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Penta-band microstrip patch antenna with small frequency ratios using metamaterial for wireless applications

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Abstract

A novel shape penta-band microstrip patch antenna is presented in this paper. The proposed antenna shows five operating frequencies and can be used for various wireless applications, i.e. 2.58 GHz for non-direct line of sight, wireless Internet service providers, and compatible with Navini Networks; 3.17 and 3.42 GHz for WiMAX; 4 GHz for C-band application such as weather radar systems; and 5.3 GHz for higher WLAN. Very small frequency ratios of the values 1.2286, 1.078, 1.169, and 1.325 are achieved between two consecutive resonant frequencies. Antenna design techniques for achieving five bands are presented and discussed step by step. The analysis is done by Ansoft HFSS v.15, and results are verified with experimental results of fabricated prototypes.

Introduction

Now-a-days, single antenna is desired for more than one application. Many researchers have made large efforts to design such kind of antennas, which can be used for multiband operations [1–3]. Several researchers have worked in the field of multiband antennas [4]. Small frequency ratios between two consecutive resonant frequencies are a great challenge to achieve while designing a multiband antenna [5, 6]. In the same regard, several types of antenna structures with small frequency ratio have been designed for different wireless applications [7–10]. Directional wide-band antenna with asymmetric fed has been presented in order to optimize antenna gain [11, 12]. A printed parasitic element with metamaterial also has been embedded with a wide-band antenna for desired multiband operation [13–16]. Wide impedance bandwidth also has been achieved with multiband operation by using slotted antenna [17–19]; however, reported antennas are based on multiple feeding networks, which introduce some deficiencies in the performance including mutual coupling and spurious radiations from feed. As the recent requirement for commercial communication applications, multiband antennas should be operated in non-direct line of sight (NLOS), wireless Internet service providers (WISP), C-band application such as weather radar systems (3.7–4.2 GHz), Mobile-WiMAX (2.5/3.3/3.5 GHz), and higher WLAN (5.05–5.35 GHz) [9–23].

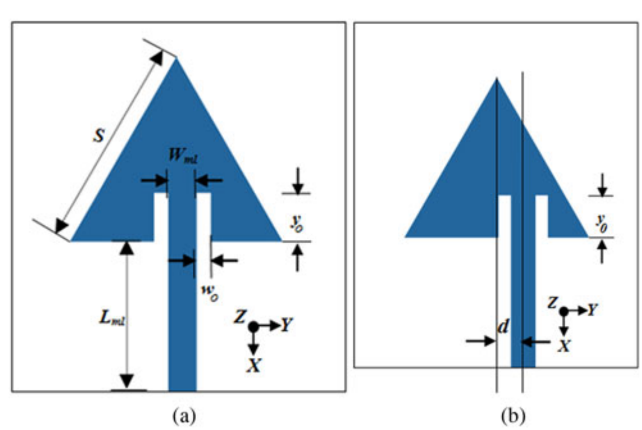

Fig. 1. Schematic representation of the triangular patch antenna with (a) inset feed and (b) asymmetric offset inset feed.

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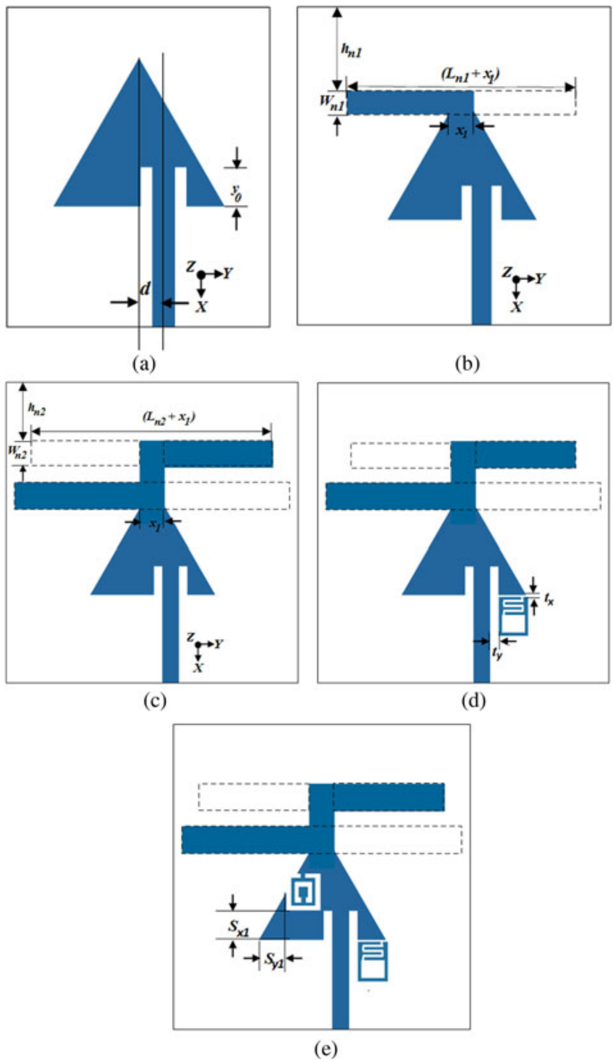

Fig. 2. Schematic representation and step-by-step evolution of the proposed design; (a) case I – *Ant_1*, (b) case II – *Ant_2*, (c) case III – *Ant_3*, (d) case IV – *Ant_4*, and (e) case V – *Ant_5*.

Table 1. Design specification of antenna designs along with their metamaterials

Design	Parameter	Value (mm)	Parameter	Value (mm)
Ant_1	S	17	y_0	2.77
	w_o	0.5	L_{ml}	8.435
	W_{ml}	3.011	d	2.125
Ant_2	L_{n1}	28.9345	x_1	1.8
	W_{n1}	3.7	h_{n1}	10.5
Ant_3	L_{n2}	23.8248	h_{n2}	5.8
	W_{n2}	3.7		
Ant_4	t_x	0.2	t_y	0.5
Ant_5	S_{x1}	3.35	S_{y1}	2.9885
Rectangle SRR	S_g	0.7	S_c	0.35
	S_d	0.6	a_{ext}	2.5
IDCLLR	L_r	5	W_r	4
	W_g	0.1	W_s	0.2
	W_d	0.3	W_l	5
	W_c	0.6		

In this article, a penta-resonant, novel-shaped patch antenna along with dipole and metamaterial is proposed with very small frequency ratio. Design steps are presented and discussed along with its performance parameters. The proposed design characteristics are analyzed using Ansoft HFSS v.15 based on finite element method and results are matched with the measurement of fabricated antenna's prototypes. The proposed antenna is low profile and fabricated on an FR-4 Epoxy substrate, which is cheaper and commercially available. It can be easily fabricated on a single substrate using standard photolithography process, which is a merit of the proposed antenna over available literature.

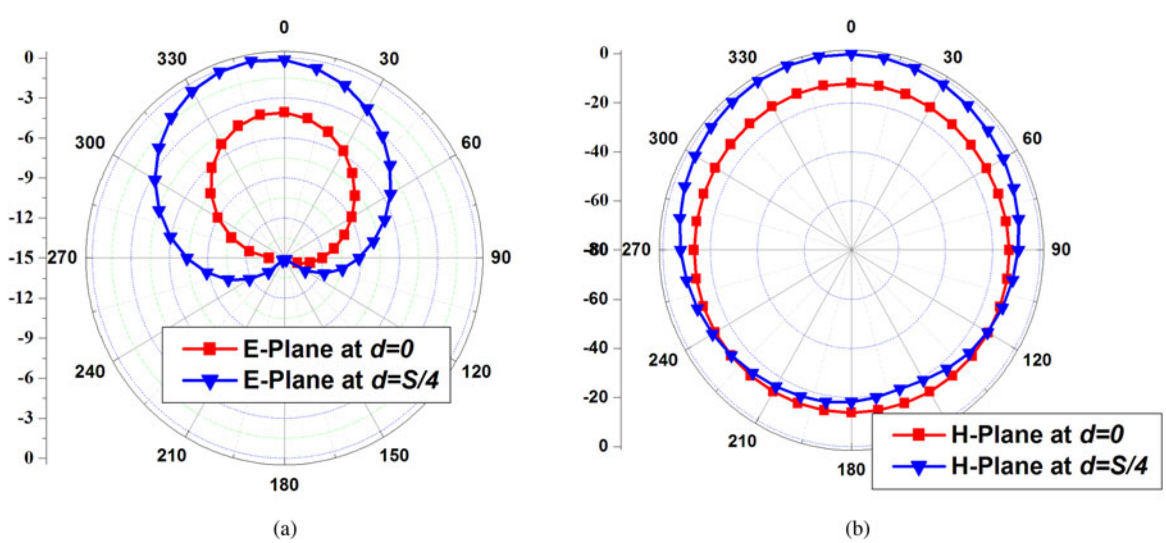

Fig. 3. The radiation pattern of a triangular patch antenna for different values of offset distance *d*; (a) *E*-plane, (b) *H*-plane.

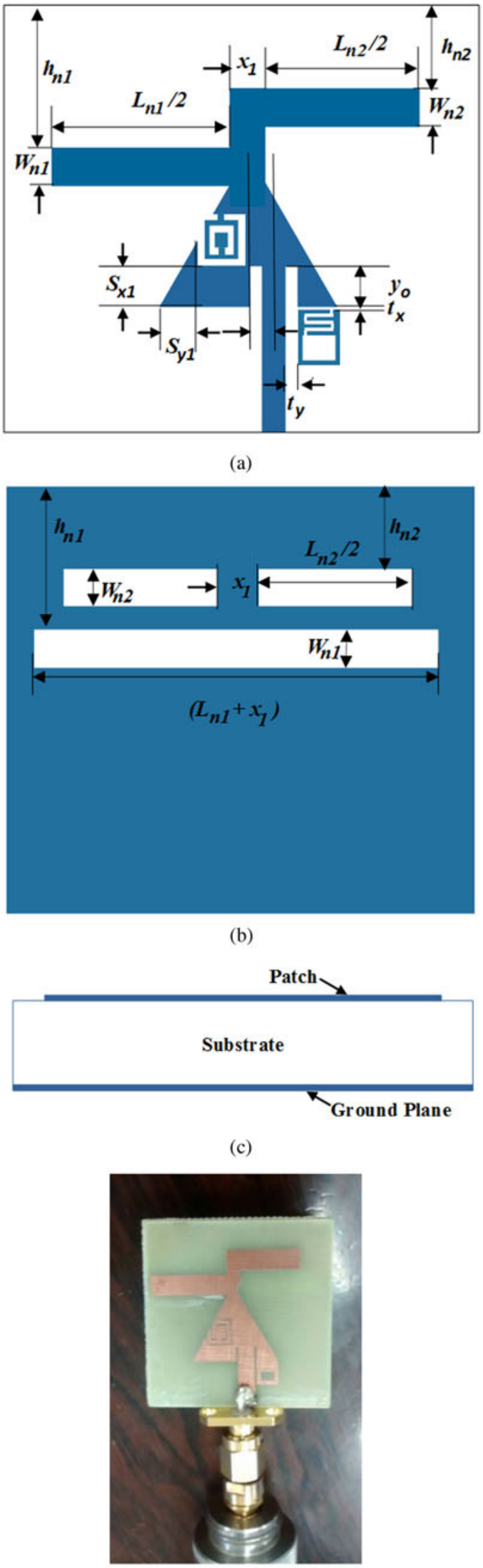

Fig. 4. Schematic representation of the proposed design *Ant_5*; (a) top view, (b) ground plane, (c) side view, and (d) fabricated prototype.

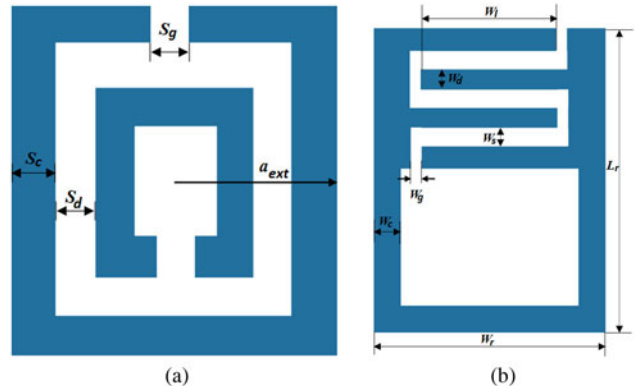

Fig. 5. Schematic representation of a single unit; (a) rectangle SRR, (b) IDCLLR.

Proposed structure

The schematic representation and design steps of the proposed structure are presented in Figs 1 and 2. An equilateral triangular patch of edge S is taken as a reference in Fig. 1(a). This equilateral triangular patch is fed by a microstrip line of length L_{ml} and width W_{ml}. The input impedance of the patch is matched with the characteristics impedance of microstrip line through inset feed of length y_0 and slot width w_0. The structure is designed for 5 GHz and detailed parameters are given in Table 1.

Length L_{ml} of the microstrip line is calculated as [24, 25]

$$L_{ml} = \frac{c}{4f_r\sqrt{\varepsilon_{effml}}}, \tag{1}$$

where

$$\varepsilon_{effml} = \frac{\varepsilon_r + 1}{2} + \frac{0.5(\varepsilon_r - 1)}{\sqrt{1 + 12(h/W_{ml})}}, \tag{2}$$

$$S = S_{eff} - \frac{4h}{\sqrt{\varepsilon_r}}, \tag{3}$$

where S, S_{eff}, h, and ε_r are the edge of the equilateral triangular patch, the effective length of the edge of the equilateral triangular patch, height of the dielectric substrate, and relative dielectric constant of the dielectric substrate, respectively.

Effective length S_{eff} is calculated as [25]

$$S_{eff} = \frac{2C}{3f_r\sqrt{\varepsilon_{eff}}}, \tag{4}$$

where C, ε_{eff}, and f_r are the speed of light in free space, effective dielectric constant, and resonance frequency, respectively.

Further, the asymmetric feed is introduced in the equilateral triangular patch as shown in Fig. 1(b). The microstrip line is shifted toward its right by a distance d for asymmetric feed. Offset feed method for triangular patch antenna has been reported for the enhancement of impedance bandwidth [11, 12]. Asymmetric feed provides directional radiation in the end-fire direction (z-direction) as shown in Fig. 3. It is observed that antenna starts to radiate in the end-fire direction as the offset distance d is increased to the value of $S/4$.

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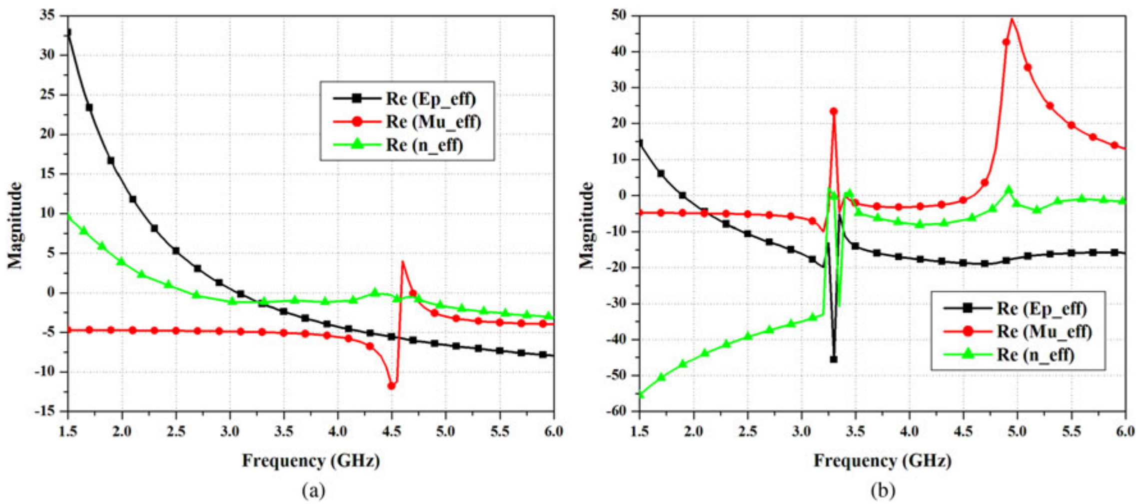

Fig. 6. Metamaterial characteristic of a single unit; (a) rectangular SRR, (b) IDCLLR.

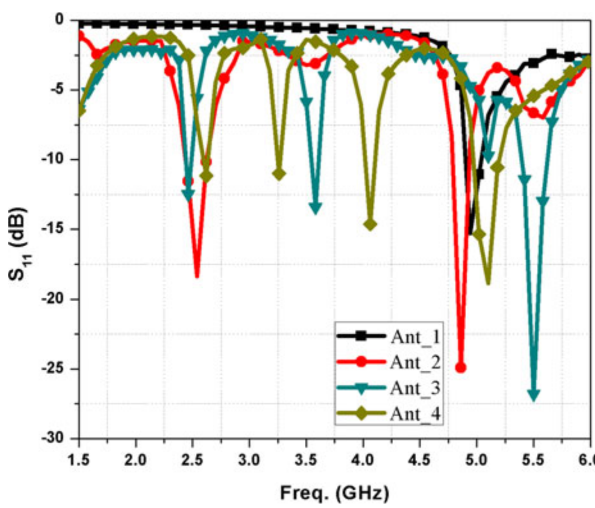

Fig. 7. S_{11} characteristics with the frequency of *Ant_1*, *Ant_2*, *Ant_3*, and *Ant_4*.

Table 2. Frequency ratio of the proposed design *Ant_5* in comparison with recent works

Multiband antenna	Number of resonating bands	Minimum frequency ratio
[3]	2	1.28
[4]	2	1.21
[5]	2	1.05
[6]	2	1.03
[17]	2	1.28
[18]	2	1.10
[19]	2	1.10
[20]	3	1.528
[21]	3	1.613
[22]	4	1.086
Proposed design *Ant_5*	5	1.078

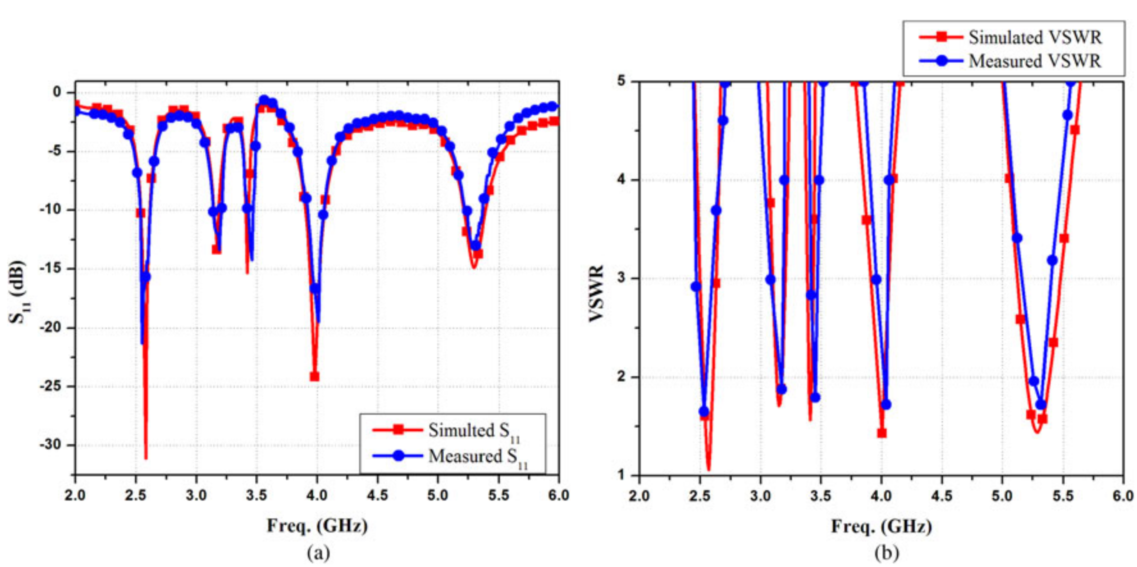

Fig. 8. Measured and simulated characteristics with the frequency of the proposed antenna *Ant_5*; (a) S_{11}, (b) VSWR.

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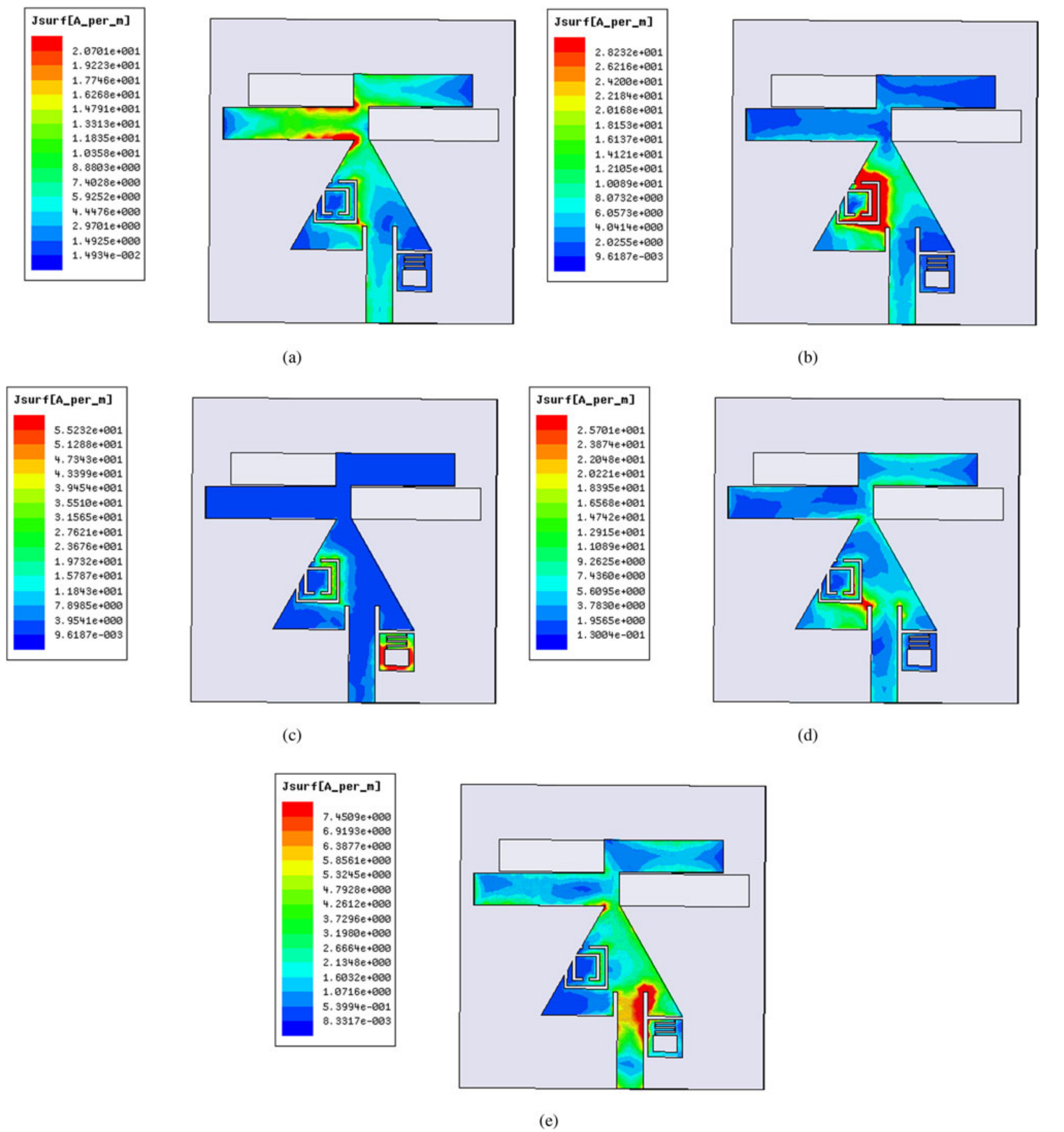

Fig. 9. Current distributions at (a) 2.58 GHz, (b) 3.17 GHz, (c) 3.42 GHz, (d) 4 GHz, and(e) 5.3 GHz.

The schematic representation and step-by-step evolution of the proposed structure are shown in Fig. 2. In case I, offset feeding is introduced in the equilateral triangular patch to achieve the directional radiation pattern and the antenna structure is referred as *Ant_1*, which is shown in Fig. 1(b).

For case II, a dipole is designed for 2.5 GHz and embedded with a triangular patch, which is referred as *Ant_2* and shown in Fig. 2(b). Half-length of the dipole is embedded with a patch on the signal plane, whereas a slot of length $(Ln_1 + x_1)$ is embedded on the ground plane; in which, x_1 is the width of the connecting strip. The length L_{n1} and width W_{n1} of the first dipole are calculated from equations (5) and (6), respectively.

Half-length $L_n/2$ of the dipole is the quarter wavelength and calculated as

$$\frac{L_n}{2} = \frac{\lambda_{eff}}{4} = \frac{c}{4f_r\sqrt{\varepsilon_{eff}}}, \tag{5}$$

where c, ε_{eff}, and f_r are the speed of light in free space, effective

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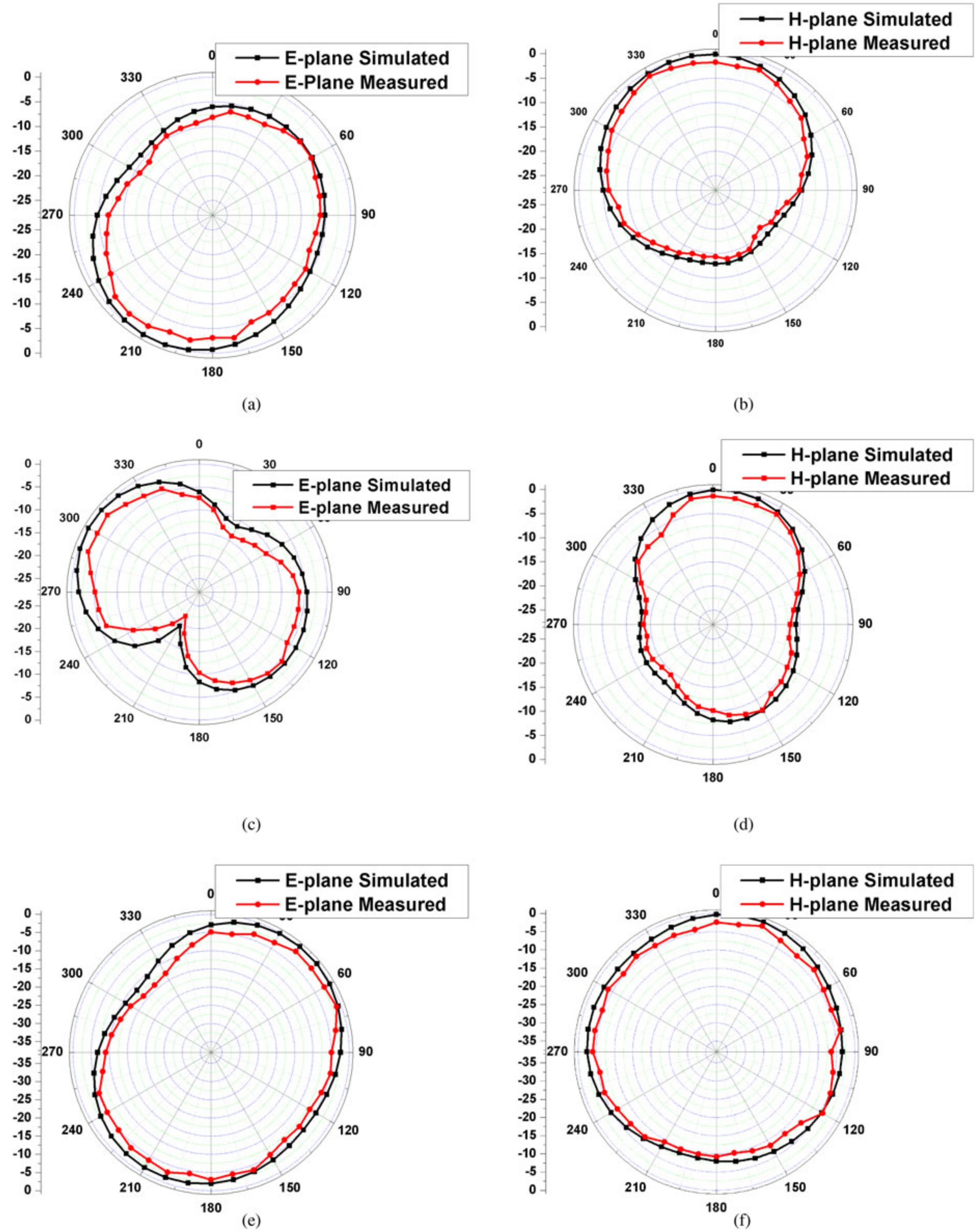

Fig. 10a. Measured and simulated normalized radiation pattern of the proposed antenna; (a) *E*-plane at 2.58 GHz, (b) *H*-plane at 2.58 GHz, (c) *E*-plane at 3.17 GHz, (d) *H*-plane at 3.17 GHz, (e) *E*-plane at 3.42 GHz, (f) *H*-plane at 3.42 GHz, (g) *E*-plane at 4 GHz, (h) *H*-plane at 4 GHz, (i) *E*-plane at 5.3 GHz, and (j) *H*-plane at 5.3 GHz.

permittivity ($\varepsilon_{eff} \leq \varepsilon_r$), and resonating frequency of dipole, respectively. Resonant frequency f_r of the dipole is taken as 2.5 GHz in this study.

Width W_{n1} of the dipole corresponding to its length L_{n1} is related to its impedance and calculated by equation (6) [25]. The impedance of the dipole is matched to the input impedance of the edge of the microstrip patch.

$$W_n = \frac{\pi L_n}{exp((R_{in}(x=0)/120) + 2.25)}, \tag{6}$$

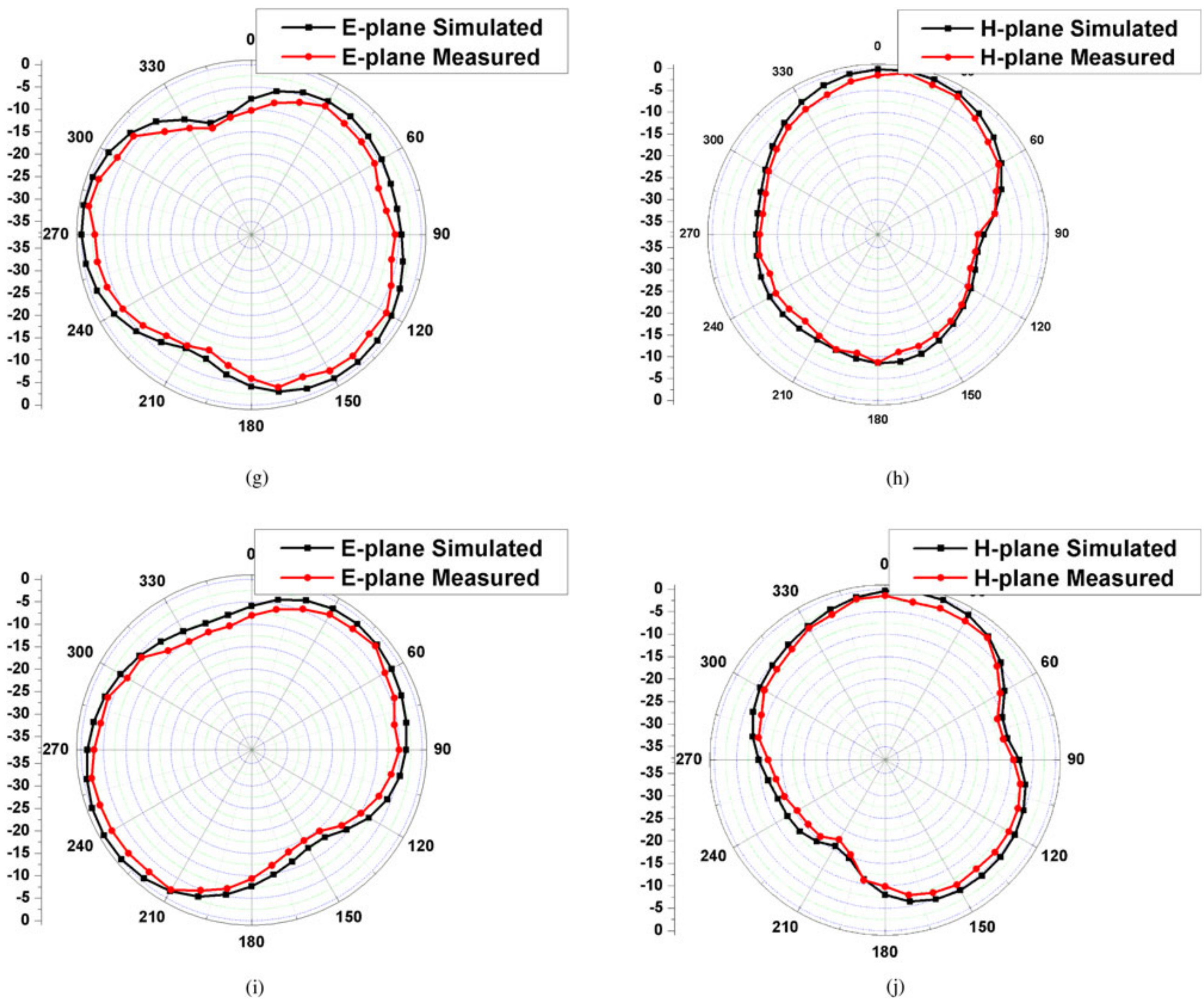

Fig. 10b. Continued.

where R_{in} $(x = 0)$ is the input impedance at the edge of microstrip patch antenna and calculated by equation (7) [24]:

$$R_{in}(x = 0) = \frac{50}{cos^2(\pi S_0/S)}, \quad (7)$$

where S is the edge of the equilateral triangular patch and S_0 is the length of the transmission line corresponding to 50 Ω impedance.

In case III, one more dipole is embedded and the structure is referred as *Ant_3*, which is shown in Fig. 2(c). The second dipole is designed for 4 GHz, and the length L_{n2} and width W_{n2} are calculated by equations (5) and (6), respectively. Their relevant values are adjusted up to the minimum extent to maintain the resonant peak at the specific frequency by parametric analysis.

In case IV, an inter digital capacitor-loaded loop resonator (IDCLLR) [13, 14] is embedded below the right corner of the edge of the triangular patch as shown in Fig. 2(d) and the structure is referred as *Ant_4*.

In case V, a slot and a slit of rectangular split-ring resonators (SRR) [15, 16] are embedded in the left corner of the triangular patch as shown in Fig. 2(e) and the structure is referred as *Ant_5*. The top and bottom views of a schematic representation of the proposed *Ant_5* (case V) are shown in Figs 4(a) and 4(b), respectively. The dimensions of a single unit cell of rectangular SRR and IDCLLR are shown in Fig. 5, and the real permittivity, permeability, and refractive index of the unit cell are shown in Figs 6(a) and 6(b). The detailed dimensions of all the structures are listed in Table 1.

Analysis and result discussion

The FR-4 Epoxy substrate of dimensions 35 mm × 35 mm × 1.5748 mm is used to analyze the proposed antennas. Fabrication is done by standard photolithography process and measurement is done by Agilent™PNA-L Series Network Analyzer and Agilent™ Spectrum Analyzer. A fabricated prototype of *Ant_5* is depicted in Fig. 4(d). Figure 7 shows the S_{11} variation with the frequencies *Ant_1*, *Ant_2*, *Ant_3*, and *Ant_4*

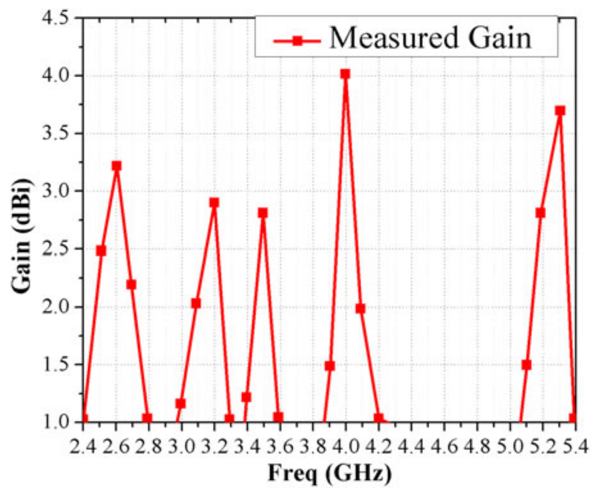

Fig. 11. Measured gain variation with the frequency of the proposed antenna.

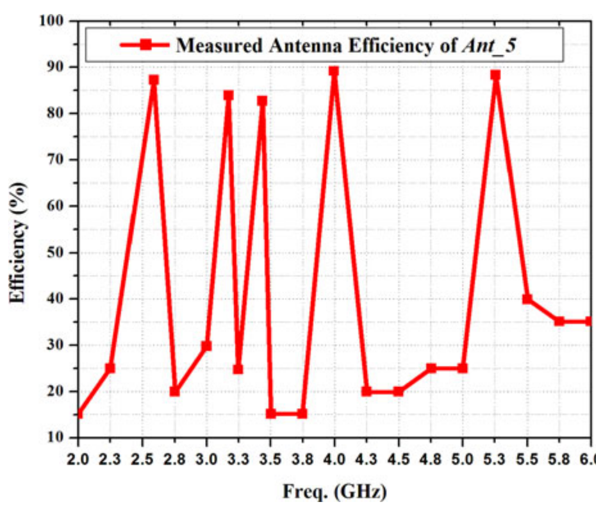

Fig. 12. Measured antenna efficiency variation with the frequency of the proposed antenna *Ant_5*.

corresponding to cases I–IV. *Ant_5* shows five resonating frequency bands with very small frequency ratios as shown in Fig. 8. S_{11} and VSWR characteristics with the frequency of *Ant_5* is shown in Figs 8(a) and 8(b), respectively. All five resonating bands are achieved by the presented mathematical design equations; however, the least parametric analysis is done to achieve sharp resonance for the specific applications. *Ant_5* resonates at 2.58, 3.17, 3.42, 4.0, and 5.3 GHz with very small frequency ratios of the values 1.2286, 1.078, 1.169, and 1.325 between two consecutive resonant frequencies, respectively. A comparative study is shown in Table 2.

The current distribution of the proposed antenna *Ant_5* at each resonant frequency is shown in Fig. 9. The working mechanism of the proposed antenna could be defined with the help of the shown current distribution: (i) dipoles embedded in the front of the triangular patch and ground are mainly contributing to generate 2.58 GHz frequency as shown in Fig. 9(a); (ii) 3.17 GHz frequency is achieved due to a slot and a slit of rectangular SRR, which can be clearly observed in Fig. 9(b); (iii) IDCLLR combined with a slit and a slot are playing a role in generating 3.42 GHz frequency; and finally (iv) 4 and 5.3 GHz frequencies are achieved due to the triangular patch with inset feed as shown in Figs 9(d) and 9(e), respectively.

Radiation patterns of the proposed antenna *Ant_5* are shown in Fig. 10. *E*-plane patterns of *Ant_5* are shown in Figs 10(a), 10(c), 10(e), 10(g), and 10(i); whereas *H*-plane patterns are shown in Figs 10(b), 10(d), 10(f), 10(h), and 10(j) at 2.58, 3.17, 3.42, 4.0, and 5.3 GHz frequencies, respectively. It is observed from Fig. 10 that *Ant_5* shows good radiation characteristics in both major planes. Measured results are in good agreement with the simulated results.

Figure 11 shows the measured gain variation with the frequency of the proposed antenna. *Ant_5* shows antenna gain of about 3.23, 2.9, 2.8, 4.01, and 3.49 dBi at frequencies 2.58, 3.17, 3.42, 4, and 5.3 GHz, respectively. Antenna efficiency is shown in Fig. 12, and it is observed that the proposed antenna *Ant_5* shows antenna efficiency around 87.5, 83.05, 82.45, 89.35, and 88.93% at respective bands. Performance of proposed *Ant_5* is compared in Table 3.

Table 3. Performance of the proposed design *Ant_5* in comparison with recent works

Multiband antenna	Number of resonating bands	Bandwidth (%)					Gain (dBi)				
		I	II	III	IV	V	I	II	III	IV	V
[3]	2	16	12.5	–	–	–	5	5	–	–	–
[4]	2	5.88	6.08	–	–	–	1.35	3.5	–	–	–
[5]	2	1.9	2	–	–	–	4.05	2.5	–	–	–
[6]	2	0.98	1.2	–	–	–	5.1	4.8	–	–	–
[17]	2	17	21	–	–	–	3.81	3.12	–	–	–
[19]	2	2.99	2.72	–	–	–	4.5	4.5	–	–	–
[20]	3	4.7	3.7	2.4	–	–	1.7	1.4	2.5	–	–
[22]	4	1.2	2	1.9	0.9	–	4.1	6.2	8	6.2	–
[23]	4	0.7	2.1	2.2	1.4	–	4.8	4	6	8	–
Proposed design *Ant_5*	5	4.65	4.1	3.8	5.2	5.8	3.23	2.9	2.8	4.01	3.49

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Conclusion

A novel-shaped penta-resonant antenna is designed and analyzed. The proposed antenna is resonating at 2.58, 3.17, 3.42, 4, and 5.3 GHz with a very small frequency ratio of the values 1.2286, 1.078, 1.169, and 1.325 between two consecutive resonant frequencies, respectively. Simulated results of the designed antenna are verified with measured results of the fabricated antenna. Proposed antenna shows good radiation characteristics and may be used for multiple wireless applications such as 2.58 GHz for NLOS, WISP, and compatible with Navini Networks (2.5–2.690 GHz); 3.17 and 3.42 GHz for WiMAX (3.3/3.7 GHz in Asia); 4 GHz for C-band application such as weather radar systems (3.7–4.2 GHz); and 5.3 GHz for higher WLAN (5.05–5.35 GHz).

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