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Reconfigurable Wide Bandwidth Using Novel Extraction Technique of Slotted Monopole Antenna with RF CNT Network

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Abstract

This work first moment focuses on the concept of reconfigurable wide bandwidth using novel extraction technique of slotted monopole antenna with RF carbon nanotube (CNT) network. The entire approach is folded into four different designs. The first design proposes a monopole antenna where asymmetric flower type corners and mushroom shape encloses by T-slot is cut on the patch. This new shaped antenna covers wide impedance bandwidth of about 14.5 GHz within range from 21.5 to 36 GHz. The proposed antenna observed that lower bands are excited with new resonating modes by inserting T-slot upon mushroom shape while higher bands are effected due to asymmetric flower type corners on the patch. A wide range of gain from 16.3 to 20.5 dB with maximum axial ratio bandwidth of 2.8% is also succeed. Measured and simulation results for proposed antenna shows good agreement with each other. In second design, a novel extraction technique is used for equivalent model of slotted monopole antenna which shows promising agreement with the original geometry. Thirdly, introduces RF CNT equivalent model which demonstrates its ability to resonant at wideband within range of 12.4–25.1 GHz with 68% of fractional impedance bandwidth. Finally, RF equivalent model of slotted monopole antenna is integrated with CNT for the proper operation. The fabrication of integration network scenario proves notability of reconfiguration in aspect of wide bandwidth with the compactness. A frequency switchable notability dominant some excited additional resonant modes using proper impedance matching between proposed antenna and RF CNT. This proposed work is fascinating to our integration network which fully covered K-band and almost for Ka-band application.

Keywords Reconfigurable antenna · RF CNT · Integration network · Microstrip bend

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1 Introduction

Nowadays high frequency reconfigurable antennas have showing interest in the field of navigation based communication where Ka and K bands are used for radar detector applications. It is well known that the capability of reconfigurable antennas changing their resonant frequency and operate at specific band along the multi-serviced radio spectrum. It requires less area for antenna terminals, therefore they are more versatile for wireless devices. Such capability is also of interest for cognitive radio systems [1]. Significant research on frequency agile antennas were reported in the last few years such as in [2–10]. In [2, 3], the varactor diodes are embedded into radiating edges of patch antenna and to allow for electronic tuning, whereas in [4] a PIN diode switch controls the length of the current path on the patch surface, producing feature of frequency reconfigurability. Both methods have been employed together to a differential-fed patch antenna for a wider tuning range [5]. Like that, a report on the frequency agile PIFA antennas also published in [6, 7]. Moreover, a switchable matching circuit is used to reconfigure an antenna frequency band upon tuning its circuit components for modifying the antenna aperture [8, 9]. A frequency switchable wide bandwidth of 6.5–14.7 GHz monopole antenna using PIN diode is reported for wireless applications [10]. The reconfigurable antenna is also very valuable for many modern wireless communications such as secure communications, multi-frequency communications, vehicle speed tests and so on [8, 11]. The reconfigurable ability of antenna with the extraction technique of its equivalent model still not reported by any researcher or scientist. An extracted technique for equivalent model of slotted antenna can provide passive networks which is useful for observation of its internal behavior. Previously several authors found many solutions for extraction passive networks of the slotted microstrip antennas such as transmission line model, smith chart analysis etc. [12, 13]. In addition to this, recently carbon nanotubes are embedded within slotted antenna is an emerging technique which introduced tuning effects in frequency band of operation. The robust stability of CNT further improves device reliability in harsh environment with wide process compatibility for integration with dissimilar materials in aspect of mechanical and electrical [14]. A CNT model incorporation with passive networks offers numerous opportunities and enabling novel applications.

In this work, switch wide frequency bandwidth using novel extraction technique of proposed antenna with CNT model is presented. The extraction equivalent model of antenna is integrated with CNT model which demonstrates reconfigurability whose frequency ranging from 18 to 33 GHz. The paper is organized as follows: Sect. 2 describes design consideration of proposed antenna with the extraction mechanism of its equivalent model while parametric studies of antenna with simulated and measured results are given in Sect. 3. A reconfigurable mechanism of proposed antenna with the CNT model is explained in Sect. 4 and finally conclusion is followed by Sect. 5.

2 Design Consideration and Extraction Mechanism

It is well known that antennas could be convert itself behavior into passive networks with the circuit applications. This section comprises into two Sects. 2.1 and 2.2 respectively. Section 2.1 involves proposed antenna design specifications using its layout geometry. While in Sect. 2.2 gives description about extraction technique for equivalent model of proposed antenna.

2.1 Antenna Structure and Design

The geometry of proposed antenna design is shown in Fig. 1a, b respectively. The construction consists of rectangular monopole antenna where cutting of asymmetric flowers type corners with mushroom shape encloses by T-slot on the patch is used. The antenna design is implemented on rogers RTduriod5870 substrate having thickness (hs) of 0.762 mm,

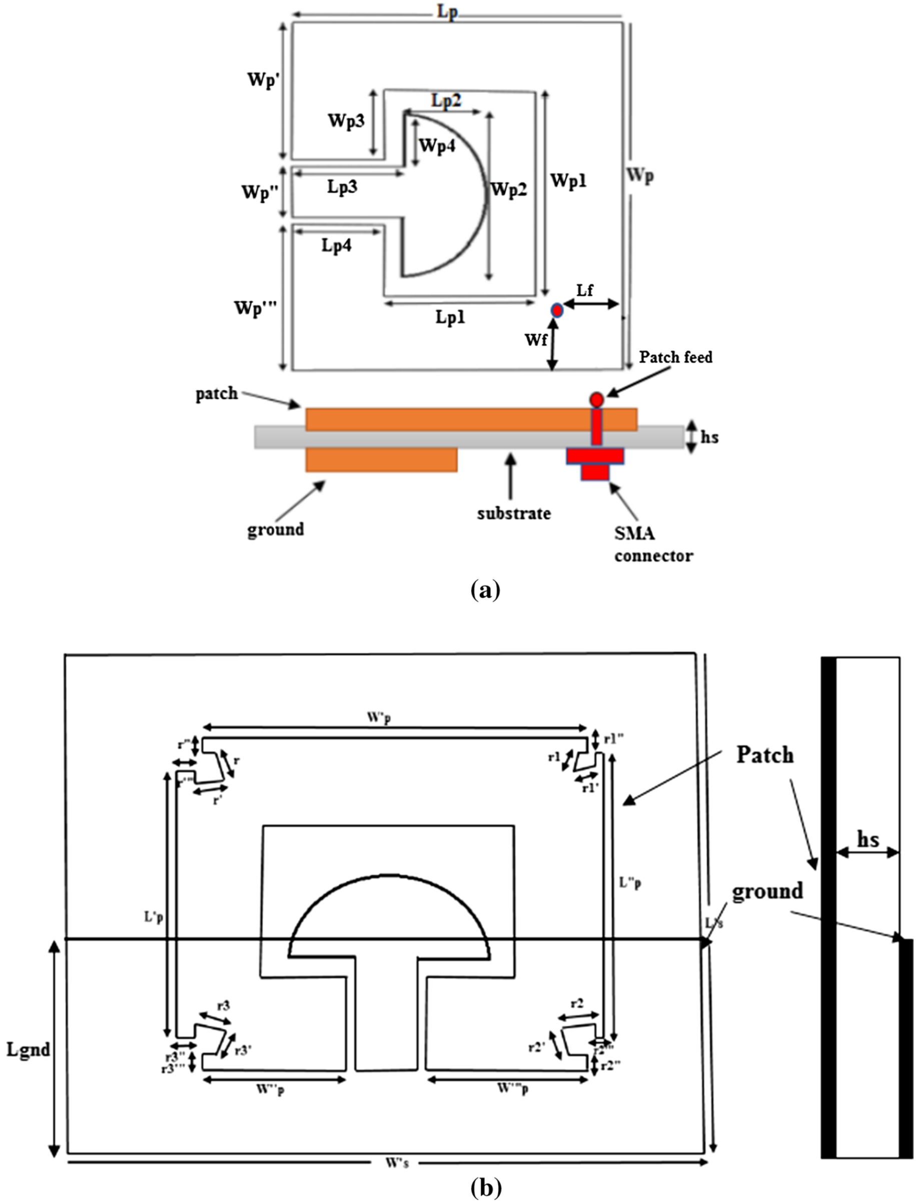
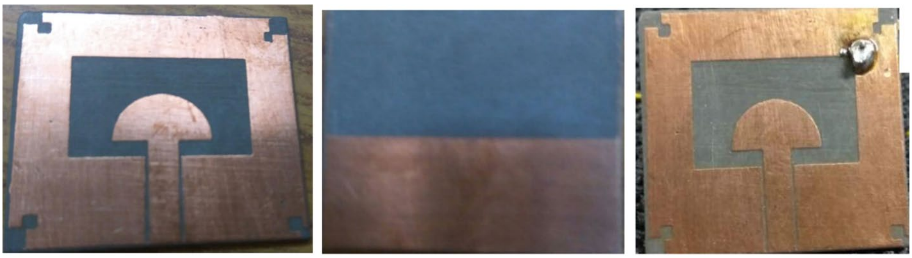


Fig. 1 Geometry of proposed antenna design. **a** Patch with feed network. **b** Top, back and side view

relative permittivity (ε_r) 2.33 and tangent loss (tanδ) of 0.0012 respectively. A rectangular patch antenna is excited using coaxial feed network whose dimension (Wf and Lf) are measures from edges of the patch and structure view can be seen in Fig. 1a. A dimension of square patch is (L_p*W_p) while monopole ground (L_{gnd}*W'_s) is chosen. A rectangular patch is designed at resonant frequency of 28.5 GHz. The defected ground (monopole) provides wide impedance bandwidth including the operating frequency. As cutting the mushroom shape within T-slot on the patch, it is observed that impedance bandwidth is enhanced at the lower side with include one notch at 23.9 GHz. A typical shaped asymmetric flower is another cutting at the corners on the patch, but at this moment impedance bandwidth is much improved with the suppression of notch and covers frequency band of 21.5–36 GHz. The naming of dimensions for the asymmetric flower shaped corners from range of (r, r′, r″, r‴) to (r3, r3′, r3″, r3‴) is chosen. The full wave simulation of proposed antenna is carried out on Ansoft HFSS. The fabricated pictures of the proposed antenna are shown in Fig. 2. The value of dimensions of the proposed antenna are shown in Table 1 as two parts naming 1(a) and 1(b) respectively. The fabricated pictures of proposed antenna with front and bottom view are shown in Fig. 2. Next subsection describes extraction technique for equivalent model of proposed antenna.

2.2 Equivalent Circuit Model

For better understanding the extraction technique of proposed antenna layout, an equivalent circuit model is built using electromagnetic (EM) software package in advanced design system (ADS)v.14 platform. A EM package is initializing with the theory of Quad-flat-No-lead (QFN) in this platform. An interesting note that extraction technique of typical cutting antenna is used first moment in this work. Figure 2 is shown equivalent model of proposed antenna layout. To explanation the extraction technique, this subsection involved two steps for finding the whole inductor-capacitor circuit model of antenna. First step involves ability of individual calculation for the slotted patch and the monopole ground with theory of QFN. The components such as inductors L1 and L3, capacitors C2 and C3, microstrip bend MSBend1 and MSBend2 are extracted whenever QFN package insert on slotted patch. While C1, C4 and MSBend2 are extract when QFN package insert on monopole ground. The additional inductor L2 which is parallel to C2 is used for the feed network. The 90 degree microstrip bend (MSBend) component is used for the reduce complexity of equivalent model of antenna. M. Kirschning developed empirically analytical model for MS Bend that consists inductor-capacitor equivalent circuit which can be seen in Fig. 3 as



(a) (b) (c)

Fig. 2 Fabricated pictures of proposed antenna. **a** Front view. **b** Back View. **c** Antenna with feed

Table 1 Value of dimensions of the proposed antenna into two parts

Dimensions	Lp	Wp	Wp′	Wp″	Wp‴	Lp1	Lp2	Lp3	Lp4	Wp1	Wp2	Wp3	Wp4	L′p	L″p	Lgnd
a																
Values (mm)	4.07	2.9	1.1	5	0.6	2.2	0.9	1.3	1.8	1.1	1.9	0.8	0.6	3.4	3.3	5.1

Dimensions	r	r′	r″	r‴	r1	r1′	r1″	r2	r2′	r2″	r2‴	r3	r3′	r3″	r3‴	W′p	W″p	W‴p
b																		
Values (mm)	0.2	0.2	0.1	0.1	0.1	0.1	0.01	0.2	0.2	0.1	0.01	0.2	0.2	0.1	0.1	2.3	0.8	0.5

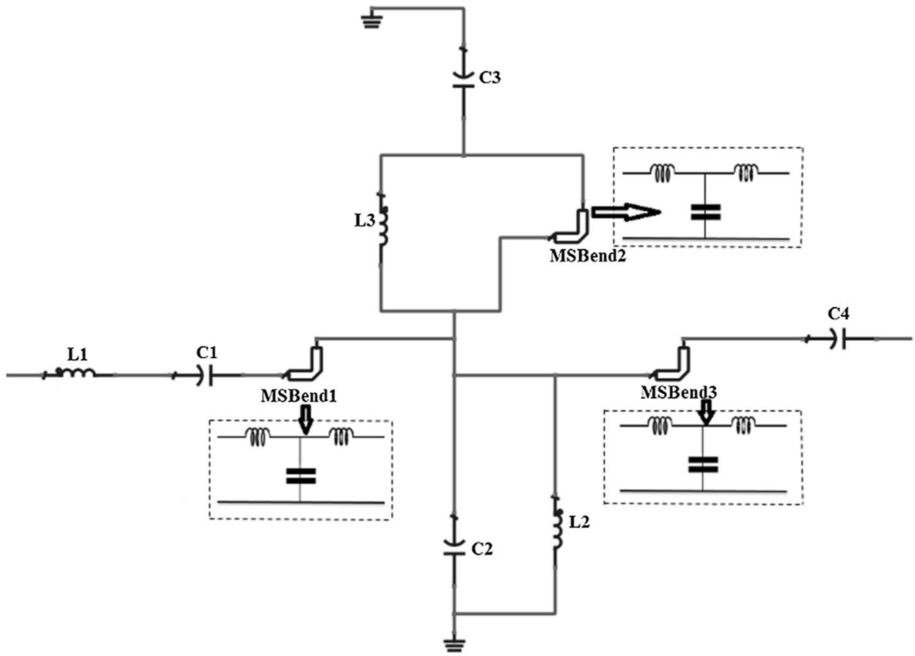


Fig. 3 A schematic diagram of equivalent model for proposed antenna

dash rectangular form. The values of capacitors in (pF/m) and inductors in (nH/m) can be calculated with the help of Eqs. (1) and (2) respectively [15].

$$\frac{C}{H} = \left(\frac{W}{H}\left[7.6 \in_r +3.8 + \frac{W}{H}\left(3.93 \in_r +0.62\right)\right]\right) \quad (1)$$

$$\frac{L}{H} = \left(441.2712\left\{1 - 1.062\exp\left[-0.177\left(\frac{W}{H}\right)^{0.947}\right]\right\}\right) \quad (2)$$

Here H is substrate thickness, $\in_r$ is dielectric constant and W is the width. While in second step, QFN package insert on complete geometry of proposed antenna for detection of connections as parallel and series which is used in Fig. 3. It is observed that resistors are compensating with each other during extraction without affecting current paths on the patch because QFN package is not considered loss parameters at high frequency. The values of extraction components of antenna are shown in Table 2. A good correlation found between the geometry of proposed antenna and its equivalent model in terms of VSWR which is shown in Fig. 4. It reveals that VSWR is less than 2.5 dB in case of equivalent model while less than 2 dB in antenna geometry within range of 21.5–36 GHz.

Table 2 Components value of proposed equivalent model of antenna

Dimensions	L1	C1	MSBend1	C2	L2	C3	L3	MSBend2	C4	MSBend3
Values	1.5 nH	12 fF	Width, W = 15.7 µm	15 fF	0.5 nH	52 fF	0.8 nH	Width, W = 11.9 µm	118 fF	Width, W = 12.8 µm

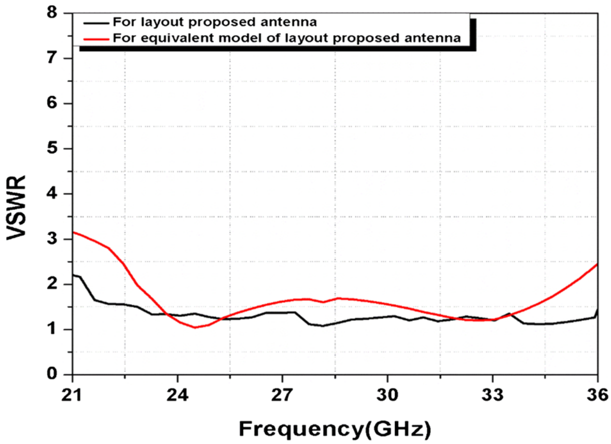


Fig. 4 Comparison plot of voltage standing wave ratio (VSWR)

3 Antenna Performance and Discussion

In this section, parametric studies of proposed antenna design would be discussed with the simulated and the measured results. Our observation of proposed antenna initializing with variation of return loss which is shown in Fig. 5. From this figure, three impedance bandwidths whose ranges of 26.2–34.2 GHz, 23–34.9 GHz and 21.5–36 GHz are achieved respectively which representing for blue, red and black color. The rectangular patch with defected ground (monopole) achieves around 8 GHz bandwidth with fractional of 26.6%. This impedance bandwidth is increased more around 4 GHz by inserting the mushroom shape inside T-slot on the patch and achieves fractional bandwidth of 42.5%. Reason for that it is due to reflecting the mirror image of current path in the mushroom shape from the edges of T-slot which is shown in dark circles of Fig. 6b. But at this moment one notch is create at 23.9 GHz within range of 23–34.9 GHz. Therefore, an additional asymmetric flowers shaped corners are cut on the patch and due to this, five resonating frequencies of 22.5 GHz, 24.8 GHz, 28 GHz,

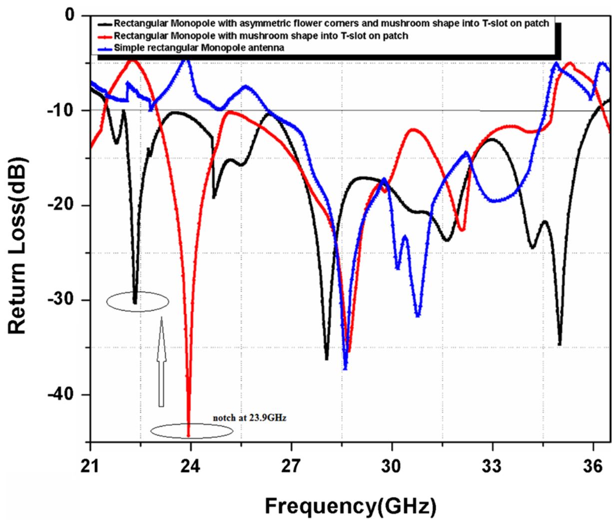


Fig. 5 Variation of return loss with respect to frequency

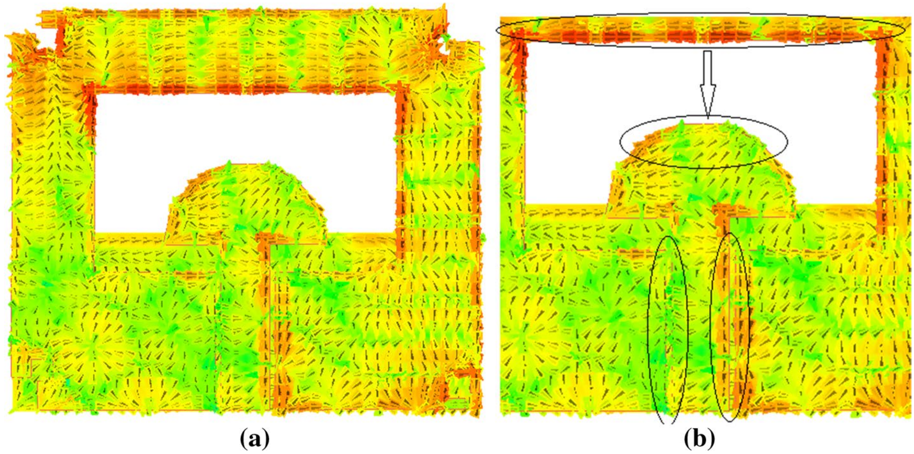
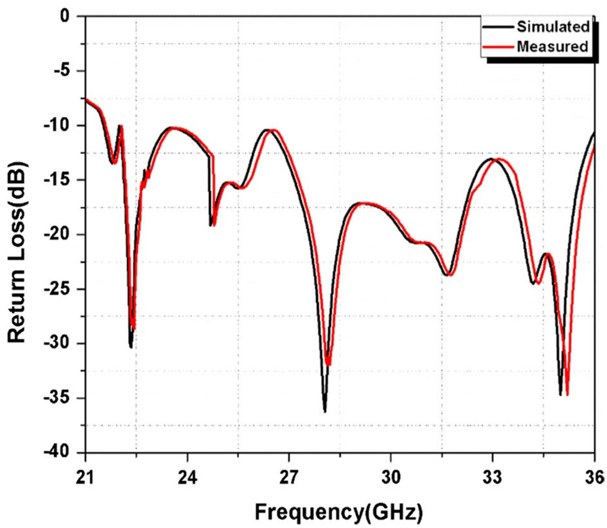


Fig. 6 Surface current distribution of proposed antenna at 22.5 GHz. **a** Front view. **b** Circles made mirror image of current path

32 GHz and 35 GHz respectively with much impedance bandwidth of 14.5 GHz are achieved. Moreover, at this moment notch is shifted at 22.5 GHz with suppression of −10 dB. Figure 6a, b is shown surface current distribution with top and back view at resonant frequency of 22.5 GHz. The measured and simulated result of return loss made good correlation between each other and can be seen in Fig. 7. The measured and simulated gain of 16.3–20.5 dBi is achieved which can be seen in Fig. 8. The highest gain is achieved due to dominating effect of inductances and capacitances which is observed at during extraction of equivalent model. The measured variation of axial ratio (ar) less than 3 dB with respect to resonating frequencies of the proposed antenna within range of 21.5–36 GHz is shown in Figs. 9 and 10 respectively. It is clear at the point of observation that the proposed antenna exhibits six different axial bands in the frequency range of 21.6–21.9 GHz (ar1), 23.2–23.5 GHz (ar2), 27.4–27.6 GHz (ar3), 31.3–31.7 GHz (ar4), 34.4–34.9 GHz (ar5) and 34.9–35.5 GHz (ar6) with axial ratio

Fig. 7 Variation of return loss (for fabricated picture of Fig. 2)



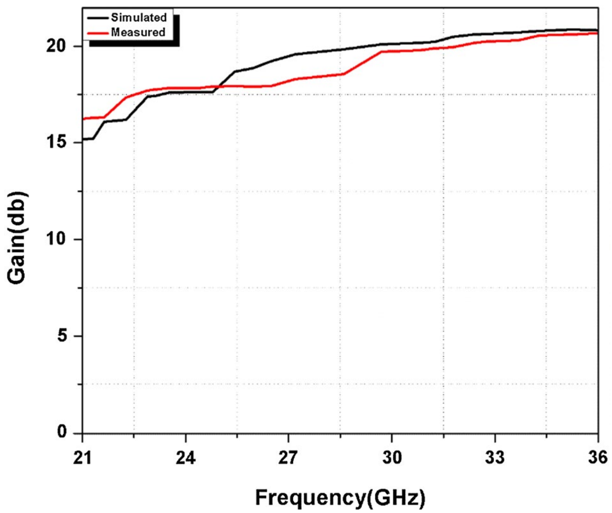
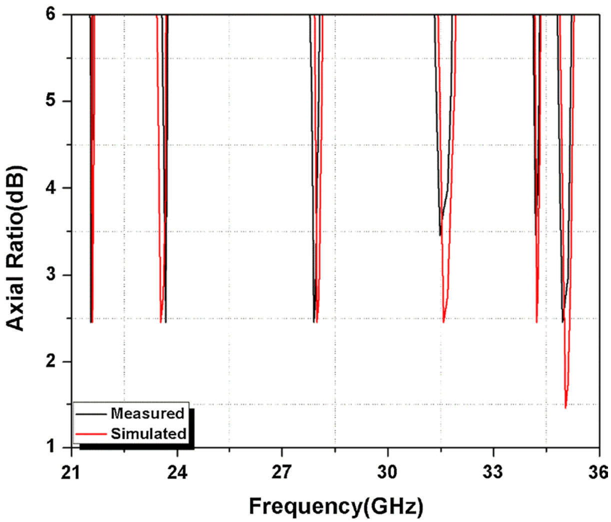


Fig. 8 Variation of gain with respect to frequency (for fabricated picture of Fig. 2)

Fig. 9 Variation of axial ratio with respect to frequency (for fabricated picture of Fig. 2)



bandwidths of 1.3%, 1.2%, 3.6%, 1.2%, 1.4% and 2.8% respectively. With highest resonant frequency of 35 GHz, maximum of 2.8% 3-dB axial ratio bandwidth is achieved. The simulated far field radiation patterns at different resonating frequencies are plotting in Figs. 11, 12, 13, 14 and 15. These radiation pattern gives E-phi, E-theta for E-plane and H-phi, H-theta for H-plane when phi rotates from −90° to +90°. From these figures, it is reveals that phi and theta pattern merges at angles of −90° to +90° and these angles are dependent upon resonant frequency. It is observed that radiation sketches from the angle of −108° and −160° at 22.5 GHz, −132° and −183° at 24.8 GHz, −124° and −175° at 28 GHz, −124° and −176° at 32 GHz and −129° and −180° at 35 GHz for E and H-plane. The next section focuses on reconfigurability feature of proposed antenna with RF CNT model.

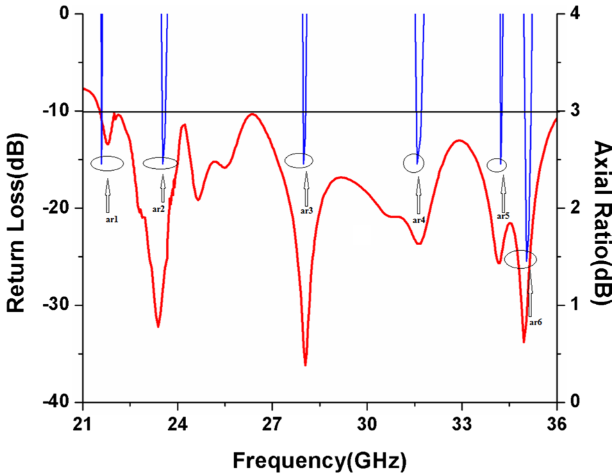


Fig. 10 Variation of Axial ratio at different resonant frequencies of proposed antenna

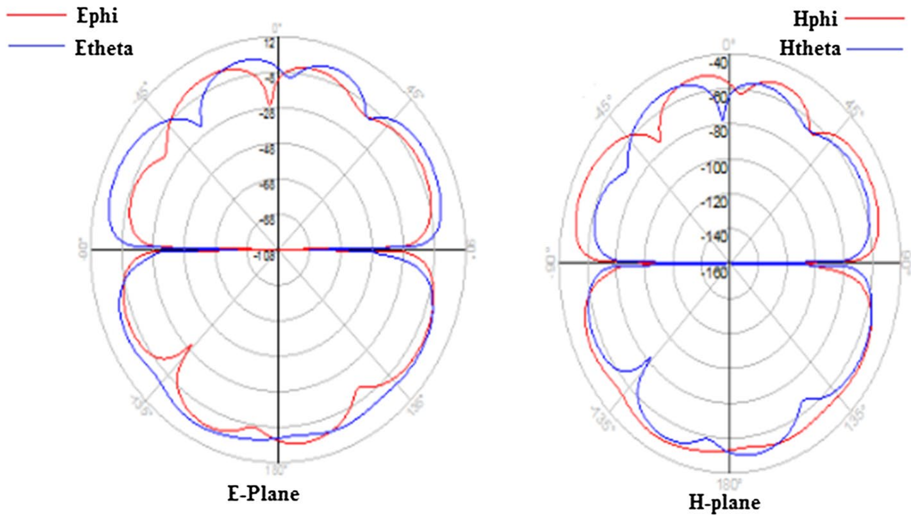


Fig. 11 Radiation pattern of proposed antenna at 22.5 GHz

4 Reconfigurable Mechanism

This section showing the behavior of reconfigurable for proposed antenna equivalent model with the RF CNT network. This is essential part where reconfigurable wide bandwidth using carbon nanotube acts as a transmission line is provided. The detail description of reconfigurable mechanism is proposed in next Sects. 4.1 and 4.2 respectively.

4.1 Wide Band CNT Network

A carbon nanotube is a metallic graphene sheet which show marvelous conductivity and high mobility along the entire dimension. Single walled carbon nanotube formed when

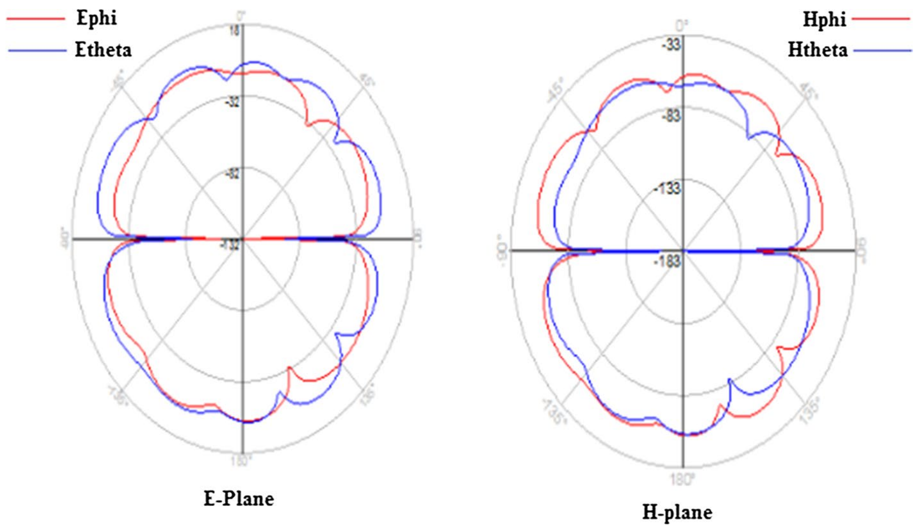


Fig. 12 Radiation pattern of proposed antenna at 24.8 GHz

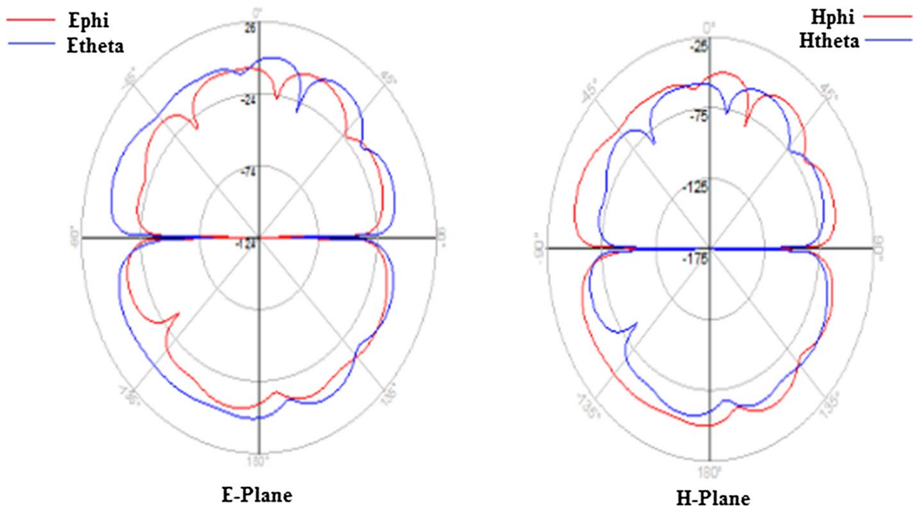


Fig. 13 Radiation pattern of proposed antenna at 28 GHz

graphene sheet is rolled up into cylinder form. In [16] P. J. Burke has developed RF circuit model based transmission line (dc to GHz to THz) properties for carbon nanotubes. Figure 16 is shown convention geometry of carbon nanotube with respect to ground plane and its transmission equivalent model. This equivalent model shows LC behavior whose ability to resonant at gigahertz and terahertz frequencies respectively. The extraction components of nanotube transmission line who's naming as distributed kinetic inductance (Lk), quantum capacitance (CQ) and electrostatic capacitance (CES) respectively. By optimizing the values of inductor and capacitor, achieves wide bandwidth from 12.4 to 25.1 GHz with

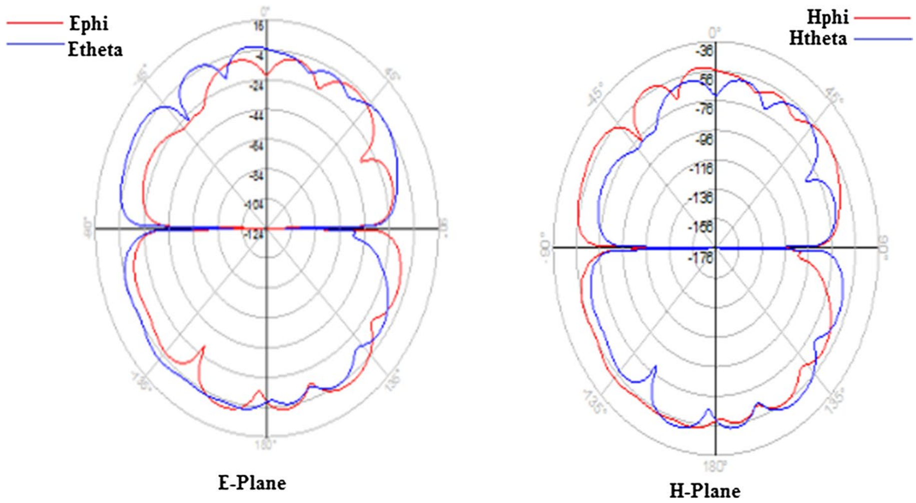


Fig. 14 Radiation pattern of proposed antenna at 32 GHz

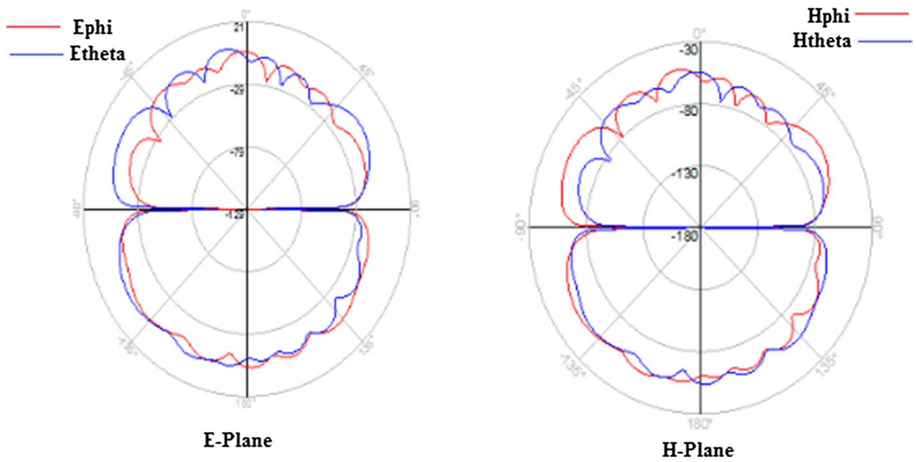


Fig. 15 Radiation pattern of proposed antenna at 35 GHz

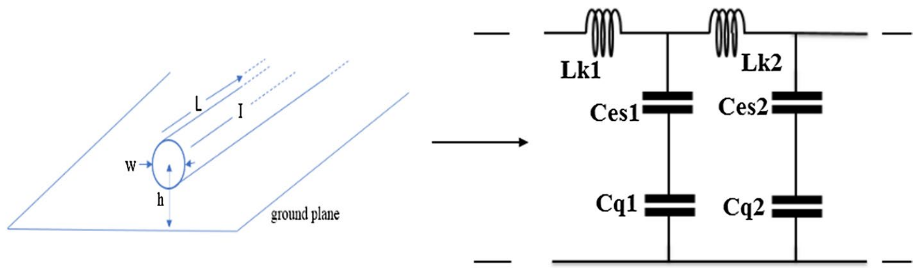


Fig. 16 Conventional Schematic of CNT with its equivalent model

Fig. 17 Variation of return loss with respected to frequency

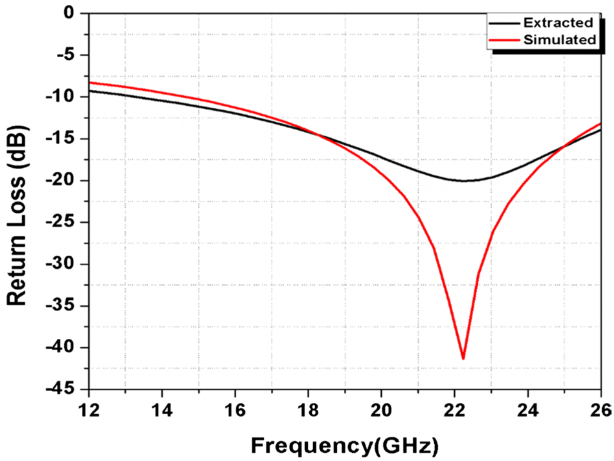


Table 3 Components value of RF circuit model of CNT

Components	Lk1	Lk2	Ces1	Ces2	Cq1	Cq1
Values	15 nH	18.3 nH	112 aF	32 aF	325 fF	120 fF

resonating frequency of 22.5 GHz which can be seen in Fig. 17. According to this result, single walled carbon nanotube and its extraction model made good correlation between them. Table 3 is shown component values of RF circuit for CNT.

4.2 Integration Strategy for Proposed Antenna with CNT

Figure 18 is shown integration scenario for equivalent model of proposed antenna with CNT. This integration scenario provides a feature of reconfigurability for wide impedance bandwidth along with compactness within desired band of operation. The capacitance C4 shows tuning effect between the equivalent model of antenna and CNT which can be seen

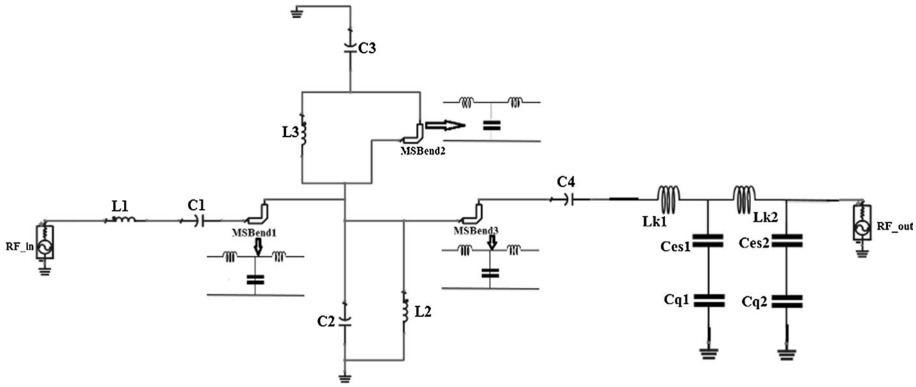
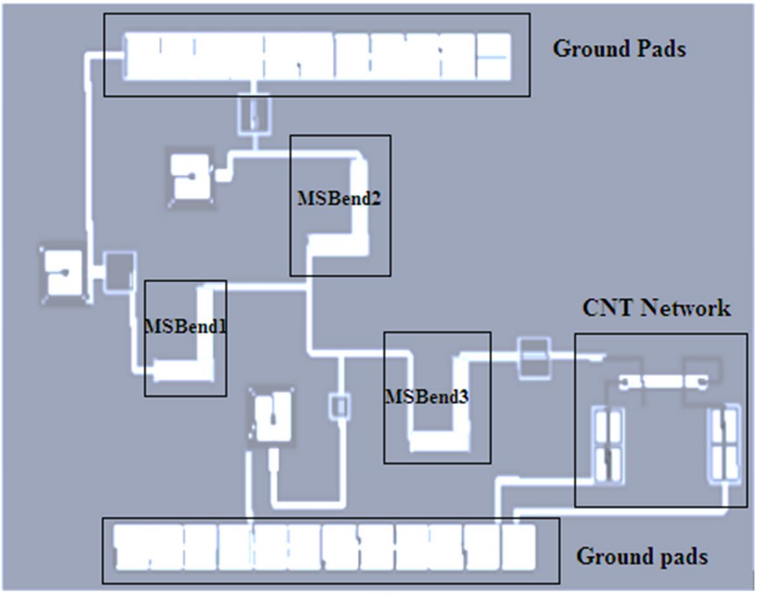


Fig. 18 Schematic diagram for equivalent model of proposed antenna with the CNT

(a)



(b)

Fig. 19 Integration network of proposed antenna with CNT, **a** its layout picture, **b** on-wafer fabricated view

in Fig. 18. The value of C4 is chosen as 114 fF and this value is dominant for the impedance matching between the antenna and the CNT model. From the analysis of smith chart, it is observed that the output impedance for equivalent model of antenna is (46 + j0.05) Ω

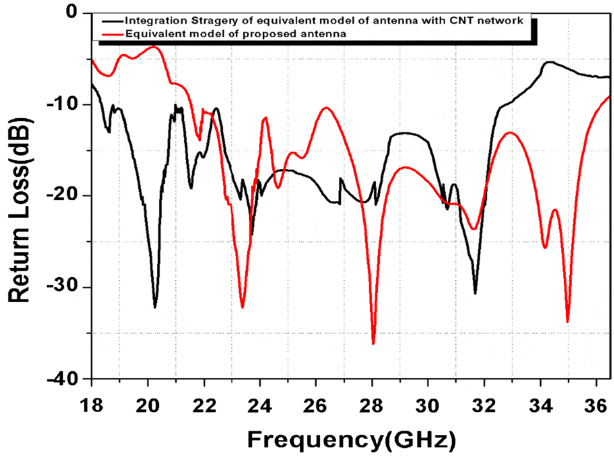


Fig. 20 Measured return loss with respect to frequency

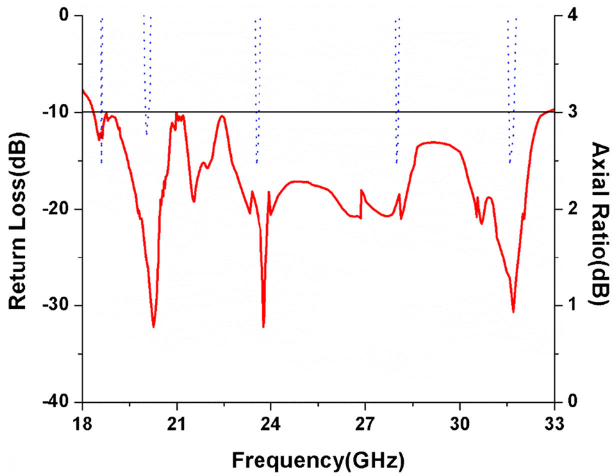


Fig. 21 Axial ratio bands at different resonating frequency for shifted band when proposed antenna integrated with CNT (Measured)

which is approximately matched to input impedance of CNT is (46.5 + j0.07) Ω. Therefore, the value of C4 is calculated at this matched impedance and which show tunable effect within wide band of operation from 18 to 36 GHz. For performance validation, integration network is layouted and fabricated on the RT during substrate. The layout and on-wafer fabricated picture of proposed integration network is shown in Fig. 19a, b respectively. Murata manufacturing RF inductors and RF capacitors are supported to this integration network. Figure 20 is shown measured comparison plot of impedance bandwidth between the proposed antenna and the integration strategy. The impedance bandwidth of 21.5–36 GHz is tuned with the value of C4 and after tuned it reach to 18–33 GHz without any loss of resonating frequencies. This tuned behavior of whole shifted bandwidth to left side demonstrates feature of reconfigurability with the compactness. The axial ratio bandwidth is also examined within desired band of operation. Figure 21 is shown axial ratio bands at different resonant frequencies within range of 18–33 GHz.

5 Conclusion

This work concludes reconfigurable antenna using novel extraction technique of slotted monopole antenna with RF CNT network. The proposed antenna achieved wide impedance bandwidth from 21.5 to 36 GHz with wide range of gain. The maximum axial ratio bandwidth of 2.8% is also achieved using this antenna. The novel extraction technique of proposed antenna with its equivalent model made good agreement in terms of VSWR. Finally, an equivalent model is integrated with RF CNT network which shows feature of reconfigurability with the compactness. The achieved reconfigurability for the proposed integration network would be useful for K and K-band applications.

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