TEST Engineering & Management

May-June 2020
ISSN: 0193-4120 Page No. 6853 - 6858

Unraveling Substrate thickness Barrier in 5G Mid-Frequency Antenna Design

Shine Let G*, G Josemin Bala, L Diana Evangeline, C Benin Pratap
Karunya Institute of Technology and Sciences, Coimbatore, India
*Corresponding Author Email Id: shinelet@gmail.com

Article Info
Volume 83
Page Number: 6853 - 6858
Publication Issue:
May-June 2020

Article History
Article Received: *19 November 2019*
Revised: *27 January 2020*
Accepted: *24 February 2020*
Publication: *18 May 2020*

Abstract:
To integrate with the existing communication modules, an electrically small uniplanar antenna operating at 5G mid-frequency band (3.4 GHz to 3.8 GHz) is designed. FR4 is the commonly used substrate in printed circuit board and its thickness may be 0.8 mm or 1.6 mm. The uniplanar antenna designed for 1.6 mm substrate thickness can be used for 0.8 mm substrate thickness with 0.9 mm increase in feed length. The overall dimension of the designed antenna is 0.274λ x 0.204λ mm^2, where 'λ' is the resonant frequency at 3.5 GHz. The proposed antenna design in two different substrates provide a fractional bandwidth of 11 % with reasonable gain greater than 2 dBi and radiation efficiency greater than 95 % for the entire operating 5G mid-frequency band.

Keywords: *5G mid-frequency band, Antenna, Asymmetric Coplanar Strip, Radiation Efficiency, Slot antenna*

I. INTRODUCTION

FAST growing wireless networking and the need for high data rates for internet connectivity are eagerly awaiting the adoption of fifth generation (5G) technologies. The need for mobile data will increase, along with increased user mobility. International Telecommunication Union-Recommendation Sector (ITU-R) and third generation partnership project (3GPP) fix the spectrum resources for 5G, which are allocated for Internet-of-Things (IoT) applications, cellular communication, short-distance communication and fixed wireless services [1], [2]. In [2], 3.4 GHz to 3.6 GHz frequency band is globally suggested for the potential deployment of 5G in mobile communication. As per 3GPP, n77, n78 and n48 are the spectrum bands for 5G New Radio (5G-NR) which covers 3.4 GHz to 3.6 GHz frequency band centered at 3.5 GHz [3].

This paper provides the design studies of antenna on two different low profile substrate thicknesses of 0.8 mm and 1.6 mm operating at 5G frequency band. Since the communication system has multiple functional units in one board, the built antenna should be smaller in size by maintaining performance in terms of bandwidth, efficiency, gain, etc. The literatures have suggested antennas with different shapes, different feeding techniques to operate at 5G frequency band [4], [5], [6], [7], [8], [9], [10]. For a microstrip patch antenna design, the dimensions have to be fixed by considering the fabrication constraints [11], [12]. Microstrip feed, coaxial feed, coplanar waveguide (CPW) feed, asymmetric coplanar strip (ACS) feed etc. are the different feeding techniques used in antenna design to achieve a certain frequency band of operation [13]. For CPW and ACS feed, the antenna design occupies a single side of the substrate. This paves the way for a uniplanar antenna structure with compact size with no compromise in required bandwidth, efficiency and radiation characteristics [14].

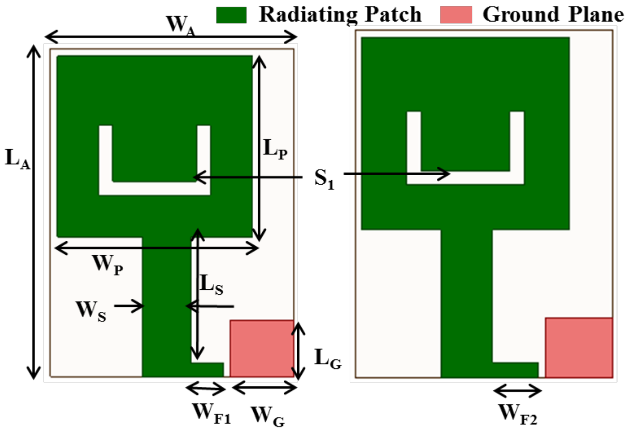
For the miniaturization of the antenna and to have good radiation efficiency, ACS feeding technique is considered in this paper. Along with feeding technique, slot structures are integrated into the

May-June 2020
ISSN: 0193-4120 Page No. 6853 - 6858

antenna design to accomplish miniaturization. Different shapes of slot such as open ended U-slot [14], E-shape slot [15], L-shape slots [10] are discussed in the literature. A short ended U-shape slot is deliberated in this paper. By introducing the slot in the patch, with electrically small size, the antenna can operate in 3.4 GHz to 3.8 GHz.

II. 5G MID-FREQUENCY ANTENNA DESIGN

The proposed slotted patch antenna is designed on a glass epoxy FR4 substrate having relative permittivity (ε_r) 4.4 and loss tangent 0.02. A commonly used substrate in integrated circuits is FR4, which has a thickness of either 1.6 mm or 0.8 mm. The substrate dielectric constant is invariably related to the designed antenna radiation efficiency. The slotted antenna designed for a substrate of thickness 1.6 mm can be used for a substrate of thickness 0.8 mm with a change in feed length. Fig. 1(a) and Fig. 1(b) show the antenna designed for a substrate of thickness 1.6 mm (Antenna$_{1.6}$) and 0.8 mm (Antenna$_{0.8}$) respectively.



(a) (b)

Fig. 1. Antenna with Substrate Thickness (a) 1.6 mm (b) 0.8mm

By tuning the feed length, the designed antennas are made to operate at 5G mid frequency communication band 3.4 GHz to 3.8 GHz, centered at 3.5 GHz. Fig. 2 shows the U-shape slot structure with dimensions. The overall dimension of the designed antenna is (0.274λ x 0.204λ) mm^2, where 'λ' is considered as the resonant frequency at 3.5 GHz.

Initially, the patch dimensions are considered based on the design of microstrip antenna described by Balanis [16]. The patch width and length obtained for substrate of thickness 1.6 mm are 26.08 mm and 18.519 mm respectively at the resonant frequency 3.5 GHz. Considering ACS feed and slot in the patch, dimensions of the designed patch is reduced almost by 30 % and is given by L_p x W_p mm^2.

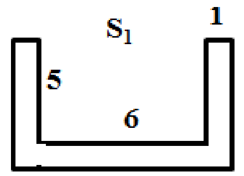


Fig. 2. Slot Structure with dimensions in millimeters (mm)

TABLE 1
Dimensions of antenna in millimeters (mm)

L_A	W_A	L_P	W_P	L_S
23.5	17.5	13	14	9
W_S	L_G	W_G	W_{F1}	W_{F2}
3.3	4	4.6	2.4	3.3

To easily integrate with the existing monolithic microwave integrated circuit, a uniplanar design is considered. An L-shape ACS feed is provided to the antenna. As antenna$_{1.6}$ feed length increases by 0.9mm, antenna$_{0.8}$ functions at the 5G mid frequency band. The width of the feedline (W) considered is same for both the antennas. Since the substrate thickness (h) is different, the characteristics impedance obtained based on Eq. (1) is 77.826Ω and 57.77Ω for antenna$_{1.6}$ and antenna$_{0.8}$ respectively [17].

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_{eff}}} ln\left(\frac{8h}{W} + \frac{W}{4h}\right), & \frac{W}{h} < 1 \\ \frac{377}{\sqrt{\epsilon_{eff}}\left[\frac{W}{h} + 1.393 + 0.667 ln\left(\frac{W}{h} + 1.444\right)\right]}, & \frac{W}{h} \geq 1 \end{cases} \quad (1)$$

For antenna$_{1.6}$, the ratio width of feedline to height of the substrate is less than one and the antenna$_{0.8}$ has a W/h ratio greater than one. Also, the antenna proposed to the requirements of electrically small antennas. For an electrically small antenna, the electrical length of the antenna (kr) should be less

May-June 2020
ISSN: 0193-4120 Page No. 6853 - 6858

than one [14], where k is the free-space wave number, given by $\frac{2\pi}{\lambda}$ and 'r' represents the minimum radius of an imaginary sphere which encloses the designed antenna including the radiating patch and the ground plane [18]. Here L_A represents the maximum dimension of the antenna. From L_A, the approximate minimum radius which covers the entire antenna is given by $0.55L_A$. The electrical length of the designed antenna for the resonant frequency is $kr = 0.9474 < 1$, thus by definition the proposed antennas are electrically small. Relation between size of the antenna and the lower bound radiation quality factor (Q_{LB}) is given in Eq. (2). Q_{LB} obtained is 2.231. As Q_{LB} increases, the antenna operating bandwidth decreases.

$$Q_{LB} = \frac{1}{kr} + \frac{1}{(kr)^3} \tag{2}$$

Fractional bandwidth of 11 % is obtained for the operating frequency range 3.4 GHz to 3.8 GHz. A U-shape short-ended slot is introduced in the radiating patch, along the feed line to achieve the desired operating frequency band. Total length of the slot structure is 16 mm. Without a slot structure, the antenna operates at a frequency band higher than the desired band. When the slot structure is introduced near the feed line, the amount of fringing from the slot influences the resonant frequency of the antenna. Also, the current distribution of the antenna is altered.

More comprehension and study of the functioning of the proposed antenna is achieved by portraying surface current distributions at 3.5 GHz as shown in Fig. 3 and Fig. 4. The figures show the current distribution of $antenna_{0.8}$ and $antenna_{1.6}$ with and without a slot structure. Therefore, the appropriate 5G mid frequency band is obtained by the incorporation of a slot structure. An electrically small antenna size is also obtained by the use of the slot structure. Table. 1 provides the dimensions of the designed antenna. Using parametric analysis, the optimum width and length for the patch, slot and ground structure are decided.

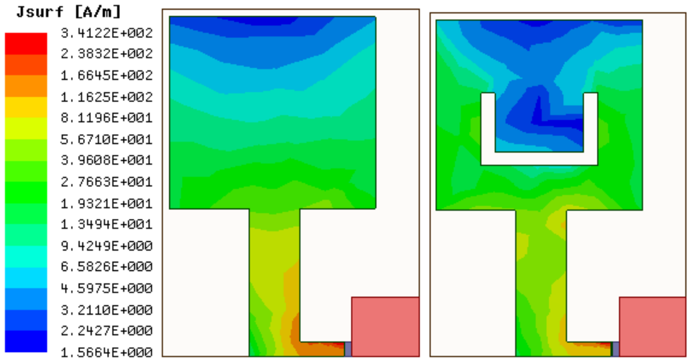


Fig. 3. Current Distribution of $Antenna_{0.8}$ without and with slot structure

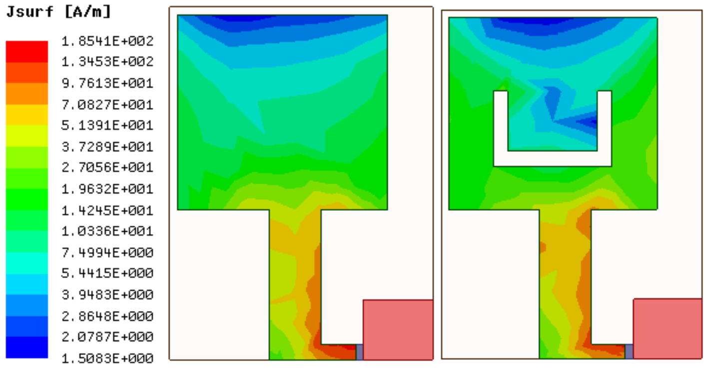


Fig. 4. Current Distribution of $Antenna_{1.6}$ without and with slot structure

III. RESULTS AND DISCUSSIONS

The proposed antenna simulations are carried out using Ansys HFSS software.

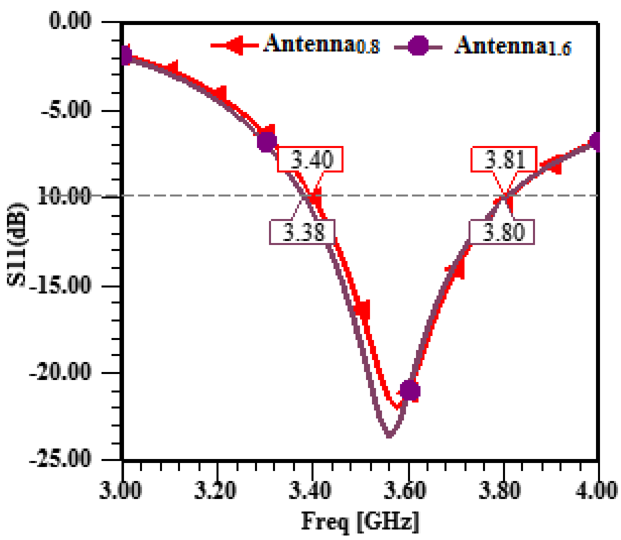


Fig. 5. Reflection Coefficient of the proposed antenna

Simulated reflection coefficient (S11) for the designed $antenna_{0.8}$ and $antenna_{1.6}$ are shown in

May-June 2020
ISSN: 0193-4120 Page No. 6853 - 6858

Fig.5. The structure designed for the two antennas is the same, except for the feed length. The $antenna_{0.8}$ operates at the frequency range from 3.4 GHz to 3.81 GHz and $antenna_{1.6}$ has the operating frequency range 3.38 GHz to 3.8GHz. The frequency range is determined at S11 = -10dB, this indicates that almost 90 percent of the signal fed to the antenna is transmitted without reflection. S11 is related to voltage standing wave ratio (VSWR) as (1+S11) / (1-S11). Fig. 6 depicts the VSWR versus frequency characteristics for the designed antennas. The prerequisite bandwidth 400 MHz proposed for global 5G mid-frequency band is achieved without any constraint in the FR4 substrate thickness.

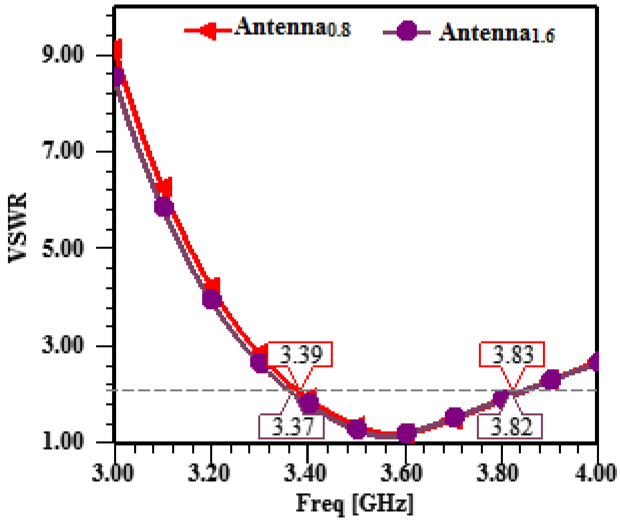


Fig. 6. VSWR of the proposed antenna

A. Gain and Efficiency

Gain is another useful parameter describing the performance of the designed antenna. It indicates how much input signal given to the antenna is radiated as radio waves. The designed antennas have reasonable gain from 2.02 dBi to 2.18 dBi for the entire 3.4 GHz to 3.8 GHz operating range, and are shown in Fig. 7. Gain of the antenna is directly related to directivity and radiation efficiency of the antenna. Radiation efficiency also deals with the ratio of the amount of power radiated to the accepted power from the transmission circuit. The radiation efficiency attained for the entire operating band is depicted in Fig. 8. For $antenna_{0.8}$ and $antenna_{1.6}$, the achieved radiation efficiency is between 95 % and 99 %. This proves that the designed antennas transmit the signal with minimum loss at 5G mid-frequency band.

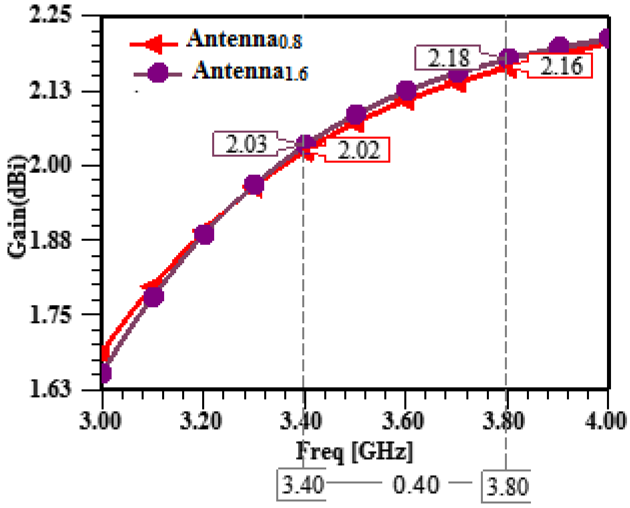


Fig. 7. Gain Vs Frequency

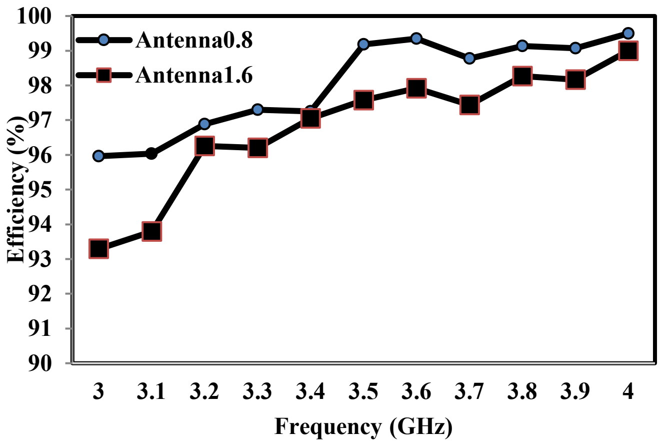


Fig. 8. Efficiency Vs Frequency

B. Radiation Pattern

The simulated two dimensional radiation patterns of $antenna_{0.8}$ and $antenna_{1.6}$ in both principal planes at 3.5 GHz are shown in Fig. 9 and Fig. 10 respectively. At ϕ = 90º (XZ- plane), both the antennas show the omnidirectional radiation pattern. A figure of '8' pattern is presented at ϕ = 0º (YZ - plane). The three dimensional gain plots at 3.5 GHz are shown in Fig. 11for $antenna_{0.8}$ and $antenna_{1.6}$.

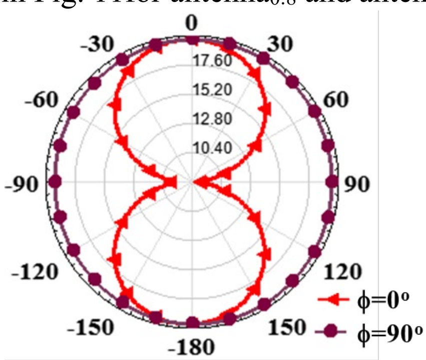


Fig. 9. Radiation Pattern of $Antenna_{0.8}$ at 3.5 GHz

May-June 2020
ISSN: 0193-4120 Page No. 6853 - 6858

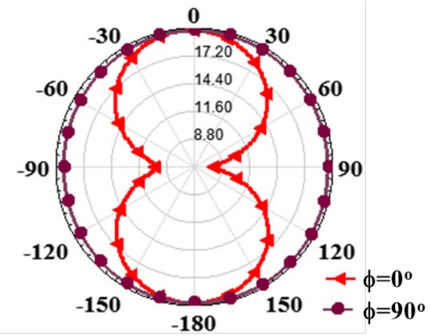
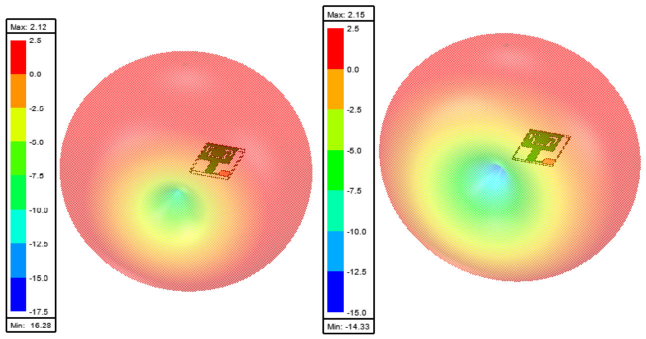


Fig. 10. Radiation Pattern of $Antenna_{1.6}$ at 3.5 GHz


(a) (b)
Fig. 11. 3D Polar plot at 3.5 GHz (a) $Antenna_{0.8}$ (b) $Antenna_{1.6}$

The proposed antenna performance is compared with the existing state-of-the-art literatures and is shown in Table 2. Most of the literatures provide any one analysis either peak gain or radiation efficiency of the antenna. For mobile hand-held device applications, the designed antenna is electrically small in size and provides gain and efficiency greater than 2 dBi and 95 % respectively as per the requirement.

TABLE 2
Comparison of proposed design with existing work

Year, References	**Antenna Size (mm^2)**	**Resonant Frequency (GHz)**
2019, [7]	25.2 x 48	3.5
2019, [10]	25 x 19	3.5
2019, [19]	32 x 37.2	3.5
2020, [15]	25.4 x 19.4 (Patch)	3.5
2020, [20]	154 x 100	3.701
Proposed	23.5 x 17.5	3.5

one		

IV. Conclusion

An electrically compact, ACS-fed uniplanar antenna is developed for mobile handheld devices, which can operate at 5G mid-frequency band. The antenna design structure opted is effectively used for FR4 substrate with thickness 0.8 mm and 1.6mm with change in feed length. $Antenna_{0.8}$ and $antenna_{1.6}$ have the fractional bandwidth 11 %, gain greater than 2 dBi and radiation efficiency greater than 95 % for the entire operating frequency range 3.4 GHz to 3.8 GHz. In both azimuth and elevation planes, stable radiation pattern is obtained. This paper unravels the barrier in using different substrate thickness for the similar antenna dimensions and design considered.

REFERENCES

1. G. Kang, H. Liu, and K. Li, "Analysis on the New Progress of Spectrum Planning of IMT-2020(5G)," J. Phys. Conf. Ser., vol. 1437, no. 1, pp. 1–8, 2020.
2. A. Ghosh, "5G New Radio (NR) : Physical Layer Overview and Performance," IEEE Communication Theory Workshop. p. 38, 2018.
3. 3GPP TS 38.101-1 version 15.2.0 Release-15, "5G-NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone," 2018.
4. A. K. Arya, S. J. Kim, and S. Kim, "A dual-band antenna for LTE-R and 5G lower frequency operations," Prog. Electromagn. Res. Lett., vol. 88, no. August 2019, pp. 113–119, 2019.
5. D. PARAGYA and H. SISWONO, "3.5 GHz Rectangular Patch Microstrip Antenna with Defected Ground Structure for 5G," ELKOMIKA J. Tek. Energi Elektr. Tek. Telekomun. Tek. Elektron., vol. 8, no. 1, pp. 31–42, 2020.
6. Z. An and M. He, "A Simple Planar Antenna for Sub-6 GHz Applications in 5G Mobile Terminals," ACES J., vol. 35, no. 1, pp. 10–15, 2020.
7. N. Ferdous, G. Chin Hock, H. A. S. Hamid, M. N. A. Raman, T. Sieh Kiong, and M. Ismail, "Design of a Small Patch Antenna at 3.5 GHz for

5G Application," IOP Conf. Ser. Earth Environ. Sci., vol. 268, no. 1, pp. 1–4, 2019.
8. J. Guo, L. Cui, C. Li, and B. Sun, "Side-Edge Frame Printed Eight-Port Dual-Band Antenna Array for 5G Smartphone Applications," IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 7412–7417, 2018.
9. Y. L. Ban, C. Li, C. Y. D. Sim, G. Wu, and K. L. Wong, "4G/5G Multiple Antennas for Future Multi-Mode Smartphone Applications," IEEE Access, vol. 4, pp. 2981–2988, 2016.
10. S. Chetal, A. K. Nayak, and R. K. Panigrahi, "Multiband antenna for WLAN, WiMAX and future wireless applications," in 2019 URSI Asia-Pacific Radio Science Conference, 2019, no. March, pp. 3–6.
11. D. Alvarez Outerelo, A. V. Alejos, M. Garcia Sanchez, and M. Vera Isasa, "Microstrip antenna for 5G broadband communications: Overview of design issues," IEEE Antennas Propag. Soc. Symp., vol. October, pp. 2443–2444, 2015.
12. W. Hong, "Solving the Antenna Puzzle," IEEE Microw. Mag., vol. 18, no. 7, pp. 86–102, 2017.
13. P. V. Naidu, A. Kumar, and R. Rajkumar, "Design, analysis and fabrication of compact dual band uniplanar meandered ACS fed antenna for 2.5/5 GHz applications," Microsyst. Technol., vol. 25, no. 1, pp. 97–104, 2019.
14. M. I. Magray, G. S. Karthikeya, K. Muzaffar, and S. K. Koul, "Electrically small acs-fed flipped mimo antenna for usb portable applications," Prog. Electromagn. Res. C, vol. 95, no. July, pp. 141–152, 2019.
15. V. P. Kodgirwar, S. B. Deosarkar, and K. R. Joshi, "Design of adaptive array with E-shape slot radiator for smart antenna system," Prog. Electromagn. Res. M, vol. 90, no. December 2019, pp. 137–146, 2020.
16. C. A. Balanis, Antenna Theory - Analysis and Design. John Wiley & Sons, 2016.
17. D. M. Pozar, Microwave Engineering, Fourth Edi. John Wiley & Sons, 2012.
18. A. D. Yaghjian and S. R. Best, "Impedance, Bandwidth, and Q of antennas," IEEE Trans. Antennas Propag., vol. 53, no. 4, pp. 1298–1324, 2005.
19. U. Patel and T. Upadhyaya, "Design and analysis of μ-negative material loaded wideband electrically compact antenna for WLAN/WiMAX applications," Prog. Electromagn. Res. M, vol. 79, no. December 2018, pp. 11–22, 2019.
20. K. M. Smitha, K. K. Aju John, and T. Mathew, "CPW fed SRR loaded monopole antenna for triple band operations," Int. J. Electr. Comput. Eng., vol. 10, no. 3, pp. 3145–3151, 2020.