Comparing Different Orders of Interdigital Filtering-Antenna Selectivity for 5G Application

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Comparing Different Orders of Interdigital Filtering-Antenna Selectivity for 5G Application

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In this paper, filter and antenna integration is studied to obtain a compact device for wireless front-end equipment. Filtering antennas are advanced due to their selectivity performance, which is represented by a flat gain response. This study compares the selectivity of filtering antennas based on second- and third-order filters. Both antennas are designed to operate at 4.65 GHz for 5G application at middle band with a bandwidth of 6.45%. The first antenna is an integration of a rectangular radiator and an interdigital resonator based on second-order filters. The antenna obtained a bandwidth impedance of -10 dB for 300 MHz and a maximum gain of 6 dBi. The second design consists of a rectangular radiator and two interdigital resonators based on the third-order filter as the feedline. Having the same bandwidth as the first design, the second design achieved a flat gain of 5.9 dBi in the operational bandwidth. The third-order filtering antenna design showed better selectivity with sharper gain compared to the first design; a maximum gain of 5.9 dBi was obtained for both. The two designs were fabricated and measured for validation. Simulation and measurement results showed good agreement.

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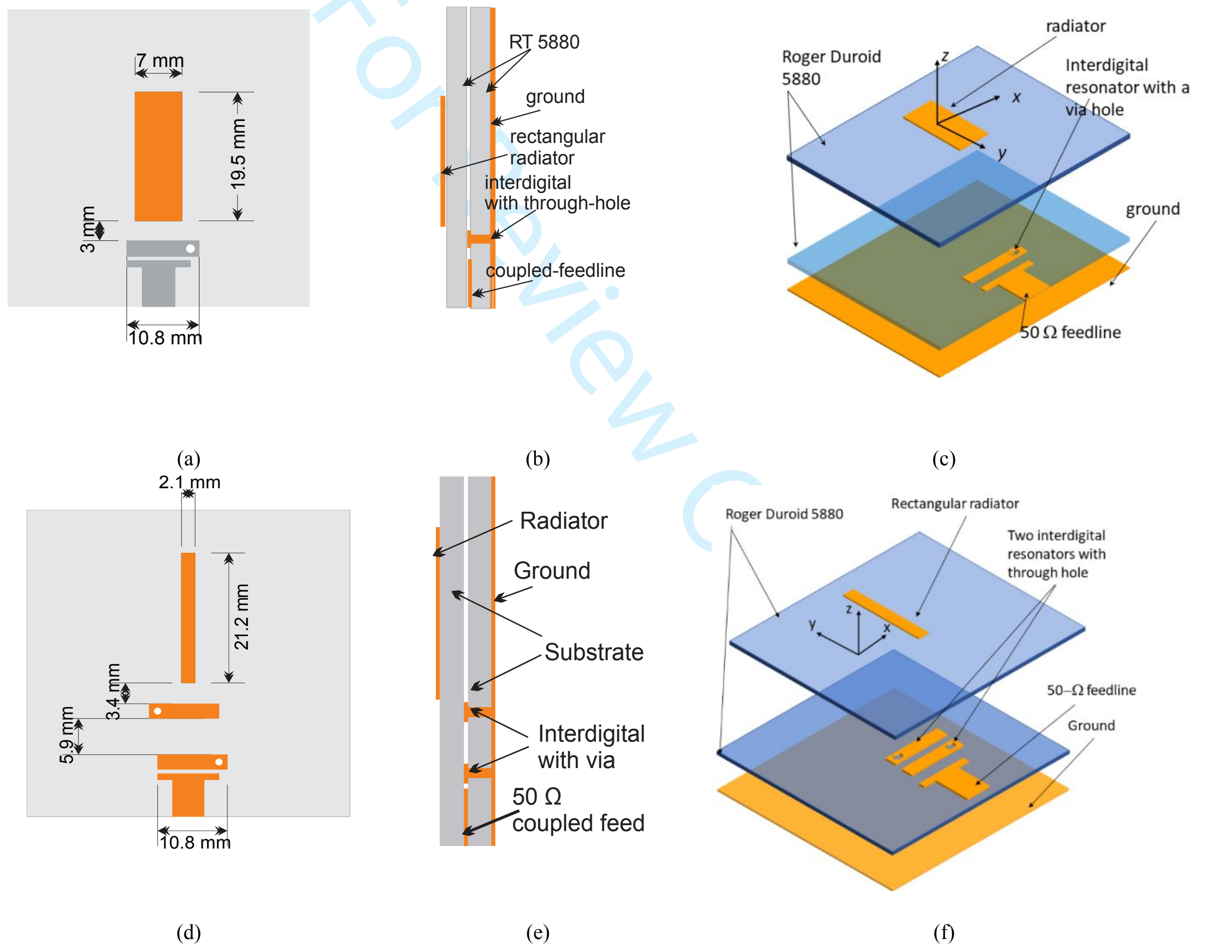
I. INTRODUCTION

Future wireless telecommunication equipment requires multifunctional, integrated, and compact devices. Antennas and filters are the circuits at the wireless front end, which were traditionally parted. However, nowadays, the integration of the two circuits (known as a filtering antenna) is widely researched [1]–[5]. A filtering antenna adds a radiator with a selectivity feature, which is represented by a flat gain within the operational bandwidth and two radiation nulls at the upper and lower frequencies. The most common methods to design the filtering antennas are replacing the last filter stages with a radiator [6]–[9] Some resonators have been used to design a filtering antenna, e.g., hairpin [13], [14], stub resonator [8], [15], U-resonator [16], [17], ring resonator [18], and interdigital resonator [3], [19]. The co-design of antenna and filter to obtain a miniaturized front-end antenna with selectivity is based on the filter design. In other words, the order used affects the filter selectivity, which applies to the filtering antenna based on co-design. Reference [20] compares antennas and filters of different orders using simulation tools; a square-ring resonator was used, but the study has no measurement validation results.

Reference [3] used two interdigital resonators to design two filtering antennas with vertical and 45° polarization features; however, no measurement result was presented for the antenna with vertical polarization based on the third-order filter. Although the measurement for this type of filtering antenna was demonstrated by [19], the design is not based on the second-order filter because the radiator extraction is sufficiently wide to obtain slant polarization. The antenna based on a second-order filter has less selectivity compared with the antenna based on a third-order filter, and no extraction is performed.



In the co-design of a filtering antenna, radiator extraction is essential because, with various radiator sizes, we can generate the same frequency operation but with different radiation values. Furthermore, the radiation quality significantly affects the operating bandwidth produced by the filtering antenna, which must have the same value as the external quality of a filter in the co-design.

In this study, we propose a comparison design of filtering antenna using an interdigital resonator based on second- and third-order filters validated by measurement results. Both designs use a rectangular radiator and are integrated to obtain an operational frequency of 4.65 GHz with a bandwidth of 6.45% for 5G application. The antenna is proximity fed with all structures couple connected. The design is validated by measurement results, which are consistent with the simulations.

II. DESIGN AND METHOD

In this paper, we discuss filter antennas with different orders. The first design, called Ant. I, is a filtering antenna based on second-order filters, while the second design, i.e., Ant. II, is based on third-order filter extraction. The geometric structure of Ant. I can be seen in Figure 1 (a) where it consists of two layers of substrates; a 7 mm × 19.5 mm rectangular radiator is on the first layer, and, in the second layer, there is a feeding circuit consisting of a resonator coupled with a 50-ohm transmission line. Fig. 1 (b) shows the design from the side view, and Fig. 1 (c) is the exploded view. Both Ant. I and Ant. II use an interdigital resonator (2.4 × 10.8 mm) and a through hole with a diameter of 1.2 mm.

Table 1. Parameter filter extraction for second order and third order filter

Parameter	2nd order	3rd order
Ripple (dB)	0.2	0.2
g_o	1	1
g_1	0.843	1.2276
g_2	0.622	1.1525
g_3	1.3554	1.2276
g_4		1
Frequency (GHz)	4.65	4.65
BW (GHz)	0.3	0.3
FBW	0.064516	0.064516129
Q_{ext}	13.0665	19.0278
Q_{rad}		19.0278
$K_{1,2}$	0.070268	0.054239964
$K_{3,4}$	-	0.054239964

Fig. 2 (a) shows the geometric structure of Ant. II; it consists of a 2.1 × 19.5 mm radiator on the top substrate, which is proximity coupled with the feeding network on the second substrate. Two interdigital resonators coupled with a 50-ohm transmission line are on the second substrate. A through hole with a diameter of 1.2 mm is set alternately at each end of the resonator's arm. There is 3.4-mm space between the radiator and resonator and a 5.9-mm space between the two alternate resonators. The 50-ohm transmission line is coupled with a 0.7-mm gap. All structures are printed on two layers of 50 × 50 mm substrates. Fig. 2 (b) shows the antenna from the side view, which consists of a rectangular radiator on the top substrate and a feeding circuit at the bottom. Figure 2 (c) shows the exploded view of the design.

The two designs are based on second- and third-order extraction filters. Both antennas are designed to operate at a frequency of 4.65 GHz and an operating bandwidth of 300 MHz or 6.45%. Following [21], all lowpass filter parameters with ripple 0.2 dB are presented in Table 1. Furthermore, by using (1) and (2) outlined in [22], the coupling parameters, radiation quality (Q_{rad}), and external quality (Q_{ext}) can be calculated, the results of which are shown in Table 1.

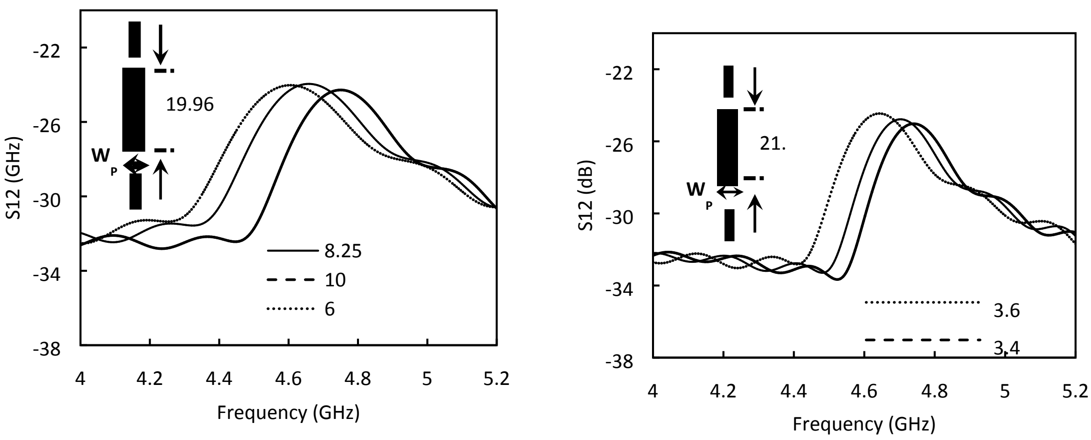
Next, we extract the radiator and resonator using (3), (4), and CST simulation tools. The structure extraction is conducted to obtain the resonance frequency and Q_{rad} for Ant. I and Ant. II. The radiator extraction also proves that, to obtain a 4.65-GHz resonance, we can use different sized rectangular radiators as in Ant. I and Ant. II. The length (L_{p}) and width (W_{p}) of the Ant. I radiator shown in Fig. 3 (a) is 19.96 mm and 8.25 mm, respectively, to generate a 4.65-GHz operational frequency and Q_{rad} of 13.06. Q_{rad} of 19.02 and operational frequency of 4.65 GHz can be obtained when Lp and Wp of the Ant. II radiator is 21.2 mm and 2.8 mm, as shown in Fig. 3 (b). Fig. 4 (a) shows the relation between W_{p} and Q_{rad} at an operating frequency of 4.65 GHz; to obtain higher Q_{rad} values, W_{p} should be reduced. Fig. 4 (b) shows the coupling between resonator and radiator with Q_{rad} values of 13 and 19 for Ant. I and Ant. II, respectively. It also shows that the distance between resonator and radiator (C_{B}) to obtain the associated coupling value (0.0702 and 0.0542) is around 3.7 mm for Ant. I and 3.6 mm for Ant. II. To obtain the interdigital resonator's operating frequency and Q_{ext} value, we followed [3]. For Ant. II based on third-order filter extraction, it is necessary to obtain the coupling between two resonators. A coupling value of 0.0542 is obtained using the extraction curve from [3] when the distance between the two resonators is approximately 5.2 mm. Finally, the initial dimensions of the two designs are achieved from these extractions.

$$Q_{\mathrm{ext}} = \frac{g_n g_{n+1}}{FBW} \quad (1)$$

$$M_{\mathrm{i,i+1}} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \quad (2)$$

$$Q_{\mathrm{rad}} = \frac{f_c}{\Delta f} \quad (3)$$

$$M_{\mathrm{n,n+1}} = \frac{{f_{n+1}}^2 - {f_n}^2}{{f_{n+1}}^2 + {f_n}^2} \quad (4)$$



(a) (b)

Fig. 3. Parameter study of (a) Geometric structure of Ant. II, (b) side view and (c) perspective view.

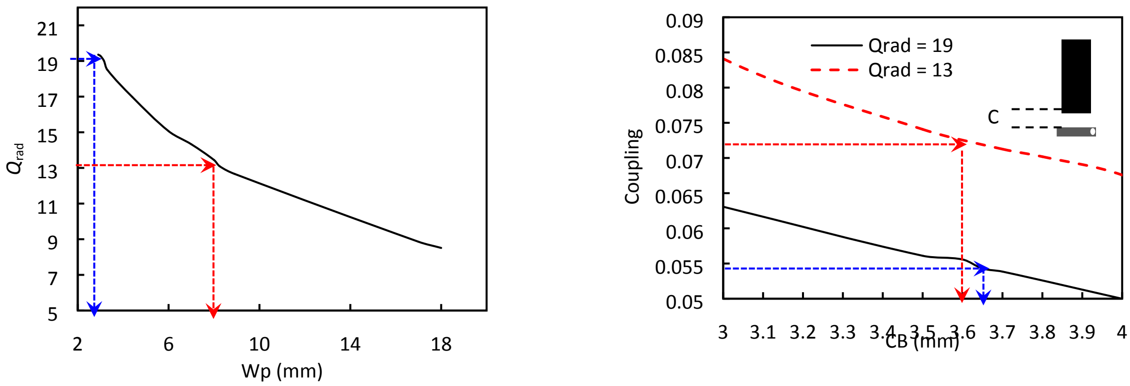


Fig. 4. (a) The extraction of Q_{rad} under different W_{p} and (b) coupling under different Q_{rad} and C_{B}

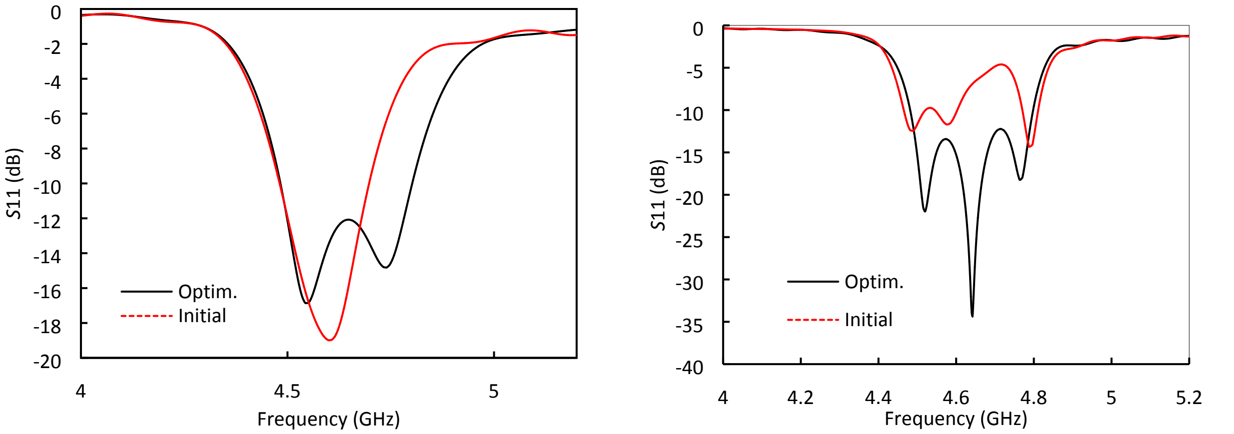
III. RESULTS AND DISCUSSION

From the S_{11} response of Ant. I in the initial design of Fig. 5 (a), it is evident that the red curve does not convey the character of a second-order filter due to its single minimum value, and neither the bandwidth nor the center frequency parameters meet the desired values. Moreover, the design optimization results on the black curve show the S_{11} response, which is identical to a second-order filter response with two minimum values. The center frequency occurs at 4.65 GHz with an S_{11} of −12.1 dB and a bandwidth impedance of −10 dB for a range of 4.48–4.8 GHz, as required.

Fig. 5(b) shows the initial design of Ant. II, where the S_{11} response has three minimal values. However, the − 10-dB bandwidth impedance is yet to be obtained. After optimization, as shown via the black curve, the −10-dB bandwidth impedance for a frequency range of 4.482–4.798 GHz is achieved with a center frequency of 4.65 GHz and a minimum S_{11} value of − 34 dB.

Fig. 6(a) compares the S_{11} values and gain response of the two designs. Ant. I with an S_{11} response as a second-order filter has a gain of 5.89 dBi; the gain hovers around 5 dBi up to a frequency of 4.825 Ghz, which is not the operating bandwidth. Alternatively, Ant. II with a third-order filter S_{11} response has a gain of 1 dBi at 4.825 GHz and decreases sharply compared to the 5.92-dBi maximum gain at a 4.75-GHz operating bandwidth. Thus, Ant. II has better selectivity than Ant. I. Moreover, Ant. II also shows a flatter gain along its operational bandwidth compared with Ant. I.

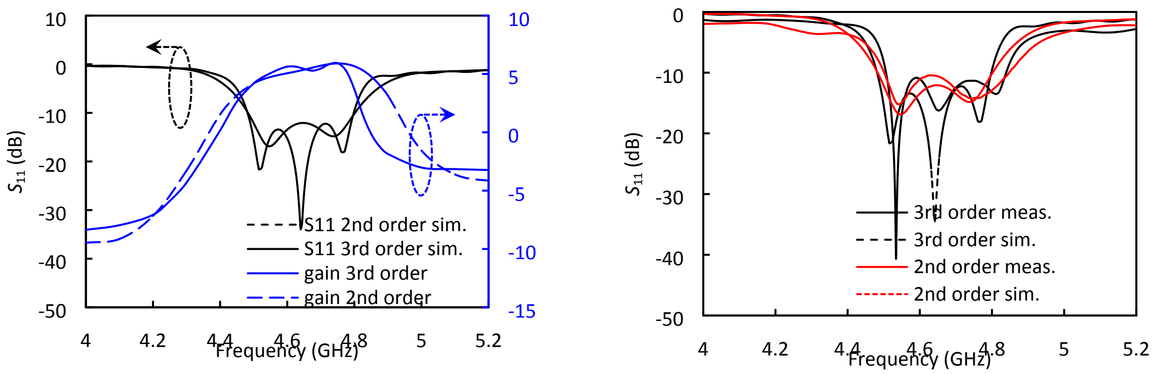
For validation purposes, both designs were fabricated and measured in an anechoic chamber. The fabricated filtering antennas are shown in Fig. 6(b). Using a ZNB 40 vector network analyzer, S_{11} and gain response were measured. Fig. 6(b) compares the S_{11} values obtained from the simulation and measurement results for Ant. I, from which it is evident that Ant. I has a − 10-dB bandwidth impedance for a range of 4.501–4.847 GHz, which is 9% wider (and shifted to a higher frequency) compared to the simulation results. Fig. 6(b) compares the S_{11} values obtained from the simulation and measurement results of Ant. II, from which it is evident that the measurement results shift to a higher frequency and have a 10% wider bandwidth for a range of 4.506–4.839 GHz compared to the simulation results.



(a) (b)

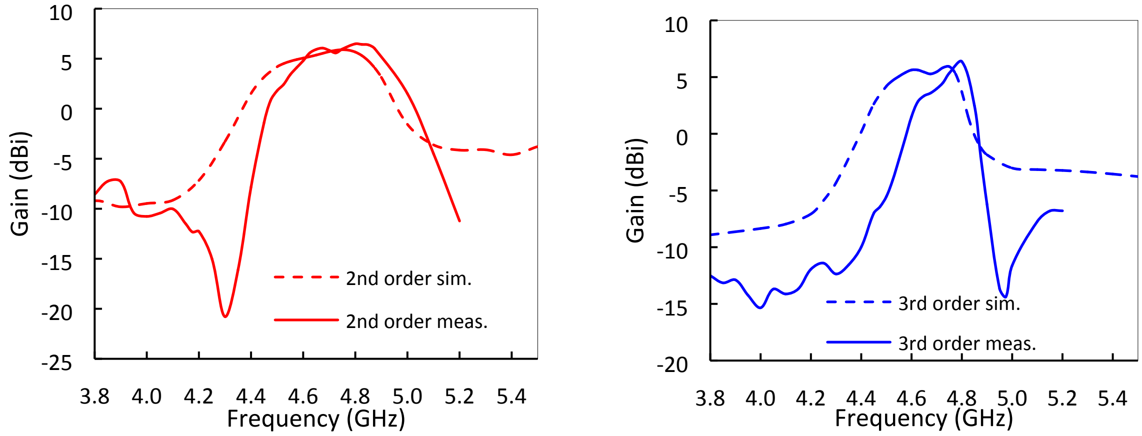
Fig. 5. (a) The initial and optimized design of second-order and (b) third-order interdigital filtering antenna.

Fig. 7(a) shows the gain measurement results for Ant. I, from which it is evident that a shift from the simulation result occurs to a higher frequency with maximum value of 6.48 dBi at 4.8 GHz, which is 0.6 dB higher than the simulation results. Figure 7(b) shows that Ant. II's maximum gain is 6.37 dBi at 4.8 GHz, which decreases sharply to − 15 dBi at 4.89 GHz, this indicates the gain blocking of 21 dB both in the lower and upper frequency. Similar to the S_{11} response, the gain response of both antennas also shifts towards higher frequencies. The discrepancy between the simulation and measurement results can be attributed to the two-layer design. In particular, an air gap may exist between the layers, which explains the shift in operational frequency; otherwise, the shift may be due to substrate permittivity tolerance and fabrication errors. The fabricated photographs of both designs are shown in Fig 8 (a) and (b). They show that the Ant. I's radiator has a wider size compares to the Ant. II's. From these results it shown that Ant. II has a better selectivity along the operational bandwidth compares to Ant. I, though both have the same bandwidth impedance.



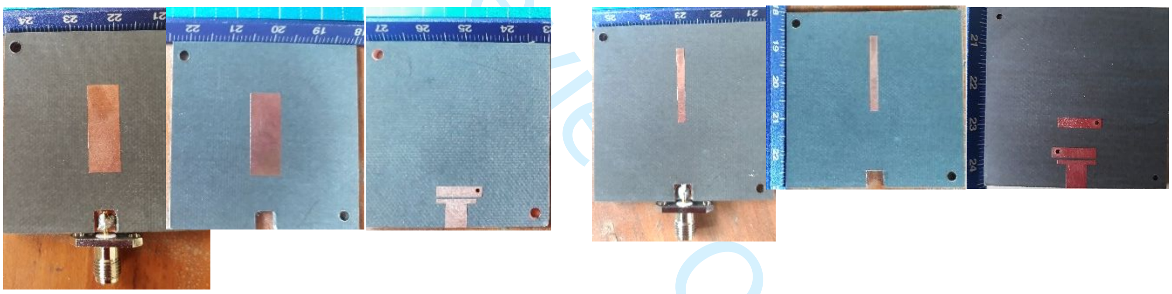
(a) (b)

Fig. 6. (a) The optimized S_{11} and gain simulation comparison of the second-order and third-order and (b) the S11 measurement and simulation results comparison of the 2nd order and 3rd order filtering antennas



(a) (b)

Fig. 7 (a) The Ant. I's gain comparison of simulation and measurement results, (b) The Ant. II's gain comparison of simulation and measurement results.



(a) (b) (c) (d) (e) (f)

Fig. 8 Fabrication (a) assembled (b) radiator on the first layer (c) filtering circuit of Ant. I, (d) assembled (b) radiator on the first layer (c) filtering circuit of Ant. II

IV. CONCLUSION

In this paper, second and third-order interdigital filtering antennas were designed. Both filtering antennas have the same bandwidth and ripple, but the second-order antenna filter has a wider radiator and lower Q_{rad} values compared to the third-order filtering antenna. The simulation results showed that the third-order interdigital filtering antenna has better selectivity compared to the second-order one, with a relatively flat gain over the operational bandwidth. Both antennas were fabricated and measured, and the simulation and measurement results are consistent.

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