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Design of a 3-D Integrated Wideband Filtering Magneto-Electric Dipole Antenna

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ABSTRACT A new design of 3-D integrated wideband filtering magneto-electric dipole antenna with high selectivity is presented. The proposed antenna is mainly composed of a horizontal planar dipole and a vertically oriented shorted patch antenna. A pair of C-slots is etched on the planar dipole to obtain sharp skirt selectivity near both band-edges. In addition, a slotline loaded with the patch antenna provides good impedance matching. The proposal exhibits a quasi-elliptic gain response with three introduced radiation nulls without additional filtering circuits. To verify the design concept, a prototype is fabricated and measured. The result exhibits an impedance bandwidth of 55.4% with SWR ≤ 1.5 from 1.58 to 2.79 GHz. Moreover, the low back radiation levels (≤ -16 dB), stable radiation patterns with low cross polarization levels (≤ -26 dB), and an average antenna gain of 7.8 dBi are achieved within the operating band. In addition, an out-of-band suppression level, better than 17 dB, is reached.

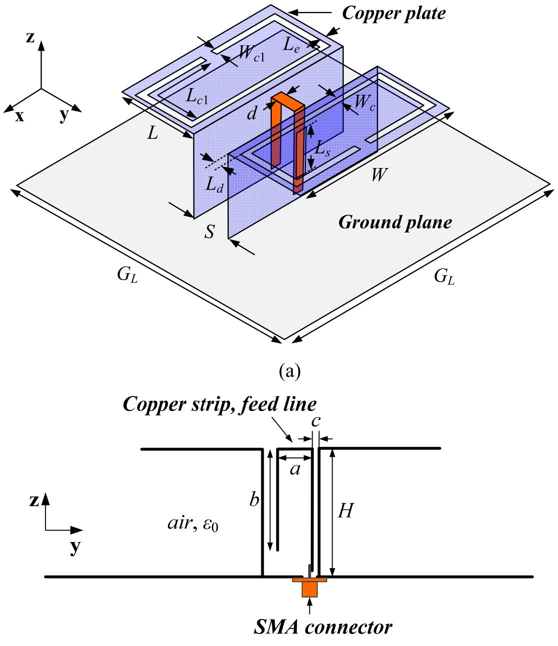
INDEX TERMS 3-D, magneto-electric dipole, wideband, quasi-elliptic, filtering response.

I. INTRODUCTION

The ever increasing demand for low-cost and compact modern wireless communication systems leads to the requirement of highly integrated multi-function microwave circuits. Corresponding to this trend, a filtering antenna with both functions of specified radiation and good frequency selectivity has been receiving more and more attention. Over the past few years, much effort has been devoted to the exploration of a variety of high-performance filtering antennas as reported in [1]–[8].

As one typical filtering antenna, an antenna radiator is skillfully utilized as the last resonator or output port of a bandpass filter [1]–[4]. Nice filtering performance has been reached with a synthesis approach of the filter. Nevertheless, since multiple resonators are usually involved in an effective filter design, the circuit often require a large area. In addition, with the introduced insertion loss of filters, this type of filtering antennas exhibit degraded radiation efficiency and gain, especially in broadband designs where more resonators are required. To overcome this, filtering antennas based on a fusion-design concept are designed in [5]–[8]. Different from the aforementioned methods of an extra filter, the filtering functions of these antennas are implemented by employing parasitic components into the radiators or feeding structures. For an instance, a metasurface-based antenna with sharp frequency selectivity is realized by utilizing one shorted via and two separated coupled slots [8]. Without intricate filtering circuit, compact designs are obtained. However, all these designs [5]–[8] can only supply relative narrow bandwidth. There is still a challenge about whether one simple structure can be utilized to realize satisfactory wideband radiation performance and filtering response simultaneously.

Several years ago, a broadband unidirectional antenna named the magneto-electric dipole was proposed with a 43.8% impedance bandwidth (SWR $\leq$ 1.5) [9]. It was demonstrated that good electrical properties, such as symmetric radiation patterns, low back radiation, stable antenna gain within operation band are achieved by combining a magnetic dipole and an electric dipole. Due to these attractive characteristics, the ME dipole becomes an ideal candidate in wireless communication systems. Therefore, the ME dipole has been continuously studied in the last decade [10]–[14].



(a)

(b)

FIGURE 1. The proposed antenna configuration. (a) 3D view; (b) side view.

TABLE 1. Dimensions of proposed antenna.

Parameter	W	W_c	W_{c1}	L	L_{c1}
Value /mm	60 (0.440λ)	0.5 (0.004λ)	3 (0.022λ)	30 (0.220λ)	42.3 (0.310λ)
Parameter	L_e	L_d	L_s	S	a
Value /mm	1.5 (0.011λ)	3 (0.022λ)	19 (0.139λ)	13 (0.095λ)	8 (0.059λ)
Parameter	b	c	d	G_L	H
Value /mm	28.5 (0.209λ)	1 (0.007λ)	4.43 (0.032λ)	150 (1.100λ)	30 (0.220λ)

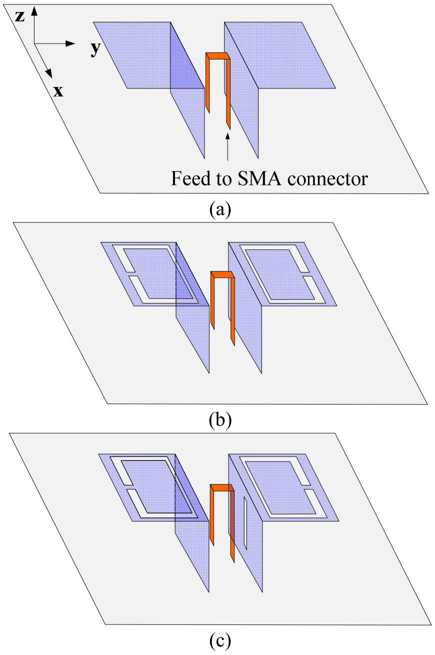
λ is the free-space wavelength at the center frequency.

In this paper, a 3-D integrated wideband filtering magneto-electric dipole is proposed for the first time. By embedding two C-slots into a planar dipole of the designed 3-D ME dipole, high band-edge frequency selectivity for good band-pass filtering gain performance are obtained. Additionally, a slotline is inserted into a vertically oriented shorted patch antenna to provide good impedance matching. It is worth stressing that although U-slot has been introduced to patch antenna for notch band in [15], it is not yet reported that how to apply different slots into 3-D ME dipole for good filtering response. A wider bandwidth with good radiation performance compared to the non-filtering ME dipole is exhibited in the proposal. Moreover, without utilizing any filtering circuit, a quasi-elliptic bandpass response in the boresight gain is also achieved. To validate the design concept, a prototype antenna is implemented and tested for LTE applications. Both Experimental and simulated results are in good agreement.

II. FILTERING ANTENNA DESIGN

A. ANTENNA CONFIGURATION

The configuration of the proposed 3-D filtering antenna is shown in Fig. 1, with detailed dimensions in Table I for operation at around 2.2 GHz. Basically, the antenna is made of two horizontal planar C-slots etched patches, a pair of vertically oriented slotline loaded shorted patches, a Γ-shaped

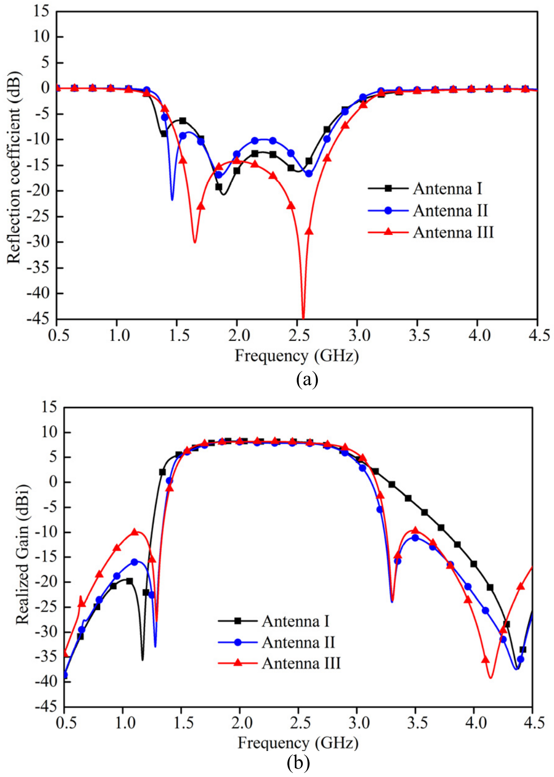


(a)

(b)

(c)

FIGURE 2. Configurations of the antennas: (a) referenced Antenna I: conventional Γ-shaped probe-fed ME dipole; (b) referenced Antenna II: conventional ME dipole with two C-slots; (c) Antenna III: the proposed antenna with both a pair of C-slots and an additional loaded slotline.



(a)

(b)

FIGURE 3. Simulated results of the referenced and proposed antennas. (a) reflection coefficient; (b) realized gain.

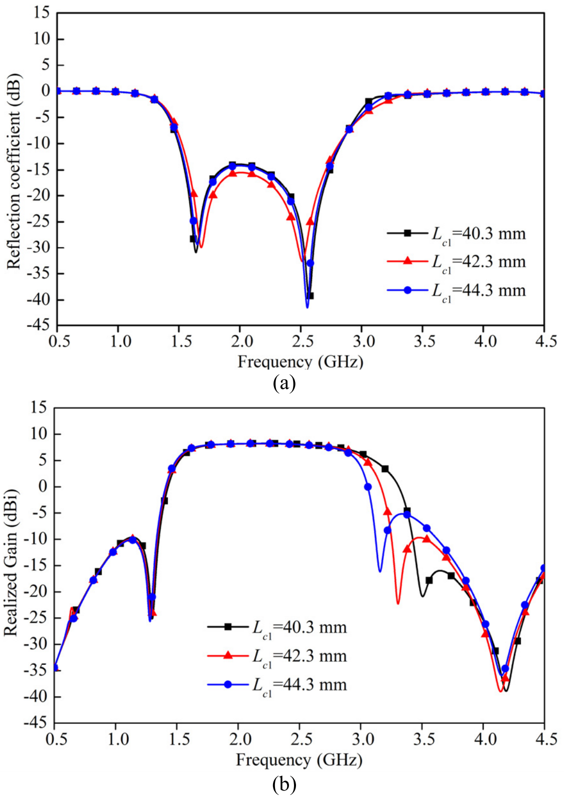


FIGURE 4. **Effect of the length L_{c1} of C-slots: (a) reflection coefficients; (b) realized gains.**

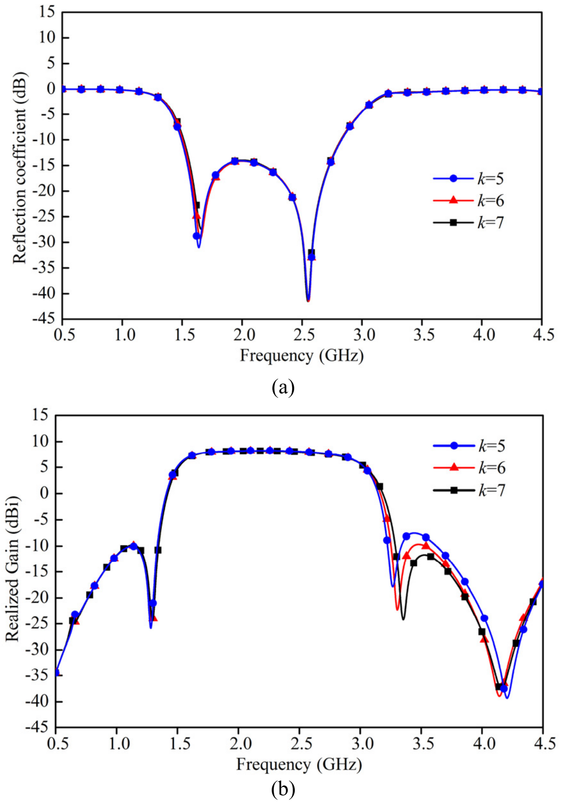


FIGURE 5. **Effect of the ratios $k = W_{c1}/W_c$; (a) reflection coefficients; (b) realized gains.**

probe feed, a ground plane and an SMA connector. Both two horizontal C-slots etched planar patches function as an electric dipole while the vertical slotline loaded shorted patches work as a shorted quarter-wavelength patch antenna. The planar dipole and the shorted patch antenna form the filtering ME dipole. To excite the antenna, the Γ-shaped strip line folded by a rectangular copper line is employed as a probe feed [9]. The operating principle of the ME dipole is similar with that discussed in [9] and [10] and will not be given in this paper. The operating mechanism of the C-slots and the slotline will be illustrated in the following sections.

B. ANTENNA OPERATION PRINCIPLE

To explain the operation principle of the proposed filtering antenna, the comparisons of the antennas with and without the C-slots and the slotline are given. Fig. 2 shows the configurations of two referenced antennas, and the proposal: (I) a conventional Γ-shaped probe-fed ME dipole as proposed in [9], (II) a ME dipole with a pair of C-slots as developed in this work for the first time, and (III) the proposed antenna with both a pair of C-slots and an additional loaded slotline. For convenient comparison, all the three antennas keep same dimensions. The corresponding reflection coefficients and realized gains as a function of frequency are shown in shown in Fig. 3. It can be found in Fig. 3(b) that there is very poor filtering response for Antenna I. It is because that two inherent radiation nulls created by combining the planar dipole and the shorted patch antenna in [9] are far away from the two band edges. This antenna exhibits two resonant modes in the passband as observed in Fig. 3(a), with a SWR $\leq$ 1.5 impedance bandwidth given by 43.8%. However, there is a narrow-band resonant response near the lower band edge at around 1.3 GHz, which is caused by the Γ-shaped feed [9]. When a pair of C-slots is etched on the planar dipole in Antenna II, the currents on upper and lower sides of the slots exhibit out-of-phase, creating one additional radiation null emerges at 3.3 GHz ($\sim 0.5Nc/l_o$, l_o is the total length of the C-slot). As illustrated in the figure, the total reflection S_{11} is about 0 dB at the additional radiation null, which means the input power has transmitted into the antenna and most of the power reflect back at this frequency point. Due to the existence of this radiation null, the roll-off rate at the upper band-edge is significantly improved. Moreover, with the loading effect of the utilized C-slots, the two inherent radiation nulls of the conventional ME dipole move close to the band edges, which enhances the skirt selectivity at both band edges. As a result, a good filtering performance is realized. However, the impedance matching deteriorates in the interested operating band. To obtain a satisfied impedance matching, an additional slotline is inserted into the vertically shorted patch in Antenna III. As indicated by the red solid

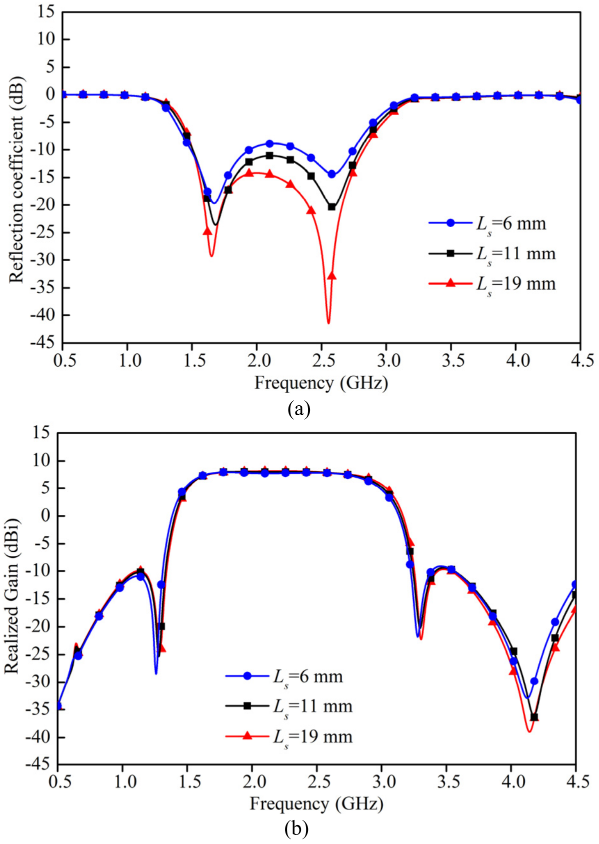


FIGURE 6. Effect of the length L_s of C-slots: (a) reflection coefficients; (b) realized gains.

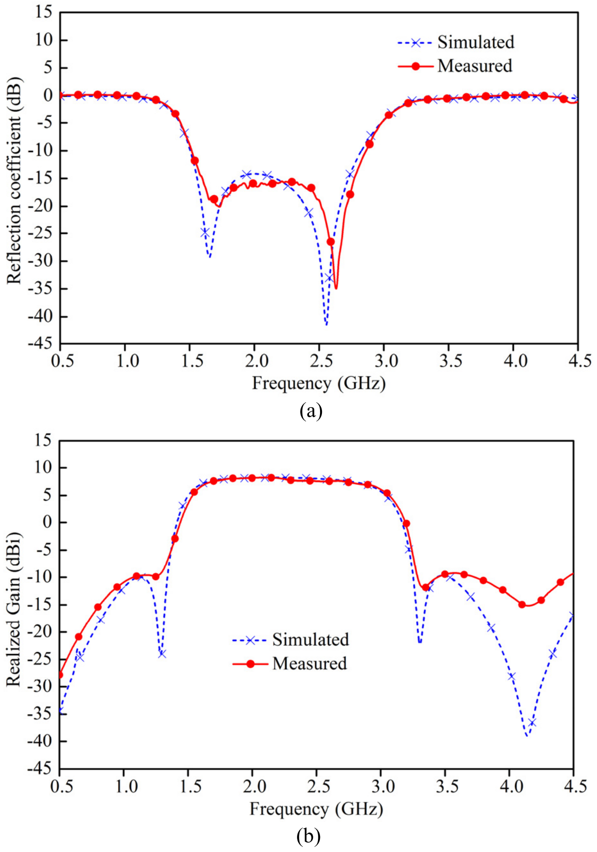


FIGURE 7. Simulated and measured results: (a) reflection coefficients; (b) realized gains.

line in Fig. 3, good matching is achieved with an impedance bandwidth (SWR $\leq$ 1.5) of 55.8% and an average gain of 7.9 dBi. Moreover, good filtering performance is maintained except that the suppression level at lower band edge decreases to a certain extent due to the loaded slotline. It is worth mentioning the suppression levels at both passband edges can still achieve 18 dB, ensuring the proposed antenna with good filtering performance.

III. PARAMETER STUDY

To further characterize the proposed filtering ME dipole, a parameter study is carried out utilizing Ansys HFSS. When one parameter is studied, the others are kept constant as given in Table I. The results provide a useful guideline for practical designs.

A. EFFECT OF C-SLOTS

The first investigation was the effect of the C-slots. Fig. 4 indicates the simulated reflection coefficients and realized gains with different lengths L_{c1} of the C-slots, respectively. Observed that the resonant frequencies and the input impedance vary slightly with an increment of L_{c1}. However, they significantly change the upper band edge of the gain response. The radiation null at 3.3 GHz moves to the lower frequency with the increase of L_{c1} while the other two radiation nulls are maintained. This is as expected because longer C-slots lead to a lower resonance frequency. With a larger length L_{c1} = 44.3 mm, the antenna exhibits a high frequency selectivity at edge of the upper band. Nevertheless, a poor out-of-band suppression is brought. As a compromise, a middle value of L_{c1} = 42.3 mm is utilized in the prototype. Fig. 5 depicts the reflection coefficients and realized gains with different ratios ($k = W_{c1}/W_c$), respectively. The reflection coefficients are insensitive to the variation of k. The gain response varies slightly at the edge of the upper band. With reference to Fig. 5(b), a larger k is good for improving the suppression level. Moreover, we have also investigate the effect of the parameter L_d. Note that L_d has negligible influence on the reflections and gain responses and the results are omitted for brevity.

B. EFFECT OF SLOTLINE

The effect of the length L_s of the slotline was studied. As shown in Fig. 6, the realized gain response is maintained but the input impedance changes significantly with the increase of L_s. The width of the slotline was also investigated and it has similar phenomena as the length L_s of the slotline. These properties can be utilized to obtain good impedance matching.

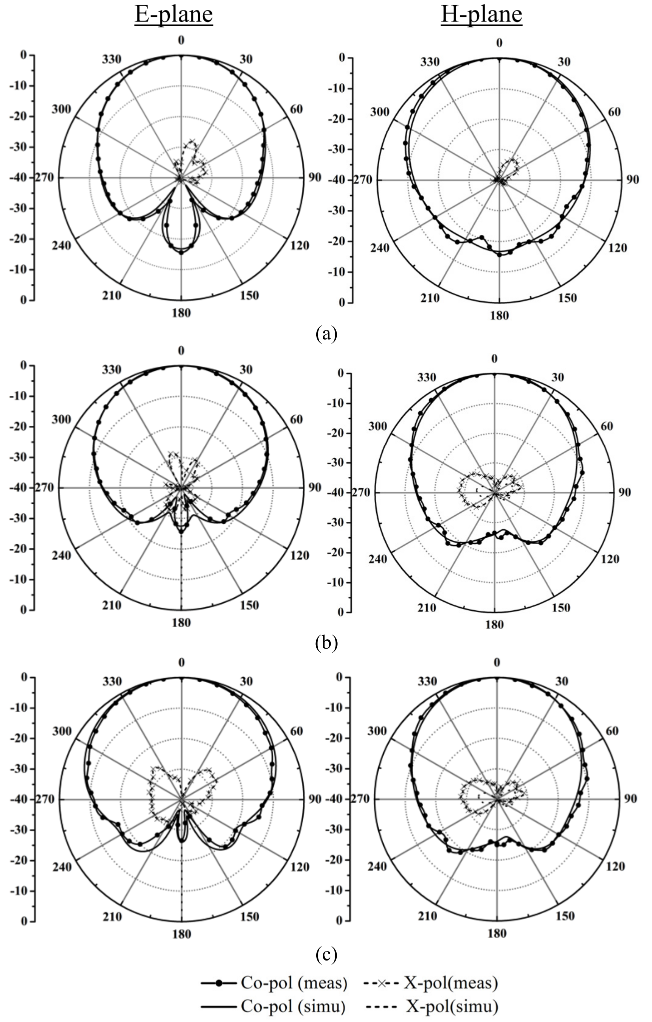


FIGURE 8. Simulated and measured radiation patterns in E- and H-planes: (a) 1.7 GHz; (b) 2.2 GHz; (c) 2.7 GHz.

IV. RESULTS AND DISCUSSION

For validation, a prototype antenna operating at 2.2 GHz was implemented. In the design, simulation was accomplished by utilizing Ansys HFSS. Measured reflection coefficients were carried out on an Agilent N5244A network analyzer, while measured radiation patterns and antenna gains were obtained by using a Satimo Startlab system. Fig. 7(a) shows its simulated and measured reflection coefficients, which are in good agreement. It can be seen from the figure that the proposed antenna exhibits 55.4% impedance bandwidth (SWR $\leq$ 1.5) from 1.58 to 2.79 GHz. Fig. 7(b) displays the realized boresight gains with quasi-elliptic bandpass response. Both measured and simulated results are in good agreement. Within the operating band, the gain curve is flat and displays an average value of 7.8 dBi. It is similar to that of the conventional ME dipole antenna. Two radiation nulls at 1.25 and 3.30 GHz are close to the passband edges, bringing in a sharp frequency selectivity. Additionally, better than 17 dB out-of-band suppression is achieved within the interested out-of-band frequencies. The simulated and measured radiation patterns of the antenna at 1.7, 2.2, and 2.7 GHz are shown in Fig. 8. As can be seen from the figure, stable boresight radiation is obtained across the entire operating band. The measured cross-polarized levels are less than −26 dB. Better than 16 dB front-to-back ratio is achieved within the interested band. In addition, the 3-dB beamwidths of the H- and E-plane are 75° and 78°, respectively. It is worth mentioning that since the operating frequency band of the filtering antenna is mainly determined by the size of the planar dipole and the shorted patch antenna where the width is $W\sim 0.5\lambda$ and lengths are $L\sim 0.25\lambda$ and $H\sim 0.25\lambda$), the proposed design is also suitable for operating frequency lower than approximately 6 GHz where the fabrication tolerance is acceptable. For high-frequency applications, such as MMW systems, the proposed fabricated structure is difficult to be build, such as in [16]. But the realization method is still able to be applied in the high-frequency ME dipole antenna.

V. CONCLUSION

In this paper, a novel 3-D integrated wideband filtering ME dipole has been investigated, exhibiting both nice radiation and decent filtering response. Its operation principle has been thoroughly studied and a parametric study was provided to show the influences of various parameters. Sharp skirt selectivity and high out-of-band suppression levels are achieved by the elaborate combination of the C-slot and slotline. Compared with the conventional ME dipole, the proposed antenna not only exhibits a good filtering performance without sacrificing the good impedance matching and relative high realized gain simultaneously, but also achieves a wider operating bandwidth. Without additional filtering circuit, the antenna configuration is elegant. To verify the proposed method, a prototype operating at 2.2 GHz has been implemented. The antenna exhibits a 55.4% impedance bandwidth with SWR $\leq$ 1.5, an average gain 7.8 dBi, and a 17 dB out-of-band suppression level.

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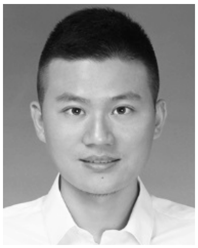

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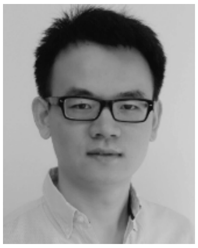

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