IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 16, 2020, accepted November 30, 2020, date of publication December 8, 2020, date of current version December 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3043320

Cavity-Backed Patch Filtenna for Harmonic Suppression

JUHO YUN[1], SON TRINH-VAN[1], JOON-YOUNG PARK[2], YOUNGOO YANG[1], (Senior Member, IEEE), KANG-YOON LEE[1], (Senior Member, IEEE), AND KEUM CHEOL HWANG[1], (Senior Member, IEEE)

[1]Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 440-746, South Korea
[2]Naval RADAR Team, Hanwha Systems, Yongin 449-885, South Korea

Corresponding author: Keum Cheol Hwang (khwang@skku.edu)

This work was supported by the Research Fund of Hanwha Systems.

ABSTRACT A co-design consisting of a filtering antenna integrating a cavity-backed patch antenna and a low-pass coaxial filter is proposed for size reduction of the RF front-end. The cavity-backed patch antenna is developed to exhibit a broad impedance bandwidth and a unidirectional radiation pattern. The low-pass coaxial filter is implemented to suppress harmonic resonances and gain in the stop-band of the antenna and is embedded directly inside the antenna cavity to realize a compact small-footprint co-designed filtering antenna structure. Two prototypes of the proposed filtering antennas, which integrate cavity-backed patch antennas with 4^{th} and 5^{th} order low-pass coaxial filters and with the overall dimensions of $0.697\lambda_0 \times 0.585\lambda_0 \times 0.236\lambda_0$ and $0.697\lambda_0 \times 0.585\lambda_0 \times 0.320\lambda_0$ (where λ_0 is the free space wavelength at 3.15 GHz), respectively, are fabricated and measured. The experimental results show fractional bandwidths of 25% and 23.8% and gain suppression levels exceeding 11 dB and 22 dB in the stop-bands for the filtering antennas with the 4^{th} and 5^{th} order filters, respectively. The measured gain is more than 6.5 dBi in the pass-band for both filtering antennas. In addition, excellent agreement is obtained between the simulated and measured results.

INDEX TERMS Cavity-backed antenna, co-design, filtering antenna, low-pass filter, RF front end.

I. INTRODUCTION

In recent years, there has been an increasing level of demand for multifunction, multipurpose RF front-end components with miniaturization designs for use in wireless communication systems [1]–[6]. For these applications, the antenna and filter are the two most essential components at the front end of a typical RF system, but they are usually larger components compared to other RF components. Thus, there have been numerous studies that aimed to miniaturize the overall size of RF front ends by integrating an antenna and a filter into a single module, referred to as a co-designed filtering antenna [7]–[12].

Traditionally, RF components are usually connected via a standard 50-Ω such as a coaxial connector, resulting in a bulky structure. In addition, in order to match the input and output impedances of each component with the 50-Ω interface, a matching network is also required inside each component, which increases the complexity, size, and total losses of the overall system. However, if the components can be integrated into a single module, the impedance at the interfaces between the components can also be used to optimize the performance of the overall system, hence eliminating the need for matching networks inside each component. Therefore, a co-designed filtering antenna that combines an antenna and a filter into a single module is more advantageous over the traditional cascaded method in terms of complexity, size, and losses. Thus far, a variety of filtering antennas have been proposed using a planar microstrip line [7]–[9] and a substrate-integrated waveguide (SIW) [10]–[12]. In some of the reported designs, the antenna acted as a dispersive complex load for the filter, including coupled planar resonator filters connected to microstrip patch antennas [7] and a coupled SIW resonator filter connected to a planar coaxial collinear antenna [10]. In other filtering antennas, the antenna served as both a radiator and as the last resonator of the filter simultaneously. Examples include planar monopole antennas integrated with different types of coupled-line filters [8], [9]

The associate editor coordinating the review of this manuscript and approving it for publication was Mohammad Tariqul Islam.

and coupled SIW cavity filters cascaded behind slot antennas [11], [12].

As metallic cavity structures have high power capacities and low insertion losses, they are widely used in the design of the high-Q filters installed in the base stations of wireless communication systems [13]. In relation to this, a 3-D metallic cavity-backed antenna has a feasible design that allows it to attain a unidirectional radiation pattern, as indicated in earlier studies [14], [15]. Therefore, a co-designed filtering antenna based on a metallic cavity structure would be an important advance [16]. In recent work [17], a broadband duplex-filtenna using a 3-D metallic cavity structure was presented. In this design, however, the antenna and filter are cascaded through a small section of a 50-Ω coaxial cable, resulting in a large footprint.

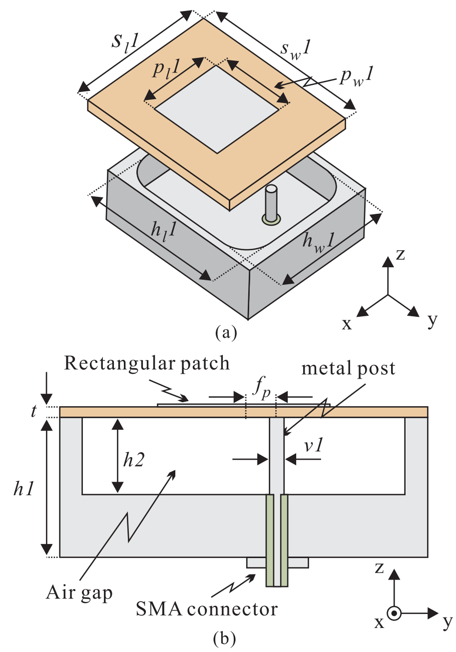

FIGURE 1. Configuration of the cavity-backed patch antenna: (a) overall view, (b) side-cut view.

TABLE 1. Design parameters of the cavity-backed antenna (Units: mm).

Parameter	Value	Parameter	Value	Parameter	Value
s_l1	55.7	s_w1	66.4	p_l1	29
p_w1	28	h_l1	53.1	h_w1	41.1
f_p	9	$h1$	21	$h2$	12.1
t	1.27	$v1$	3.1		

In this communication, we present a compact small-footprint cavity-backed filtering antenna. The filter is directly inserted inside the antenna cavity at the feed position and replaces the feeding part of the antenna. The 4^{th} and 5^{th} order low-pass coaxial filters are designed and integrated with wideband cavity-backed patch antennas effectively to suppress the harmonic resonances and gains in the stop-bands of the antennas. The proposed cavity-backed filtering antenna has a smaller volume as compared to a traditional antenna cascaded with a filter. A simulation is conducted using the ANSYS high-frequency structure simulator (HFSS). The performance of the proposed filtering antenna is verified through its fabrication and measurement.

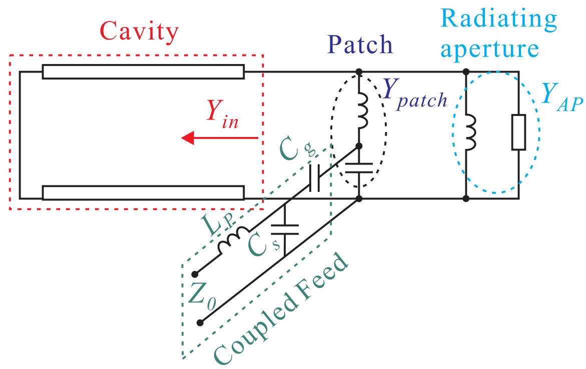

FIGURE 2. Equivalent circuit of the cavity-backed patch antenna.

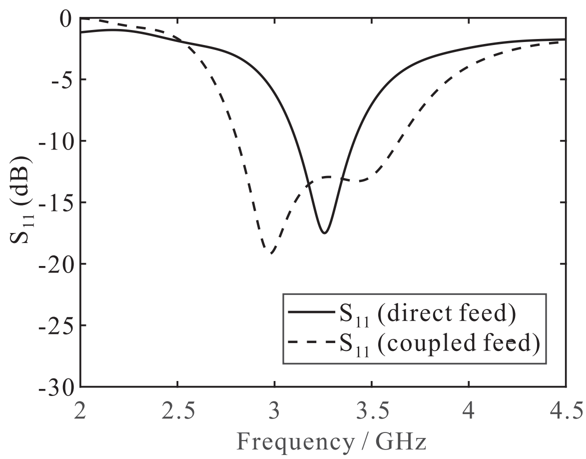

FIGURE 3. Comparison of reflection coefficients according to the feeding method.

II. ANTENNA DESIGN

A. CAVITY-BACKED PATCH ANTENNA DESIGN

Figure 1 shows the geometry of the proposed cavity-backed patch antenna. The antenna consists of a rectangular patch of size $p_w1 \times p_l1$, a Taconic TLE-95 ($\epsilon_r = 2.95$, tan$\delta = 0.0028$) substrate with a thickness of $t = 1.27$ mm, and an air-filled metallic cavity. The inner dimensions of the cavity are $h_w1 \times h_l1 \times h2$. The overall dimensions of the antenna are $s_w1 \times s_l1 \times h1$. The antenna is excited by a metal post inside the cavity through the coupled feeding technique. The metal post with a diameter of $v1$ is assembled with a SMA connector and is located f_p away from the center of the cavity-backed antenna. The antenna is designed to operate on the S-band at a designed frequency of 3.15 GHz. The optimized parameters of the cavity-backed antenna are listed in Table 1.

In the process of designing a cavity-backed patch antenna, a coupled feed is used to improve the bandwidth. An

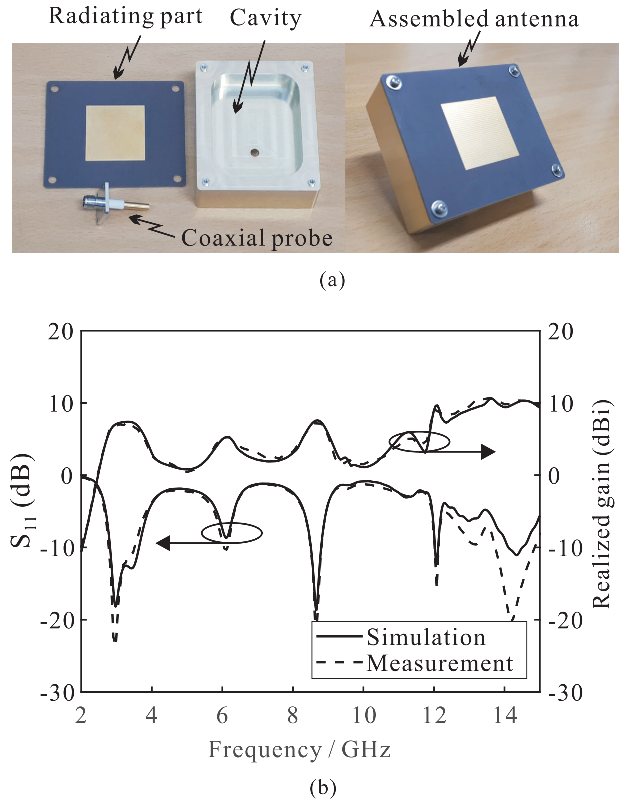

FIGURE 4. **(a) Photograph of the fabricated antenna, and (b) simulated and measured reflection coefficients and gains of the proposed cavity-backed patch antenna.**

equivalent circuit, as shown in Figure 2, is introduced to describe the mechanism by which to obtain a wide bandwidth through a coupled feed. The cavity can be modeled as a shorted waveguide with admittance of Y_{in} when viewed from the aperture. Y_{in} depends on the height of the cavity, and it represents an inductive property for an electrically short cavity model. The aperture part of the cavity is modeled as a circuit with admittance of Y_{AP}, and Y_{AP} is also inductive for a small aperture [18]. Because both the cavity and the radiation aperture are inductive, the resonance of the cavity-backed patch antenna is caused by the capacitance of the patch. However, it is difficult to implement a wide bandwidth with only resonance by the patch, and the bandwidth is expanded by generating additional resonance through a coupled feed. In the equivalent circuit of the coupled feed part, C_g refers to the capacitance between the metallic post and the patch, C_s denotes the capacitance between the metallic post and the cavity wall, and L_P refers to the inductance due to the current flowing through the metallic post. In order to confirm the additional resonance caused by the coupled feed and the corresponding bandwidth expansion, the reflection coefficients according to the feeding method are compared, as shown in Figure 3. In Figure 3, direct feed refers to a feeding method that electrically connects the metal post and the patch by extending the length of the metal post. With the direct feed approach, it can be seen that only a single resonance arises, and as described above, this is the resonance caused by the patch. On the other hand, it can be seen that the use of the coupling feed causes additional resonance, which increases the bandwidth.

A prototype is fabricated for validation, as shown in Figure 4(a). The overall dimensions of fabricated prototype are 66.4 mm × 55.7 mm × 22.47 mm. Figure 4(b) shows the measured and simulated reflection coefficients and the peak gains of the proposed cavity-backed patch antenna. Good agreement is obtained between the simulation and the measurement. As shown in Figure 4, the antenna achieves a measured −10 dB reflection bandwidth of 25.12% (2.82–3.63 GHz). Within the −10 dB reflection bandwidth, a measured maximum gain of 7.3 dB is attained at 3.2 GHz. As also observed in Figure 4, there are several harmonic resonances that occur at the frequencies of 6 GHz, 9 GHz, and 12 GHz, which are multiples of the fundamental resonance frequency f_0 of 3 GHz. At these harmonic frequencies, the peak gains are also very high. Because harmonic resonance also transmits and receives signals in the unwanted frequency range, it is necessary to suppress the harmonic resonances with a low-pass filter.

B. LOW-PASS COAXIAL FILTER DESIGN

This subsection presents the design of a coaxial-type low-pass filter, which is then integrated with the designed cavity-backed patch antenna to suppress the harmonic resonances and gains in the stop-band of the antenna. Figure 5 presents an illustration of the configuration of the low-pass coaxial filter. The structure of the overall low-pass coaxial filter consists of inner and outer conductors, as depicted in Figure 5(a). The coaxial filter has a different order and characteristics depending on the structure of the inner conductor. The inner conductor consists of a cascading structure of capacitive and inductive steps. According to the number of steps, the order of the coaxial filter is determined. We selected 4^{th} order and 5^{th} order Chebyshev low-pass filter prototypes. Corresponding side-cut views are shown in Figures 5(b) and 5(c). As indicated, in the 4^{th} order filter, the inner conductor has four steps, whereas the inner conductor of the 5^{th} order filter has five steps.

These characteristics can also be seen through the equivalent circuit shown in Figure 6. Figure 6 presents the equivalent circuit of a 4^{th} order low-pass filter and a 5^{th} order low-pass filter. The inductance and capacitance consist of a ladder network structure, with each inductance and capacitance referring to the step of the inner conductor described above. In the equivalent circuit, each element has a value defined as a g-value. In general, the g-value is the value normalized to the value at which the source resistance g_0 becomes 1. In the equivalent circuit of an n^{th} order low-pass filter, g_i(i=1 to n) represents the value of the inductance or capacitance, and g_0 and g_{n+1} indicate the input impedance and the output impedance, respectively.

In order to design the filter, it is necessary to calculate the element value g to implement the Chebyshev response characteristics [13]. In this paper, both low-pass coaxial filters are designed to have a cutoff frequency of 4 GHz and a reflection coefficient of less than -15 dB in the pass-band. The input and output impedances of the filter are both set to 50-Ω. The g-values for the 4^{th} order Chebyshev response are $g_0 = 1$, $g_1 = 1.1955$, $g_2 = 1.3001$, $g_3 = 1.8626$, $g_4 = 0.8345$, and $g_5 = 1.4326$, and the g-values for the 5th order Chebyshev response are $g_0 = 1$, $g_1 = 1.2328$, $g_2 = 1.3591$, $g_3 = 2.0599$, $g_4 = 1.3591$, $g_5 = 1.2328$, and $g_6 = 1$. With the calculated g-values, the lengths of the inductive step and capacitive step constituting the inner conductor of the filter are computed as follows [13]:

$$d_L = \frac{g_L}{2\pi} \frac{R_0}{Z_{high}} \frac{1}{f_c\sqrt{\mu\epsilon}}. \quad (1)$$

$$d_C = \frac{g_C}{2\pi} \frac{Z_{low}}{R_0} \frac{1}{f_c\sqrt{\mu\epsilon}}. \quad (2)$$

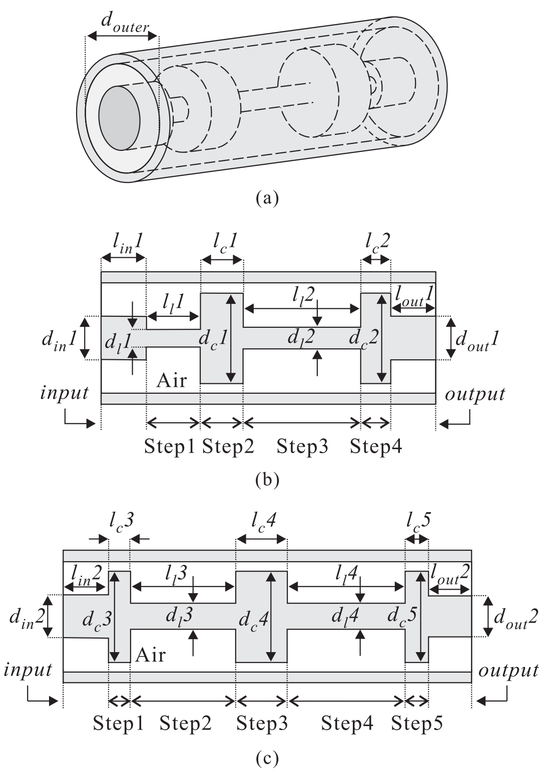

FIGURE 5. Configuration of the low-pass coaxial filter: (a) overall view, (b) side-cut view of 4^{th} order filter, and (c) side-cut view of 5^{th} order filter.

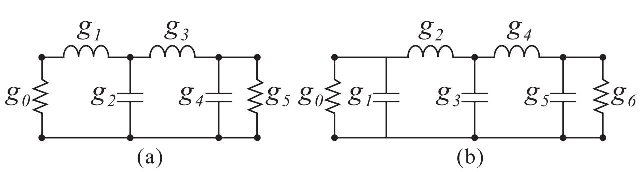

FIGURE 6. Equivalent circuits of low-pass filters: (a) 4^{th} order filter, (b) 5^{th} order filter.

Here, g_L and g_C are determined by the g-values, which are calculated above as follows: if the g-value is used to calculate the length of the inductive step, then it will replace g_L in (1); in contrast, if g is used to calculate the length of a capacitive step, then it will replace g_C in (2). R_0 and f_c represent the reference impedance and the cutoff frequency, respectively. Z_{low} and Z_{high} are impedances of the capacitive and inductive steps. $Z_{low} = 10$-Ω and $Z_{high} = 100$-Ω are used in this design. Based on the calculated parameters, an additional tuning process is also needed to adjust the parameters so as to attain better performance. The final parameters of the 4^{th} order and 5^{th} order low-pass coaxial filters are shown in Table 2.

TABLE 2. Design parameters of the low-pass coaxial filters (Units: mm).

Parameter	Value	Parameter	Value	Parameter	Value
d_{outer}	6	$d_{in}1$	2.6	$d_{in}2$	2.6
$d_{out}1$	2.6	$d_{out}2$	2.6	$l_{in}1$	2
$l_{in}2$	2	$l_{out}1$	2	$l_{out}2$	2
d_l1	0.9	d_l2	0.82	d_l3	1.04
d_l4	1.14	d_c1	4.92	d_c2	4.84
d_c3	4.78	d_c4	4.78	d_c5	4.5
l_l1	6.17	l_l2	7.35	l_l3	7.27
l_l4	7.36	l_c1	2.47	l_c2	1.61
l_c3	2.38	l_c4	4.71	l_c5	2.46

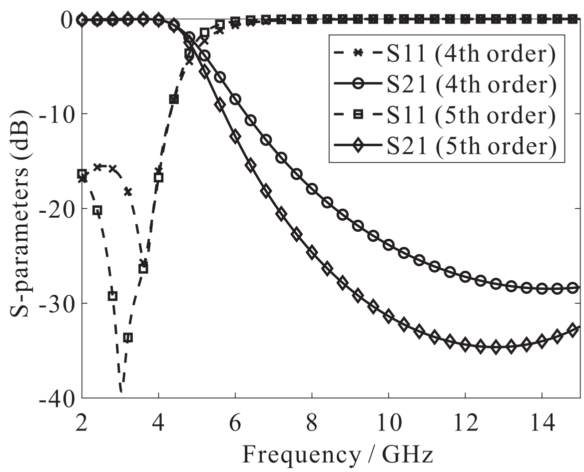

FIGURE 7. Response characteristics of 4^{th} order and 5^{th} order low-pass coaxial filters.

Figure 7 illustrates the response characteristics of the designed low-pass coaxial filters. As observed, these two filters achieve an S_{11} value of less than -15 dB in the entire pass-band. The S_{21} results show that both filters have a cutoff frequency of 4 GHz. These results are consistent with the design specifications; hence, the low-pass coaxial filters are shown to be well designed. In addition, as depicted in Figure 7, the higher the filter order is, the sharper the skirt characteristics become and the better the filtering characteristics. Clearly, the 5^{th} order filter has better characteristics as compared to the 4^{th} order filter. However, as the order of the filter increases, the overall length of the filter also increases. Therefore, the order should be selected in consideration of the size and characteristics of the filter. In this work, the 4^{th} order and 5^{th} order filters are selected to design filtering antennas.

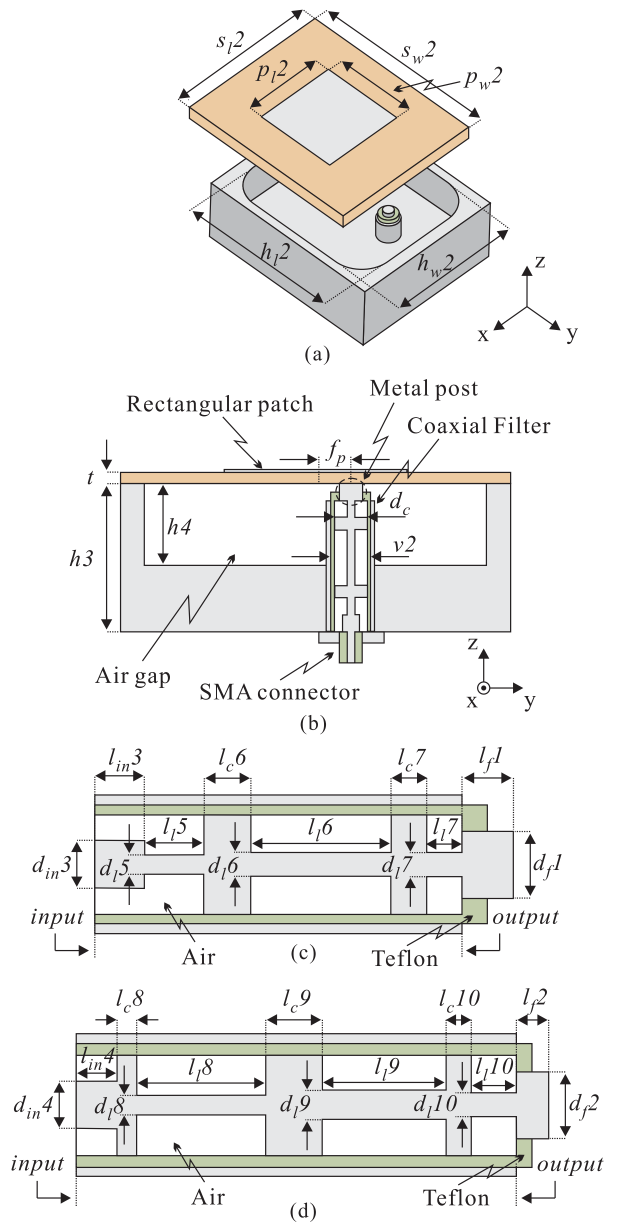

FIGURE 8. Configuration of the proposed cavity-backed co-designed filtering antenna: (a) overall view, (b) side-cut, (c) side-cut view of the 4^{th} order filter, and (d) side-cut view of the 5^{th} order filter.

TABLE 3. Design parameters of the cavity-backed filtering antennas (Units: mm).

Parameter	Value	Parameter	Value	Parameter	Value
s_l2	55.7	s_w2	66.4	d_c	5
$v2$	6	$d_{in}3$	2.4	$d_{in}4$	2.4
$l_{in}3$	2.5	$l_{in}4$	2.5	d_f1	3.4
d_f2	3.4	l_f1	2.6	l_f2	1.8
d_l5	1	d_l6	1.2	d_l7	1.2
d_l8	1	d_l9	1.2	d_l10	1.7
l_l5	3	l_l6	7.1	l_l7	1.8
l_l8	8	l_l9	8	l_l10	2.6
l_c6	2.4	l_c7	1.8	l_c8	1.2
l_c9	3.5	l_c10	1.6	t	1.27

C. CAVITY-BACKED FILTERING ANTENNA DESIGN

With the designs of antenna and filter shown in subsections A and B, respectively, the cavity-backed co-designed filtering antenna is implemented. Figure 8 depicts the configuration of the proposed cavity-backed co-designed filtering antenna. The low-pass coaxial filter is directly inserted inside the antenna cavity at the feed position, replacing the feeding part of the cavity-backed patch antenna (see Figures 8(a) and 8(b)). The bottom part of the metal post is reduced so that the filter can be inserted, while its top part remains. The input of the filter is connected by a standard 50-Ω SMA connector, whereas the output of the filter is connected to the top part of the metal post to excite the rectangular patch antenna. The feeding signal is sent to the metal post through the low-pass coaxial filter. This signal is then coupled to a rectangular patch, and radiation occurs. The output impedance of the filter is optimized to attain better impedance matching between the antenna and the filter without 50-Ω constraints. Two filters, in this case a 4^{th} order and a 5^{th} order low-pass coaxial filters, are used for integration with the cavity-backed patch antennas. The configurations of these two filters are illustrated in Figures 8(c) and 8(d). For the fabrication of the coaxial filters, to maintain the distance between the inner and outer conductors, the gaps between the conductors must be filled with a material, such as a dielectric material. For this reason, we use a hollow cylinder of Teflon, which has

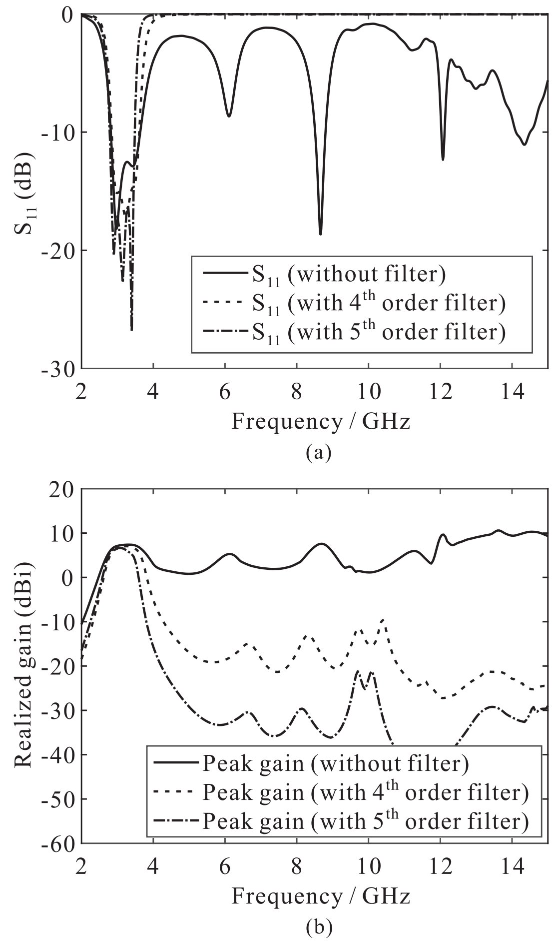

FIGURE 9. Comparison of the cavity-backed patch antenna and cavity-backed filtering antennas: (a) reflection coefficients and (b) peak gains.

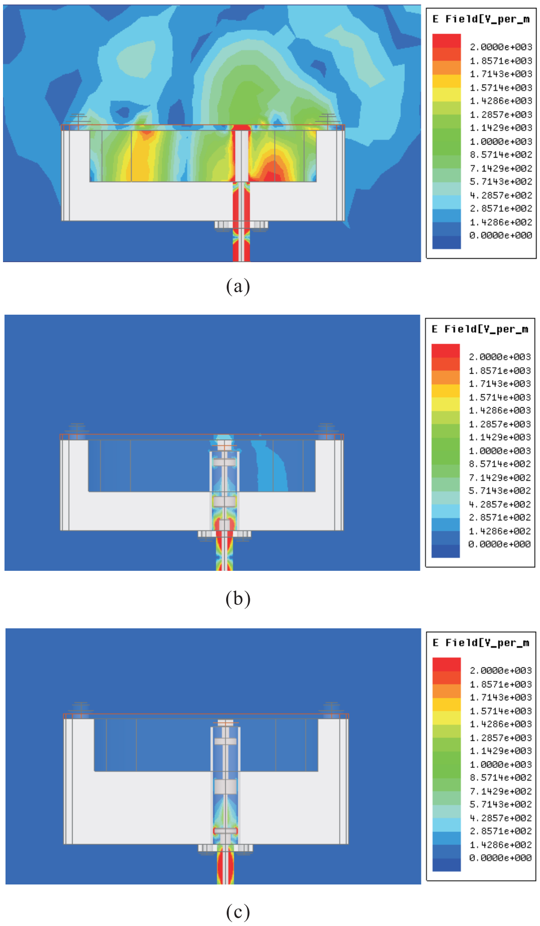

FIGURE 10. E-field distribution of the cavity-backed antenna shown in the form of a cross-section at 8.65 GHz: (a) without a filter, (b) with a 4^{th} order low-pass coaxial filter, and (c) with a 5^{th} order low-pass coaxial filter.

a dielectric constant of 2.1 and which is inserted between the inner and outer conductors of the filters. In addition, the Teflon is extended by half of the length of the metal post to hold the metal post. The design parameters are optimized to achieve optimum performance. The optimized parameters of the filtering antennas are shown in Table 3. For the filtering antenna using the 4^{th} order filter, the design parameters are $p_l2 = 26.9$ mm, $p_w2 = 27$ mm, $h3 = 21.2$ mm, $h4 = 12.1$ mm, $f_p = 5.3$ mm, $h_l2 = 53.1$ mm, and $h_w2 = 41.1$ mm, whereas for the filtering antenna using the 5^{th} order filter, the design parameters are $p_l2 = 26.7$ mm, $p_w2 = 29.2$ mm, $h3 = 29.2$ mm, $h4 = 12.1$ mm, $f_p = 4.5$ mm, $h_l2 = 52.1$ mm, and $h_w2 = 43.3$ mm.

Figure 9 shows a comparison of the simulated reflection coefficients and peak gains of the cavity-backed patch antenna and the cavity-backed co-designed filtering antennas. As can be observed in Figure 9(a), the cavity-backed patch antenna without a filter has a −10 dB impedance bandwidth of 2.82–3.63 GHz (25.12%). Meanwhile, the cavity-backed co-designed filtering antennas with the 4^{th} order low-pass coaxial filter and the 5^{th} order low-pass coaxial filter

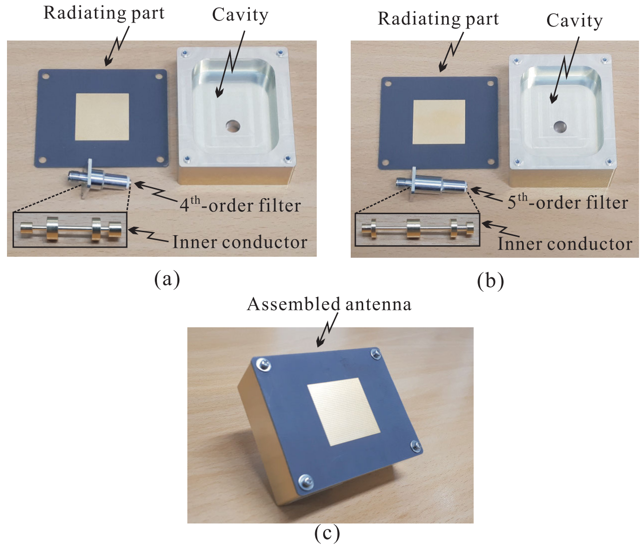

FIGURE 11. Fabrication model: (a) cavity-backed co-designed filtering antenna with the 4^{th} order low-pass coaxial filter before assembly, (b) cavity-backed co-designed filtering antenna with the 5^{th} order low-pass coaxial filter before assembly, and (c) after assembly.

achieve −10 dB impedance bandwidths of 2.84–3.61 GHz (23.88%) and 2.79–3.49 GHz (22.29%), respectively. In addition, as indicated in Figure 9(a), the harmonic resonances that occur at the frequencies of 6 GHz, 9 GHz, and 12 GHz in the cavity-backed patch antenna are wholly suppressed due to their integration with the low-pass filters, demonstrating the feasibility of the co-design. Figure 9(b) presents the results of the peak gains of the antennas with and without filters. All three antennas have similar gains in the pass-band. In the stop-band, the gain of the co-designed filtering antennas is significantly reduced as compared to that of the cavity-backed patch antenna without a filter. The gain reduction exceeds 11 dB and 22 dB for the co-designed filtering antennas with the 4^{th} and 5^{th} order low-pass coaxial filters, respectively. In addition, the skirt and filtering characteristics of the design integrating the 5^{th} order filter is more improved than those of the design integrating the 4^{th} order filter.

Figure 10 presents E-field distribution of the cavity-backed antenna in the form of a cross-section. A simulation is conducted to compare the radiation characteristics with and without an integrated filter in the harmonic band (8.65 GHz). Figure 10(a) shows the E-field distribution of a cavity-backed antenna without a filter, where it can be seen that the intensity of the field radiated from the antenna is high. On the other hand, as shown in Figures 10(b) and 10(c), when a filter is integrated into the cavity-backed antenna, there is very little E-field emitted from the antenna. In addition, the field intensity of the cavity-backed antenna with the 5^{th} order filter (see Figure 10(c)) is weaker than that of the cavity-backed antenna with a 4^{th} order filter (see Figure 10(b)).

Through the results shown in Figure 9 and Figure 10, it is confirmed that the proposed filter-integrated cavity-backed antenna has excellent filtering characteristics in the stop band and radiation characteristics in the pass band.

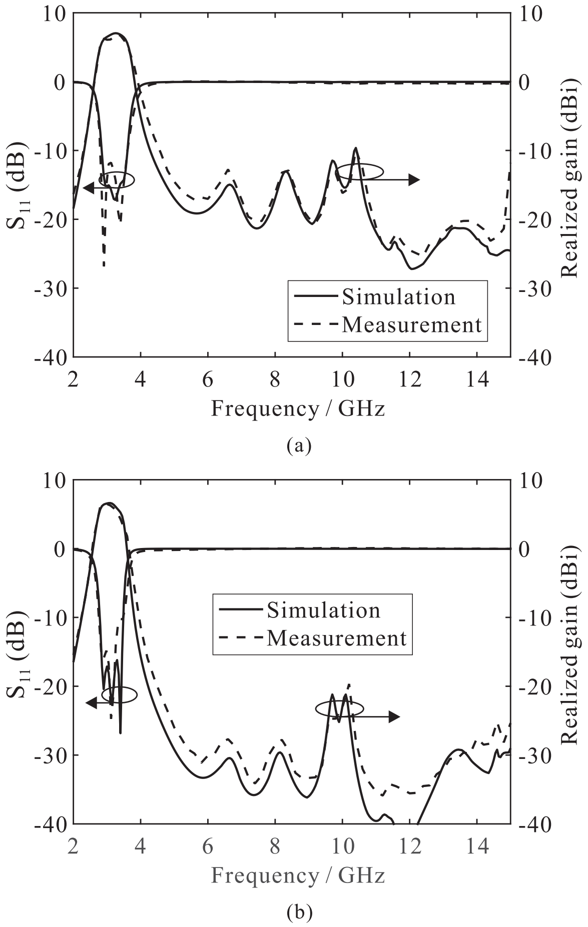

FIGURE 12. Simulated and measured results of the reflection coefficients and peak gains of (a) the cavity-backed co-designed filtering antenna with a 4^{th} order low-pass coaxial filter and (b) the cavity-backed co-designed filtering antenna with a 5^{th} order low-pass coaxial filter.

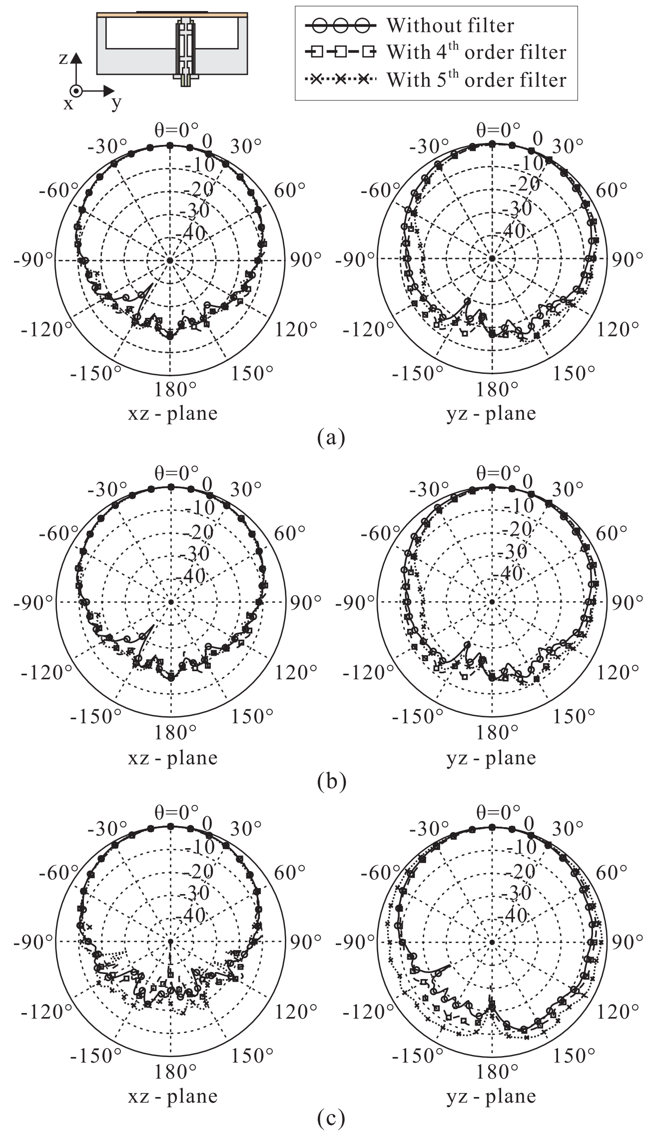

FIGURE 13. Measured normalized radiation patterns of the cavity-backed patch antenna with and without coaxial filter: (a) 2.9 GHz, (b) 3.15 GHz, and (c) 3.4 GHz.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Two prototypes, i.e., the cavity-backed co-designed filtering antennas with the 4^{th} order and 5^{th} order low-pass coaxial filters, were fabricated for experimental validation. Figure 11 shows photographs of these two prototypes. The overall dimensions of the prototype co-designed filtering antenna with the 4^{th} order filter are 66.4 mm × 55.7 mm × 22.47 mm (corresponding to $0.697\lambda_0 \times 0.585\lambda_0 \times 0.236\lambda_0$; λ_0 is the wavelength at the designed frequency of 3.15 GHz), identical to the overall dimensions of the prototype cavity-backed patch antenna (shown in Section II.A). This indicates that proposed co-designed filtering antenna has a lower profile as compared with the traditional cascading antenna with a filter. The overall dimensions of the prototype co-designed filtering antenna with the 5^{th} order filter are 66.4 mm × 55.7 mm × 30.47 mm, corresponding to $0.697\lambda_0 \times 0.585\lambda_0 \times 0.320\lambda_0$. The height of this prototype is slightly increased because a longer filter with a higher order is implemented.

Figure 12 depicts the simulated and measured results of the reflection coefficients and gains for the two prototype antennas. In both designs, resonance does not occur in bands other than the S-band. The simulation and measurement results are in good agreement. The cavity-backed co-designed filtering antennas with 4^{th} and 5^{th} order low-pass coaxial filters achieve measured −10 dB impedance bandwidths of 2.8–3.6 GHz (25%) and 2.76–3.48 GHz (23.08%), respectively. As also observed in Figure 12, the maximum gain measured in the pass-band is more than 6.5 dBi for both prototypes. In addition, in the stop-band, the measured gain suppression exceeded 11 dBi and 22 dBi for the cavity-backed co-designed filtering antennas with 4^{th} and 5^{th} order low-pass coaxial filters, respectively, as compared to the standalone cavity-backed patch antenna.

Figure 13 compares the measured radiation patterns of a cavity-backed patch antenna with and without a coaxial filter. Regardless of the integration of the filter, the radiation pattern

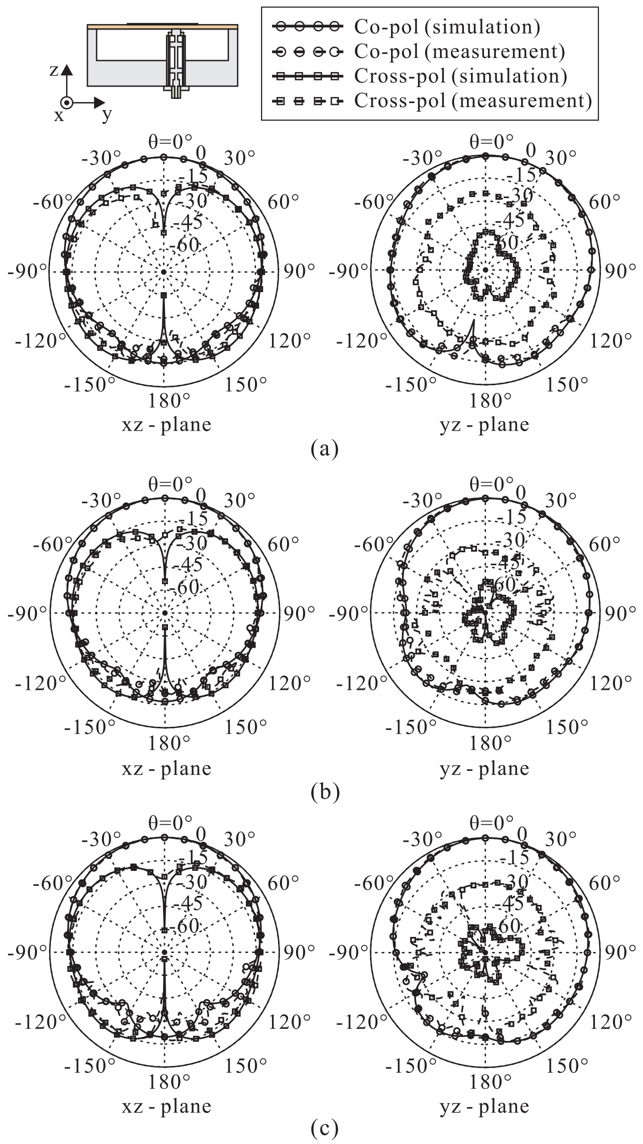

FIGURE 14. Simulated and measured normalized radiation patterns of the cavity-backed co-designed filtering antenna with a 4^{th} order low-pass coaxial filter: (a) 2.9 GHz, (b) 3.15 GHz, and (c) 3.4 GHz.

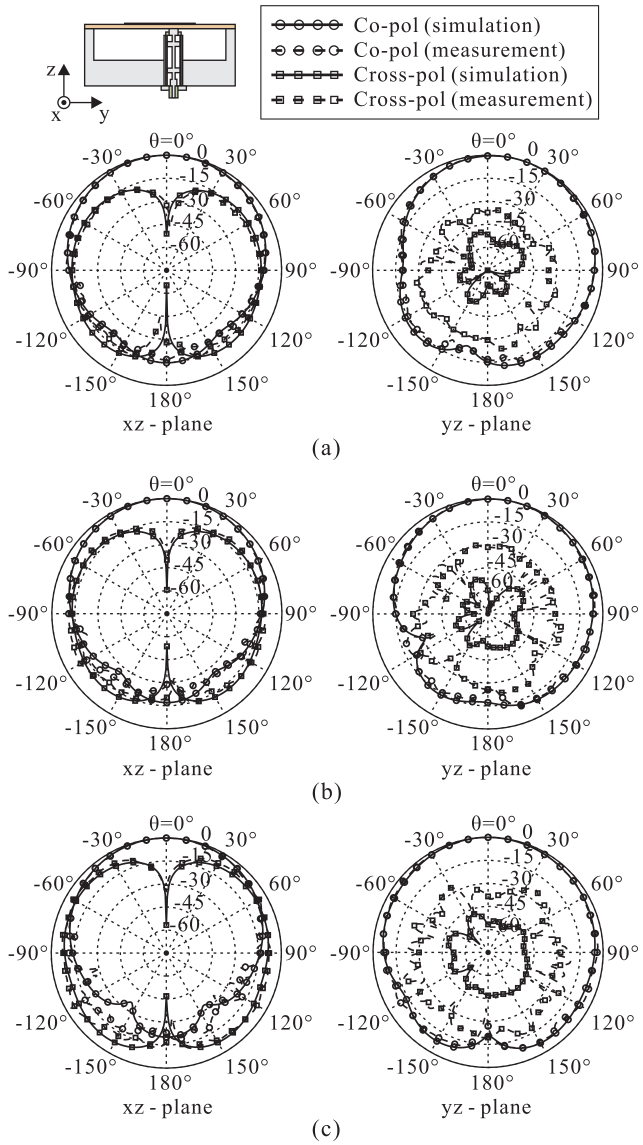

FIGURE 15. Simulated and measured normalized radiation patterns of the cavity-backed co-designed filtering antenna with a 5^{th} order low-pass coaxial filter: (a) 2.9 GHz, (b) 3.15 GHz, and (c) 3.4 GHz.

does not change within the passband and has unidirectional radiation characteristics. Hence, it can be seen that the filter integrated in the cavity does not have much of an effect on the radiation pattern. Figure 14 and Figure 15 show the radiation patterns when a 4^{th} order low pass filter and a 5^{th} order low pass filter are integrated into the cavity, respectively. Simulation and measurement results are shown, and the intensity of co-polarization is more than 24.98 dB higher than that of cross-polarization in the boresight direction. On the $yz-$plane, the radiation pattern is slightly tilted in the $+y$-direction due to the off-center feed position. The proposed filtering antennas are designed to have low back-radiation for radar applications. Both types of filtering antennas have a front-to-back ratio of 16.9 dB or more, as can be seen in the radiation pattern graph. In addition, the 3 dB beamwidth at the center frequency is 79° in the E-plane direction and 84° in the H-plane direction in both cases. Accordingly, the gain reduction is expected to be insignificant when steering the beam within the ±40° range.

Table 4 shows a comparison between the proposed filtenna design and previous filtennas in the literature. Compared to the planar filtenna designs in [8] and [9], our designs have much higher gains, wider impedance bandwidths, and unidirectional radiation patterns, all of which are desirable for radar applications. Although the SIC-backed slot filtennas [11] [12] have a lower profile, our filtennas achieve a wider impedance bandwidth by approximately three times and occupy a smaller antenna footprint. Compared to a previous cavity-backed slot filtenna [16], the size of our design is smaller overall. Specifically, to realize 5^{th} order filtenna

TABLE 4. Comparison of different type of filtering antennas.

Antenna	Overall size (λ_0^3)	BW	Peak gain (dBi)	Radiation pattern	Filter order	Antenna type
[8]	$0.36\lambda_0 \times 0.25\lambda_0 \times 0.005\lambda_0$	16.3%	2.4 dBi	omnidirectional	3	planar monopole antenna
[9]	$0.38\lambda_0 \times 0.28\lambda_0 \times 0.012\lambda_0$	19.2%	2.3 dBi	omnidirectional	2	patch antenna with DGS
[11]	$0.93\lambda_0 \times 0.85\lambda_0 \times 0.10\lambda_0$	6.0%	6.1 dBi	unidirectional	4	SIC-backed slot antenna
[12]	$1.00\lambda_0 \times 1.00\lambda_0 \times 0.13\lambda_0$	8.7%	7.2 dBi	unidirectional	-	SIC-backed slot antenna
[16]	$0.89\lambda_0 \times 0.88\lambda_0 \times 0.73\lambda_0$	20.0%	6.9 dBi	unidirectional	3	cavity-backed slot antenna
	$0.97\lambda_0 \times 0.89\lambda_0 \times 1.48\lambda_0$	24.0%	7.3 dBi	unidirectional	5	cavity-backed slot antenna
Proposed design	$0.70\lambda_0 \times 0.59\lambda_0 \times 0.24\lambda_0$	25.0%	7.0 dBi	unidirectional	4	cavity-backed patch antenna
	$0.70\lambda_0 \times 0.59\lambda_0 \times 0.32\lambda_0$	23.8%	6.6 dBi	unidirectional	5	cavity-backed patch antenna

(DGS: defected ground structure, SIC: substrate integrated cavity)

design [16], earlier researchers use two cavities, resulting in a very high-profile structure. Meanwhile, we only use one cavity and insert a 5^{th} order low-pass coaxial filter inside the cavity, achieving a low-profile 5^{th} order filtenna design. Therefore, it is concluded that the proposed filtering antenna can outperform other filtering antennas.

IV. CONCLUSION

A compact, small-footprint cavity-backed co-designed filtering antenna integrating a broadband cavity-backed patch antenna and a low-pass coaxial filter was designed, fabricated, and tested. Prototype 4^{th} and 5^{th} order low-pass coaxial filters were developed for integration. The filtering antenna with the 4^{th} order filter has dimensions of $0.697\lambda_0 \times 0.585\lambda_0 \times 0.236\lambda_0$, identical to those of standalone cavity-backed patch antenna, but exhibits gain suppression of more than 11 dBi in the stop-band. When integrated with a 5^{th} order filter, the filtering antenna has dimensions of $0.697\lambda_0 \times 0.585\lambda_0 \times 0.320\lambda_0$ and exhibits better gain suppression of more than 22 dBi in the stop-band. The measured fraction bandwidths of these two filtering antennas are 25% and 23.8%, respectively. Moreover, both filtering antennas achieve a measured gain of more than 6.5 dBi throughout the pass-band. Therefore, the proposed filter-integrated cavity-backed antenna is an excellent candidate for both size miniaturization of the RF front ends and for harmonic suppression.

REFERENCES

[1] C. T. P. Song, P. S. Hall, and H. Ghafouri-Shiraz, "Novel RF front end antenna package," *Proc. Inst. Elect. Eng. Microw. Antennas Propag.*, vol. 150, no. 4, pp. 290–294, Aug. 2003.

[2] J.-H. Lee, N. Kidera, G. DeJean, S. Pinel, J. Laskar, and M. M. Tentzeris, "A V-band front-end with 3-D integrated cavity filters/duplexers and antenna in LTCC technologies," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 7, pp. 2925–2936, Jul. 2006.

[3] S. Shinjo, K. Nakatani, K. Tsutsumi, and H. Nakamizo, "Integrating the front end: A highly integrated RF front end for high-SHF wide-band massive MIMO in 5G," *IEEE Microw. Mag.*, vol. 18, no. 5, pp. 31–40, Jul./Aug. 2017.

[4] G. Sung, "Compact dual-band bandpass filter using U-shaped stepped-impedance resonators with parallel coupled structures," *J. Electromagn. Eng. Sci.*, vol. 18, no. 2, pp. 73–77, Apr. 2018.

[5] P. Kim and Y. Jeong, "A coupled line impedance transformer for high termination impedance with a bandpass filtering response," *J. Electromagn. Eng. Sci.*, vol. 18, no. 1, pp. 41–45, Jan. 2018.

[6] Y. Jeon and S. Bang, "Front-end module of 18–40 GHz ultra-wideband receiver for electronic warfare system," *J. Electromagn. Eng. Sci.*, vol. 18, no. 3, pp. 188–198, Jul. 2018.

[7] J. Zuo, X. Chen, G. Han, L. Li, and W. Zhang, "An integrated approach to RF antenna-filter co-design," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 141–144, 2009.

[8] W.-J. Wu, Y.-Z. Yin, S.-L. Zuo, Z.-Y. Zhang, and J.-J. Xie, "A new compact filter-antenna for modern wireless communication systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1131–1134, 2011.

[9] X. Chen, F. Zhao, L. Yan, and W. Zhang, "A compact filtering antenna with flat gain response within the passband," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 857–860, 2013.

[10] C. Yu, W. Hong, Z. Kuai, and H. Wang, "Ku-band linearly polarized omnidirectional planar filtenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 310–313, 2012.

[11] Y. Yusuf and X. Gong, "Compact low-loss integration of high-Q 3-D filters and highly efficient slot antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 4, pp. 857–865, Apr. 2011.

[12] K. Xu, J. Shi, X. Qing, and Z. N. Chen, "A substrate integrated cavity backed filtering slot antenna stacked with a patch for frequency selectivity enhancement," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, pp. 1910–1914, 2018.

[13] R. J. Cameron, C. M. Kudsia, and R. R. Mansour, *Microwave Filters for Communication Systems: Fundamentals, Design, Applications*. Hoboken, NJ, USA: Wiley, 2007.

[14] I. A. Navarro and C. Kai, "A ka-band cavity-enclosed aperture-coupled circular patch antenna and array for millimeter-wave circuit integration," in *IEEE Antennas Propag. Soc. Int. Symp. Dig.*, 1992, pp. 313–316.

[15] S. M. Amjadi and K. Sarabandi, "A low-profile, high-gain, and full-band SubArray of cavity-backed slot antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3456–3464, Jul. 2017.

[16] Y.-M. Wu, S.-W. Wong, H. Wong, and F.-C. Chen, "A design of bandwidth-enhanced cavity-backed slot filtenna using resonance windows," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1926–1930, Mar. 2019.

[17] B.-L. Zheng, S.-W. Wong, L. Zhu, and Y. He, "Broadband duplex–filtenna based on low-profile metallic cavity packaging," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 8, no. 8, pp. 1451–1457, Aug. 2018.

[18] M. Martinis, K. Mahdjoubi, R. Sauleau, S. Collardey, and L. Bernard, "Circuit models explaining bandwidth behavior of small circular cavity backed patch antennas," in *Proc. 8th Eur. Conf. Antennas Propag. (EuCAP)*, The Hague, The Netherlands, Apr. 2014, pp. 3652—-3656.

JUHO YUN was born in Seoul, South Korea, in 1991. He received the B.S. degree from the Department of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, South Korea, in 2016. He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, Sungkyunkwan University. His research interests include design of filtering antennas, optimization algorithms for electromagnetic applications, and wide-angle beam steering antenna.

SON TRINH-VAN was born in Hanoi, Vietnam, in 1986. He received the B.Sc. (Eng.) degree in electronics and telecommunications from the Hanoi University of Science and Technology, Hanoi, Vietnam, in 2010, and the Ph.D. degree from the Division of Electronics and Electrical Engineering, Dongguk University, Seoul, South Korea, in 2015. He is currently a Postdoctoral Researcher with the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea. His research interests include design of circularly polarized antennas, and millimeter-wave antennas and arrays.

JOON-YOUNG PARK received the B.S. degree in electronics engineering from Donga University, Busan, South Korea, in 1997, and the M.S. degree in electronics engineering from Kyungpook National University, Daegu, South Korea, in 1999. He was a Senior Researcher with Gammnu, Suwon, South Korea, where he was involved in the development of various antennas, including base station antenna for communication systems. Since 2002, he has been with Hanwha Systems, Yongin, South Korea, where he is currently a Chief Engineer. His current research interests include phased array antenna systems, design of active array, and advanced optimization algorithm for array antenna for radar applications.

YOUNGOO YANG (Senior Member, IEEE) was born in Hamyang, South Korea, in 1969. He received the Ph.D. degree in electrical and electronic engineering from the Pohang University of Science and Technology (POSTECH), Pohang, South Korea, in 2002. From 2002 to 2005, he was with Skyworks Solutions Inc., Newbury Park, CA, USA, where he designed power amplifiers for various cellular handsets. Since March 2005, he has been with the School of Information and Communication Engineering, Sungkyunkwan University, Suwon, South Korea, where he is currently a Professor. His research interests include RF/mm-wave power amplifiers, RF transmitters, and dc–dc converters.

KANG-YOON LEE (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees from the School of Electrical Engineering, Seoul National University, Seoul, South Korea, in 1996, 1998, and 2003, respectively. From 2003 to 2005, he was with GCT Semiconductor Inc., San Jose, CA, USA, where he was a Manager of the Analog Division and worked on the design of CMOS frequency synthesizer for CDMA/PCS/PDC and single-chip CMOS RF chip sets for W-CDMA, WLAN, and PHS. From 2005 to 2011, he was an Associate Professor with the Department of Electronics Engineering, Konkuk University. Since 2012, he has been with the School of Information and Communication Engineering, Sungkyunkwan University, where he is currently an Associate Professor. His research interests include implementation of power integrated circuits, CMOS RF transceiver, analog integrated circuits, and analog/digital mixed-mode VLSI system design.

KEUM CHEOL HWANG (Senior Member, IEEE) received the B.S. degree in electronics engineering from Pusan National University, Busan, South Korea, in 2001, and the M.S. and Ph.D. degrees in electrical and electronic engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2003 and 2006, respectively.

From 2006 to 2008, he was with Samsung Thales, Yongin, South Korea, where he was involved with the development of various antennas for wireless communication and radar systems. From 2008 to 2014, he was an Associate Professor with the Division of Electronics and Electrical Engineering, Dongguk University, Seoul, South Korea. He joined the Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, South Korea, in 2015, where he is currently a Professor. His research interests include advanced electromagnetic scattering and radiation theory and applications, design of multi-band/broadband array antennas, and optimization algorithms for electromagnetic applications.

Dr. Hwang is a Life Member of KIEES and a member of IEICE.