CPW FED ULTRA COMPACT RADIATOR FOR 2.4 GHZ WIRELESS AND ISM APPLICATIONS

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Abstract

A Uniplanar CPW fed electrically small radiator suitable for WiFi 802.11b, 802.11g, 802.11n, Bluetooth, ZigBee IEEE802.15.4 and ISM application is developed and presented. Physical structure of the developed antenna is very compact of the order of 0.12λg × 0.10λg × 0.02λg which makes it very suitable for almost all the 2.4GHz based wireless applications. Parametric studies of the antenna is performed and from the results obtained design equations of the structure is developed and verified. Computational model of the antenna is also developed using FDTD and the results are compared and discussed. Antenna offers uniform radiation characteristics with good radiation efficiency and gain.

Keywords:

CPW Fed, Electrically Small, Short Based, Uniplanar

1. INTRODUCTION

Antenna plays a major and prime role in communication systems just like the sense organs in human beings, because they are used to perceive data from external world. As the size of communication gadgets decreases, it will create very interesting and complicated problems to antenna designers, so that they can design the compact antennas very first. The size reduction of antenna should not compromise its performance such as radiation pattern, gain efficiency etc too. Different techniques through which compactness can be achieved is discussed in various literatures.

A compact antenna suitable for 2.4GHz WLAM application is presented in [1] whose radiating element consists of a semicircular slot and an arc-shaped slot which are placed very near to the feed point. A reflector-based antenna which operates in two bands is presented in [2] which is huge when compared to our design. A pattern reconfigurable antenna based on PIN diodes is presented in [3] which comprises of complex structural specifications.

Yadav and Baudha [4] presents a partial reflective ground plane-based monopole suitable for 2.4GHz application which is also not so compact. A dual band antenna suitable for 2.4 and 60 GHz is presented by Sun et al. [5]. A single band circular polarized antenna based on two circular slots is presented by the authors in [6]. A flexible antenna based on two inverted U slots is presented in [7] which has extreme low thickness but with more surface area. A microstrip based single band antenna with a multilayer huge structure is discussed in [8].

Planar Inverted F single band Antenna having two stacked rectangular patch is discussed by the authors in [9]. In [10] a triple layer structure having a circular patch inside a rectangular loop patch with dual mode operation is discussed. An enhanced gain X shaped antenna structure is presented in [11] which is not compact at all. A complex structure based wearable antenna with a square patch inside a ring is discussed in [12].

A meta-material based defective ground single band antenna having dual planar structure is presented in [13]. In [14], a dual radiator-based antenna with J and L slots is presented which is very complicated structure. A 3D spiral structure is used for the effective reduction of size of antenna in [15] but which is not a planar one. Shorting Vias based compact antenna is presented in [16] which is very complicated in structure wise considerations.

In this article, we introducing an ultra-compact electrically small radiating structure operating at 2.4 GHz, which is found to be the most compact antenna ever discussed in literatures till now. Developed antenna found its applications on different areas such as ISM and wireless applications like WiFi 802.11b,802.11g, 802.11n, Bluetooth, ZigBee IEEE802.15.4 etc. Antenna offers uniform radiation characteristics within the band of operation with an apple shaped radiation pattern, very good radiation efficiency and with moderate gain. All these characteristics and compact size make this structure a very suited candidate for various wireless gadgets.

2. EVOLUTION OF ANTENNA

Evolution of the structure of compact radiator is depicted in Fig.1. It is developed from an extended ground nonconventional coplanar waveguide (CPW) fed structure having signal strip length less than ground plane length as shown in structure 1.

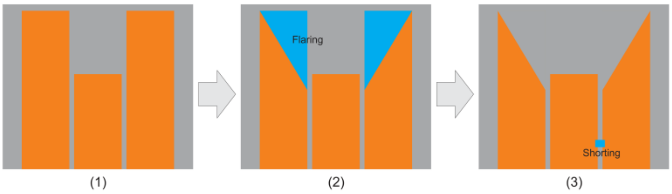


Fig.1. Evolution of the Compact Antenna

A flaring is introduced in both the ground planes by removing right angled triangular portions from each ground planes as shown in structure 2 of Fig.1. As the third step, a short is introduced in between one ground plane and signal strip which is our final antenna structure.

The simulated reflection co efficient (S_{11}) curves of all the three above structures are shown in Fig.2. From the Fig.it may be noted that for first two structures, there is no resonances but the introduction of the slot makes a resonant frequency near 2.4 GHz

Structure of the developed ultra-compact antenna with all the dimensional notations is given in Fig.3. Gap ‘g’ and signal strip width W_s of the structure are selected to meet 50Ω input impedance.

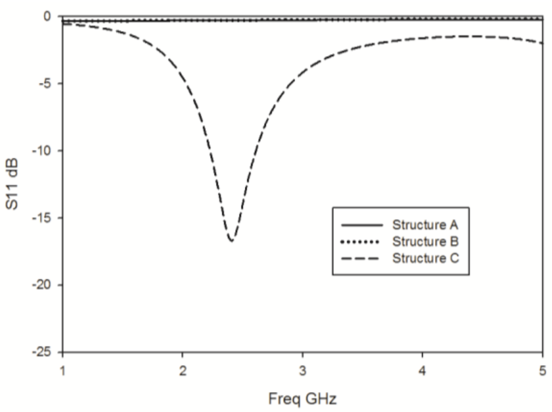


Fig.2. S_{11} of three structures shown in Fig.1

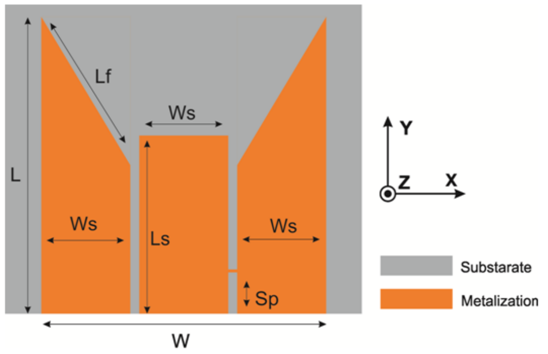


Fig.3. Structure with dimensional notations

3. PARAMETRIC OPTIMIZATION

To optimize the structure and to develop an application band-based prototype, a set of parametric analyses were performed with the help of ANSOFT HFSS software and the results obtained are discussed in this session.

As the first parametric variation, signal strip length Ls of the structure varied by keeping all other parameters constant. Result obtained is depicted in Fig.4. and it is found that the resonance gets lowered with increase in L_s. This is due to the increase in surface current path length with L_s.

The position of short is found to be very crucial in determining the resonance. The variation of S_{11} with short position S_p is given in Fig.5. It is found that the resonance gets a drastic up shift with increase in the parameter S_p.

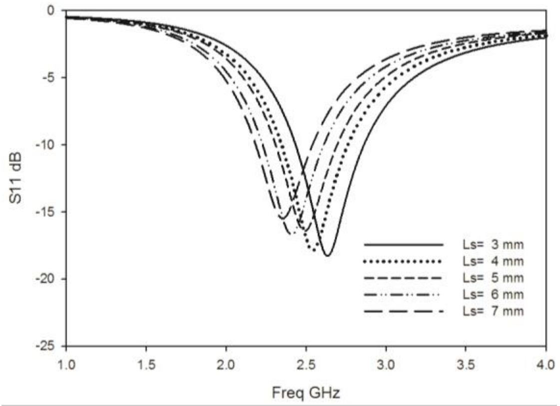


Fig.4. Effect of *Ls* on S_{11}

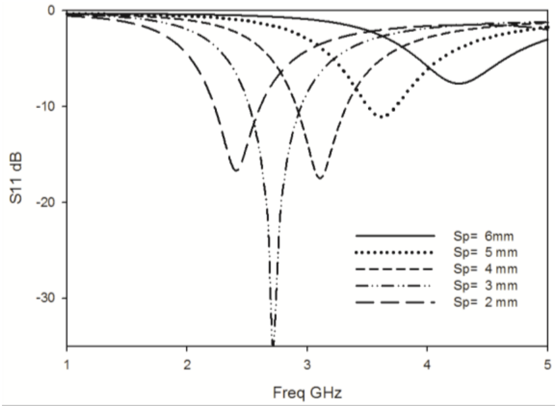


Fig.5. Effect of S_p on S_{11}

All other parameters like L, L_f widths of ground planes etc have minute effect on resonance and in all these cases, resonance remains unaltered with these parameters. Thus, it can be noted that the resonance determining factors in this structure are length of the signal strip and short position. From the parametric analysis, design equations of all the dimensions in terms of guided wavelength (λ_g) are developed and are detailed in Table.1.

Table.1. Parameters in terms of Guided Wavelength

Parameter	Design Equations
L	0.105163 λg
W	0.126195 λg
L_s	0.078872 λg
L_f	0.055736 λg
S_p	0.026291 λg

where λ_g corresponding to the guided wavelength corresponding to resonance and is calculated from free space wavelength λ using the expression:

$$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eff}}} \tag{1}$$

where ε_{eff} is the effective dielectric constant and is calculated from dielectric constant ε_r of the substrate using the equation

$$\varepsilon_{eff} = (\varepsilon_r+1)/2 \tag{2}$$

To validate these design equations, three different antennas in different substrates are designed and simulated. All the antennas are found to be resonates at a frequency which is placed closely to designed frequency. Parameters of the antenna designed using the developed equations and the results obtained are given in Table.2 and from the last two rows, it is evident that the design equations are universally valid for all kinds of substrates and all frequencies.

Table.2. Validation of Design Equations

Parameters	Antenna A	Antenna B	Antenna C
ε_r	2.2	4.4	10.2
L (mm)	4.79	8	7.4
W (mm)	5.75	9.6	8.88
L_s (mm)	3.59	6	5.55

L_f (mm)	2.54	4.24	3.92
S_p (mm)	1.19	2	1.85
Designed Freq (GHz)	5.2	2.4	1.8
Resonates at (GHz)	5.194	2.4058	1.806

4. RESULTS AND DISCUSSIONS

From the validation process of the antenna design equations performed, one antenna resonating at 2.4 GHz (Antenna B) is selected for making the prototype and for experimental studies and measurements. The structural specification of the antenna are depicted in table 3. Overall volume of the antenna is found to be 8 × 9.6 × 1.6 mm^3 (0.12λg × 0.10λg × 0.02λg) which makes the structure most compact one and entitled to the category of an electrically small antenna.

Table.3. Optimized dimensions of the structure

L	***W***	***L$_s$***	***W$_s$***	***L$_f$***
8 mm	9.6 mm	6 mm	3 mm	4.24mm
Sp	***g***	***h***	**tan *δ***	***ε***
2 mm	0.3 mm	1.6 mm	.002	4.4

Simulated and measured S parameter of the antenna were in good agreement and is shown in Fig.6. The 2:1 VSWR bandwidth of the antenna ranges from 2.2 to 2.7 GHz (Bandwidth of 500 MHz) which is wide enough to cover Wi-Fi 802.11b,802.11g, 802.11n, Bluetooth, ZigBee IEEE802.15.4 and ISM application.

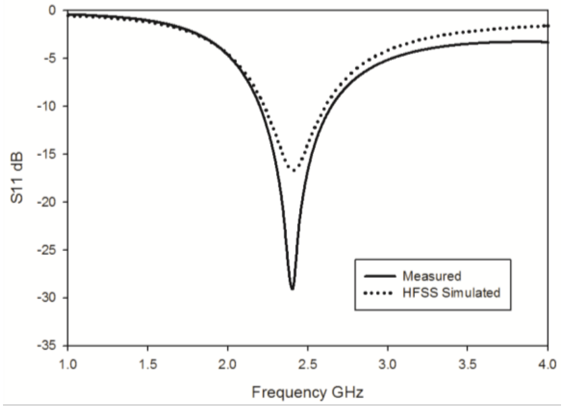
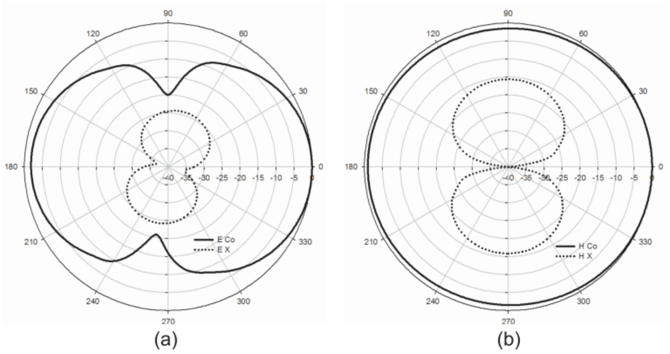


Fig.6. Measured and Simulated S_{11}

Two-dimensional energy distribution of the antenna around the structure in two principal planes are given in Fig.7. Polarization of the antenna is found to be linear with high degree of cross polar purity in both E and H plane.



(a) (b)

Fig.7. Measured Radiation Patterns (a) E plane and (b) H plane

Simulated 3D pattern of the antenna at 2.4GHz, obtained from ANSOFT HFSS is depicted in Fig.8. Antenna offers an apple shaped radiation pattern similar to a half wave dipole at resonance.

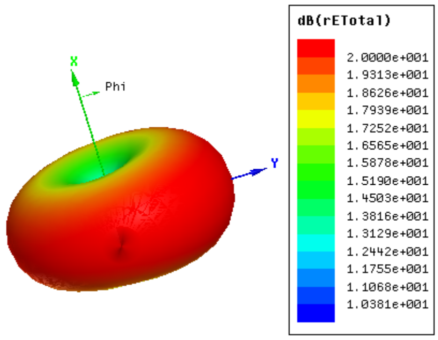


Fig.8. 3D Radiation Pattern

To obtain the technical knowhow of radiation mechanism, the surface current plot of the antenna is analysed thoroughly. The vector surface current plot of the antenna is given in Fig.9. Entire metallic surface contributes to radiation in this structure. One important factor to be noted in this structure is that the direction changes of surface current in right and left ground plane. In normal CPWs all the ground plane currents are in same direction. This directional change is due to the presence of the short in between signal strip and right ground plane. Current in signal strip also forcefully changes its current direction due to the short. As a result of these multiple folding in current path, current path length increases and which in turn results in lowering of the resonant frequency.

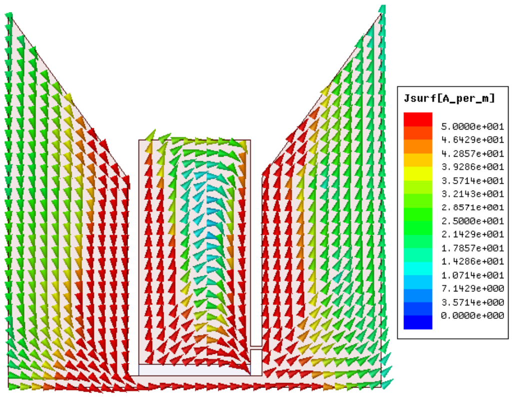


Fig.9. Vector Surface Current pattern

Wheeler cap method and Standard horn testing method are used to measure the radiation efficiency and gain of the antenna respectively.

The radiation efficiency is found to be 89% as its average value which shows the excellent and uniform radiation behaviour of the antenna in the entire band. The peak gain of the antenna is found as 2.65dBi around 2.39GHz with an average value of 2.6 dBi in the band. Both Efficiency and gain plot of the antenna are given in Fig.10.

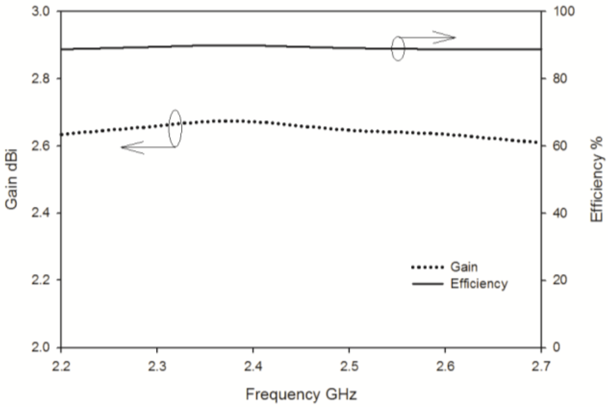


Fig.10. Efficiency and Gain plot

4.1 FDTD ANALYSIS

To unveil the mechanism behind radiation and other theoretical aspects about the CPW Fed Ultra Compact Radiator for 2.4GHz Wireless and ISM Applications, a mathematical model of the same is generated and simulated using FDTD method. The specification of Yee cell used in modelling are Δi=0.1mm, Δj=0.1mm and Δk=0.1mm. A total of 8000 repeated iterations are performed for better convergence with time step size Δt=0.5pS. FDTD computational domain with specified parameters are shown in Fig.11.

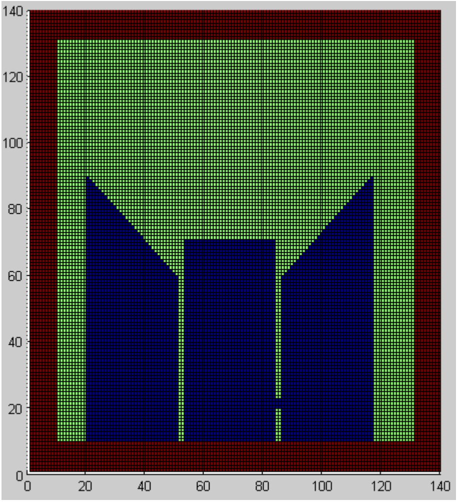


Fig.11. FDTD Computational Domain

For calculating the reflection characteristics in a wide frequency range, a narrow Gaussian pulse (Half power time period 10pS) is used as excitation. Time delay for excitation is selected as 90pS. A Perfectly Matched Layer (PML) absorption boundary condition explained in [17] is used as Absorbing Boundary Condition here.

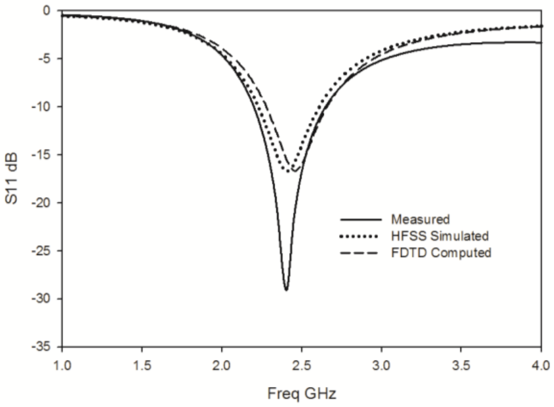


Fig.12. FDTD Computed and Measured S11

Measured, HFSS simulated and FDTD computed S11are found to be almost similar with excellent cross matching and can be verified from the Fig.12.

5. CONCLUSION

An ultra-compact uniplanar antenna suitable for 2.4GHz ISM and wireless applications like WiFi 802.11b,802.11g, 802.11n, Bluetooth, ZigBee IEEE802.15.4 etc. is developed and presented. Antenna offers uniform radiation characteristics within the band of operation with an apple shaped radiation pattern, very good radiation efficiency and with moderate gain. Universal design of the structure is developed and validated with the help of HFSS simulation software. FDTD modelling of the antenna is developed and results are compared with measured results.

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PARAMETRIC EXTRACTION AND EQUIVALENT CIRCUIT MODELLING OF SINGLE BAND ANTENNAS

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Abstract

A simple and powerful equivalent circuit modeling suitable and novel method for extracting distributed parameters of a single band antenna which can be generalized is presented. From these two techniques, an equation for distributed components in terms of dimensional parameters and effective dielectric constant is developed. Validity of the developed equation is analyzed using simulation software and the results are in close matching. In future, this method can be elaborated to develop generalized modeling for multi band and wide band antennas.

Keywords:

Antenna, Equivalent Circuit Modelling, RLC Circuit, Series Resonance, Q Factor, Bandwidth

1. INTRODUCTION

Antenna is a radiating structure which is capable of emitting/receiving electromagnetic radiation at a certain frequency. Antenna is designed to be operated in a band of frequencies and that is termed as antenna bandwidth. It is often very difficult for antenna engineers to design an antenna with an accurate resonant frequency with a particular bandwidth, because it is depended on various physical, electrical and magnetic parameters. There comes the use of equivalent circuit modelling. Equivalent circuit modelling is the process of constructing a lumped element circuit which possess the resonant and bandwidth characteristics of antenna. From this model, a technical person is easily capable of calculating various parameters of the antenna. If the developed equivalent circuit model can be generalized, it can be used for accurate designing antennas and can be used for easily converting one antenna with particular characteristics into another.

Two general power sources based complicated equivalent circuit model in introduced in [1]. Wang et al. [2] presents a new equivalent circuit for antenna which is transformed from *S*-domain parameters. Floquet Modal Expansion of Surface Current Distributions based equivalent circuit modelling is presented in [3]. Circuit modelling for general PCB meta-rings antenna is discussed by the authors in [4]. An analytical model for proximity coupled microstrip antenna is introduced in [5]. Equivalent circuit model suitable for antennas with lumped components like PIN diodes is explained in [6]. Circuit modelling of frequency re configurable Ku band antennas is discussed by Karmakar et al. [7]. A Schottky diode based large signal equivalent model of microwave circuits is presented in [8]. Hossain et al. [9] introduces a novel circuit modelling for wideband absorbers, which is suitable for low frequencies in microwave range. A circuit approach for anisotropic frequency-selective surfaces and meta-surfaces is presented in [10]. Naseri et al. [11] presents a modelling which is suitable for linear and circular polarized microwave surfaces. Anyhow, in all the above discussed design or modelling, the equivalent circuit formation and parameter extraction is rather complex and time consuming. Various signal processing strategies are also incorporated in some models. Another problem with these is lack of generalization. Presented modelling is suitable for the discussed antennas/surfaces only.

In this article, we are presenting a simple method for parametric extraction of distributed components and generalized equivalent circuit modelling which is very much suitable for single band antennas. Parametric extraction is done with the help of well-known series resonance equations. The extracted parameters are analysed for different dimensional factors and a generalized equation for calculating distributed components is arrived. Validity of the developed equations are also analysed and presented.

2. THEORY OF SERIES RESONANCE

Antenna is considered as a self-resonating structure which having its on resonant frequency caused due to various structural parameters. According to [12], a single band antenna is equivalent to a series RLC circuit having a resonant frequency and selectivity. A series RLC circuit with AC expiation is shown in Fig.1.

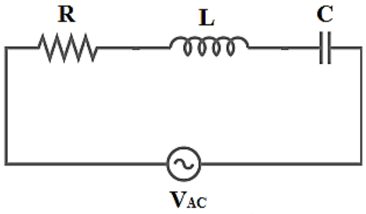


Fig.1. Series RLC Circuit with AC Excitation

The magnitude of impedance of the circuit is given by

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2} \tag{1}$$

At DC condition, the capacitor acts as a blocking capacitor and the current through the circuit is zero. As frequency of excitation increases, a complex current (current with a phase shift with voltage) will flow through the circuit. The magnitude and phase shift of the current waveform will be a function of frequency and circuit parameters. According to well-known characteristics of inductance and capacitance, it is clear that the inductive reactance increases while the capacitive reactance decreases with frequency. At a magic point called resonance, the capacitive and inductive reactance will have same magnitude but opposite phase, and thus they will cancel each other resulting in an impedance which is equal to resistance in the circuit.

Equation for finding out resonant frequency is as follows:

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

At resonance

$$Z=R; \text{ At resonance} \tag{3}$$

As we deviate the frequency towards left of resonant frequency, the capacitive reactance will be larger and which results in a magnitude of impedance greater than R. The same phenomena will happen when we move towards the right to the resonant frequency too with a difference that, here the inductive reactance is larger. Thus, impedance will be minimum at resonance which implies that the current will be maximum at resonance. Current will decrease from maximum value, as we move from resonant frequencies to either side. This will create a band pass characteristic to current curve which indicates that the resonant circuit has a bandwidth which is defined as the range of frequencies for which current is greater than or equal to 0.707 times the maximum current.

Selectivity or Q-factor or Quality factor is the ability of the circuit to select a particular frequency from a range of frequencies. Q-factor and bandwidth of the circuit are inversely proportional [13] and related to the resonant frequency and bandwidth through the well-known equation.

$$Q = \frac{f_r}{BW} = \frac{2\pi f_r L}{R} = \frac{1}{2\pi f_r CR} \tag{4}$$

Thus from Eq.(2), it is clear that the resonant frequency is a function of *L* and *C* only. Eq.(4) clearly states that the *Q* is a function of all the three-circuit component viz. *R, L* and *C*.

3. THEORETICAL ANTENNA MODELLING

Antenna is also a resonating structure with a resonant frequency and bandwidth. Its reflection co efficient will gives both these parameters. By equating the series RLC circuit discussed above with a single band antenna, the equivalent circuit parameters of the antennas can be extracted using simple mathematical methods.

Algorithm for extracting distributed *R*, *L* and *C* parameters of the antenna is described as follows.

Step 1: Obtain the Resonant Frequency f_r, S_{11} value and -10dB Bandwidth (BW) from reflection coefficient

Step 2: Calculate the value of *R* by solving the Eq.(5).

$$10^{\frac{S_{11}}{20}} = \frac{R - Z_0}{R + Z_0} \tag{5}$$

where Z_0 is the characteristic impedance of the transmission line used. In our case, it is 50Ω.

Step 3: Calculate Q using first expression of Eq.4.

Step 4: Calculate Inductance by the formula

$$L = \frac{QR}{2\pi f_r} \tag{6}$$

This is obtained by rearranging 2nd part of Eq.(4).

Step 5: Calculate Capacitance by the formula

$$C = \frac{1}{2\pi QRf_r} \tag{7}$$

This is obtained by rearranging 3rd part of Eq.(4).

After extracting the circuit parameters from reflection co efficient, we have to relate these values to the dimensional parameters of the antenna. For this another algorithm is used and the stepwise explanation of this is as follows.

Step 1: Perform parametric analysis of the antenna; extract the distributed parameters for all the variations.

Step 2: Obtain the curve between each dimensional parameter and extracted component. Using curve fitting method of statistics, we can obtain a relation between dimensional and distributed parameter.

Step 3: By combining all the individual relation of one-dimensional parameter, obtain the offset values (constant) if any.

Step 4: Generalize the relation obtained in step 3 by replacing dimension with fractional guided wavelength or by incorporating effective dielectric constant

As an example, extraction of circuit parameters of single band dipole antenna fed by a coplanar strip discussed in [14] is discussed here. Antenna has four different dimensional parameters which are crucially affects the resonance. Structure of slot line fed antenna under study is shown in Fig.2.

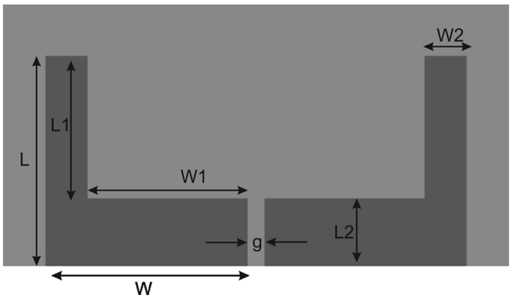
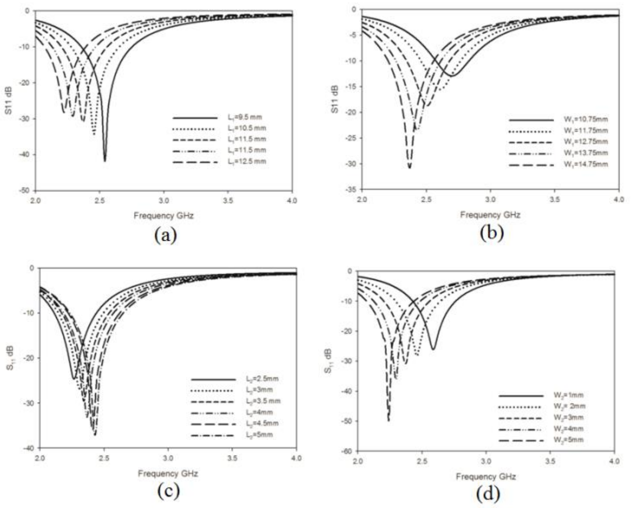


Fig.2. Structure of Slot-line fed single band Dipole

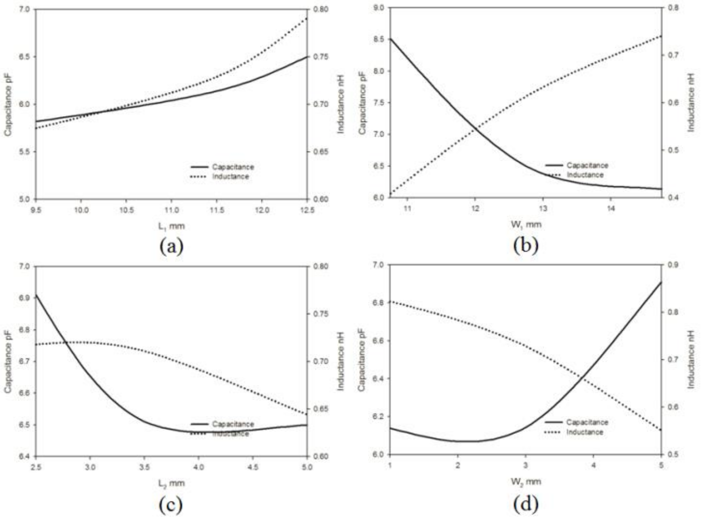
The reflection co efficient curves obtained using dimensional variations in L_1, W_1, L_2 and W_2 are depicted in Fig.3.



(a) (b) (c) (d)

Fig.3. Parametric Analysis

Since antenna offers perfect matching at resonance, the resistance value obtained using Eq.(5) in each variation is nearly 50Ω. The capacitance and inductance of the antenna varies considerably with all these parameters and the curve showing variation of distributed parameters with dimensional parameters are shown in Fig.4.



(a) (b) (c) (d)

Fig.3. *L* and *C* with dimensional parameters

On curve fitting the graphs obtained in Fig.4, the relations of various dimensional parameters on *C* and *L* are obtained are given in Table.1.

Table.1. Expression for *L* and *C* with different dimensional parameters

Parameter	Relation
L_1	$L = L_1(0.0116L_1\text{-}0.218) + 1.6931$ $C = L_1(0.0667L_1\text{-}1.24) + 11.5833$
L_2	$L=L_2(-0.0151L_2+0.0834)+0.6037$ $C=\frac{1}{L_2}\left(\frac{31.4243}{L_2^2}-\frac{10.92}{L_2}-0.199\right)+6.7251$
W_1	$L = W_1(-0.0097W_1 + 0.3304) - 2.021$ $C = W_1(0.2063W_1 - 5.85) + 47.5829$
W_2	$L=W_2(-0.0104W_2 + 0.1304) + 0.431$ $C=W_2(0.0955W_2 - 0.7655) + 7.58$

By combining all the above relations, we can obtain the expression for capacitance as:

$$C = 54.64 + L_1\left(0.0667L_1 - 1.24\right) + W_1\left(0.2063W_1 - 5.85\right)$$
$$+W_2\left(0.0955W_2 - 0.7655\right) + \frac{1}{L_2}\left(\frac{31.4243}{L_2^2} - \frac{10.92}{L_2} - 0.199\right) \quad (8)$$

The inductance can be combined and written as

$$L=-1.3036+L_1(0.0116L_1\text{-}0.218)+L_2(-0.0151L_1+0.0834)+$$
$$W_1(-0.0097W_1+0.3304)+W_2(-0.0104W_2+0.1304) \quad (9)$$

As the next step, we have to generalize the equation for all dielectric constants by incorporating effective dielectric constant in Eq.(8) and Eq.(9). For this convert all length by equivalent fraction of guided wavelength. Then the generalized equations are:

$$C = 20.27 + 0.379\sqrt{\varepsilon_{ef}}\left[L_1\sqrt{\varepsilon_{ef}}\left(0.0667L_1\sqrt{\varepsilon_{ef}} - 1.24\right)\right]$$
$$+\frac{1}{L_2\sqrt{\varepsilon_{ef}}}\left(\frac{31.4243}{\varepsilon_{ef}L_2^2} - \frac{10.92}{L_2\sqrt{\varepsilon_{ef}}} - 0.199\right) + W_1\sqrt{\varepsilon_{ef}} \quad (10)$$
$$\left(0.0955W_2\sqrt{\varepsilon_{ef}} - 5.85\right) + W_2\sqrt{\varepsilon_{ef}}\left(0.0955W_2\sqrt{\varepsilon_{ef}} - 0.7655\right)$$

and

$$L = -1.3036 + 0.364\sqrt{\varepsilon_{ef}}\left[L_1\sqrt{\varepsilon_{ef}}\left(0.012L_1\sqrt{\varepsilon_{ef}} - 0.22\right)\right]$$
$$+L_2\sqrt{\varepsilon_{ef}}\left(-0.0151L_2\sqrt{\varepsilon_{ef}} + 0.0834\right)$$
$$+W_1\sqrt{\varepsilon_{ef}}\left(-0.0097W_1\sqrt{\varepsilon_{ef}} - 0.3304\right) \quad (11)$$
$$+W_2\sqrt{\varepsilon_{ef}}\left(-0.0104W_2\sqrt{\varepsilon_{ef}} - 0.1304\right)$$

4. RESULTS AND DISCUSSIONS

Relations obtained in Eq.(10) and Eq.(11) are validated for different commercially available substrates using the high frequency simulation tool Ansoft HFSS. All the antennas are designed to operate in 2.4GHz ISM bands and the structural parameters of the antenna used for simulations are depicted in Table.2.

Table.2. Antenna parameters

Name	Dielectric constant	L_1	L_2	W_1	W_2
Antenna 1	10.2	7.95	2.43	8.15	2.1
Antenna 2	6.15	10	3.04	10.21	2.5
Antenna 3	4.4	11.5	3.5	11.75	3
Antenna 4	2.2	14.9	4.55	15.25	3.9

Obtained inductor and capacitor values using Eq.10 and 11 and a comparison of resonating frequency and bandwidth are depicted in Table.3.

Table.3. Validation of Equations

Name	*L* (nH)	*C* (pF)	***BW*** **(GHz)**		***F**$_r$* **(GHz)**	
			HFSS	Calculated	HFSS	Calculated
Antenna 1	0.7275	6.0926	0.457	0.435	2.40	2.39
Antenna 2	0.7296	6.1300	0.460	0.430	2.38	2.38
Antenna 3	0.7313	6.1501	0.455	0.431	2.38	2.37
Antenna 4	0.7236	6.0758	0.442	0.436	2.42	2.40

The simulated and calculated values are close enough and which indicated the universal validity of the equations for antenna structures given in Fig.2.

5. CONCLUSION

In this paper, a simple, powerful and generalized equivalent circuit modelling suitable for single band antenna is presented. A novel method for extracting distributed parameters of the antenna is also discussed. From these two techniques, a generalized equation for distributed components in terms of dimensional parameters is developed. Validity of the developed equation is analysed using simulation software and the results are in close matching. In future, this method can be elaborated to develop generalized modelling for multi band and wide band antennas.

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