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Honeycomb shaped fractal antenna with dual notch characteristic for UWB applications

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Defected ground structure;
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Abstract. This paper presents a feasible way to construct a honeycomb structured microstrip antenna for UWB (Ultra-Wide Band) applications with dual notch characteristics. The antenna is designed based on the concept of the initial stage of honeycomb nest construction and Defected Ground Structure (DGS) with dual notch for UWB applications. The two notches for WiMAX (3.5 GHz center frequency) and WLAN (5.5 GHz center frequency) are introduced by etching two asymmetrical quarter-wavelength slots in the ground. The compact antenna of size 12×20 mm^2 with simple geometry achieves very wide bandwidth of $3.1 - 13.8$ GHz (covers UWB and higher frequency band) with dual notch characteristics.

1. Introduction

Nature is an exceptionally large and unique laboratory comprising efficient explanations on and solutions to numerous technical and scientific problems. Honeycomb structures inspired by the Mother Nature's bee honeycomb construction process have tremendous potentials and applications in various fields including mechanical engineering, nanofabrication, chemical engineering, architecture, aerospace engineering, biomedicines, and RF (Radio Frequency) and microwave. The ideas and theories taken from nature have inspired many novel designs of antennas for various wireless applications [1–3].

The fractal patterns exist around every corner of nature. The fractal structure of honeycomb evolving from natural honeycomb is a tessellation of uniformly distributed double-layer hexagonal shapes. There are mainly two viewpoints on how the shape of honeycomb cells becomes hexagonal. One is that the particular structure is merely the result of physics law. The other point of view suggests that honeybees are skilled engineers that operate under simple rules. With the advent of new technology, the application of honeycomb structure is growing on nano and micro scales. Various micro and nano antennas based on honeycomb structure have been proposed for various applications [4–7].

The wide-band antennas were built with monopoles of various shapes or fractal shapes [8,9]. At a particular frequency, the antenna must normally maintain a minimum size, usually in the order of quarter wavelengths. These factors affecting the antenna performance in telecommunication systems have remained restricted for a long time. Fractal

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electromagnetic engineering embodies a comparatively fresh domain of research that amalgamates aspects of fractal geometry with electromagnetics. Research within this stream has lately given rise to a rich category of innovative structures for antennas along with metamaterial rudiments. Fractals are space-filling structures that could be utilized as electromagnetic devices to efficiently accommodate long electrical lengths into tiny areas. Honeycomb is the most suitable fractal shape found in nature for the design of patch antennas [7].

Since FCC (Federal Communication Commission) regulated the frequency range of $3.1-10.6$ GHz for the Ultra-Wideband (UWB) applications, much attention has been paid to the growing demand for UWB antennas for the UWB technology [10,11]. For millimeter-wave applications, a honeycomb fractal antenna array of size 97×7 mm^2 was introduced in [5]. The broad bandwidth of 14.337 GHz (25.347–39.684 GHz) was obtained with 4.15 dBi (single component) and 12.7 dBi (antenna array) gain. For wireless applications, Desai et al. [6] presented a hexagon fractal antenna of bandwidth 1.31–6.81 GHz and a gain of 6.8 dBi and 40×45 mm^2 size. This referenced study [7] presented an 80×80 mm^2 honeycomb-shaped antenna for Ku band communication at a frequency of 11.85 GHz with a gain of 8.87 dBi. The CPW (Coplanar Waveguide) fed hexagonal fractal antenna of size $39 \times 36.5 \times 1.524$ mm^3 design was proposed for UWB applications [12]. The modeling of the PIN (Positive-Intrinsic-Negative) diode RF (Radio Frequency) switch on HFSS (High-Frequency Structure Simulator) was presented for reconfigurable antenna applications [13]. A simple compact-size antenna with the partial ground is added with a frequency reconfigurable property to switch from the ultra-wideband to narrowband mode. In [14], plasmonic mode propagation properties of graphene-based terahertz PCA (Photoconductive Antennas) are studied. Some of the nature-inspired algorithms are applied to antenna optimization [15,16].

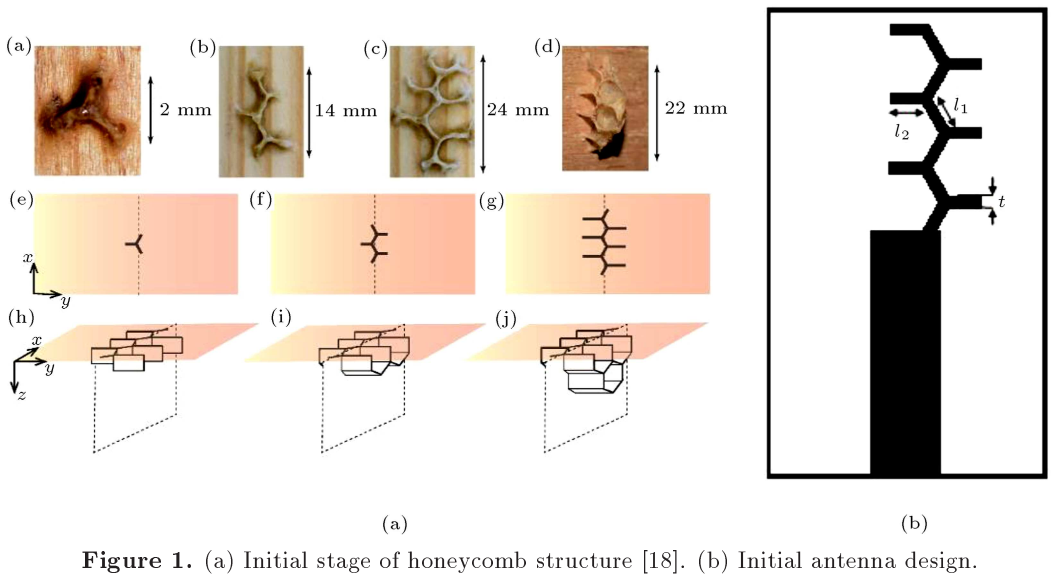
In this paper, the honeycomb structure construction is considered for the design of the conducting patch of an antenna. This paper presents a honeycomb-structured fractal antenna with dual-band notch rejection characteristics for UWB applications.

2. Antenna design

2.1. Initial antenna design

The mechanism through which honeybees assemble honeycomb cells in such a particular order is nevertheless an open discussion. When the honeycomb structure is subjected to different loads and stresses, much attention should be paid to the mechanical properties [17]. In this paper, the honeycomb structure is explored for the microstrip antenna design. A critical understanding of the construction principle of the honeycomb structure to design an antenna is important. In order to construct the honeycomb antenna, the focus of attention is the initial structure of the honeycomb. By considering this initial honeycomb-structured construct procedure [18], the design of an antenna is initiated, as shown in Figure 1. Figure 1(a) shows the first stage of honeycomb construction, and Figure 1(b) shows the antenna patch using conducting material. The antenna is constructed on the FR-4 substrate of size 20×12 mm^2.

As can be observed from the above antenna design, the antenna forms the quarter-wavelength or half-wavelength monopole. The length of the radiating patch is approximately a quarter of the wavelength and the total length l_{total} is given by:



(a) (b)

Figure 1. (a) Initial stage of honeycomb structure [18]. (b) Initial antenna design.

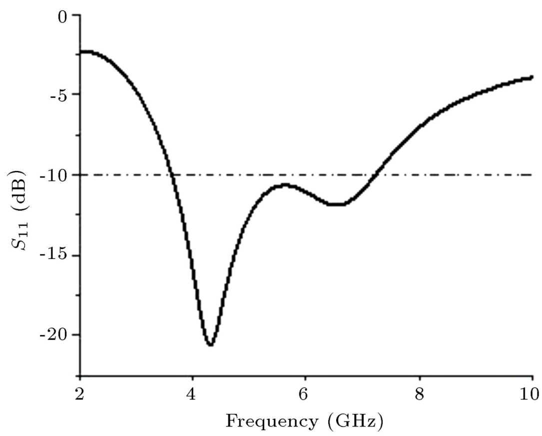


Figure 2. Return loss variation for quarter-wavelength patch.

$$l_{total}\frac{\lambda_0}{4}=\frac{\lambda_r}{4\sqrt{\varepsilon_{eff}}}=\frac{C}{4f_r\sqrt{\varepsilon_{eff}}}, \tag{1}$$

$$\varepsilon_{eff}=\frac{\varepsilon_r+1}{2}, \tag{2}$$

where C is the speed of light in the free space, λ_r the free space wavelength, ε_{eff} effective dielectric constant, and f_r the resonant frequency of the quarter-wavelength monopole [19]. The total patch length l_{total} for the above design is approximately 10 mm (l_1 = 1.4 mm, l_2 = 2 mm, and t = 0.5 mm). The resonating frequency for the quarter-wavelength monopole of 10 mm length is 4.4 GHz. According to the obtained return loss characteristics shown in Figure 2, the resonating frequency is 4.3 GHz and the obtained bandwidth ranges from 3.6 to 7.2 GHz (3.6 GHz).

The initial design is optimized by the tessellation of the hexagonal fractal shapes in a circular manner and hence, the initial design of quarter wavelength is modified into the honeycomb shape [20], as shown in Figure 3.

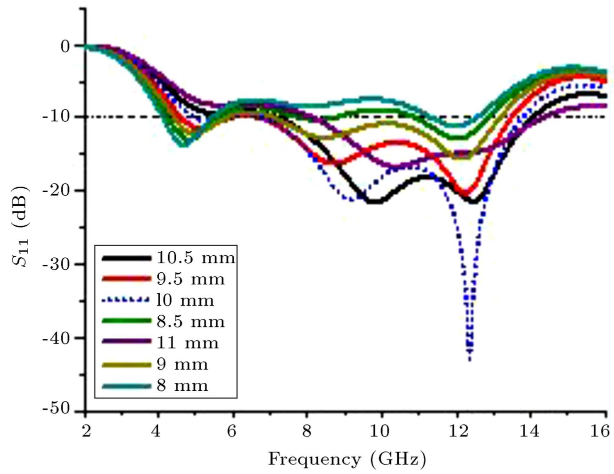


Figure 4. Variation of return loss (S_{11}) with frequency for different ground sizes.

For a wide bandwidth, the parametric analysis of ground is conducted by changing the ground size. Figure 4 shows the variation of return loss (S_{11}) with frequency for different ground sizes. By observing the obtained graphs closely, it can be noted that the results are optimum when the ground length L_1 is 10 mm. With a ground length of 10 mm, the bandwidth ranges from 6.749 to 13.743 GHz, which covers the part of UWB and Ku-band.

To further enhance the bandwidth in the UWB range, the ground is modified into Defected Ground Structure (DGS) by inserting a triangular slot in the upper part of the partial ground plane [21]. In addition to the triangular slot, hexagonal patches are introduced in the patch, as shown in Figure 5. Incorporation of hexagon shapes into the patch and triangular slot in the partial ground further improves the bandwidth of an antenna by changing the current distribution and electrical path lengths. The electrical path length for

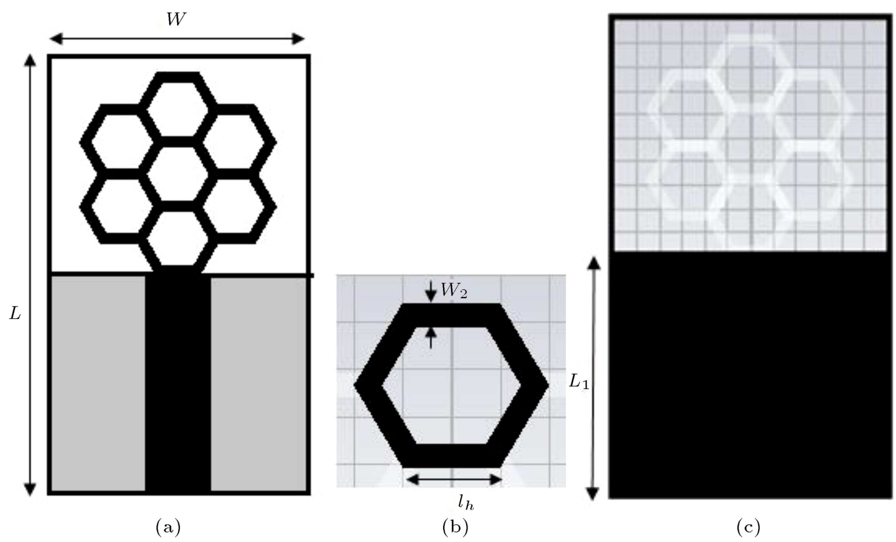


Figure 3. (a) Honeycomb shaped fractal antenna, (b) single hexagonal fractal, and (c) back view of antenna.

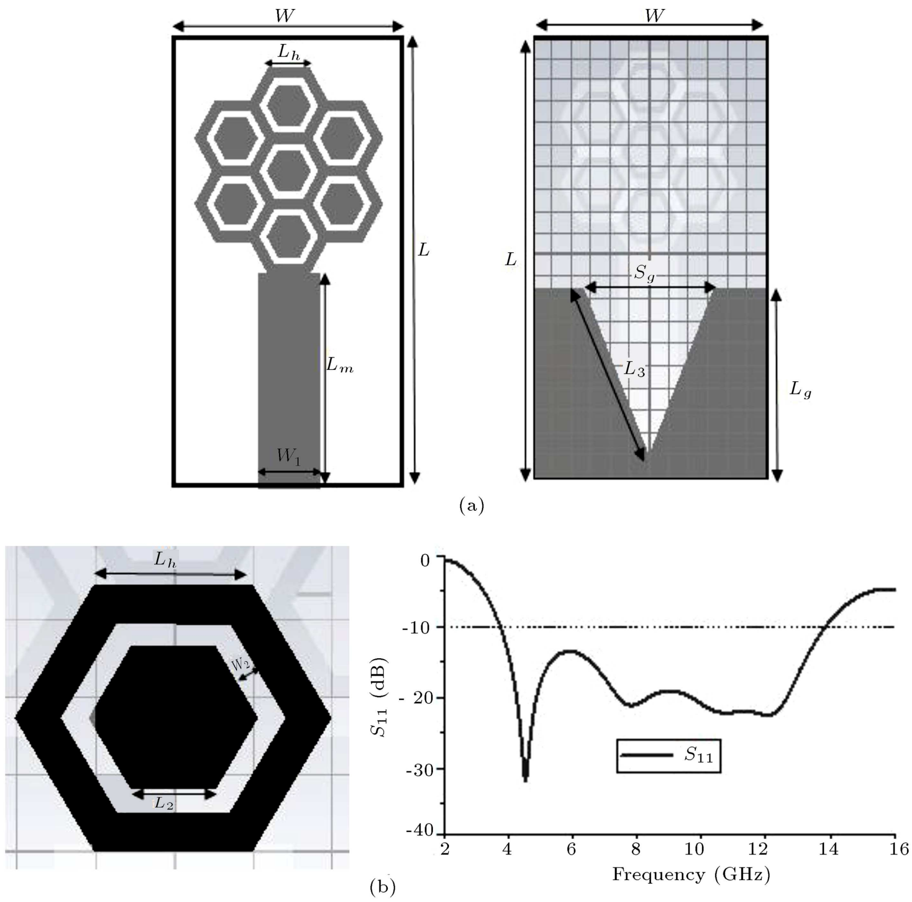


Figure 5. (a) Honeycomb structure filled with hexagonal front view (left panel) patches and with DGS (right panel). (b) Single hexagonal fractal with filled patch (left panel) and return loss variation (right panel).

the ground without a triangular slot is $L_g + W$ (8.5 mm+12 mm = 20.5 mm). The electrical path length is changed into $L_g + l_3 + l_3 +$ $(W - S_g)$ (8.5 mm + 8.2 mm + 8.2 mm + (12 mm −6.67 mm) = 30.23 mm). The impedance bandwidth is highly enhanced from 6.749 − 13.743 GHz to 3.74 − 13.85 GHz, as shown in Figure 5.

2.2. Dual-band notch antenna

After obtaining wide bandwidth, the next step is to address the issue of interference in the coexisting microwave systems by introducing slots in the ground, as shown in Figure 6. The first notch for WiMAX (3.25 − 3.85 GHz) is introduced by etching the quarter-wavelength ($\lambda_g/4$) slot of length 10.5 mm. Here, λ_g is the guided wavelength for the corresponding notch-band center frequency. As depicted in Figure 7, slot 1 introduces a notch for WiMAX. Similarly, the WLAN notch is introduced at the center frequency of 5.5 GHz by etching a quarter-wavelength inverted L-shaped slot in the ground, as shown in Figure 8. The inverted L shape is chosen to accommodate the quarter-wavelength slot in a very-compact-size DGS. The length of the quarter-wavelength slot is calculated, as given in Eq. (1) [19,22].

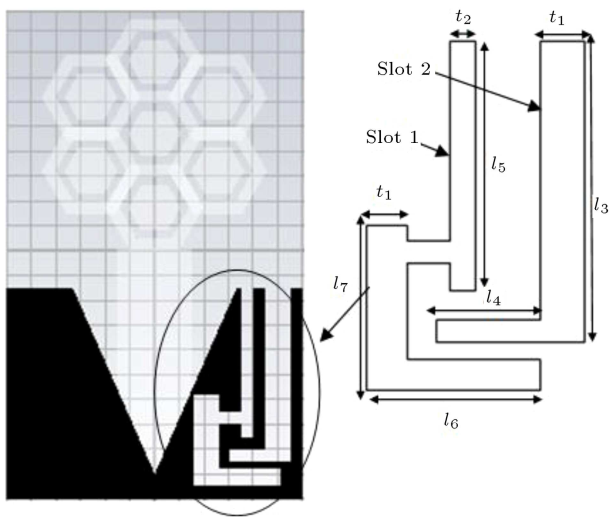


Figure 6. Quarter-wavelength slots in DGS for band notch characteristics (proposed antenna design) and enlarged view of ground slots.

3. Results and discussions

The effective lengths of the two slots (slots 1 and 2) are 10.5 mm and 7.75 mm, respectively. Here, the

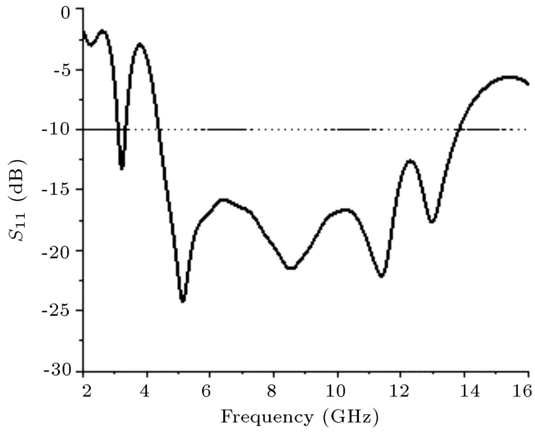


Figure 7. WiMAX notch by quarter-wavelength slot.

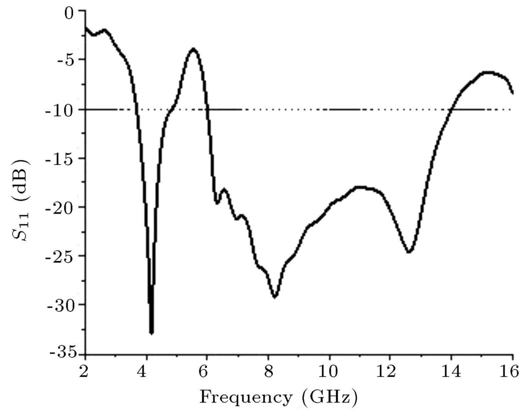


Figure 8. WLAN notch by qutaer-wavelength slot.

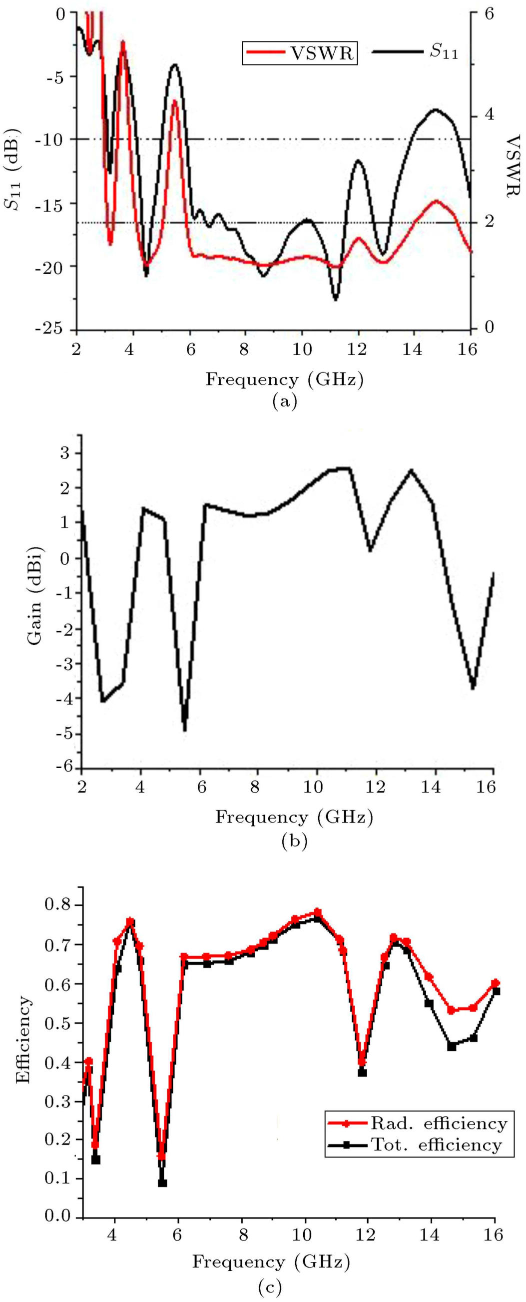


Figure 9. (a) Return loss and VSWR variation with frequency, (b) gain variation with different frequency, and (c) efficiency variation with frequency.

effective lengths of slots are considered $\lambda_g/4$ instead of $\lambda_g/2$ to accommodate the slots in very compact size ground and to reduce the design complexity. When both slots are added together, the obtained return loss, VSWR (Voltage Standing Wave Ratio), gain characteristics, and efficiency variations are displayed in Figure 9. The band rejection notches are created at the center frequencies of 3.5 GHz and 5.5 GHz to mitigate the issue of interference. The gain is reduced to -2.7 dBi and -4.75 dBi at the WiMAX and WLAN notches, respectively, and a maximum gain of 2.6 dBi is acquired at 11 GHz, as shown in Figure 9(b). Due to the introduction of band notches at 3.5 GHz and 5.5 GHz, the gain is reduced at these two frequencies. In addition, at the reaming frequency band, the gain variation is positive and above 0 dBi. The efficiency of an antenna is reduced at band notch frequencies, as shown in Figure 9(c). The optimized antenna parameters are shown in Table 1.

To get an insight into antenna characteristics, the surface current distributions and normalized radiation pattern are shown in Figures 10 and 11, respectively, at resonating frequencies. Figure 10(b) shows the surface current distribution at band notch frequencies for WLAN and WiMAX. The current is mainly distributed in slots 1 and 2 and is responsible for the current disturbance and, thus, for the notch creation. The current flows around the periphery of the L-shaped slots, acting, in turn, as a resonator and preventing signal propagation. As can be noted from the current distributions shown at notch band frequencies, at a frequency of 3.5 GHz, maximum current is distributed around 3.5 GHz and it plays an essential role in the creation of WiMAX band notch. Moreover, the maximum current is flowing at the periphery of slot 2, resulting in a band notch for the WLAN at 5.5 GHz. At

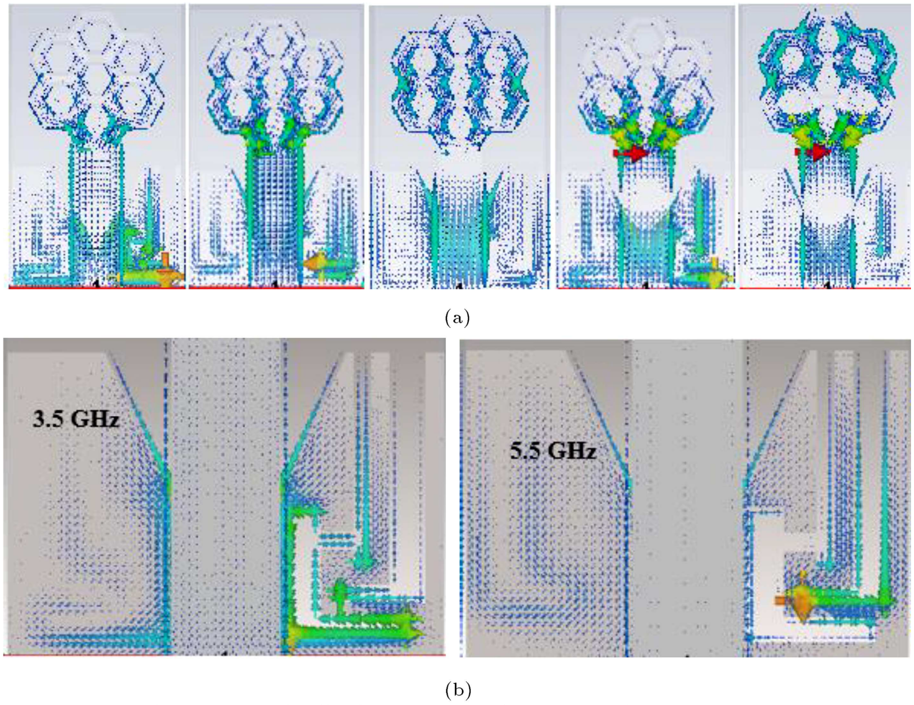


Figure 10. (a) Surface current distributions at resonating frequencies (3.2, 4.5, 8.7, 11.2, and 12.8 GHz). (b) Surface current distribution in slots at band notch frequencies.

Table 1. Optimized parameters of an antenna.

Parameters	Value (mm)	Parameters	Value (mm)
L	20	L_g	8.5
W	12	S_g	6.67
$W1$	3	l_3	8.2
L_1	10	l_h	2
W_2	0.3	L_2	1
W_3	0.5	l_1	1.4
t	0.5	l_2	2
l_4	1.5	l_5	6
l_6	3.5	l_7	3.7

higher frequencies, the current is flowing in the patch and responsible for the high frequency resonance.

In thermal equilibrium considering the collective effects of absorption, reflection, and emission in the case of practical materials, the universality of cavity radiation collapses. Radiation inside the cavity depends on the walls, external temperature, and frequency of observation. Thus, the frequency in a perfectly reflecting or arbitrary cavity may differ from that emitted from the ideal case. Emitted radiation pattern inside the considered hexagonal honeycomb cavity follows the back-and-forth wave propagation that depends on the honeycomb cavity wall [23]. Cavity radiation is detached from the nature of the cavity wall and some other external factors like temperature and frequency of observation if cavity walls are of symmetrical shape or plane nature. The contained radiation inside the cavity has the same radiation nature [24]. Observed simulated results of EM wave patterns at resonant frequencies, as shown in Figure 11, illustrate that the emitted radiation patterns are not symmetrically distributed in the hexagonal-shape cavity and they are dependent on the cavity wall of the mimicked honeycomb. Kirchhoff's law in terms of radiated emissive power (E) and absorptivity (a) is given as [25].

$$E = a.f\,(T,\nu)\,. \tag{3}$$

We know that the sum of emissivity (ε) and reflectivity (k) is always equal to 1 for all materials.

$$\varepsilon + k = 1.$$

However, this rule is also the validation of emissivity ε and absorptivity a [26,27]. Thus, we have:

$$a + k = 1,$$

or

$$a = 1 - k,$$

$$E = (1-k)\,.f\,(T,\nu)\,. \tag{4}$$

This equation contains reflectivity of cavity material that totally depends on the nature of the cavity's wall.

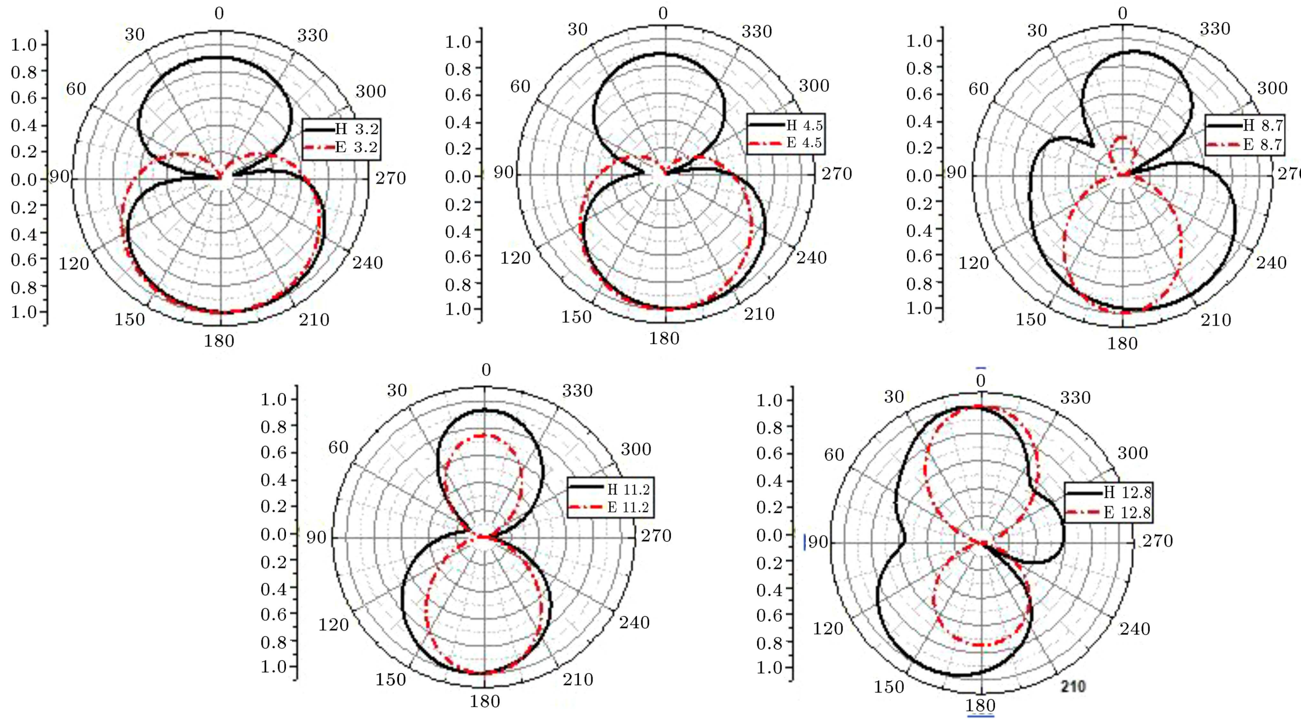


Figure 11. Radiation pattern at resonating frequencies (3.2, 4.5, 8.7, 11.2, and 12.8 GHz).

Table 2. Comparisons of the proposed work with the reported antenna.

Reference	**Size of antenna (in mm^2)**	**BW**	**Gain**
Ullah et al. 2017 [5]	97 × 7	14.337 GHz (25.347–39.684 GHz)	4.15 dBi (single antenna)
Desai et al. 2018 [6]	40 × 45	(1.31–6.81 GHz)	6.8 dBi
Bhatoa et al. 2016 [7]	80 × 80	11.85 GHz (Single frequency)	8.87 dBi
Aissaoui et al. 2016 [12]	39 × 36.5	(3.1–13.67 GHz) 10.57 GHz	Not given
Proposed design	**20 × 12**	**10.70 GHz (3.1–13.80 GHz) with dual notch**	**2.6 dBi**

Through Eq. (3), we can calculate the total emissive and absorptive power for the proposed geometry.

The simple geometry and compact size of antenna have achieved dual notch characteristics in addition to the very wide bandwidth of 10.7 GHz ($3.1 - 13.8$ GHz). The comparison between the proposed design and the reported work is shown in Table 2.

4. Conclusion

The compact honeycomb-shaped fractal antenna based on the concept of the initial stage of honeycomb nest construction with dual notch characteristics was presented for Ultra-Wideband (UWB) applications. The antenna obtained very wide bandwidth from 3.1 to 13.8 GHz with WiMAX and WLAN rejection notches at 3.5 GHz and 5.5 GHz, respectively. Stable radiation pattern and notch band characteristic make an antenna suitable for Ultra-Wide band (UWB) application with high immunity from the existing interference.

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Kanad Ray (Senior Member, IEEE) received the MSc degree in Physics from Calcutta University and the PhD degree in the same field from Jadavpur University, West Bengal, India. He has been a Professor of Physics and Electronics and Communication and is currently working as the Head of the Department of Physics, Amity School of Applied Sciences, Amity University Rajasthan (AUR), Jaipur, India. His current research areas of interest include cognition, communication, electromagnetic field theory, antenna and wave propagation, microwave, computational biology, and applied physics. He has been serving as an Editor for various Springer book series. He was an Associate Editor of the Journal of Integrative Neuroscience (The Netherlands: IOS Press).

Sanyog Rawat is presently affiliated with Electronics and Communication Engineering Department, Manipal University Jaipur. He has been into teaching and research for more than 16 years. He graduated with Bachelor of Engineering (BE) in Electronics and Communication, Master of Technology (MTech) in Microwave Engineering, and PhD in the field of Planar Antennas. He has published more than 80 research papers in peer-reviewed International Journals, Book series, and IEEE conferences. He has supervised nearly 30 MTech Dissertations and 05 PhDs and guiding 06 PhD scholars. He has organized several workshops, seminars, and national and international conferences. He has served as a member in the editorial board of various national and international Journals. His current research interests include reconfigurable RF printed circuits and passive and active microwave integrated circuits. He has visited countries like Japan, Thailand, Malaysia, UAE, and Indonesia for academic and research work. He is also a member of several academic and professional bodies, i.e., Senior Member IEEE, Life Member IE, and ISLE.