Cavity-Backed Patch Filtenna for Harmonic Suppression

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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 4th and 5th order low-pass coaxial filters and with the overall dimensions of 0.697λ₀ × 0.585λ₀ × 0.236λ₀ and 0.697λ₀ × 0.585λ₀ × 0.320λ₀ (where λ₀ 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 4th and 5th 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]...
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-$\Omega$ coaxial cable, resulting in a large footprint.

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.

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

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $s_1$     | 55.7  | $s_2$     | 66.4  | $p_1$     | 29    |
| $p_w$     | 28    | $h_1$     | 53.1  | $h_w$     | 41.1  |
| $f_p$     | 9     | $h_2$     | 21    | $h_2$     | 12.1  |
| $t$       | 1.27  | $v_l$     | 3.1   |           |       |

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### 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 $p_w \times p_l$, 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 $h_w \times h_l \times h_2$. The overall dimensions of the antenna are $s_w \times s_l \times h_1$. The antenna is excited by a metal post inside the cavity through the coupled feeding technique. The metal post with a diameter of $v_l$ 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
In the equivalent circuit of the coupled feed part, by generating additional resonance through a coupled feed, only resonance by the patch, and the bandwidth is expanded. The patch antenna is caused by the capacitance of the patch. Because both the cavity and the radiation aperture are inductive, the resonance of the cavity-backed patch antenna is due to the capacitance between the metallic post and the patch, \( Y \) in \( n \) represents the value of the inductance or capacitance, and \( g \) refers to the step of the inner conductor described above. 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. The inductive and capacitance \( g \) values range from 1 to \( n \). The \( g \)-values represent 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 4th 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]:

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

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

![Figure 5](image-url)  
**FIGURE 5.** Configuration of the low-pass coaxial filter: (a) overall view, (b) side-cut view of 4th order filter, and (c) side-cut view of 5th order filter.

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

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $d_{\text{outer}}$ | 6 | $d_{\text{in1}}$ | 2.6 | $d_{\text{out2}}$ | 2.5 |
| $d_{\text{in1}}$ | 2.6 | $d_{\text{out2}}$ | 2.6 | $l_{\text{in1}}$ | 2.04 |
| $l_{\text{in2}}$ | 2 | $l_{\text{out1}}$ | 2 | $l_{\text{out2}}$ | 2 |
| $d_1$ | 0.9 | $d_2$ | 0.82 | $d_3$ | 1.04 |
| $d_4$ | 1.14 | $d_5$ | 4.92 | $d_6$ | 4.84 |
| $l_1$ | 4.78 | $d_4$ | 4.78 | $d_5$ | 4.7 |
| $l_2$ | 7.36 | $l_1$ | 2.47 | $l_2$ | 1.61 |
| $l_3$ | 2.38 | $l_4$ | 4.71 | $l_5$ | 2.46 |

**FIGURE 6.** Equivalent circuits of low-pass filters: (a) 4th order filter, (b) 5th 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. $Z_{\text{low}}$ and $Z_{\text{high}}$ are impedances of the capacitive and inductive steps. $Z_{\text{low}} = 10-\Omega$ and $Z_{\text{high}} = 100-\Omega$ 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 4th order and 5th order low-pass coaxial filters are shown in Table 2.

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 5th order filter has better characteristics as compared to the 4th 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 4th order and 5th 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 4th order filter, and (d) side-cut view of the 5th order filter.

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

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $s_2$ | 55.7 | $s_2$ | 66.4 | $d_2$ | 5 |
| $v_2$ | 6 | $d_{in}$ | 2.4 | $l_{in}$ | 3.4 |
| $d_{in}$ | 1.9 | $l_{2}$ | 2.6 | $l_{1}$ | 1.8 |
| $l_{in}$ | 2.5 | $l_{9}$ | 7.1 | $l_{7}$ | 1.8 |
| $d_{9}$ | 8 | $l_{10}$ | 2.4 | $l_{8}$ | 1.6 |
| $l_{2}$ | 1.2 | $l_{10}$ | 1.2 |

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 4th order and a 5th 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 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 4th order low-pass coaxial filter, and (c) with a 5th order low-pass coaxial filter.

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 $-10 \text{ dB}$ impedance bandwidth 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 4th and 5th order low-pass coaxial filters, respectively. In addition, the skirt and filtering characteristics of the design integrating the 5th order filter is more improved than those of the design integrating the 4th 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 5th order filter (see Figure 10(c)) is weaker than that of the cavity-backed antenna with a 4th 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.
III. EXPERIMENTAL RESULTS AND DISCUSSION

Two prototypes, i.e., the cavity-backed co-designed filtering antennas with the 4th order and 5th 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 4th order filter are 66.4 mm × 55.7 mm × 22.47 mm (corresponding to 0.697λ0 × 0.585λ0 × 0.236λ0; λ0 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 5th order filter are 66.4 mm × 55.7 mm × 30.47 mm, corresponding to 0.697λ0 × 0.585λ0 × 0.320λ0. 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 4th and 5th 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 4th and 5th 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.

### FIGURE 12. Simulated and measured results of the reflection coefficients and peak gains of (a) the cavity-backed co-designed filtering antenna with a 4th order low-pass coaxial filter and (b) the cavity-backed co-designed filtering antenna with a 5th 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.
FIGURE 14. Simulated and measured normalized radiation patterns of the cavity-backed co-designed filtering antenna with a 4th 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 5th 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 4th order low pass filter and a 5th 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 5th order filtenna
TABLE 4. Comparison of different type of filtering antennas.

| Antenna               | Overall size \((\lambda_0^2)\) | BW     | Peak gain (dBi) | Radiation pattern | Filler order | Antenna type               |
|-----------------------|-------------------------------|--------|-----------------|-------------------|--------------|-----------------------------|
| [8]                   | 0.36\(\lambda_0\times0.25\lambda_0\times0.005\lambda_0\) | 16.3%  | 2.4 dB          | omnidirectional   | 3            | planar monopole antenna     |
| [9]                   | 0.38\(\lambda_0\times0.28\lambda_0\times0.012\lambda_0\) | 19.2%  | 2.3 dB          | omnidirectional   | 2            | patch antenna with DGS      |
| [11]                  | 0.93\(\lambda_0\times0.85\lambda_0\times0.10\lambda_0\) | 6.0%   | 6.1 dB          | unidirectional    | 4            | SIC-backed slot antenna     |
| [12]                  | 1.00\(\lambda_0\times1.00\lambda_0\times0.13\lambda_0\) | 8.7%   | 7.2 dB          | unidirectional    | -            | SIC-backed slot antenna     |
| [16]                  | 0.89\(\lambda_0\times0.88\lambda_0\times0.73\lambda_0\) | 20.0%  | 6.9 dB          | unidirectional    | 4            | cavity-backed slot antenna  |
| Proposed design       | 0.70\(\lambda_0\times0.59\lambda_0\times0.24\lambda_0\) | 25.0%  | 7.0 dB          | unidirectional    | 4            | cavity-backed patch antenna |
| Proposed design       | 0.70\(\lambda_0\times0.59\lambda_0\times0.32\lambda_0\) | 23.8%  | 6.6 dB          | 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 5th order low-pass coaxial filter inside the cavity, achieving a low-profile 5th order filtering antenna 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 4th and 5th order low-pass coaxial filters were developed for integration. The filtering antenna with the 4th order filter has dimensions of 0.697\(\lambda_0\times0.585\lambda_0\times0.238\lambda_0\), identical to those of standalone cavity-backed patch antenna, but exhibits gain suppression of more than 11 dB in the stop-band. When integrated with a 5th order filter, the filtering antenna has dimensions of 0.697\(\lambda_0\times0.585\lambda_0\times0.320\lambda_0\) and exhibits better gain suppression of more than 22 dB in the stop-band. The measured fractional 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 dB 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.

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