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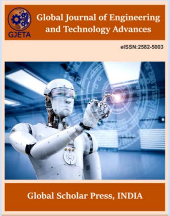

(Research Article)

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Investigation and design methods of a compact patch antennas using 3-D MMIC for various applications

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Abstract

This work focused on the design, characterization and investigation of GaAs based multi-layered compact 3D MMIC based antenna. Different patch antennas were designed and characterized along with its S-parameters. Two proposed models of multi-layered patch antenna using V-shaped feeder line and planar feeder line with a spiral transmission line in metal-2 were more compact in size and showed an improvement in performance based on bandwidth compared to the traditional planar feeder line configuration. This implies the proposed planar feed line with the spiral transmission is cost effective. The newly propose planar antenna with a spiral transmission feeder line is 49% more compact in area compared to using the normal planar feeder line. The new design also has wider bandwidth with a bandwidth of 2.99% as compared to the traditional planar with a bandwidth of 1.93%, better input return loss and a slightly lower resonance frequency. Similarly, another multilayer patch antenna was proposed using a V-shaped feeder line, This V-shaped feeder line antenna model showed a much lower resonance frequency (36.50 GHz) compared to normal planar (38.92GHz) and the planar with spiral transmission line model (38.52 GHz).

Keywords: 3-D MMICs; Multilayer technology; Modeling; simulation; Compact antenna

1. Introduction

Due to the rapid increase in the use of microwave frequencies in the medical sector, communication and radar applications and the boom in the communication industry, in recent years, antenna and their operating principles have become an important area to focus. In the past few decades, planar transmission lines and antennas have been a growing area of research. Some specifications of antennas are needed, which is integral to the design and optimization process. For example, personal communication systems (PCS), global positioning systems (GPS) and wireless local area network (WLAN) all require the antenna to be compact (miniaturize), easy to design, low in cost and perform efficiently. The antenna that best fits into these specifications is the microstrip or printed antennas [1], [2].

Most microstrip antennas have drawbacks, such as narrow bandwidth (about 1- 3%). Hence, lots of research efforts are geared towards increasing the bandwidth. Printed antennas are known for their exceedingly attractive physical attributes, such as, planar design and light weight; this makes them ideal for applications that require low profile structures and convenient elements in the design of large antenna arrays. They can be integrated specifically with MMICs in a packet, which can be attributed to their little physical size and compatible fabrication procedure. Integration of the antenna is desirable since it often leads to miniaturization, lower costs, reduced power consumption, reduced parasitic and increased design flexibility compared with systems based on discrete antennas [2]–[4]. With the increasing demand for higher frequency applications that are (*over* 30 *GHz*) and the integration with MMIC's, there is a need to develop a more compact patch antenna using the 3D MMICs technology.

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In addition, due to the increasing needs in electronic circuit miniaturization and integration, the demand for a more compact, cost-effective transmission lines and antennas which can be easily integrated with MMICs designs to lower the dispersion loss, the noise figure and increase the effective performance of such configurations have been on high. Planar antennas are substrate based and some of their attributes like easy fabrication and integration with MMIC designs increases their popularity and brings about the large volume of research interests and activities in this field [5]. Microstrip is popular, well known and characterized microwave transmission line formats for decades. Similarly, coplanar waveguide (CPW) transmission lines have also been used and studied extensively in microwave applications. However, they are not well characterized as microstrip lines. Previous research works on CPW show that it could be an alternative to the microstrip concept [6]–[9]. Microstrip and CPW are frequently chosen over other high-frequency transmission line alternatives, for example, strip line, this is because of their simplicity [10]. Despite all their advantages, they still have some disadvantages.

CPW which was first invented by Cheng P. Wen [11] in 1969 was a type of transmission line used for both MICs and MMICs [12]–[15]. One of the good properties of CPW is that, all conductors are on the same side of the substrate, which is generally uniplanar in construction. This feature allows cheap and fast production compared with the microstrip design. Recently, CPWs have attracted more attention due to their advantages, which include Ease of fabrication, reduce radiation loss as well as eliminate the need for wraparound and via holes [16]–[17].The existing monolithic two-dimensional microwave integrated circuits (2D MMIC) are mainly implemented in a planar fashion and use microstrip design-based technology. At microwave frequency and above, they would require a large amount of passive circuitry therefore occupying a lot of space and area. Furthermore, the 2D MMIC has some problems ranging from the use of a very thin substrate thus making it less reliable, very fragile due to the via-hole technology, coupling issue and high cost due to the large area it occupies. To solve these problems a three-dimensional multilayer technique 3D MMIC would be used. The design of the 3D MMIC is based on coplanar waveguide (CPW), in this design, the signal is protected by the two grounds on both sides, the circuit becomes more compact, cost-effective and improved performance. The integration of 3D MMIC based devices ae already reported for diode [18], pHEMT [19], Limiter [20], and switch [21].

The 3D MMIC antenna design approach used in this research work to the best of my knowledge is the first to use a CPW spiral feeder line and V-shaped feeder to design an antenna at Microwave frequency. This novel approach can be used to design patch antennas at microwave frequency with bandwidth up to 3% and very compact antennas.

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2. Simulation set up

The S-parameters of a transmission line or an antenna can be extracted using EM simulation tools. Accurate EM simulation is needed to predict the electrical properties of MMIC components this is because of their relatively small physical structure, the dielectric layer, multiple conductors and isolation of passivating layers which make post fabricating tuning very difficult. For the purpose of this research work, Momentum Electromagnetic simulator on Advanced design system (ADS) software was used. Momentum electromagnetic simulators often called a 2.5D simulator, this is because it only allows 2D conductors and currents in planar layers but computes 3D fields. Momentum is fully integrated into ADS as in figure1.

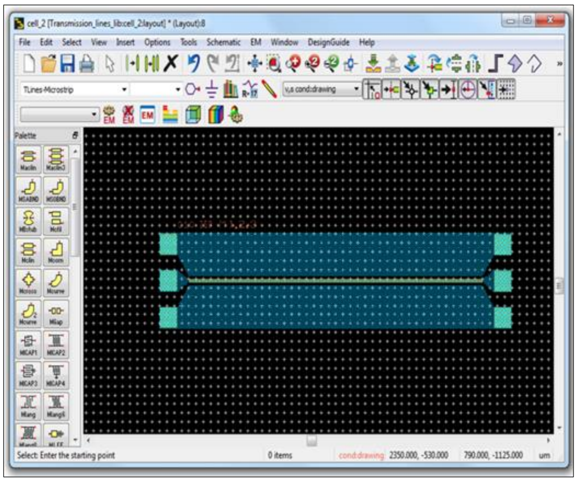
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Figure 1 Layout of CPW transmission line on ADS

2.1. Theory of simulation set up, characterization and extraction

Extraction and characterization of RF components of transmission lines and antennas are very useful in studying their behaviors. The extracted S-parameter from simulations and measurement can easily be used to calculate properties like characteristics impedance (Z_o), dissipation loss (D_{Loss}), and effective dielectric constant, ε_{eff}. The equations used in calculating some of the transmission line parameters are presented based on solution of Telegrapher's transmission line equation [1].

From this reference, the matrix equations for calculating the propagation constant and characteristics impedance are shown as:

$$|S| = \frac{1}{D_s}\begin{pmatrix} (Z_{sys}{}^2 - Z_o{}^2)\sinh \Upsilon l & 2Z_{sys}Z_o \\ 2Z_{sys}Z_o & (Z_{sys}{}^2 - Z_o{}^2)\sinh \Upsilon l \end{pmatrix} \quad \text{..................} (1)$$

Where, $D_s = 2Z_{sys}Z_o \cosh \Upsilon l + (Z_{sys}{}^2 - Z_o{}^2)\sinh \Upsilon l$ ……………. (2)

where l = length of the cable, Z_{sys}= System impedance = 50 Ω. From the above matrix equation, the following equations can be derived considering a reciprocal transmission line that is since S_{11}=$S_{22}$and S_{12}= S_{21}.

$$Z_o = \sqrt{\frac{(1+S_{11})^2 + S_{21}{}^2}{(1-S_{11})^2 - S_{21}{}^2}} \quad \text{……………. (3)}$$

$$e^{-\Upsilon l} = \frac{1 - S_{11}{}^2 + S_{21}{}^2}{2S_{21}{}^2} + \sqrt{\frac{(S_{11}{}^2 - S_{21}{}^2 + 1)^2 - (2S_{11})^2}{(2S_{21})^2}} \quad \text{……………. (4)}$$

Since the propagation constant is given by

$$\Upsilon = \alpha + j\beta \quad \text{……………… (5)}$$

Where α and β are the real and imaginary parts of the complex propagation constant. β gives the phase velocity while α shows the loss. The imaginary part of this equation (β) can be used to calculate the effective dielectric constant obtained from the Telegrapher's transmission line equation:

$$\varepsilon_{r(effective)} = \left(\frac{\beta c}{2\pi f}\right)^2 \quad \text{……………… (6)}$$

Where c = speed of light and f = frequency. To show the losses in these CPW multilayer transmission line, it is also essential to plot the dissipation loss against frequency . Considering a two-port network where the power transmitted is

$$1 - |S_{11}|^2 \quad \text{……………… (7)}$$

The output power can, therefore, be approximated as$|S_{21}|^2$. Thus, the D_{Loss} can be expressed as

$$D_{Loss} = 10Log\left(\frac{1-|S_{11}|^2}{|S_{21}|^2}\right) \text{……………… (8)}$$

3. Results and discussions

3.1. Parameter sensitivity test

Parameter sensitivity test of a multi-layered patch antenna is important to know how different parameters of the antenna affect its performance such as the bandwidth, resonance frequency and depth of the input return loss (S_{11}). The parameters to be considered include the height of the substrate (h) and the thickness of the metal (*t*). In this work, all the parameters, the height (h) of the substrate (GaAs) in the multilayer patch antenna is varied while other parameters are left constant to see the effect of substrate thickness on the performance of the designed patch antenna (See figure 2).

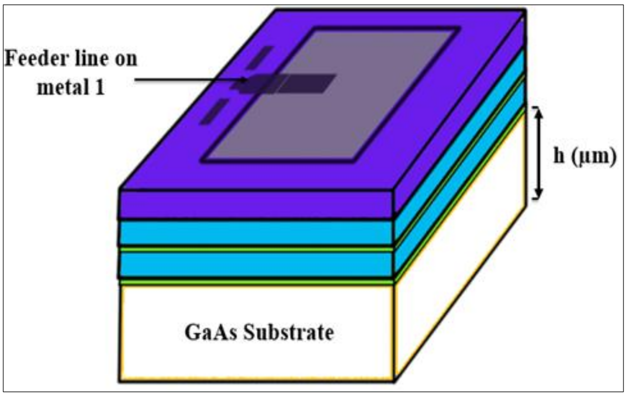

Figure 2 Multilayer patch antenna with substrate (GaAs) with height h (µm)

The multi-layered patch antenna was simulated for a height of substrate (*h*) ranging from 250µm - 450µm and the result of the input return loss obtained is shown in figure 3. It was observed that the thickness of the substrate of the patch antenna (*h*) affects the bandwidth, depth of input return loss and resonance frequency. A thicker substrate results in a wider bandwidth and lower resonance frequency and also a lower input return loss as seen in figure 4. However, there could be some disadvantages such as less coupling level due to the thickness of the substrate as in table 1.

Table 1 Coupling level due to the thickness of the substrate

Height of substrate (µm)	-10 dB Bandwidth (GHz)	Depth of input return loss	Resonance Frequency
250		-8.5	43
300	0.1	-12.5	42.2
350	0.4	-16	41
400	0.8	-26	40.3
450	1.5	-27.5	39.2

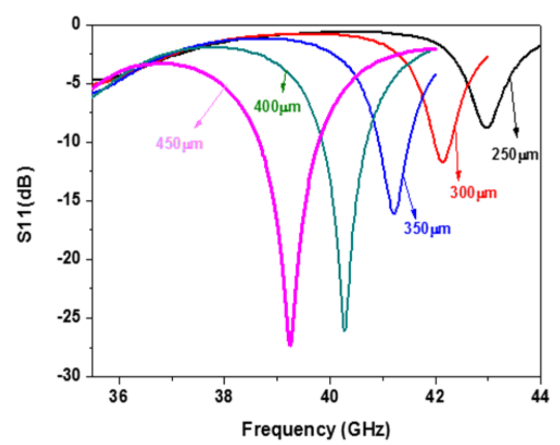

Figure 3 Effect of substrate thickness (h) on resonance frequency and bandwidth of patch antenna

In this simulation, all parameters are kept constant while the thickness of the metal (M2) is varied between 1to 20µm. The result obtained is shown in figure 5. The result shows a slight reduction in resonance frequency with an increase in metal thickness. This could be associated with the skin depth of the metal. Thus, with an increase in the metallization of the structure, the metal patch placed on the surface can slightly reduce the resonance frequency.

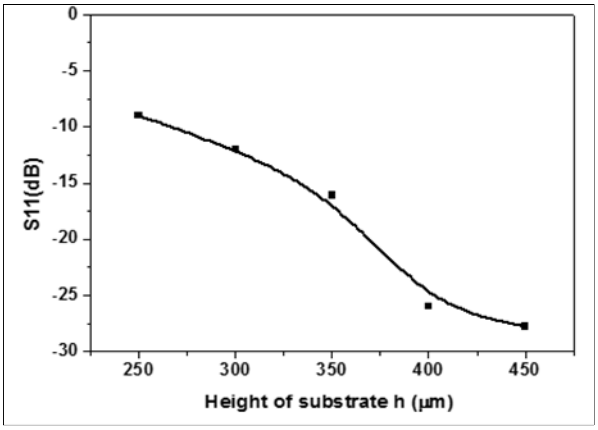

Figure 4 The correlation between the substrate height (h) and the depth of input return loss (S_{11})

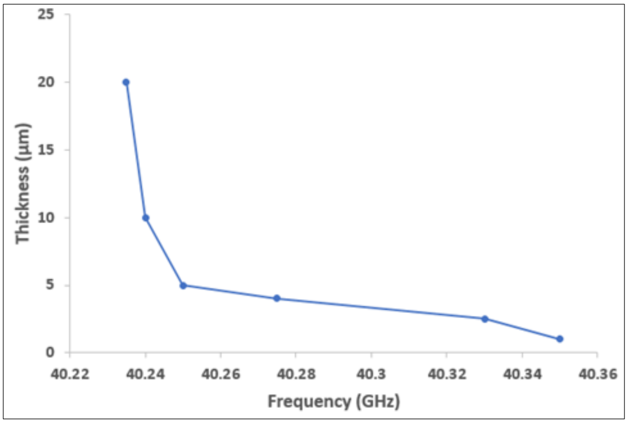

Figure 5 Effect of metal thickness t (µm) on the resonance frequency

3.2. Propose single patch compact multilayer patch antenna

In this section, two different single patch antennas were designed to operate around 35-40 GHz. Using a planar, V-shaped and spiral feeder line to feed the patch antennas which are all 50 Ω transmission lines. Figures 6 and 7 show the structure, top view and dimensions of the designed antenna on metal 2 using planar feeder line. Figure 8 shows the simulated results of the input return loss obtained when the planar feed line patch antenna was simulated on ADS momentum EM. From the above result, the resonant frequency is 38.91 GHz and the B.W at – 10 dB

$$B.W = \frac{(39.30 - 38.55)GHz}{38.91GHz} \times 100 = 1.93\%$$

Figure 8 shows the input return loss obtained when the V-shaped feed line with (w =12µm) patch antenna was simulated on ADS momentum EM.

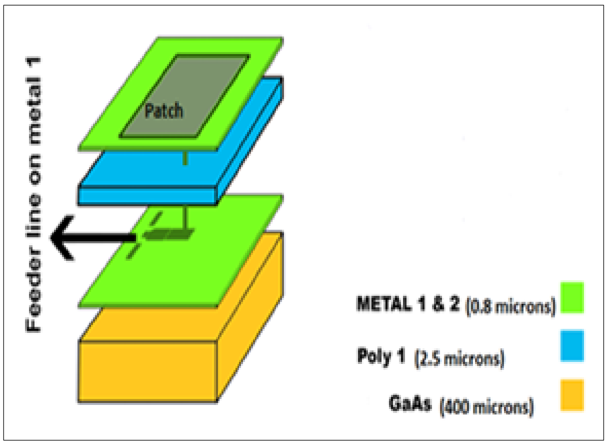

Figure 6 Layout of Multilayer structure on GaAs substrate and layout of patch antenna on metal 2

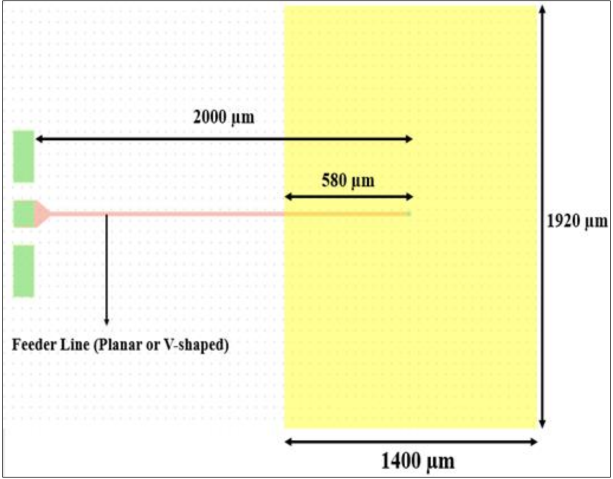

Figure 7 Top view of patch antenna using planar or V-shaped feeder line and dimensions on ADS

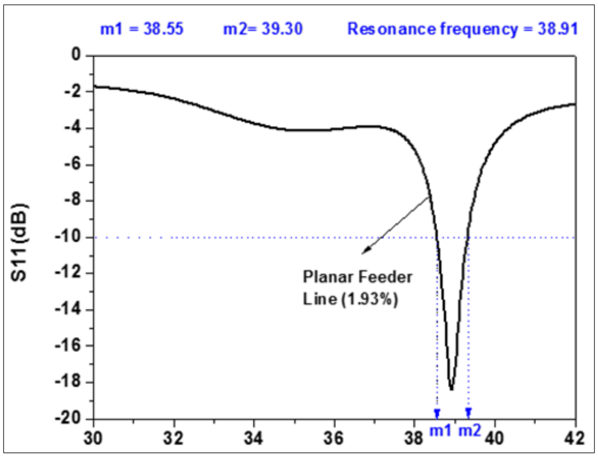

Figure 8 Simulated input return loss of proposed single patch antenna using a planar feeder

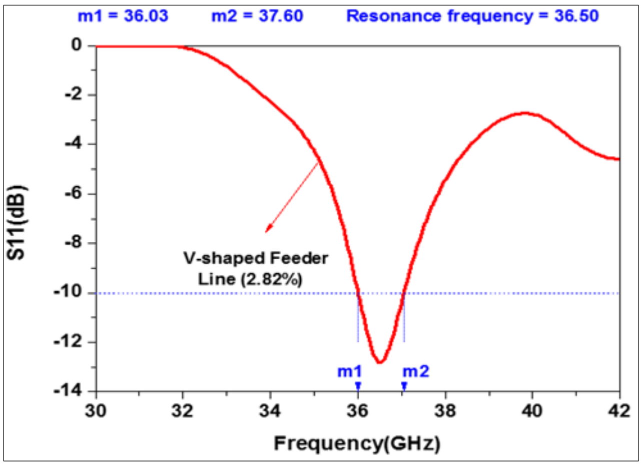

Figure 9 Simulated input return loss for single patch antenna using a V-shaped feeder line on ADS EM simulator

From the results of V-shaped feeder line antenna figure 9, the antenna resonates at 36.50 GHz and the bandwidth (B.W) at – 10 dB

$$B.W = \frac{(37.60 - 36.03)\,\mathrm{GHz}}{36.50 GHz} \times 100 = 2.82\%$$

Comparing the performance of the patch antennas using planar and V-shaped feeder lines for the same patch antenna dimensions (figure 10), it was observed that the V-shaped feeder line configuration is more efficient and effective because it gives a lower resonance frequency and a wider bandwidth for the same patch antenna configuration. This could be attributed to the fact that the lower permittivity substrate (V-shaped feeder) and the slight increase in the height of the substrate due to an extra polyimide layer leads to increase in the fringing length extension of the patch antenna (ΔL), thereby reducing the resonance frequency and slightly increase the bandwidth.

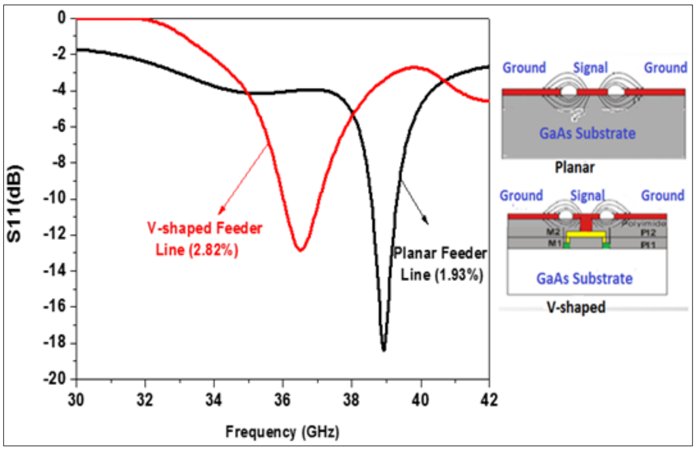

Figure 10 Input return loss of a single patch antenna using planar and V-shaped feeder line using the same dimensions

3.3. Planar Feeder with Spiral Transmission Line on metal 2

A very short plane feeder with a spiral transmission line on metal 2 is proposed and investigated in this section. The proposed design is aimed at reducing the overall area of the patch antenna which makes the multilayer structure more compact. In this sector of the report, a spiral feeder line on metal 1 was used to feed the multi-layered patch antenna and simulated to obtain the return loss. See figure 11 and 12 layout and top view.

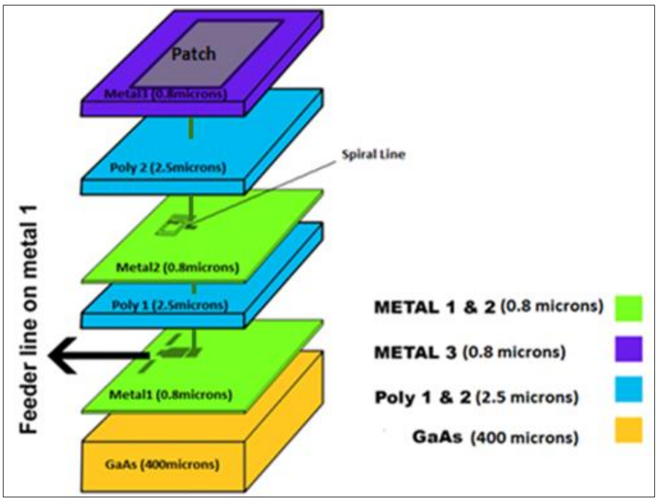

Figure 11 Multilayer layout of patch antenna using a planar feeder with spiral transmission line on metal 2

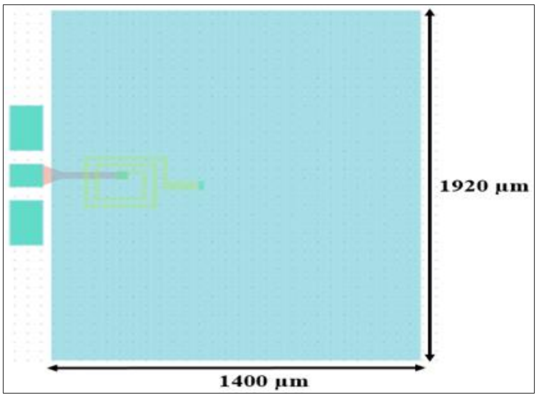

Figure 12 Top view of patch antenna using Spiral feeder line

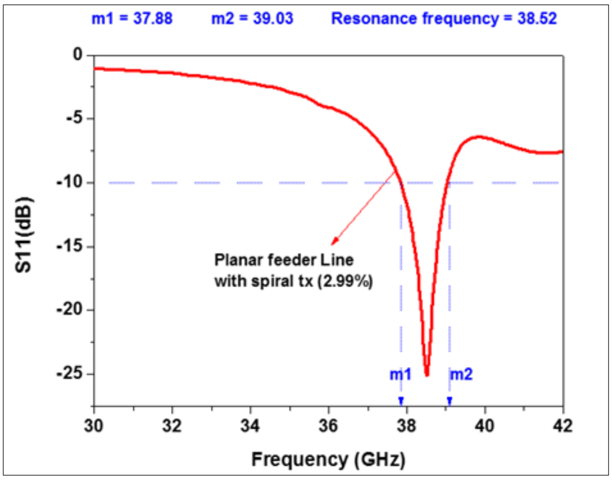

Figure 13 Input return loss of patch antenna using spiral feeder line

After the simulation, the result of input return loss (S11) obtained is shown in figure 13. From the above result the antenna resonates at 36.50 GHz and the bandwidth (B.W) at – 10 dB is

$$B.W = \frac{(39.03-37.88)\,\mathrm{GHz}}{38.52GHz}\times 100 = 2.99\%$$

Since the patch antenna size for the spiral feeder line with planar and V-shaped feeder line is all the same, Figure 14 depicts their comparison showing the input return loss for the three (3) different feeder lines

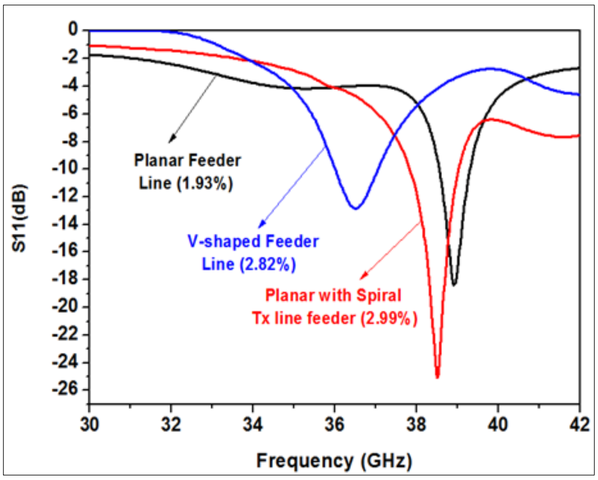

Figure 14 Input return loss of patch antenna using planar, V-shaped and spiral feeder line using same dimensions

From the result shown in the figure above it can be seen the spiral, and v-shaped feeder line configuration has a lower resonance frequency compared to the planar feeder line. This can be attributed to being due to the grater length extension caused by the fringing effect which makes the resonance frequency lower than that of the planar feeder line and also to the fact that a V-shaped and planer with spiral feeder line has a thicker substrate than the planar. However, it should be noted that from the results, the spiral feeder line patch antenna is the most compact and it also has a lower resonance frequency as compared to the planar. The table 2 below shows how compact the spiral transmission line feeder configuration is compared to the planar transmission line.

Table 2 Calculation of area occupied by planar feeder line antenna and planar feeder with spiral transmission line antenna

Dimension of Planar feeder line patch antenna (f ≈ 38.91 GHz)			**Dimension of Planar feeder with spiral transmission line on M2 patch antenna (f ≈ 38.52 GHz)**		
Length of feeder line = 2000 µm			**Length of feeder line = Spiral**		
L	W	L1	L	W	L1
1.440 mm	1.920 mm	0.580 mm	1.440 mm	1.920 mm	Spiral
Area occupied = 2.860 × 1.920 = 5.491200 mm²			Area occupied = 1.440 × 1.920 = 2.764800mm²		

Comparing the spiral configuration to the purely planar configuration there is a 0.497% reduction in the area of the patch antenna. Therefore, the planar feeder with spiral transmission line antenna is more compact than the traditional planar patch antenna. Similarly, the V-shaped feeder line patch antenna has a lower resonance frequency compared with a planar feeder line patch antenna of exactly equal dimensions, this suggests that compactness of a multi-layered patch antenna can be achieved using this concept in designing miniaturized multilayer microstrip. See table 3 comparing a planar, V-shaped and the newly proposed planar with spiral transmission line configuration of a multilayer patch antenna.

Table 3 Properties of proposed multilayer patch antenna models compared with normal planar feeder line configuration

Property	**Normal Planar configuration**	**V-shaped configuration**	**Planar with spiral transmission line Configuration**
Characteristics impedance Zo	50 Ω	50 Ω	50 Ω
Patch size	1.400mm × 1920mm	1.440mm × 1920mm	1400mm × 1920mm
Resonance Frequency	38.91 GHz	36.50 GHz	38.52 GHz
Area Occupied	5.4192 mm2	5.4192 mm2	2.7648 mm2
Compactness	Compact	Lowest resonance frequency which suggest compactness	Very compact
Bandwidth	1.93%	2.82%	2.99%
Current crowding effect	High at the edges of the feeder line	Lower on the edges of the feeder line	Low current crowing on feeder line
Cost	Higher cost	Lower cost due low resonance frequency	Relative lowest cost

4. Conclusion

Investigation of different CPW multilayer antenna and transmission lines have been well and successfully designed and characterized. The newly propose planar with spiral transmission line feeder line was 49% more compact in area compared to using the normal planar feeder line, it is also more compact about (22%) compare to the design of available literature to the best of my knowledge. The new design also showed wider bandwidth, better input return loss and a slightly lower resonance frequency. Similarly, another multilayer patch antenna was proposed using a V-shaped feeder line. This model showed a much lower resonance frequency (36.50 GHz) compared to normal planar (38.92GHz) and the planar with spiral transmission line model (38.52 GHz). This suggest compactness can be achieved by utilizing this important characteristic similar to what was concluded in available literature. The lower resonance frequency can be attributed to higher length extension as a result of lower effective dielectric constant of the V-shape feeder line model. It is also worth mentioning that the V-shape model has a lowed current crowding effect compared to the normal planar model of feeder line. The two newly proposed concepts of feeder line in multilayer patch antenna can be used in designing miniaturized, compact and lower cost of patch antennas. Finally, multilayer patch antenna using CPW technology is suitable for 3D MMIC application and achieving compactness of a millimeter frequency range patch antenna which has been demonstrated in this research work.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest.

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