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Analysis of a loop type ground radiation antenna based on equivalent circuit model

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Abstract: A loop type ground radiation antenna has been analysed using an equivalent circuit model in this study. The proposed circuit model has been selected in such a way that the design parameters of the ground radiation antenna can be mapped onto the circuit. To demonstrate the accuracy of the model, a specific ground radiation antenna is designed in a full wave electromagnetic simulator and the equivalent circuit model of the antenna is optimised in a circuit simulator. The simulation results of the circuit simulator and full wave simulator are compared. Expressions of return loss and input impedance of the equivalent model have also been obtained. The proposed circuit model can be used to develop insight and describe the behaviour of the network parameters of the antenna.

1 Introduction

Ever increasing development in mobile devices has emphasised the importance of embedded electrically small antennas. Researchers of these antennas seek to design compact and high performance antennas for mobile devices. The planar inverted F antenna (PIFA) [1] and loop type ground radiation antenna (GRadiAnt) [2–9] have gained special attention for their good efficiency and compact features. Both types of antennas are the result of different feeding mechanisms of the ground plane (chassis) of a mobile device. Various feeding techniques of GRadiAnt have been discussed in [10]. The PIFA is a well investigated antenna and its equivalent circuit models have also been discussed in [11, 12]. The loop type GRadiAnt antenna has not yet been as extensively analysed as the PIFA.

The operation mechanism of the loop type GRadiAnt antenna is based on abstract electromagnetic theory [13–15]. The theory cannot be directly applied to a specific design of a loop type GRadiAnt antenna. The literature explaining the design mechanism of the antenna is scarce. Therefore, the current design approach of the antenna is based on the past experience of design engineers, optimisation through electromagnetic simulator and educated guesses. In this investigation, an effort has been made to bridge the gap between the theory and the modern design approach of the loop type GRadiAnt antenna. For this purpose, the antenna has been analysed using an equivalent circuit model. The network parameters of the antenna can be explained in a relatively simple way, once it is translated into an equivalent circuit. The circuit model has been selected in such a way that the design parameters of the GRadiAnt antenna such as the area of the feeding loop, radiating loop and the lumped components can be mapped onto the circuit. The expressions of input impedance and the reflection coefficient of the proposed one-port network are also obtained. To demonstrate the accuracy of the proposed model, a typical loop type ground radiation antenna with rectangular ground clearance is designed in a full wave simulator (HFSS) at 2.45 GHz. It is demonstrated that the components of the equivalent circuit can be tuned in a circuit simulator (advanced design system) such that the *S* and *Z* parameters closely match with that of the full wave simulation. Although the equivalent circuit model cannot describe the radiation properties of the antenna, it can describe the behaviour of the *S* and *Z* parameters of the antenna. Moreover, the trend of the network parameters can also be predicted for changing the physical dimensions or the values of lumped components of the antenna. The model can also be helpful in developing insight of the operation mechanism of the loop type GRadiAnt antenna.

2 Theoretical foundation of GRadiAnt antenna

In this section, an overview of the theory is presented on which the operation mechanism of the GRadiAnt antenna is based. The purpose of the GRadiAnt antenna is to induce appropriate current modes on the ground plane. The current distribution on the ground plane can be explained using the theory of characteristic modes of the ground plane [13]. The total current density on the ground plane is a linear combination of the characteristic modes. The optimum location of the GRadiAnt antenna is evaluated using the reaction theorem of electromagnetic theory [14] given below

$$\langle \boldsymbol{E}^c, \boldsymbol{J}^s \rangle = -\iiint \boldsymbol{E}^c \cdot \boldsymbol{J}^s dv = -I^s \int \boldsymbol{E}^c \cdot d\boldsymbol{l} \tag{1}$$

$$\langle \boldsymbol{H}^c, \boldsymbol{M}^s \rangle = -\iiint \boldsymbol{H}^c \cdot \boldsymbol{M}^s dv = -K^s \oint \boldsymbol{H}^c \cdot d\boldsymbol{l} \tag{2}$$

where $\boldsymbol{E}^c$ and $\boldsymbol{H}^c$ denote the electric and magnetic fields, respectively, of the characteristic modes of the ground plane. $\boldsymbol{J}^s$ is the impressed electric current density provided by the current source I^s whereas $\boldsymbol{M}^s$ is the impressed magnetic current density provided by the voltage source K^s. According to (1), electric coupling can be enhanced by placing an impressed source $\boldsymbol{J}^s$ into the region of the ground plane where the electric field is maximal. The feeding mechanism of the PIFA antenna is regarded as a current source I^s and therefore, the optimum location of the PIFA structure is near the edge of the ground plane. Equation (2) suggests that the magnetic coupling can be improved by placing the magnetic source $\boldsymbol{M}^s$ into the region of the ground plane where the magnetic field is maximal. The feeding mechanism of the loop type GRadiAnt antenna is regarded as a voltage source K^s, and the optimum location of $\boldsymbol{M}^s$ is near the middle of the ground plane. Generally, the ground plane of mobile devices is rectangular in shape. It has been shown in [2, 4] that optimum coupling can be achieved by placing the GRadiAnt antenna at the middle of the longer side of the ground plane.

The magnetic coupler in a loop type GRadiAnt antenna can be designed in several ways. One of the techniques is to etch a rectangular ground clearance that contains the feeding loop. In order to obtain the optimum bandwidth, the feed structure needs to be effectively coupled with the ground plane. The coupling between the feed structure and the ground plane determines the bandwidth of the antenna and is proportional to $\langle \boldsymbol{H}^c, \boldsymbol{M}^s \rangle$. Moreover, the antenna bandwidth is inversely proportional to the radiation quality factor (Q_{rad}) defined as

$$Q_{\text{rad}} = \frac{\omega W_s}{P_{\text{rad}}} \propto \frac{1}{BW} \tag{3}$$

where W_s represents the sum of time average stored electric energy (W_e) and magnetic energy (W_m), P_{rad} is the radiated power and BW denotes the bandwidth of the antenna. For a loss free one-port network, the electric and magnetic energies can be expressed as [16]

$$W_e = \frac{|I|^2}{4}\left(\frac{dX}{d\omega} - \frac{X}{\omega}\right) \tag{4}$$

$$W_m = \frac{|I|^2}{4}\left(\frac{dX}{d\omega} + \frac{X}{\omega}\right) \tag{5}$$

where X is the reactance of the network. Equations (6) and (7) suggest that stored energy is determined by the slope of the reactance X. This implies that a wide impedance bandwidth can be obtained by decreasing the slope of X. Generally, the ground plane acts as a low Q resonator whereas the antenna structure is a high Q resonator. Therefore the antenna structure dominantly selects the operating frequency. Optimum bandwidth can be obtained by controlling the slope of the antenna reactance and the coupling between the GRadiAnt antenna and the ground.

The theoretical detail presented here, describes the operation of a loop type GRadiAnt antenna in an abstract fashion, however, it cannot be directly applied to the design or explain the behaviour of a specific loop type GRadiAnt antenna. In this endeavour, the GRadiAnt antenna has been modelled using an equivalent circuit to explain the antenna mechanism in a relatively simple way.

3 Equivalent circuit model

The geometry of a typical loop type GRadiAnt antenna is shown in Fig. 1*a*. The antenna structure is fabricated on a ground plane of width G_W and height G_H. The rectangular clearance is etched at the middle of the longer edge of the ground plane forming the outer loop. The width and length of the rectangular clearance are represented by S_W and S_H, respectively. The feeding loop of the width F_W and height F_H is located inside the rectangular clearance. The feeding loop contains the capacitor C_f, which controls the coupling of the antenna element with the ground. The outer loop contains the capacitor C_r, which controls the resonance frequency. The structure consisting of a rectangular clearance and a feeding structure is often termed as the antenna element [5] and is shown in Fig. 1*b*.

In order to obtain the lumped parameters of the antenna element, consider Fig. 1*b*. The current circulating in a loop induces an inductive behaviour; therefore, the inductance of the feeding loop is indicated by L_f and that of the outer loop is indicated by L_r. The series resistance of L_r is indicated by R_r whereas the series resistance of the feeding loop has been neglected due to the smaller size of the loop. The ground plane is modelled as a series RLC circuit. Practically, the antenna element is electromagnetically coupled with the ground plane which is modelled by a coupling transformer with turn ratio N.

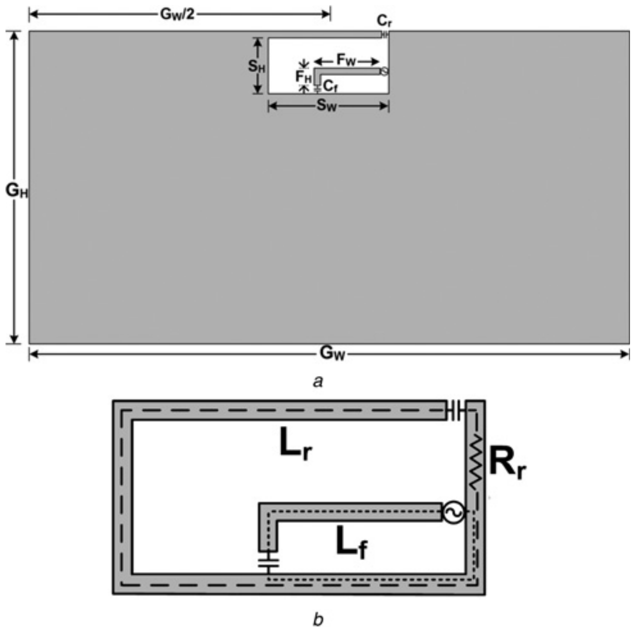

Fig. 1 *Geometry of a typical loop type GRadiAnt antenna*
a Geometry of GRadiAnt antenna
b Antenna element

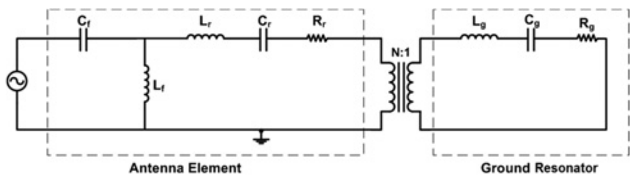

Fig. 2 *Equivalent circuit model of the GRadiAnt antenna*

The complete model of the GRadiAnt antenna is shown in Fig. 2. It can be observed that all of the physical parameters of the GRadiAnt antenna have been translated into the circuit model. The expressions of input impedance and reflection coefficient of the circuit can be obtained using its ***ABCD*** matrix. In this regard, the circuit can be subdivided into three parts, the antenna element (AE), the coupling transformer (CT) and the ground resonator (GR). The ***ABCD*** matrices of the individual segments of the circuit are as follows (see (6))

$$CT = \begin{bmatrix} N & 0 \\ 0 & \dfrac{1}{N} \end{bmatrix} \tag{7}$$

$$GR = \begin{bmatrix} 1 & 0 \\ \left[R_g + j\left(\omega L_g - \dfrac{1}{\omega C_g}\right)\right]^{-1} & 1 \end{bmatrix} \tag{8}$$

where AE, CT and GR are the ***ABCD*** matrices of the antenna element, coupling transformer and the ground resonator, respectively. Since all the segments of the circuit are connected in cascade form, the ***ABCD*** matrix of the complete circuit will be the product of (6)–(8). The resultant ***ABCD*** parameters of the

$$AE = \begin{bmatrix} 1 - \dfrac{1}{\omega^2 L_f C_f} & \left(R_r - \dfrac{R_r}{\omega^2 L_f C_f}\right) + j\left(\omega L_r - \dfrac{1}{\omega C_r} - \dfrac{1}{\omega C_f} - \dfrac{L_r}{\omega C_f L_f} + \dfrac{1}{\omega^3 L_f C_f C_r}\right) \\ \dfrac{-j}{\omega L_f} & \left(1 + \dfrac{L_r}{L_f} - \dfrac{1}{\omega^2 L_f C_r}\right) - j\left(\dfrac{R_r}{\omega L_f}\right) \end{bmatrix} \tag{6}$$

Table 1 Dimensions of the simulated design in mm

G_W	G_H	S_W	S_H	F_W	F_H
50	25	10	4.5	5.5	1.4

complete network are as follows

$$A = N\left(1 - \frac{1}{\omega^2 L_f C_f}\right) + \frac{1}{N}\left(R_{BAE} + jX_{BAE}\right)\left(R_{CG} - jX_{CG}\right) \quad (9)$$

$$B = \frac{1}{N}\left[R_r\left(1 - \frac{1}{\omega^2 L_f C_f}\right) + j\left(\omega L_r - \frac{1}{\omega C_r} - \frac{L_r}{\omega L_f C} + \frac{1}{\omega^3 L_r C_f}\right)\right] \quad (10)$$

$$C = -\frac{N}{\omega L_f}j + \frac{1}{N}\left(1 + \frac{L_r}{L_f} - \frac{1}{\omega^2 L_f C_r} - j\frac{R_r}{\omega L_f}\right)\left(R_{CG} - jX_{CG}\right) \quad (11)$$

$$D = \frac{1}{N}\left(1 + \frac{L_r}{L_f} - \frac{1}{\omega^2 L_f C_r}\right) - j\frac{R_r}{\omega L_f} \quad (12)$$

$$R_{BAE} = R_r - \frac{R_r}{\omega^2 L_f C_f}$$

$$X_{BAE} = \omega L_r - \frac{1}{\omega C_r} - \frac{1}{\omega C_f} - \frac{L_r}{\omega L_f C_f} + \frac{1}{\omega^3 L_f C_f C_r}$$

$$R_{CG} = \frac{R_g}{R^2 + \left(\omega L_g - 1/\omega C_g\right)^2}$$

$$X_{CG} = \frac{\left(\omega L_g - 1/\omega C_g\right)}{R^2 + \left(\omega L_g - 1/\omega C_g\right)^2}$$

The input impedance and S_{11} of the circuit can be calculated using (9)–(12) in the following expressions [17]

$$Z_{in} = \frac{A}{C} \quad (13)$$

$$S_{11} = \frac{A + B - C - D}{A + B + C + D} \quad (14)$$

The adequacy of the model has been examined in the following section by comparing the simulation results of a specific design of the GRadiAnt antenna in a full wave simulator and a circuit simulator.

4 Antenna design and its equivalent circuit

The geometry of the GRadiAnt antenna simulated in HFSS is shown in Fig. 1. The antenna is designed to resonate at 2.45 GHz and FR-4 [$\varepsilon_r = 4.4$, $\tan(\delta) = 0.02$, $h = 1$ mm] is used as a substrate. The values of C_r and C_f are 0.15 and 0.55 pF, respectively.

The dimensions of the simulated design are given in Table 1 and the simulation results are shown in Fig. 3. The −10 dB bandwidth of the antenna is 422 MHz. According to Chu's theory [18], the GRadiAnt antenna without the ground plane has a narrow bandwidth due to its smaller electrical size. The larger bandwidth in the simulation is due to the fact that the antenna effectively utilises the ground plane for radiation. Further, it is observed that increasing the clearance area or the value of C_r, decreases the resonance frequency and vice versa. Fig. 3*a* shows the effect of increasing the value of the capacitor C_r where the simulated values are 0.12, 0.15 and 0.18 pF. Similarly, increasing the value of C_f increases the coupling of the antenna element with the ground plane and rotates the locus of S_{11} clockwise on the Smith chart, as shown in Fig. 3*b*. In order to observe the excited currents on the antenna and the ground plane, vector surface current density (A/m) of the structure is shown in Fig. 4. It can be observed that the feeding loop excites loop type current around the resonance loop. The resonance loop in turn excites the current modes on the ground plane that cause radiation. The current density on the ground plane consist of various modes, e.g. the fundamental mode, which has a dipole type and the second order mode which has loop type current pattern and so on.

The antenna is fabricated and its measured results are presented in Fig. 5. The experimental values of C_r and C_f are 0.12 and 0.5 pF, respectively. The measured and simulated return loss is shown in Fig. 5*a* where a good agreement can be observed. The bandwidth of fabricated antenna is 520 MHz. Fig. 5*b* shows the measured radiation pattern of the antenna at 2.45 GHz, which resembles an omnidirectional pattern. The radiation efficiency of the antenna is 71.1%.

In order to obtain the values of the lumped components of the equivalent circuit, the antenna element shown in Fig. 1*b* is simulated in a full wave simulator. The inductances L_f and L_r can be obtained at the design frequency by simulating rectangular micro-strip loops with the same dimensions as that of the antenna element without capacitors. The obtained values of L_f and L_r are 7.91 and 30.37 nH, respectively, whereas the series resistance of L_r is 4.37 Ω and that of L_f is 0.2 Ω. On the other hand, the equivalent circuit model of the antenna element is tuned in the circuit simulator using the values of the lumped components obtained from the full wave simulation. In the circuit simulation of the antenna element, the transformer and RLC circuit representing the ground resonator are replaced by a short circuit. The results of the full wave simulation and circuit simulation are compared from 2 to 2.8 GHz in Fig. 6. The antenna element acts as a high Q parallel

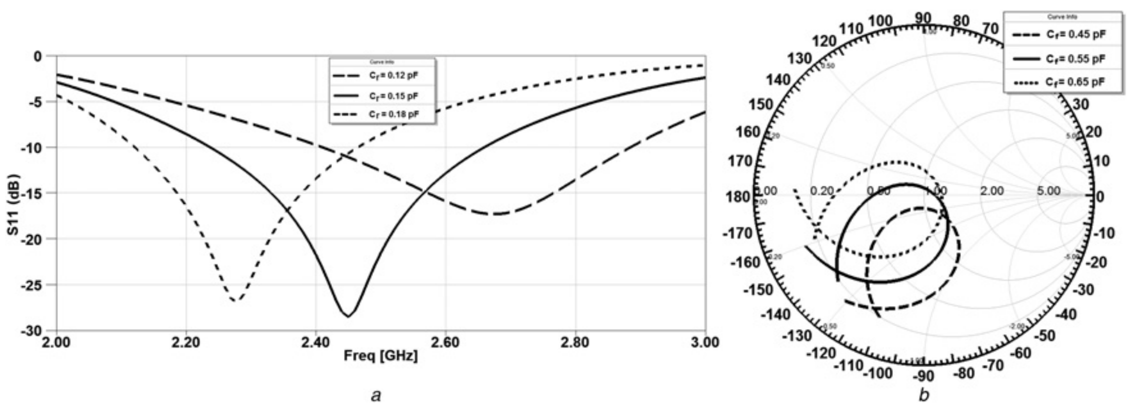

Fig. 3 *Simulation results of the antenna*

a Return loss of simulated antenna for various C_r
b Change in C_f

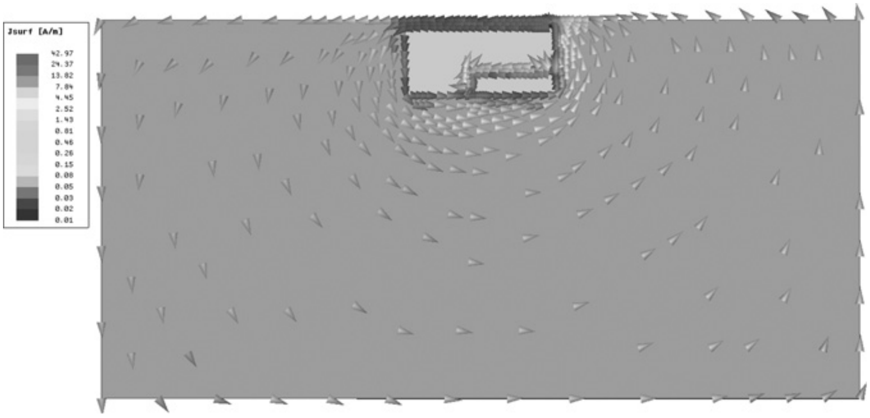

Fig. 4 *Simulated surface current density*

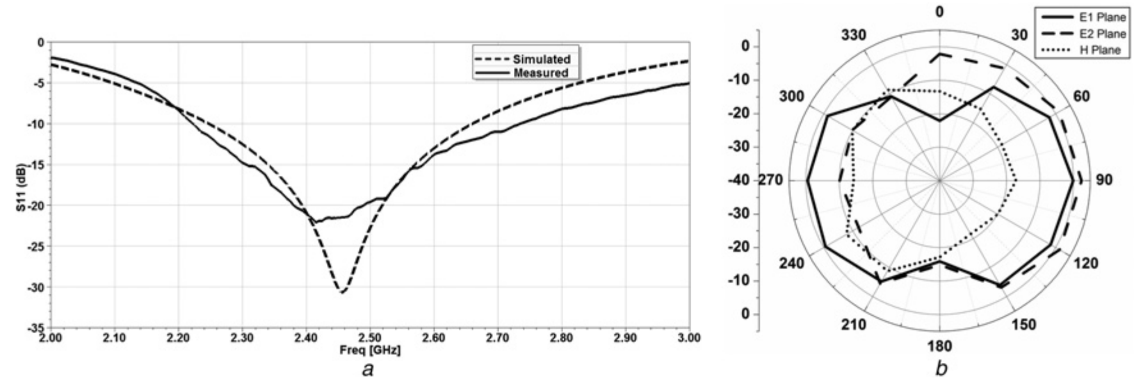

Fig. 5 *Experimental results of the antenna*

a Measured and simulated return loss of the antenna
b Measured radiation pattern at 2.45 GHz

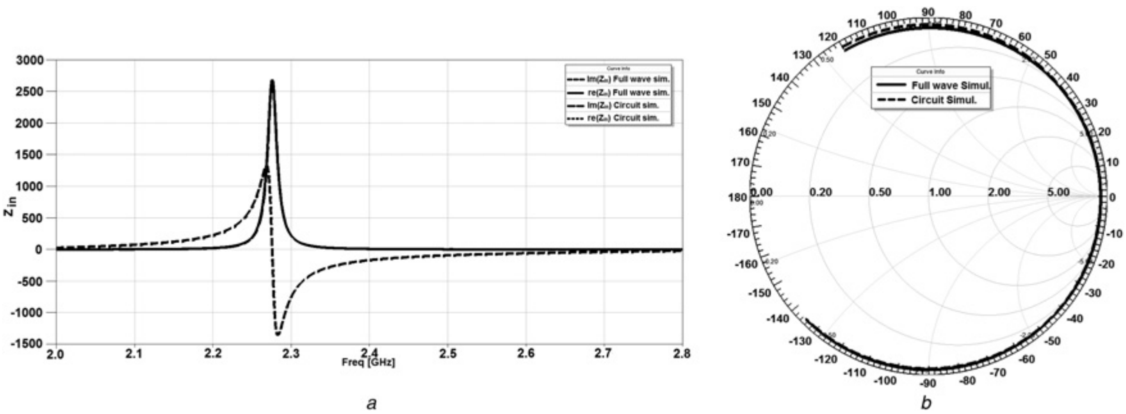

Fig. 6 *Comparison of impedance parameters of the antenna element and its equivalent circuit*

a Input impedance
b S_{11}

resonator where the Q factor of the antenna element is 158.05 and the resonance frequency is 2.276 GHz. It can be observed that the input impedance and S parameter (S_{11}) of the antenna element can be modelled with reasonable precision using the equivalent circuit model. The reason is that the dimensions of the antenna element in GRadiAnt antennas are approximately one-tenth of the operating wavelength. The modelling of the complete GRadiAnt antenna would be interesting, as in this situation, the dimensions of the antenna are comparable to the operating wavelength. In order to model the GRadiAnt antenna with the ground plane, the ground resonator and coupling transformer have been added to the circuit representing the antenna element and then tuned to match the full wave simulation. The comparison is shown in Fig. 7.

The values of R_g, L_g and C_g have been obtained as the result of tuning. The values of the circuit parameters of the antenna element and the GRadiAnt antenna are listed in Table 2. The value of N is 0.9 which indicates good coupling and is consistent with the simulated design in HFSS. The equivalent model of the ground plane is also simulated separately and its S parameter is plotted on the Smith chart shown in Fig. 7*b*. It can be noted that the ground plane behaves as a low Q resonator with unloaded Q factor of 17.64 and resonance frequency of 2.5 GHz. The parameters of the

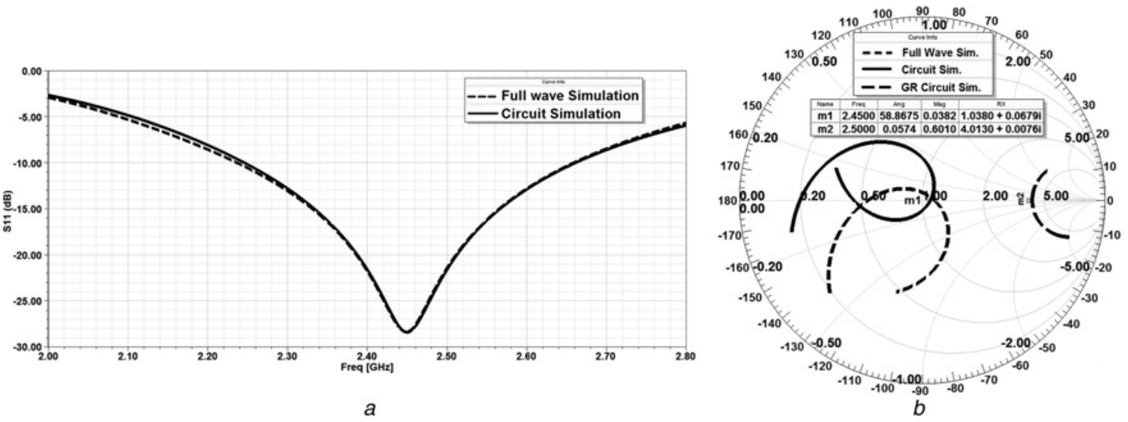

Fig. 7 *Comparison of S parameters of the GRadiAnt antenna and its equivalent circuit*
a S_{11} (dB)
b Smith chart

Table 2 Values of the antenna parameters after tuning

Model	C_f, pF	L_f, nH	C_r, pF	L_r, nH	R_r, Ω	L_g	C_g	R_g
HFSS	0.55	7.91	0.15	30.37	4.37	–	–	–
antenna element	0.778	6.43	0.14	28.65	3.14	short circuited		
complete model	0.778	6.43	0.14	28.65	3.14	35.7 nH	0.113 pF	200.65 Ω

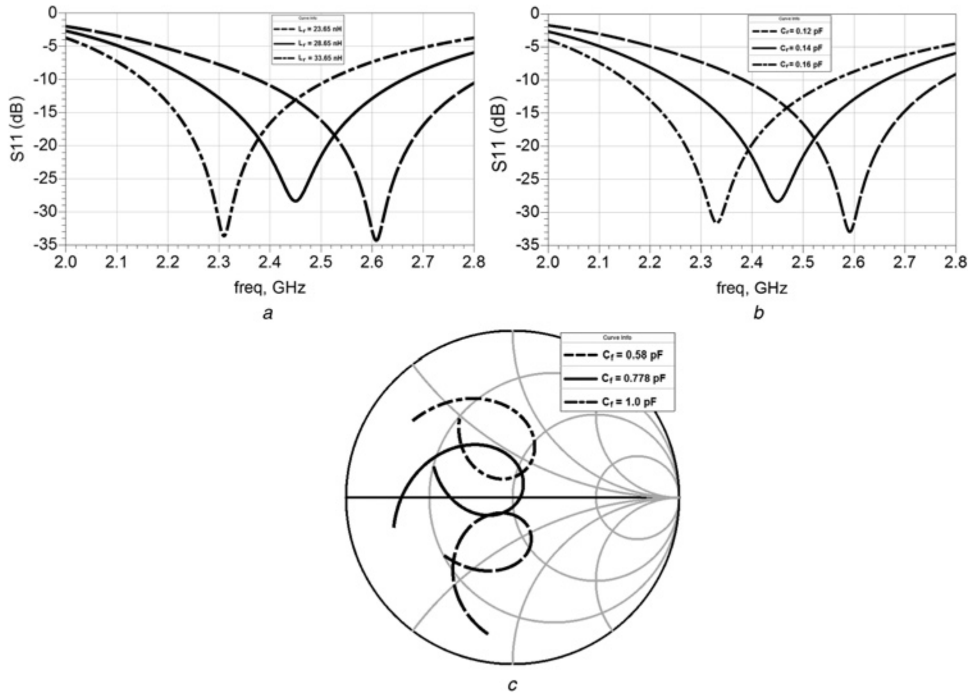

Fig. 8 *Change of the lumped component values of the equivalent circuit*
a Effect of L_r
b Effect of C_r
c Effect of C_f

ground plane cannot be obtained in a full wave simulation. Furthermore, it is observed that the *S* parameter of the circuit model and full wave simulation can only be matched at the resonance frequency. However, the return loss (in dB) can be matched with fair precision as shown in Fig. 7*a*. This implies that the bandwidth and the coupling of the antenna can be explained with the equivalent circuit. More resonant sections may be added to the circuit to minimise the difference in the results of Fig. 7*b*, however, that is not the focus of this work.

5 Discussion on proposed circuit model

The behaviour of the GRadiAnt antenna is described in terms of its equivalent circuit model in this section. It has been accomplished by observing the effects of changing values of the components of the equivalent model in circuit simulation and comparing the results with that of full wave simulation. Fig. 8*a* shows that increasing the value of L_r decreases the resonance frequency where L_r models the area of rectangular clearance. The simulated values of L_r are

23.65, 28.65 and 33.65 nH. Fig. 8*b* shows the same effect for the lumped capacitor C_r where the simulated values of C_r are 0.12, 0.14 and 0.16 pF. Fig. 8*c* shows the effect of change in C_f for the values 0.58, 0.778 and 1.0 pF. It can be seen that the increase in C_f rotates the locus on the Smith chart in the clockwise direction. Comparing the results of Figs. 3 and 8, it is inferred that the lumped components of the equivalent circuit fairly models the trend of the corresponding physical parameters of the antenna. For the ground resonator, changing the values of L_g and C_g has the same effect as changing L_r and C_r, however, increasing the value of C_g while decreasing the value of L_g increases the matching bandwidth and vice versa. Moreover, increasing the value of R_g improves impedance matching at the resonance frequency without affecting the bandwidth. This accounts for various shapes and sizes of the ground plane for a given antenna element. It can also be observed from the equivalent circuit that L_f and C_f acts as an L-type impedance matching network between the source and the rest of the circuit. This explains the operation of the feeding loop in GRadiAnt antenna.

Modelling the GRadiAnt antenna using a circuit model reveals various antenna parameters. The process of optimising the physical GRadiAnt antenna can be explained via variations in the lumped parameters of the equivalent model. The discussion may also be used as a guideline for choosing the optimum dimensions of a specific design of a GRadiAnt antenna.

6 Conclusion

The ground radiation antenna has been analysed using an equivalent circuit model in this presentation. Each component of the equivalent circuit model corresponds to a physical parameter of the ground radiation antenna. The expressions of input impedance and S_{11} of the circuit are obtained using the *ABCD* matrix technique. The values of the lumped components of the circuit are obtained using a full wave simulator and tuned in a circuit simulator. The results of the full wave simulator and circuit simulator are compared and it is observed that the equivalent circuit fairly models the ground radiation antenna. This discussion is helpful in developing insight into the operation and design of a loop type GRadiAnt antenna.

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