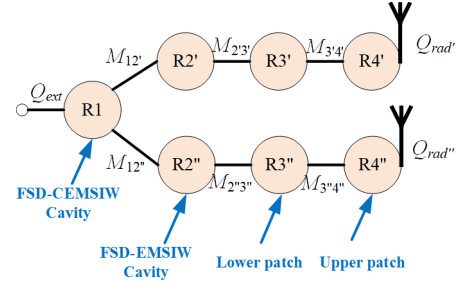


Fig. 5 Coupling topology of the filtenna arrays.

	S	1	2	3	4	L
S	0	0.9146	0	0	0	0
1	0.9146	0	0.8021	0	0	0
2	0	0.8021	0	0.6426	0	0
3	0	0	0.6426	0	0.8021	0
4	0	0	0	0.8021	0	0.9146
L	0	0	0	0	0.9146	0

Since the R1, R2' and R2'' act as a two-way power divider in the filtenna, the normalized coupling strength and the quality factor in this design can be calculated using

$$m_{12'} = m_{12''} = m_{12} / \sqrt{2} = 0.5671$$

$$m_{2'3'} = m_{2''3''} = m_{23} = 0.6426$$

$$m_{3'4'} = m_{3''4''} = m_{34} = 0.8021$$

$$m_{4'L'} = m_{4''L''} = m_{4L} = 0.9146$$

$$Q_{\text{ext}} = Q_{\text{rad}'} = Q_{\text{rad}''} = \frac{1}{m_{4L}^2 \cdot FBW} = 5.3796$$

The filtenna design procedure is listed as follows, and the summarizing design flowchart is given in Fig. 6.

- 1) Determine the design specifications of the filtenna to fulfill the applications. Comparing with the filter-only design, the antenna element number and adjacent element distance need to be decided in filtenna design.
- 2) Chose the filtenna topology and synthesize the coupling matrix $[m]$ to meet the specifications.
- 3) Simulate the standalone and coupled resonators to get the relationship between their geometric dimensions and electrical properties (quality factor Q , coupling strengths M_{ij} , and resonant frequencies f_i).
- 4) Build the initial modal based on the extracted dimension parameters according to the coupling matrix.
- 5) Tune the structural parameters until the modal satisfies the antenna specifications.

3.2 External and Internal Coupling

The external (input) quality factor Q_{ext} of the proposed filtenna can be extracted by the following equation [21]

$$Q_{\text{ext}} = \frac{f_0}{\Delta f_{\pm 90^\circ}} \quad (1)$$

where $\Delta f_{\pm 90^\circ}$ is the $\pm 90^\circ$ bandwidth concerning the absolute phase of S_{11} at f_0 . Figure 7(a) shows the relationship

between the external quality factor Q_{ext} and the location of inserted feed line l_{in} in Array-H. The Q_{ext} in Array-V can also be tuned by the input line position, and it is not given

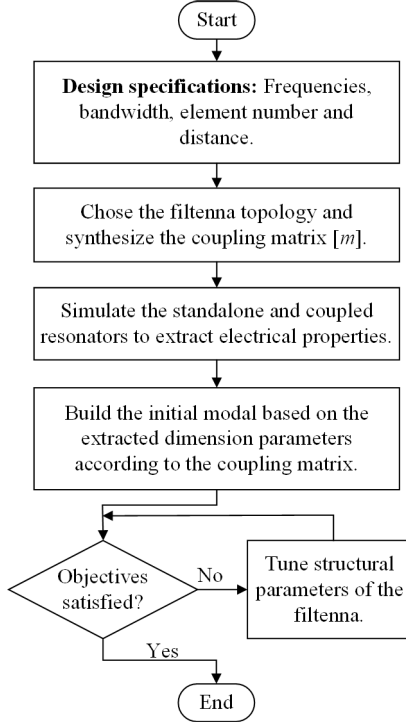


Fig. 6 Filtenna design flowchart.

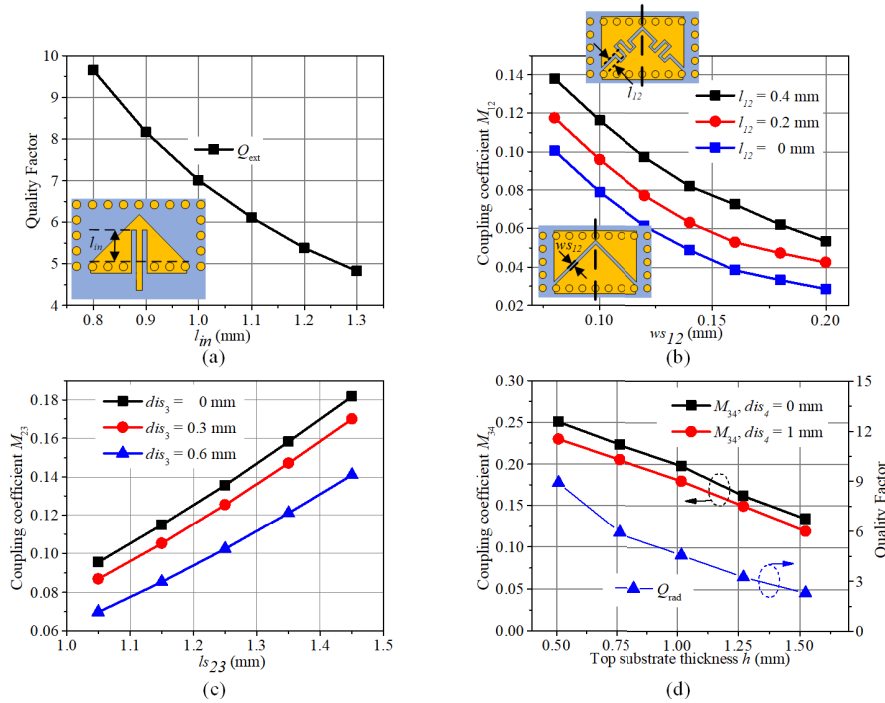


Fig. 7 (a) External quality factor Q_{ext} with different location of feed line p_{in} . (b) Coupling coefficient M_{12} with different slot width ws_{12} and interdigital length. (c) Coupling coefficient M_{23} with different slot length ls_{23} and location of slot dis_3 . (d) Coupling coefficient M_{34} and antenna radiation Q_{rad} with different top substrate thickness h .

here for the sake of brevity.

The coupling strengths between the adjacent resonators play a vital role in filtenna impedance performance. The strength can be controlled by the relevant position and distance of the resonators, and the coupling coefficient M can be estimated using [21]

$$M = \frac{f_i^2 - f_j^2}{f_i^2 + f_j^2} \quad (2)$$

where f_i and f_j are the resonant frequencies of the two coupled resonators obtained from the full-wave simulation. Figure 7(b)–(d) show the simulated coupling coefficients between the cavities and patches. It is observed that the coupling coefficient M_{12} increases when the distance ws_{12} between the first resonator (R1) and the two FSD-EMSIW cavities (R2' and R2'') decreases. Nevertheless, the minimum distance is limited by current PCB processing technology. Interdigital coupling is adopted to obtain higher coupling strength with the distance allowed by the design rule [16]. Coupling coefficient M_{23} can be controlled by varying the dimension of the coupling aperture ls_{23} . As for M_{34} , it can be tuned by the top substrate TLY-5 thickness h and the patch offset dis_4 .

3.3 Antenna Radiation Q

The top patches work as both the last-stage resonators and the radiators for the four-order filtenna subarray. The radi-

ation quality factor Q_{rad} needs to be equal to the external quality factor Q_{ext} . Q_{rad} of the patches can be obtained using the following equations [20] by simulating a standalone patch antenna fed by a lumped port.

$$S_{11}^{\phi} = \sqrt{\frac{1 + |S_{11}^{\min}|^2}{2}} \quad (3)$$

$$k = \frac{1 - S_{11}^{\min}}{1 + S_{11}^{\min}} \quad (\text{resonator is under-coupled}) \quad (4)$$

$$k = \frac{1 + S_{11}^{\min}}{1 - S_{11}^{\min}} \quad (\text{resonator is over-coupled}) \quad (5)$$

$$Q_{\text{rad}} = (1 + k) \frac{f_0}{f_2 - f_1} \quad (6)$$

where $S_{11}^{\min}$ is the minimum reflection coefficient occurring at the resonant frequency f_0 . f_1 and f_2 correspond to the frequencies when $S_{11} = S_{11}^{\phi}$.

Figure 7(d) shows the relationship between Q_{rad} and the top dielectric substrate thickness h . The top substrate thickness h should be carefully chosen in the specific filtenna design, because the thickness also controls the coupling coefficient between stacked patches.

Using the extracted design parameters from the above section and the time domain tuning technique in [22], filtennas are simulated in CST Studio Suite. The optimized geometrical dimensions of the filtennas are listed below Fig. 3.

4. Measurement and Discussion

The proposed filtenna array prototypes were fabricated and measured for demonstration. Figure 8 shows the photograph of the fabricated filtennas for two polarizations and the far-field measuring environment. Figure 9 gives the simulated and measured S-parameters and broadside realized gains of the subarrays. The measured -10 dB impedance bandwidth covers 24–30 GHz for each polarization, including the 5G mmWave bands (n257, n258, and n261). The measured bandwidths of the two prototypes slightly shift down comparing with the simulated results, which may be caused by the substrate permittivity higher than expected. The prototypes realize in-band average gains around 8.5 dBi with more than -22 dB out-of-band suppression level, which shows a good filtering function of these designs.

Figure 10 shows the normalized simulated and measured radiation pattern of the filtenna subarrays in two orthogonal planes ($\varphi = 0^\circ$ and $\varphi = 90^\circ$ plane). The measured radiation patterns agree well with the simulated ones. The 3 dB beamwidths of the two subarrays in two planes are about 74° and 48° , which ensure the wide scanning angle in the horizontal plane and $\pm 15^\circ$ limited scanning in the vertical plane. The measured cross-polarized levels are lower than -16 dB comparing with co-polarizations.

To further investigate the beam-scanning performance of the filtenna subarrays, two 16-element filtenna arrays for two polarizations are simulated in the Time Domain Solver

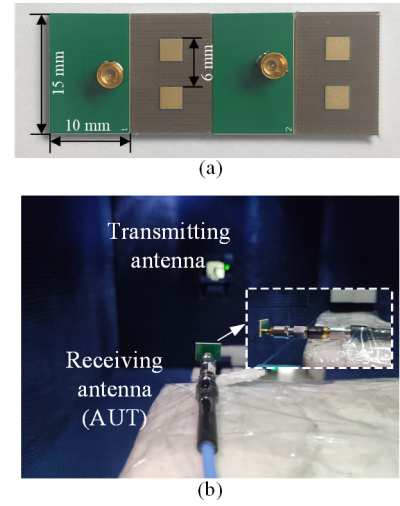


Fig. 8 Photograph of (a) the fabricated filtenna subarrays: Array-H and Array-V, (b) measuring environment.

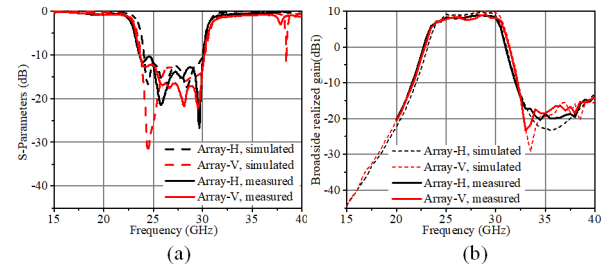


Fig. 9 Simulated and measured (a) reflection coefficient, (b) realized gain of the filtenna subarrays.

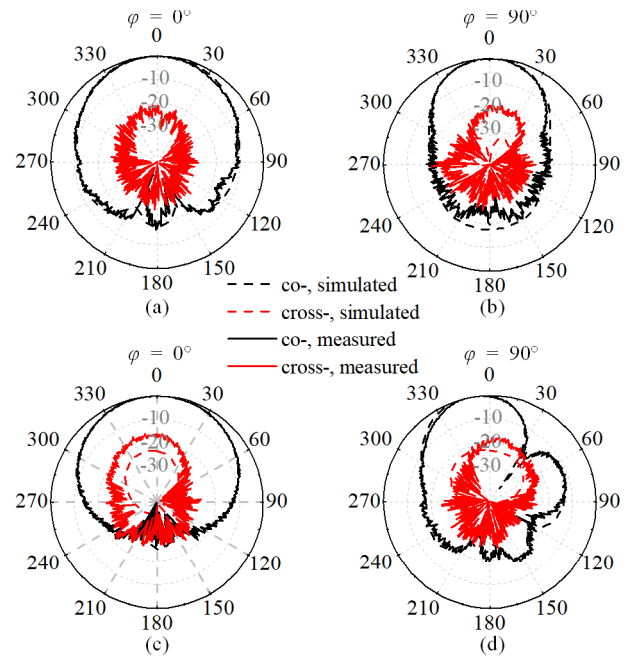


Fig. 10 Normalized simulated and measured radiation patterns of filtenna at 27 GHz. (a) Array-H, E-Plane. (b) Array-H, H-Plane. (c) Array-V, E-Plane. (d) Array-V, H-Plane.

of the CST Studio Suite. Each 4×4 patch array consists of 8 filtennas mentioned above, and the distance between the adjacent top patches is kept as 6 mm ($0.54 \lambda_0$ at 27 GHz) as depicted in Fig. 11. Input signals with appropriate time-delay are used to feed the eight filtenna subarrays in CST Studio Suite to avoid beam squint phenomenon in the wide-band antenna array [23]. For each subarray, $\pm 45^\circ$ beam-scanning coverage is realized in the horizontal plane as the

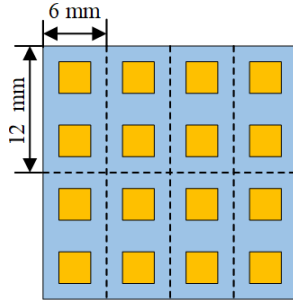


Fig. 11 Configuration of 4×4 patch array simulated in CST Studio Suite.

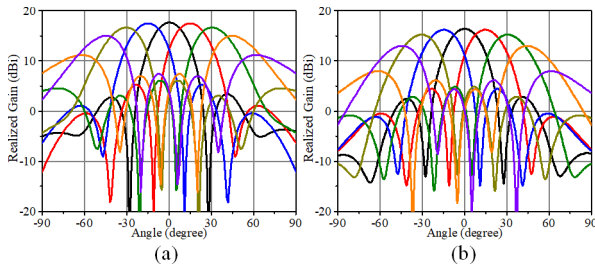


Fig. 12 Simulated beam-scanning radiation patterns of the arrays in the horizontal plane at 26 GHz. (a) Array-H, (b) Array-V.

simulated radiation pattern in Fig. 12. The simulated main lobe realized gains of the two antenna arrays with different pointing angles are also given in Fig. 13. The average in-band realized gain is about 16 dBi, and the filtering function is maintained while the main lobe is scanning to different angles.

Comparison between the presented design with other reported mmWave filtennas is listed in Table 2. The proposed filtenna subarray designs cover the 5G mmWave band (n257, n258, and n261) with satisfactory filtering functions with compact sizes. Due to the 1×2 element configuration, the filtennas support unaffected beam-scanning coverage ability in the horizontal plane and $\pm 15^\circ$ limited scanning in the vertical plane, which is suit for the 5G base station application.

5. Conclusion

In this paper, novel millimeter wave filtenna arrays have been proposed. Each antenna consists of three SIW cavities and two sets of stacked patches, and a four-order bandpass

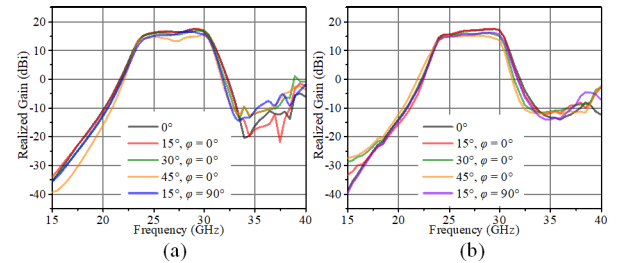


Fig. 13 Simulated main lobe realized gains with different pointing angles. (a) Array-H, (b) Array-V.

Table 2 Comparison with the previous millimeter wave filtenna.

Ref.	Antenna type	-10 dB bandwidth	Average gain (dBi)	Suppression level (dB)	F_L and F_U	Size of each element (λ_c^2)
[15]	Single element	20% (24.25 - 29.5 GHz)	5.2	15	0.24, 0.67	0.45 $\times$ 0.52
[16]	Single element	23.9% (23.2-29.5 GHz)	4.5	20	0.31, 0.41	0.35 $\times$ 0.49
[17]	1 $\times$ 4 subarray	37.0% (22 - 32 GHz)	12.5	N.A.	0.20, 0.20	0.49 $\times$ 0.34
[18]	1 $\times$ 4 subarray	1.2% (28.9 - 29.6 GHz)	8.1	N.A.	N.A.	0.52 $\times$ 1.85
[19]	2 $\times$ 2 subarray	1.6% (36.7 - 37.3 GHz)	10.8	36	0.40, 0.49	0.66 $\times$ 0.66
This work	1 $\times$ 2 subarray	22.2% (24 - 30 GHz)	8.5	22	0.30, 0.32	0.38 $\times$ 0.44

The definition of frequency selectivity [24]: $F_L = \frac{f_{10L} - f_{\Delta 15L}}{f_{10U} - f_{10L}}$, $F_U = \frac{f_{\Delta 15U} - f_{10U}}{f_{10U} - f_{10L}}$. f_{10L} and f_{10U} are the frequencies at lower and upper edges of the -10 dB impedance bandwidth. $f_{\Delta 15L}$ and $f_{\Delta 15U}$ are the lower and upper frequencies with the 15 dB gain suppression compared with average in-band realized gain.

λ_c is the wavelength at the central frequency. The size of each element is calculated by the overall size of the antenna divided by the number of elements in the antenna. Extended transmission lines for measurement are not included in the overall size for a fair comparison.

filtering response is realized. The working mechanism and design procedure have been discussed. The prototype for two polarizations has been shown a compact size, a wide bandwidth, and a good filtering response. Good agreement between the simulated and measured results validates that the filtennas can be a good candidate for 5G mmWave communication to reduce the system complexity and potential cost of the mmWave front-ends.

Acknowledgments

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