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Design and Analysis of Dual band Microstrip Antenna for Millimeter Wave Communication Applications

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Abstract: Millimeter wave (MMW) communication is a key technology to enable the seamless connectivity among the various devices in the next generation wireless network (5G and beyond). However, the antenna design at MMW frequencies is a critical challenge. In this context, this paper presents a compact dual band Rectangular Microstrip Antenna (RMSA) for MMW communication applications. The design has been carried out at 33.5 GHz (Ka band) and two symmetrical slots are integrated at the optimum position to achieve the higher resonance at 62.5 GHz in the V band of MMW spectrum. The simulation results show that the antenna performs quite well and achieves the return loss of -16.6 dB and -15.03 dB and peak gain of 4.93 and 3.67 dB at 33.5 GHz and 62.53 GHz respectively. The proposed antenna design has been further extended to a dual element antenna array and analysed for improvement of different antenna parameters like gain, directivity, bandwidth and VSWR. The feasibility of the proposed antenna has been demonstrated by experimental results. The paper also presents the parametric and equivalent circuit analysis of the designed antenna.

Keywords: Millimeter Wave Communication, Next Generation Networks, Ka band, V band, VSWR.

1. INTRODUCTION

In most of the wireless network applications, dual band antennas are preferred as they provide the benefits of reduced cost and system complexity by replacing the usage of multiple antennas for different operating frequencies [1]. In the similar way, the antennas capable of operating at the multiple frequencies in the MMW spectrum will be of great interest for next generation networking applications of MMW communication technology due to its capabilities of providing the high data rate and capacity which are the key requirements of the next generation networks like 5G and beyond [2,3]. However, designing the antennas at MMW frequencies is a critical challenge as these antennas should exhibit high gain and directivity besides the low cost, small size and should be able to operate with constant gain and high efficiency over a broad frequency spectrum in MMW range [4, 5].

In order to design a dual frequency antenna, numerous techniques are available in the literature [6, 7, 8]. However, most of them are unfeasible or impractical or have not been analysed for MMW communication applications. For instance, the stub loading technique for designing multiband antenna will not be preferred for MMW applications as it is good for narrow band applications only [9]. The technique of using perforated microstrip antenna for dual band operations has also low gain issues and needs to be revisited for high gain applications [10]. The antenna reported in [11] could be used but it requires multiple feeds and makes the antenna system complex which is not preferred for next generation networks. As such there is an utmost need of the study and analysis of the dual band antennas for MMW communication network applications.

This paper presents the design of a dual band antenna intended for MMW applications. First a single band RMSA with center frequency 33.5 GHz (Ka band) is designed using the inset feed technique. Two symmetrical and optimized slots are integrated at the edges of the patch to resonate the antenna at 62.5 GHz frequency (V band) also. Thus, the antenna operates at the dual frequencies of 33.5 GHz and 62.5 GHz respectively. The design and simulation of the proposed antenna is carried out in CST Microwave Suite. Further, in order to validate the simulation results, an electrical equivalent circuit of the designed antenna is also introduced. The proposed antenna achieves the peak gain 4.93 and 3.67 dB and return loss of -16.6 dB and -15.03 dB at 33.5 GHz and 62.53 GHz respectively. The proposed antenna design has

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been further extended to a dual element antenna array and analysed for improvement of different antenna parameters like gain, directivity, bandwidth and VSWR.

The paper has been organized into five sections. Section 1 gives the Introduction. Section 2 presents the design procedure of dual band slotted RMSA. The simulated results are discussed in section 3. It also provides the experimental study and parametric analysis of the designed antenna. The equivalent circuit analysis of the antenna is given in section 4. Finally section 5 concludes the paper.

2. DESIGN PROCEDURE

A linearly polarized dual band antenna is designed at Ka and V band of the MMW spectrum having the configuration as shown in Fig. 1. The design procedure starts by selecting the operating frequencies ‘f_1’ and ‘f_2’ which in this case are 33.5 GHz and 62.5 GHz respectively. First a single band RMSA with center frequency 33.5 GHz is designed. The physical parameters related to the design are listed in table I. These parameters have been computed using the following standard relations [12, 13, 14]:

$$W_P = \frac{c}{2 f_1 \sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

$$L_e = \frac{c}{2 f_1 \sqrt{\varepsilon_e}} \tag{2}$$

$$L = L_e - 2\Delta L$$

Where, W_P= Patch Width

L_e = Effective Length

L= Patch Length

L= Patch Length extension

f_1 = Lower band resonant frequency (33.5 GHz)

c = Velocity of light (3×10^8m/s)

ε_r = Dielectric constant of substrate

ε_e = Effective dielectric constant given by:

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{10h}{W}\right]^{-\frac{1}{2}} \tag{3}$$

$$\Delta L = 2\frac{h}{\sqrt{\varepsilon_e}} \tag{4}$$

h is the thickness of the substrate and is given by:

$$h \le \frac{0.3\lambda_1}{2\pi\sqrt{\varepsilon_r}}$$

Similarly, inset feed depth (F_i) and feed gap (g_{pf}) is given by:

$$F_i = \frac{6h}{2}$$

$$g_{pf} = \frac{c}{\sqrt{2\varepsilon_r}} \cdot \frac{4.65\times10^{-12}}{f_1}$$

The V band operation at 62.5 GHz is excited by incorporating the two symmetrical rectangular slots near the radiating edges of the patch. Since the current minimas are located at these edges, minimum perturbation is caused in TM_{10} mode. However in TM_{30} mode, the current is modified and circulates around the symmetrical slots, establishing a resonant condition with nulls close to the edges of slot. The dimensions of these symmetrical slots are obtained using following standard equations [15]:

Length of the slot: $$L_s = \frac{0.34\times c}{f_2 \times \sqrt{\varepsilon_{eff}}} - \frac{h - 1.6}{0.6} \tag{5}$$

Width of the slot: $$W_s = \frac{0.18\times c}{f_2 \times \sqrt{\varepsilon_{eff}}} \tag{6}$$

Where f_2 = Higher band resonant frequency (62.5 GHz).

h= thickness of substrate

ε_{eff} = Effective dielectric constant of the substrate

During the design process, Fr-4 (Lossy) is used as the substrate material having a dielectric constant ε_r = 4.3 and thickness ‘h’. In order to ensure the proper impedance matching and simplified design, inset feed technique is used.

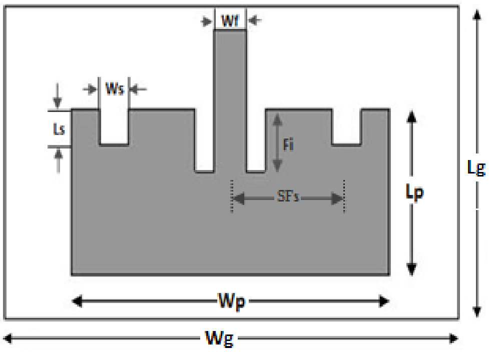


Figure 1. Configuration of the proposed dual band antenna.

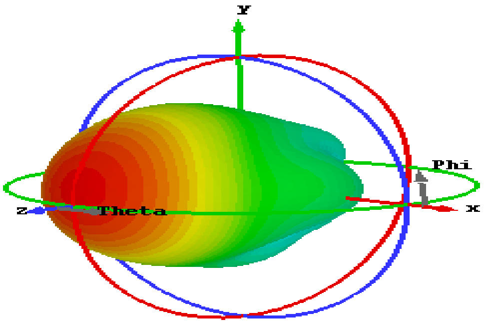
TABLE I. OPTIMISED PHYSICAL PARAMETERS OF PROPOSED ANTENNA DESIGN

Parameter	**Value (mm)**	**Parameter**	**Value (mm)**
Patch Length (Lp)	2.15	Length of Feedline (Lf)	1.78
Patch Width (Wp)	5.04	Width of Feedline (Wf)	0.50
Length of Ground (Lg)	4.30	Feed gap (g_{pf})	0.62
Width of Ground (Wg)	10.08	Inset depth (Fi)	0.79
Patch thickness (mt)	0.01	Length of Slot (Ls)	0.65
Substrate thickness (h)	0.45	Width of Slot (Ws)	0.46
Ground thickness (Gt)	0.01	Feed Slot Spacing (SFs)	1.90

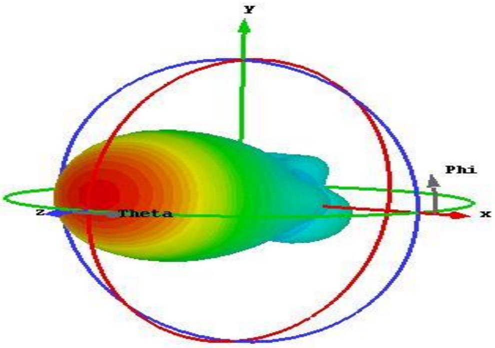
3. RESULTS AND DISCUSSION

A. Simulation Study

The characteristics of the designed RMSA such as return loss, VSWR, gain, directivity and bandwidth are investigated by performing the full wave simulations using CST Microwave Suite. The three dimensional and two-dimensional radiation pattern of the designed antenna has been plotted as shown in Fig. 2 and 3. It indicates that the antenna achieves a gain of 4.93 dB and 3.67 dB at 33.5 and 62.5 GHz respectively.

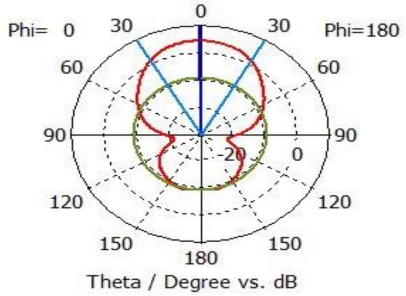


(a). 33.5 GHz

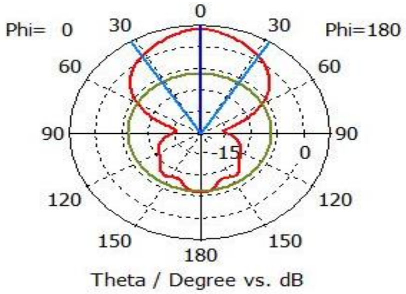


(b) 62.5 GHz

Figure 2. Three-dimensional Radiation Pattern



(a) 33.5 GHz



(b) 62.5 GHz

Figure 3. Two-dimensional Radiation Pattern

The return loss and VSWR plots are given in Fig. 4. It can be seen from the figure, very low return loss i.e. -16.6 dB and -15.03 dB is achieved at 30.5 GHz and 62.5 GHz frequencies respectively. Also, the VSWR for both operating frequencies lies between 1 and 2 which indicates that there is very good impedance matching between the antenna and feed line and reflections are very less. The other results obtained from the simulation study of the proposed antenna are summarised in table II.

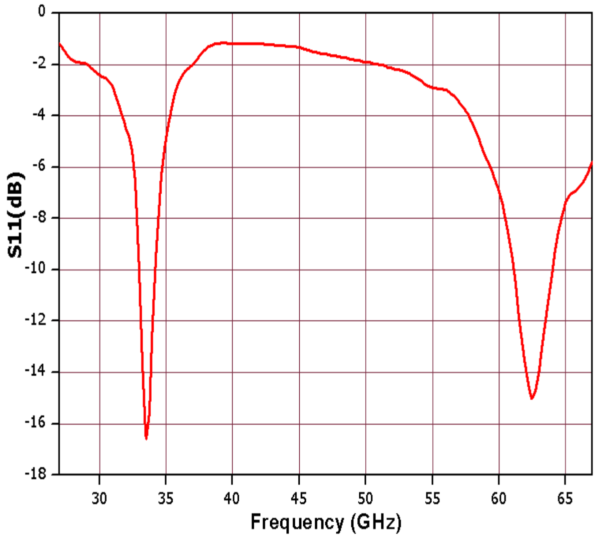


Figure 4(a). Return Loss of the proposed dual band antenna.

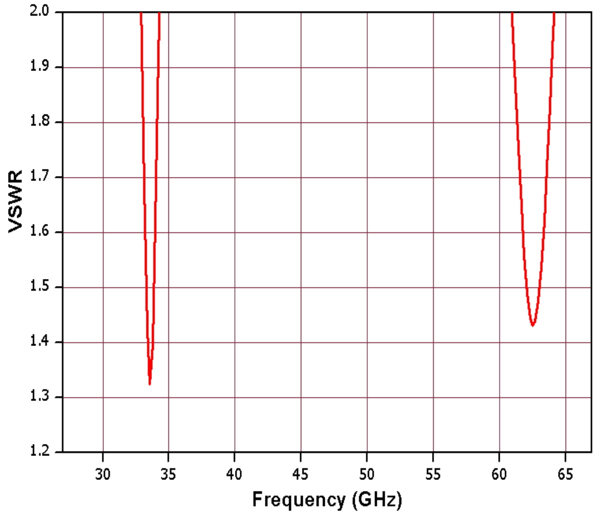


Figure 4(b). VSWR of the proposed dual band antenna.

TABLE II. RESULT SUMMARY OF PROPOSED DUAL BAND ANTENNA DESIGN

Parameter	**Operating frequency**	
	33.5 GHz	**62.5 GHz**
Return Loss(dB)	-16.6	-15.03
VSWR	1.32	1.43
BW(GHz)	1.36	2.98
Gain (dB)	4.93	3.67
Directivity (dBi)	7.17	6.23
Efficiency (%)	68.75	59.01
P_{max} (mW/m^2)	222	187

B. Gain Enhancement

The gain of the single patch antenna designed in section II is 4.93 dB at 33.5 GHz and 3.67dB at 62.5 GHz which is not sufficient for most of the Millimeter wave communication applications [16, 17]. In order to enhance the achieved gain, the proposed antenna design is extended to a two-element antenna array configuration as shown in Fig. 5. The two elements are identical and are designed according to the procedure given in section II. The spacing between the elements is 4.98mm (> 0.5λ) in order to avoid mutual coupling effect [18]. A T shaped power divider is used for impedance matching [19].

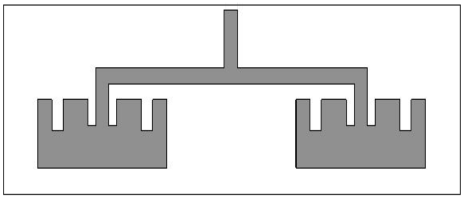


Figure 5. Layout of the two-element antenna array (Top View)

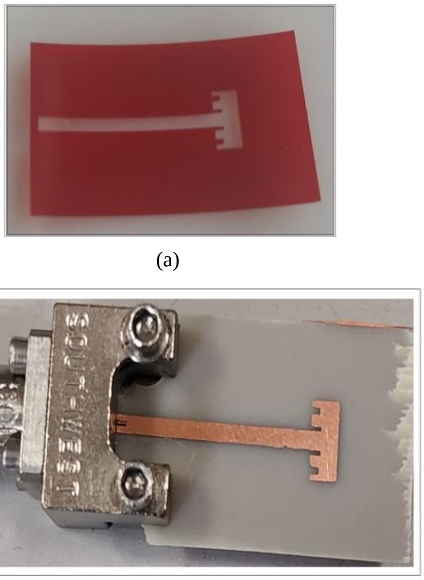
The designed antenna array is simulated and the results are summarized in table III which indicates that there is considerable enhancement in the gain as well as the directivity of the antenna at both resonances. Depending on the particular application requirements, the configuration can be further extended to 1×3, 2×2, 4 × 4 antenna arrays and so on.

TABLE III. RESULT SUMMARY OF PROPOSED DUAL ELEMENT ANTENNA ARRAY

Parameter	**Operating frequency**	
	33.5 GHz	**62.5 GHz**
Return Loss	-18.75	-17.36
VSWR	1.26	1.31
Bandwidth	1.52	3.16
Gain (dB)	8.12	7.12
Directivity(dBi)	10.65	11.2
Effeciency(%)	76.24	63.57
Pmax(mW/m^2)	491	427

C. Experimental Study

The proposed dual band antenna is fabricated using the photolithography process and its results are measured using a Vector Network Analyser (VNA). The photo prototype of the fabricated antenna and its measured return loss results are given in Fig. 6 and 7 respectively. The slight deviation between the measured and simulated results is attributed to the possible fabrication and measurement errors which are acceptable at such small antenna dimensions.



(a)

(b)

Figure 6. (a) Mask (b) Fabricated antenna under test

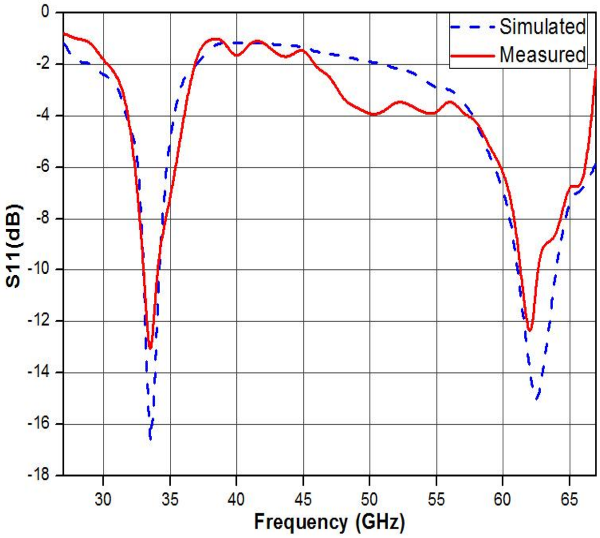


Figure 7. Measured and simulation results of return loss

D. *Parametric Analysis*

In this section we study and analyze the effect of the slot width, length and position on the characteristics of the proposed antenna in terms of VSWR, return loss and bandwidth.

1) *Effect of Slot Width and Length*

The slot width is changed from 0.36 mm (Ws1) to 0.46 mm (Ws2) and 0.56 mm (Ws3) respectively and results are plotted in Fig. 8. It is observed that the resonant frequency slightly varies and shifts towards the higher frequency as the width of the slot increases. Also, there is a slight increase in the bandwidth of the antenna as the slot width increases. The return loss is reasonably improved at larger slot width.

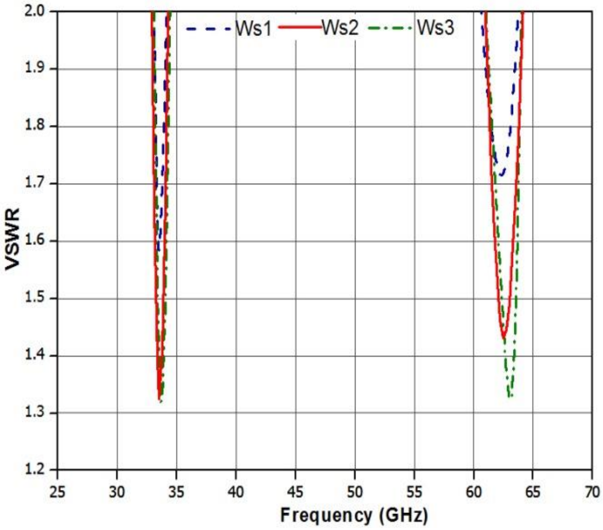


Figure 8. Effect of Changing Slot Width (Ws1=0.36 mm, Ws2=0.46 mm, Ws3=0.46 mm)

Similarly, the slot length is increased from 0.55 mm (Ls1) to 0.65 mm (Ls2) and 0.75 mm (Ls3) respectively and results are shown in Fig. 9. There is not much effect of slot length on the bandwidth however there is notably increase in the ratio of two resonance frequencies with increase in slot length. So, based on the application requirement we can choose the particular slot width and length and optimize our antenna design

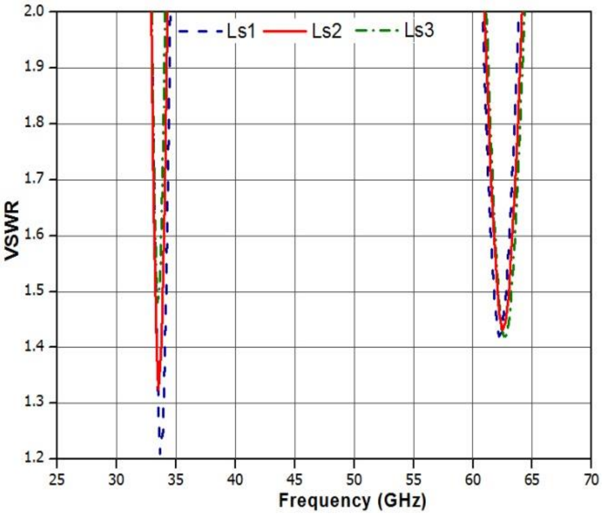


Figure 9. Effect of Changing Slot Length (Ls1=0.55 mm, Ls2=0.65 mm, Ls3=0.75 mm)

2) *Effect of Slot Position*

The slot position is changed by the changing the center to center spacing between the slot and feed line from 1.80 mm (Sp1) to 1.90 mm (Sp2) and 2.0 mm (Sp3) respectively. The results are plotted in Fig. 10. It is observed that by decreasing the spacing between slot and feed lines i.e. shifting the slot towards the feed line considerably improves the return loss of the antenna at both resonance frequencies.

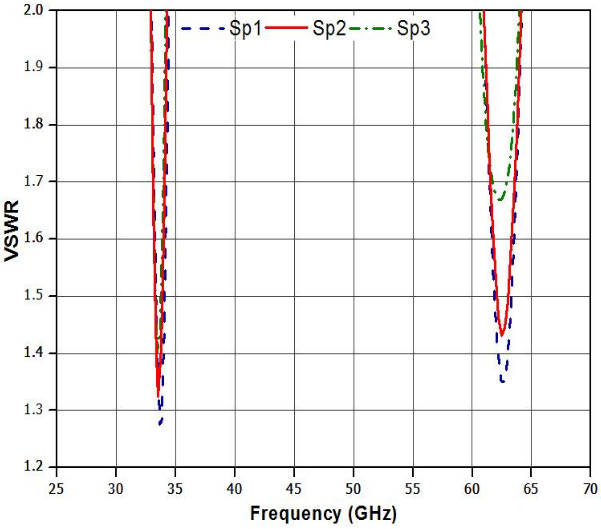


Figure 10. Effect of changing slot position (Sp1=1.80 mm, Sp2=1.90 mm, Sp3=2.0 mm)

4. EQUIVALENT CIRCUIT ANALYSIS

The designed antenna based on the Cavity model [20] acts a series combination of two resonating modes with each mode represented as a parallel RLC equivalent circuit as shown in Fig. 11, where, resistances ‘R1and R2’, capacitances ‘C1 and C2’, inductances ‘L1and L2’, correspond to the rectangular microstrip patch and symmetrical Slots respectively. The quantity ‘X_f’ represents the inductive feed point reactance and is given by: $X_f = \omega L_f$, where L_f is the feed point inductance.

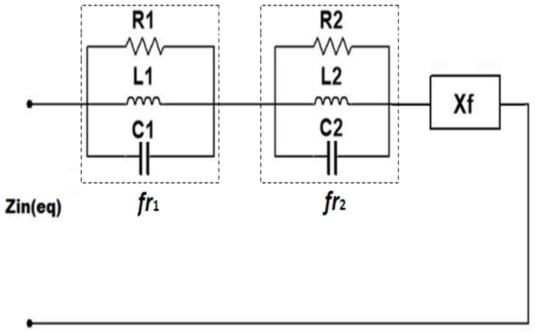


Figure 11. Equivalent Circuit of proposed antenna

The input impedance $Z_{in}(f)$ at the feed point of the equivalent circuit of the antenna can be written in terms of following equations:

$$Zin(f) = \frac{1}{\frac{1}{R1} + \frac{1}{j\omega L1} + j\omega C1} + \frac{1}{\frac{1}{R2} + \frac{1}{j\omega L2} + j\omega C2} + Xf \quad (7)$$

Or, $Zin\ (f) = (R_p + jX_p) + (R_s + jX_s) + Xf$ (8)

Where, R_p = resistance corresponding to the patch.

R_s = reactance corresponding to the patch.

.X_p = resistance corresponding to the slots.

X_s = reactance corresponding to the slots.

In terms of magnitude above equation can also be written as:

$$|Z_{in}(f)| = \frac{1}{\sqrt{\left(\frac{1}{R1}\right)^2 + \left(\frac{1}{\omega L1} - \omega C1\right)^2}} + \frac{1}{\sqrt{\left(\frac{1}{R2}\right)^2 + \left(\frac{1}{\omega L2} - \omega C2\right)^2}} + \omega L$$

The equivalent circuit parameters are obtained based on models given in [21, 22, 23] as following:

$$C_1 = \frac{\varepsilon_e \varepsilon_0 L_P W_P}{2h} \cdot \frac{1}{Cos^2(\beta)} \quad (9)$$

where, $\beta = \frac{\pi zo}{L_P}$ (10)

$$L1 = \frac{1}{2\pi f_1 C1} \quad \text{and} \quad R1 = \frac{Q}{2\pi f_1 C1} \quad (11)$$

Where L_P = Patch Length

W_P = Patch Width

ε_e = Effective dielectric constant

ε_o = Free Space Permittivity.

h = substrate thickness

zo = feed point location in z direction

f_1 = first resonant frequency (33.5 GHz)

Q = Quality factor

$$R_s = 60\{C + \ln(kL_s) - C_i(kL_s) + \frac{1}{2} Sin(kL_s)\cdot[S_i(2kL_s) - 2S_i(kL_s)] \\ + \frac{1}{2} Cos(kL_s)\cdot[C + \ln(\frac{kL_s}{2}) + C_i(2kL_s) - 2C_i(kL_s)]\}$$

$$X_s = 30\{2S_i(kL_s) + Cos(kL_s)\cdot[2S_i(kL_s) - S_i(2kL_s) \\ -Sin(kL_s)\cdot[2C_i(kL_s) - C_i(2kL_s) - C_i(\frac{kW_s}{2L_s})]]\}$$

where, C = 0.57721(Euler’s Constant)

$k = {}^{2\pi}/_{\lambda}$ (Free space Propagation constant)

$$C_i(y) = \int_0^y \frac{Sin\ y}{y}\, dy \quad (12)$$

$$S_i(y) = -\int_y^\infty \frac{Cos\ y}{y}\, dy \quad (13)$$

Where, $y = k\cdot Ls$

L_s = Length of Slot

W_s = Width of Slot

The reflection coefficient (Γ) of the equivalent circuit can be calculated as:

$$\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} \quad (14)$$

where Z_{in} = Input impedance of the antenna

Z_0 = Characteristic Impedance

Using (14), Return loss (RL) of the circuit in dB will be given by:

$$S_{11} = -20\log(\Gamma) \qquad (15)$$

Both Input impedance (Z_{in}) and Return loss (RL) of the equivalent circuit of the proposed dual band antenna are functions of the frequency and accordingly their variation with frequency were examined and plotted in Fig. 12 and 13 along with the simulated antenna results and it can be seen that a good agreement is realized between the modeled equivalent circuit and the simulated antenna results.

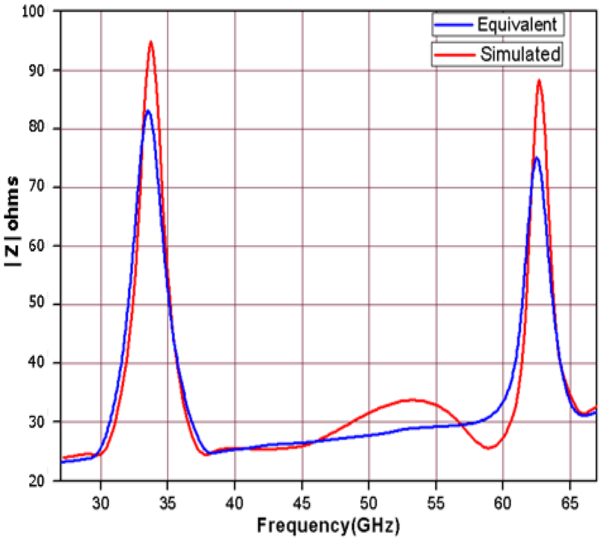


Figure 12. Input impedance of Equivalent circuit and simulated antenna

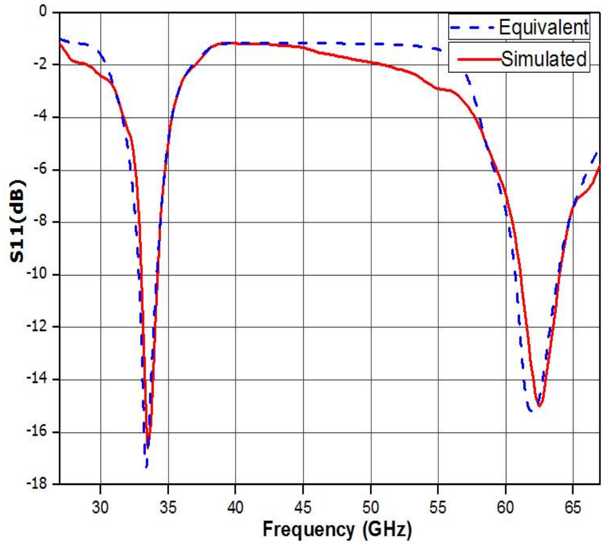


Figure 13. Return Loss of Equivalent circuit and simulated antenna

5. CONCLUSION

A compact dual band RMSA has been designed for MMW applications. The antenna resonates at 33.5 GHz (Ka band) and 62.5 GHz (V band) of MMW spectrum and provides a frequency ratio of approximately 1:2 between the two operating bands. The return loss for both the resonant frequencies is less than -15 dB and also achieves a reasonable gain of 4.93 and 3.67 dB, directivity of 7.17 and 6.23 dBi, bandwidth of 1.36 and 2.98 GHz at 33.5 GHz and 62.53 GHz respectively and operates without interference at the two bands. In order to enhance the gain and bandwidth of the antenna, the proposed antenna design has been extended to a two-element antenna which can be further extended to large antenna arrays as per the application requirements. The prototype of the proposed antenna design has been fabricated and tested successfully. The parametric and equivalent circuit analysis of the antenna has also been introduced. A good agreement was realized between the modeled equivalent circuit and the simulated antenna results.

In future, this work will be extended to design the multiband antenna which can support both MMW applications as well as low frequency applications like 4G, Wi-Fi and Wi-Max in order to make MMW communication systems to coexist with low frequency systems in next generation wireless network applications.

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