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Design and Performance Comparison of Metamaterial Based Antenna for 4G/5G Mobile Devices

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***Abstract*—**This paper presents the design and performance evaluation of multiband metamaterial based antenna operating in the 3.6 GHz (4G), 14.33 GHz, and 28.86 GHz (5G) frequency bands, for future mobile and handheld devices. The radiating element of the proposed design is made up of a conductive material supported by a 1.524 mm thicker Rogers-4003 substrate, having a relative dielectric constant and loss tangent of 3.55 and 0.0027, respectively. The substrate is backed by truncated ground plane. The future mobile communication system is based on higher frequencies, which are highly affected by the atmospheric conditions. Therefore, to overcome the path loss problem, essential enhancements and improvements must be made in the overall performance of the antenna. The traditional ground plane does not provide the in-phase reflection and surface wave suppression due to which side and back lobes are produced. This will affect the antenna performance in terms of gain and efficiency. To enhance the overall performance of the antenna, a metamaterial acting as a high impedance surface (HIS) is used as a reflector in the proposed design. The simulated gain of the metamaterial based antenna is enhanced from {2.76-6.47, 4.83-6.71 and 7.52-7.73} dB at 3.6, 14.33 and 28.89 GHz, respectively relative to the gain of the antenna backed by a traditional ground plane. The proposed antenna radiated efficiently with a radiated efficiency (>85 %) in all the three frequency bands with and without metamaterial surface. The total volume of the antenna is (L x W x h=45 x 40 x 1.524) mm^3. The antenna can be potentially used for wireless handheld devices and mobile terminal. All the simulations have been performed using the Computer Simulation Technology (CST) software.

***Keywords*—**Multiband, fourth generation (4G), fifth generation (5G), metamaterial, CST MWS.

I. INTRODUCTION

THE mobile communication system is developing at a very fast rate, and is progressing from 1G, 2G, 3G, and now 4G installed in the market for viable use. The major difference between the various generation of wireless communication is the enhancement in bandwidth and data rate day by day from kbps to Mbps and now targeting the Gbps. Recently, the fourth generation (4G) mobile devices have arrived in the market and launched in many countries to meet the higher bandwidth and higher data rate requirements. The evaluation of 4G technologies has enhanced the bandwidth requirements up to 100 MHz [1], but the upward rise in mobile data approaches the boundaries of 4G technologies. This constraint headed towards the next generation broad band wireless and mobile communication i.e. fifth generation (5G) and explain, develop and systemized system and services for this next generation [2]. Due to the overcrowding of frequencies used by the existing wireless networks and the availability of a large proportion of the unused spectrum of centimeter and millimeter wave spectrum (3-300 GHz) [3], the future 5G based mobile communication will utilize higher frequencies in the spectrum [4], which will enable it to provide a very high bandwidth and multi-Gigabit-per-second (Gbps) data rates to mobile communications [5]. But, moving towards the higher frequencies led to a new challenge like free space path loss [6] as higher frequencies are much sensitive to atmospheric attenuations [7]. To overcome this problem, one way is to make the antenna highly directive [8]. As the wireless communication system is becoming more diverse, there is a need for the multi-mode mobile devices. Thus, for future mobile devices, multiband antennas are becoming the most vital component [9].

The conventional ground plane does not deliver the in-phase reflection; and as a result, the performance of the antenna in terms of gain, directivity, and radiation efficiency is significantly affected. Recently, the antenna engineers have been attracted by new material called metamaterial surfaces [10]. These are artificially engineered material which have unique properties of electromagnetism that does not occur in natural surroundings [11]-[15]. These surfaces provide both the in-phase reflection and surface wave suppression within a specific frequency band. Therefore, in the design of antennas when these particular surfaces are used as a ground plane, the overall performance of the antenna is enhanced very much [16].

Different types of antennas incorporated with metamaterial surfaces for various applications have been reported in the past. A dual band antenna covering 9.25 GHz and 11 GHz frequency bands with a square loop Frequency Selective Surface (FSS) for gain enhancement is presented in [11]. An Electromagnetic Bandgap (EBG) structure in combination with 5G antenna covering the 15 GHz frequency band is used to suppress the side and back lobe radiations in the direction of human body [12]. Similarly, a microstrip patch antenna covering the 5.2 GHz frequency band integrated with a Double Negative (DNG) metamaterial surface is reported in [13], to enhance the overall performance of the antenna. In [14], a phased array antenna was presented for Fifth Generation (5G) applications. The frequency band covered was 28 GHz, and Metamaterial Circular Split Ring Resonator

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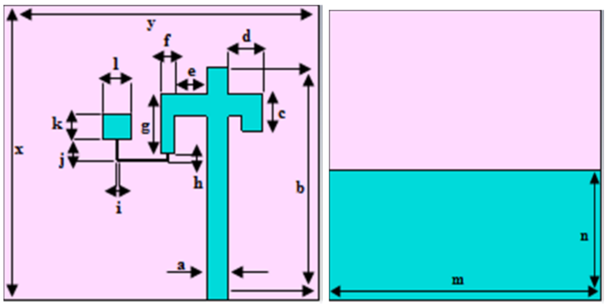
(CSRR) used to enhance the gain and directivity of the antenna. A metamaterial based dual frequency band antenna for LTE and WiMAX applications is presented in [15] to enhance the overall antenna performance. In this paper, a 4G/5G multiband antenna is proposed, its performance is analyzed using metamaterial surface as a reflector, and the significance of the metamaterial structure is clearly observed. The proposed antenna covers the widely used 4G (3.60 GHz) and 5G (14.33 GHz and 28.86 GHz) standard frequency bands.

The remaining paper is structured as follows: the main design layout and methodology of the recommended antenna is discussed in Section II. Section III presents the detailed discussion of the performance of the designed antenna without metamaterial surface. The design methodology of the metamaterial surface is discussed in Section IV. Also, the performance comparison of the proposed antenna with and without metamaterial surface has been argued in this section. Section V portraits the concluding remarks of the paper.

II. ANTENNA DESIGN

A. Traditional 4G/5G Antenna

Fig. 1 shows the geometry of the proposed multi band antenna, having an operating frequency of 3.6, 14.33, and 28.86 GHz. The design and simulation of the antenna is carried out in CST MWS. A low loss 1.524 mm thicker Rogers-4003 is chosen as a substrate material, having relative dielectric constant of 3.55 and loss tangent of 0.0027. The total volume of the proposed antenna is $L\times W\times h = 45\times 40\times 1.524\ \text{mm}^3$. To achieve the optimum gain and efficiency, the antenna is supported by a truncated ground plane.



(a) (b)

Fig. 1 Geometrical layout of the designed antenna (a) front view (b) back view

The dimensions of the designed antenna (Fig. 1), summarized in Table I, are considered by using transmission line theory [17]. The resonant lengths for desired frequencies in terms of guided wavelengths $\lambda_{3.6}$, $\lambda_{14.33}$, and $\lambda_{28.86}$, are found using the following equations:

$$L_{3.6} = {}^{\lambda_{3.6}}/_{4} \tag{1}$$

$$L_{14.33} = {}^{\lambda_{14.33}}/_{4} \tag{2}$$

$$L_{28.86} = {}^{\lambda_{28.86}}/_{4} \tag{3}$$

At the resonant frequency, the guided wavelength can be calculated by:

$$\lambda_{fr} = \frac{C}{f_r\sqrt{\varepsilon_{eff}}} \tag{4}$$

where C is the velocity of light, f_r is the resonant frequency, and ε_{eff} is the effective permittivity, given by:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{5}$$

where h is the thickness of substrate, W is the width of radiating element, and ε_{eff} is the effective relative permittivity,

TABLE I
SUMMARY OF THE DIMENSIONS OF THE DESIGNED ANTENNA

Parameter	Value (mm)	Parameter	Value (mm)
a	3	i	0.1
b	31.5	j	3
c	5	k	3.4
d	5	l	4
e	4.5	m	45
f	2	n	18
g	8	x	40
h	1.1	y	45

III. RESULTS AND DISCUSSION

A. Return Loss

The return loss versus frequency of the proposed multiband 4G/5G antenna is depicted in Fig. 2. The designed antenna is investigated using Finite Integration Technique (FIT) [18], used in CST MWS. The return loss of the proposed multiband 4G/5G antenna is -42 dB, -28.35 dB, and -35.87 dB at 3.6 GHz, 14.33 GHz and 28.86 GHz, respectively. The antenna resonates with a -10dB bandwidth of 0.57 GHz, 1.68 GHz, and 3.94 GHz at 3.6 GHz, 14.33 GHz and 28.86 GHz, respectively. It can be evident from the return loss that the antenna resonates at three frequency bands i.e. 3.6 GHz, 14.33 GHz, and 28.86 GHz, respectively. The 3.6 GHz frequency band is used for 4G, while, the rest of the two frequency bands are used for 5G cellular communication systems.

B. Voltage Standing Wave Ratio (VSWR)

Fig. 3 shows the VSWR of the proposed multiband 4G/5G antenna. The designed antenna has VSWR less than 1.1 for all the three resonant frequencies which displays good matching of the antenna being proposed. The simulated VSWR is 1.01, 1.07, and 1.04 at 3.6 GHz, 14.33 GHz, and 28.86 GHz, respectively.

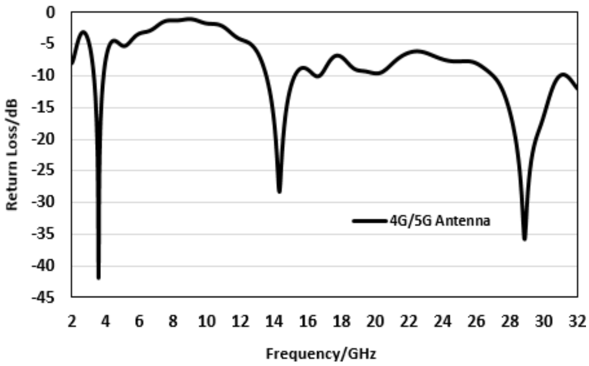


Fig. 2 Simulated return loss for the proposed 4G/5G antenna

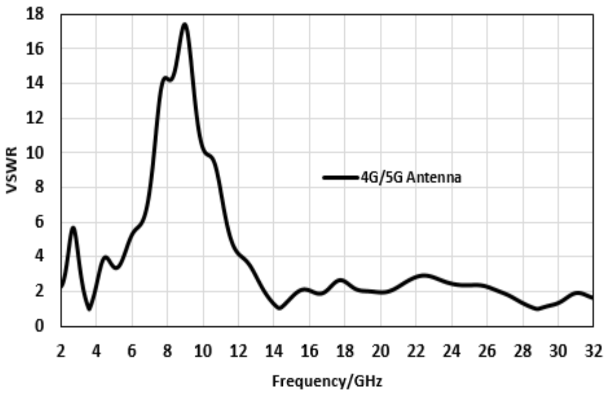
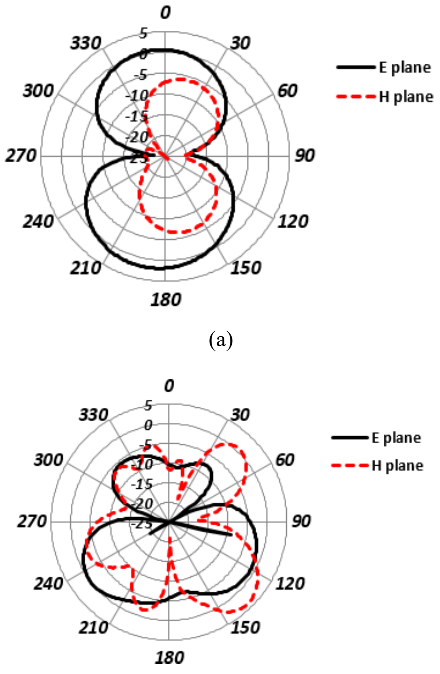


Fig. 3 VSWR of the proposed 4G/5G antenna

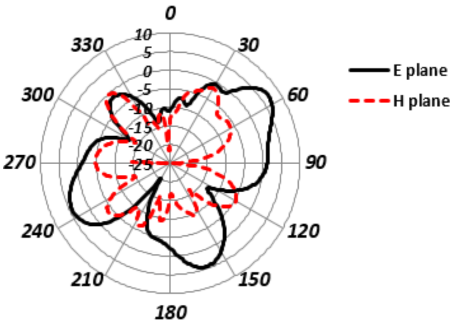
C. Radiation Pattern (2D Plots)

Gain pattern of the multiband 4G/5G antenna at 3.6 GHz, 14.33 GHz and 28.86 GHz is shown in Fig. 4.



(a)

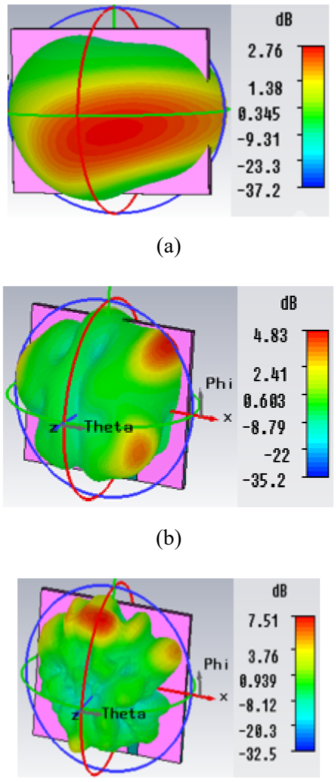
(b)



(c)

Fig. 4 2D polar gain patterns of 4G/5G antenna (a) 3.6 GHz (b) 14.33 GHz (c) 28.86 GHz

D. Radiation Pattern (3D Plots)



(a)

(b)

(c)

Fig. 5 3D gain patterns of the designed antenna at (a) 3.6 GHz (b) 14.33 GHz (c) 28.86 GHz

The 2D and 3D radiation patterns in Figs. 4, 5 show that the multiband 4G/5G antenna provides a peak gain of 2.76, 4.83, and 7.51 dB at 3.6, 14.33 and 28.86 GHz, respectively.

The designed 4G/5G antenna radiates efficiently (93.7, 91.4 and 88.3 %) at 3.6, 14.33 and 28.86 GHz, respectively.

IV. METAMATERIAL BASED 4G/5G ANTENNA

This segment covers the designing of Mushroom like metamaterial surface and its performance comparison with 4G/5G antenna.

A. Design Methodology of Metamaterial Unit Cell

Fig. 6 presents the geometry of mushroom like unit cell using a Rogers-4003 as a substrate with a thickness of 0.203 mm, backed by a finite ground plane. A Sievenpiper's [19], [20] square form model is used to design mushroom like unit cell.

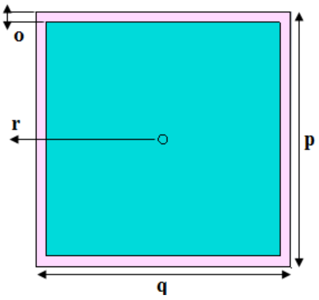


Fig. 6 Geometry of mushroom like EBG unit cell

Effective capacitance (C) and inductance (L) are the two dependent variables of the resonant frequency (f_r) of the unit cell, i.e.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

$$C = \frac{w\varepsilon_o(1+\varepsilon_r)}{\pi}\cosh^{-1}\frac{a}{g} \tag{7}$$

$$L = \mu_o h \tag{8}$$

where ε_o is the permittivity of vacuum, g is the gap between the adjacent unit cells and w is the width of the unit cell, while μ_o is the permeability of free space. The summary of the parameters of the proposed mushroom EBG unit cell is illustrated in Table II.

TABLE II
SUMMARY OF THE PARAMETERS OF THE EBG UNIT CELL

Parameter	Value (mm)	Parameter	Value (mm)
o	0.45	q	5.6
p	5.6	r	0.1

B. 4G/5G Antenna Backed by Metamaterial Surface

The 4G/5G antenna is backed by an 8 x 8 metamaterial surface as shown in Fig. 7. The metamaterial surface is used as a reflector in the proposed design to enhance the overall performance of the antenna, and is placed at 0.447λ$_0$ away from the designed 4G/5G antenna. Where λ$_0$ is the free space wavelength.

Return loss of 4G/5G antenna with and without metamaterial surface is shown in Fig. 8. As it can be seen in Fig. 8, that the value of return loss is below -10 dB at all the three desired resonance frequencies which shows that antenna is efficient with and without metamaterial surface.

Fig. 9 shows the voltage standing wave ratio (VSWR) of antenna with and without metamaterial surface. It is observed that, at all the three resonant frequencies, VSWR is less than 1.1 which shows the good matching of proposed antenna with and without metamaterial surface.

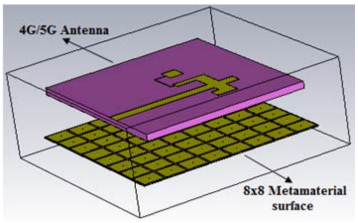


Fig. 7 4G/5G antenna backed by an 8x8 metamaterial surface

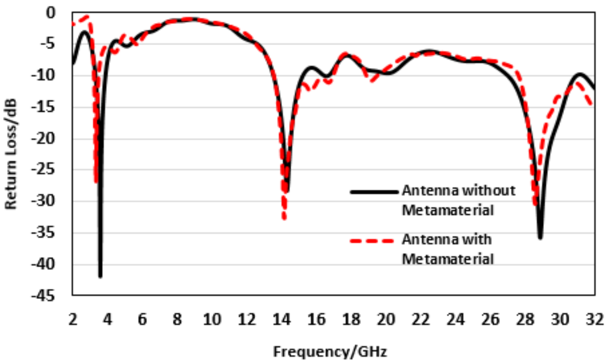


Fig. 8 Return loss comparison of the 4G/5G antenna with and without using metamaterial surface

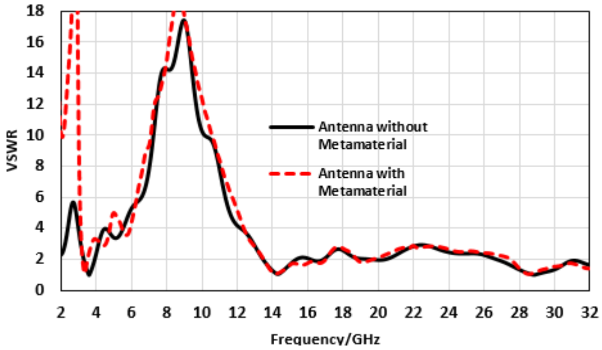
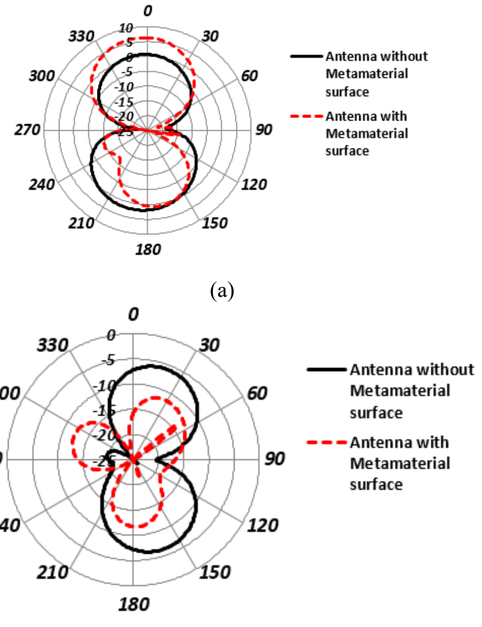


Fig. 9 VSWR comparison of 4G/5G antenna with and without metamaterial surface

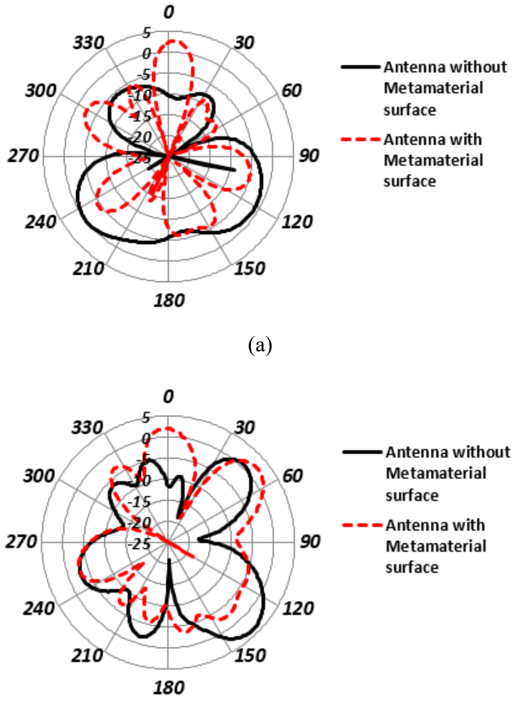
Gain plots of 4G/5G antenna with and without metamaterial surface at all the three desired resonant frequencies are given in Figs. 10-12. A good improvement has been observed in gain by using metamaterial surface from {2.76-6.47, 4.83-6.71 and 7.52-7.73} dB at 3.6, 14.33 and 28.89 GHz, respectively relative to the gain of the antenna backed by a traditional ground plane.



(a)

(b)

Fig. 10 Simulated 2D gain comparison of the designed antenna with and without metamaterial surface at 3.6 GHz in (a) E-plane and (b) H-plane

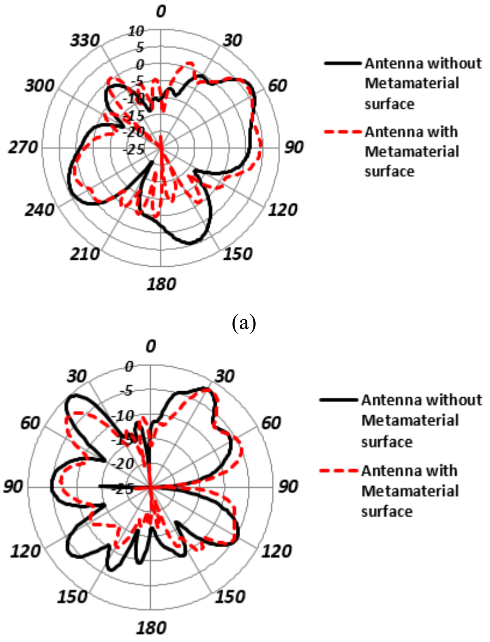


(a)

(b)

Fig. 11 Simulated 2D gain comparison of the designed antenna with and without metamaterial surface at 14.33 GHz in (a) E-plane and (b) H-plane

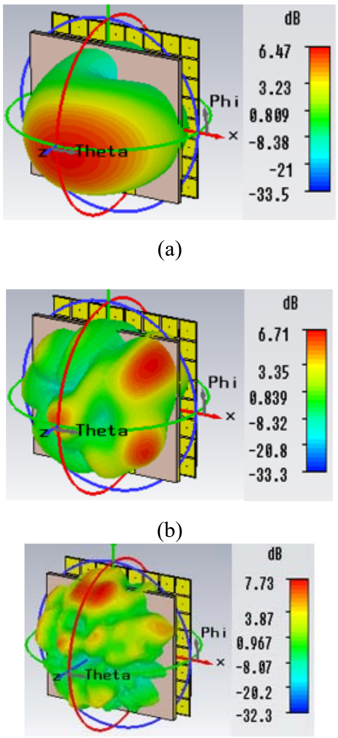
The 3D gain pattern of the 4G/5G antenna with metamaterial surface at the desired resonant frequencies is shown in Fig. 13.



(a)

(b)

Fig. 12 Simulated 2D gain comparison of the designed antenna with and without metamaterial surface at 28.86 GHz in (a) E-plane and (b) H-plane



(a)

(b)

(c)

Fig. 13 3D gain patterns of the designed antenna with metamaterial surface (a) 3.6 GHz (b) 14.33 GHz (c) 28.86 GHz

The metamaterial based antenna radiated efficiency is 86.6, 85.9 and 90 % at 3.6, 14.33 and 28.86 GHz, respectively.

V. CONCLUSION

In this work, the design and performance evaluation of the multiband metamaterial based antenna was proposed and analyzed. A 1.524 mm thicker low loss dielectric material (Rogers-4003) was used as a substrate in the design of the antenna as well as in the metamaterial surface. The overall performance of the proposed antenna was enhanced using metamaterial surface as a reflector. A significant improvement in the gain of the antenna using metamaterial surface was observed. The antenna with metamaterial ground plane radiates with more gain and efficiency in all the three bands. The size of the antenna is such that it can be used in mobile and handheld devices. The antenna can be fabricated and measurements will be taken to validate the simulated results.

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