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Silicon CPW Fed Slotted Antenna for Realization of Integrated SAR System Front-End

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Abstract—This paper investigates the design of a small antenna on a silicon substrate. The antenna on silicon substrate will be used for integration in a silicon-based GaN TR module. This Co-Planar Waveguide (CPW)-fed antenna has been successfully miniaturized up to $\lambda/4$ about 20% reductions by adding a slot to the patch antenna. Promising results are obtained from the antenna simulation and measurement. From the measurement result, the antenna bandwidth is 45% (4.8 GHz–7.5 GHz) with measured gain about 2.5 dBi over frequency range of 5 GHz–7.4 GHz.

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is an active type of microwave radar that has all-weather capabilities and is a powerful tool for tactical and remote-sensing applications due to its excellent resolution characteristics [1, 2]. Currently, there is a need to deploy a SAR systems platform on Unmanned Aerial Vehicles (UAV) for greater flexibility of operations. This offers reduced costs and provides a facility for more immediate response [3–5]. In order to accommodate the SAR system on a UAV, the system has to be small, which in turn requires a small antenna to contribute to low cost integrated system development. Full integration of the SAR system front-end including the antenna on the same substrate is an innovative solution for miniaturization. This can be achieved by using semiconductor technologies where a full integrated front-end subsystem is fabricated on silicon.

Recently, gallium nitride (GaN) has received a lot of attention in microelectronic device industries [6]. Over the past few years, many manufacturers have produced GaN-based devices which offer highly efficient power performance and robustness. GaN devices such as power amplifiers (PA), low noise amplifiers (LNA) and switches have higher power handling limits, higher breakdown voltage and lower noise figures than gallium arsenide (GaAs) as described in [7–10]. Furthermore, GaN devices have small physical dimensions compared to their capability in terms of power and cost [11]. These attractive features encourage transition to implemented Transmit/Receive (TR) modules with GaN technology. In [12–14], evidence of the GaN TR module performance has been demonstrated, and this significant performance may lead to integration at system level or system on chip (SoC). There is, however, a lack of research in fully-integrated, high performance GaN TR modules with a miniaturized antenna on the same material, silicon. There is a report about a GaN Heterojunction Field-Effect Transistor (HFET) power amplifier integrated with a microstrip antenna for RF front-end applications as mentioned in [15]. However, it is not fully integrated on the same substrate because all the devices such as the antenna, power amplifier and matching circuits were fabricated on different substrates, i.e., RT-duroid, GaN/SiC and alumina.

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Previously, researchers investigated silicon antennas with various designs and methods. A silicon substrate with high dielectric constant allows reduction in antenna size as well as a potential substrate for easy integration with RF systems. However, silicon is well known as a very lossy substrate. One of the common techniques to decrease dielectric constant and reduce losses of the silicon substrate is to create an air cavity underneath the antenna. In [16], a rectangular microstrip patch silicon antenna ($\lambda/3$) with bandwidth of 3.8% was reported where an air cavity was created underneath the antenna patch. This technique helps to reduce the substrate losses, but increase the bandwidth and decrease the antenna radiation efficiency. The simulated gain is about 3.5 dBi, and there was no measured gain reported. Another silicon antenna which was a meander dipole type, with a size of $\lambda/2$, achieved a bandwidth of 43% when the silicon substrate 300 µm thickness underneath the antenna feeding point was etched about 99% as described in [17]. However, in this study, the measured radiation pattern and gain were not provided. Both studies involved removing the silicon substrate partially underneath the antenna patch/feeding points which did not utilise the high dielectric constant of the silicon substrate, and the fabrication procedure was not simple. Then, a loop silicon antenna for body area network (BAN) applications with size $\lambda/2$ is mentioned in [18]. From the simulation results, this antenna achieved a gain of 5.1 dBi at 3.1 GHz and bandwidth 24%. However, measured results were not reported, and the antenna was not fabricated. Indeed, there is a significant technique to design a small antenna with better bandwidth impedance and ease of integration as stated in [19]. A coplanar waveguide (CPW) antenna on silicon with girth S slot in the ground has satisfied size $\lambda/2$, and the antenna measured gain is 2.5 dBi. However, the measured bandwidth is only 3% which is considered as narrow bandwidth.

Recently, a CPW-fed slotted antenna was fabricated on a high resistivity silicon (HRS) and achieved a bandwidth of 41%, and the simulated gain was 8.7 dBi at frequency 5.1 GHz [20]. However, the size of the antenna 17.28 mm×15.12 mm×0.4 mm needs to be reduced further in order to integrate to the front-end TR module of the SAR system.

This paper presents a new, small CPW silicon antenna with a slot in the patch, hence reducing the total size of the antenna. With a simple microelectronic fabrication process without additional material or metal, this small antenna can produce similar gain to [19] and operates at C band. The antenna is fabricated on a High Resistivity Silicon (HRS) substrate. This new concept of design is highly useful for integration of antenna and the front-end TR module on the same silicon substrate of the Synthetic Aperture Radar (SAR) system, hence, reducing the total size of SAR system front-end. Details on the antenna design are discussed in Section 2, followed by the parametric analyses that have been conducted for optimising the frequency bandwidth. Matching impedance and gain using the CST 2012 tool is described in Section 3. Section 4 explains the antenna fabrication while all the experimental results and discussion are shown in Section 5.

2. ANTENNA DESIGN APPROACH

The antenna initial dimensions before miniaturization are 19.2 mm×15.2 mm×0.5 mm. W and L are calculated based on standard equation for rectangular antenna and CPW properties as in [21, 22] at centre frequency, f_c (6.1 GHz), where $L = \lambda/2$ and $W = \lambda/3$. The antenna also consists of a rectangular slot and a combination of a triangular and trapezoidal patch shape with CPW feed. In planar slot antennas, the slot width and feed structure affect the impedance bandwidth of the antenna [23, 24]. Therefore, by tuning the sizes of the slot and shape of the patch feed, an optimum impedance bandwidth and better radiation pattern can be obtained. Figure 1 shows the geometry and configuration of the proposed antenna.

In order to implement a fully integrated antenna with a GaN TR module on the same substrate, the antenna needs to be small. A common way to reduce antenna size is to make slots with appropriate length and width in the ground or patch of the antenna [25–27]. Introducing the slot in the antenna patch between two conductors as in Figure 1(b) creates current flows and capacitance that can shift the frequency to a lower frequency [28]. Furthermore, the slot forces the surface current to alter the concentrations of surface current inside the ground and the patch on the antenna as shown in Figure 2(b) which influences the current density. The higher the current density is, the higher the antenna gain is produced although the antenna size is small [29].

This antenna has achieved a 20% size reduction where $L = \lambda/4$ compared with $L = \lambda/2$ as

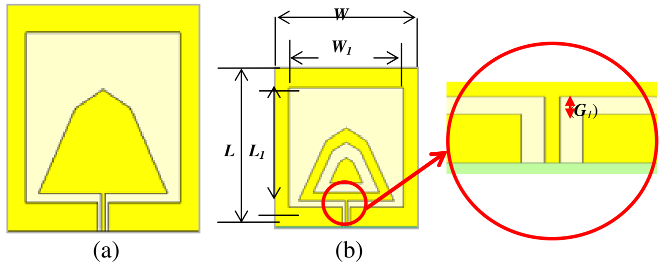

Figure 1. (a) Proposed antenna initial configuration and (b) antenna after adding the slot and miniaturization.

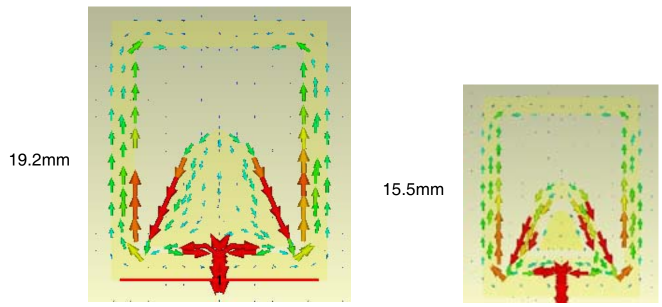

Figure 2. Antenna's surface current at 6.3 GHz (a) before and (b) after adding the slot in the patch.

reported in [20]. Also, through this technique, a better impedance matching with moderate bandwidth and slightly higher gain have been obtained than other small silicon antennas as reported in [19]. To prove this technique and maintain the operating frequency range, parametric analyses have been carried out as presented in Section 3.

This antenna has an omnidirectional radiation pattern. In order to reduce back radiation and make the antenna more directional, a finite reflector (81 mm×81 mm — Figure 7(b)) is added to the rear of the antenna. Furthermore, the reflector is substituted for an UAV body in the real applications of this system.

3. PARAMETRIC ANALYSIS FOR THE MINIATURE ANTENNA

The analysis is explored by using CST 2012. It is conducted by sweeping one parameter at a time while other parameters are maintained constant. Obviously, the length and width of any antennas are essential parameters to determine the resonant frequency, whereas the slot area affects the bandwidth. Analysed parameters are length (L), width (W), slot length (L_1), slot width (W_1) and the gap between the ground and the patch (G_1 as shown in Figure 1(b)). The thickness of the antenna is set to a constant value of 500 µm due to the thickness of the HRS wafer.

L is the distance that the electromagnetic wave travels during one complete cycle and inversely proportional to the frequency. Figure 3(a) shows that by increasing L from 14.2 mm to 19.4 mm, the frequency shifts to lower one. While increasing the W between 11.0 mm to 14.5 mm, the $|S_{11}|$ results show better matching as seen in Figure 3(b). From this observation, the optimum dimensions of L and W for the proposed antenna are 15.5 mm×13.7 mm.

For the fixed values of L and W, the length and width of the rectangle slot, L_1 and W_1, are swept, and the simulated reflection coefficient magnitudes $|S_{11}|$ (dB) for sweeping L_1 and W_1 are shown in Figures 4(a) and (b). Varying the slot shape or size will change the coupling property and thus the impedance bandwidth [30]. Figure 4(a) shows that increasing the value of L_1 widens the rectangle slot size which also makes the bandwidth wider. However, with further increase of $L_1 = 11.6$ mm, 11.9 mm and 12.5 mm, the impedance matching remains unchanged. As seen in Figure 4(b), changing the values of W_1 from 10.4 mm to 11.9 mm slightly improves the matching of the antenna. From the graphs, it is

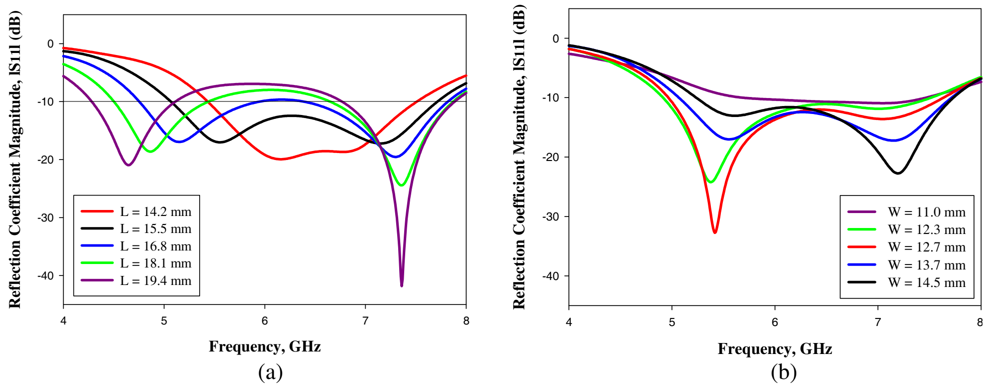

Figure 3. Simulation $|S_{11}|$ of parametric analysis for (a) L and (b) W.

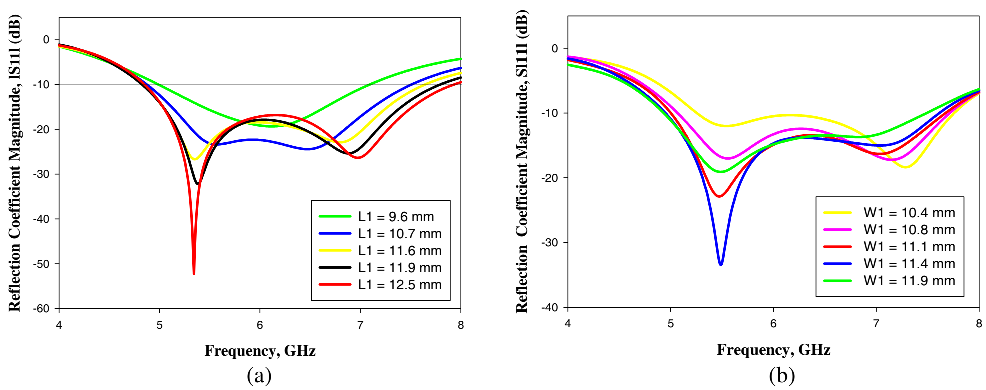

Figure 4. Simulation $|S_{11}|$ of parameter analysis for L_1 and W_1.

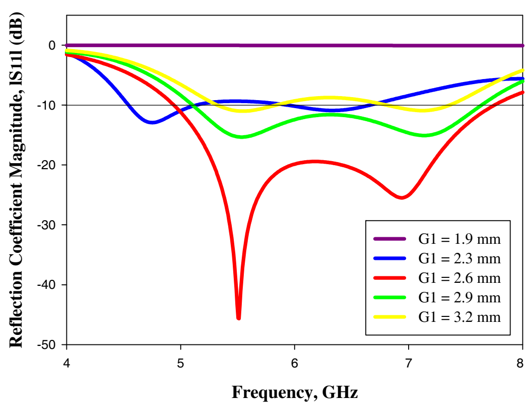

Figure 5. Simulation $|S_{11}|$ of parameter analysis for the gap between the ground and the patch (G_1).

shown that the moderate size of the rectangle slot is 11.6 mm×10.8 mm. The gap between the ground and the patch (G_1) also contributes to improving the matching impedance as shown in Figure 5. The impedance bandwidth is detuned when the gap G_1 is varied. Based on the parametric analysis, optimal dimensions of the antenna are shown in Table 1.

4. FABRICATION OF MINIATURE ANTENNA

This antenna is fabricated on HRS wafer with resistivity of 9000–15,000 ohm·cm, p-type and ⟨111⟩ orientation. The dielectric constant of the HRS is $\varepsilon_r = 11.9$, loss tangent = 0.03 and the substrate

Table 1. Optimal parameters of the antenna after size reduction.

Parameters Description	Optimal/Selected Dimension (mm)
Length, L	15.5
Width, W	13.7
Slot Length, L_1	11.6
Slot Width, W_1	10.8
Gap between the ground and the patch, G_1	2.6

thickness = 500 µm. In order to isolate the antenna and reduce the losses due to the substrate, a thin SiO_2 layer is deposited on the HRS wafer. Different thicknesses of the SiO_2 layer have been investigated previously [19], and the optimum thickness of the SiO_2 has been determined as 2 µm. It is known that the properties of silicon are appropriate as a RF substrate because of its high dielectric constant, ability to withstand higher temperatures at higher frequency, better thermal conductivity than GaAs, and it is a mature technology. This study implements electroplated gold as the conductor of the antenna with a thickness of 4.2 µm, which corresponds to skin depths at the resonant frequency of 4 GHz. The gold thickness is much greater than skin depth to ensure the antenna is not lossy. The thickness of the gold and other layers has been measured and imaged using Microscopy Image (FEI Nova NanoSEM 200) as shown in Figure 6.

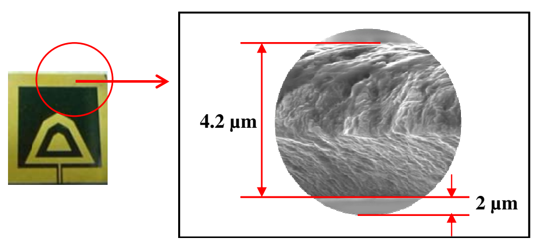

Figure 6. Prototype of antenna with skin depths of gold, 4.2 µm.

5. MEASUREMENT RESULTS AND DISCUSSION

For measurement purpose, a long coaxial cable supported by a flat brass bar soldered to the antenna ground has been implemented. This technique spreads the pressure to the cable and prevents damage to the antenna. However, it causes ripples in the radiation patterns which can be reduced by using absorbers on top of the coaxial feedline, as shown in Figure 7(c). For full integration (future work), the

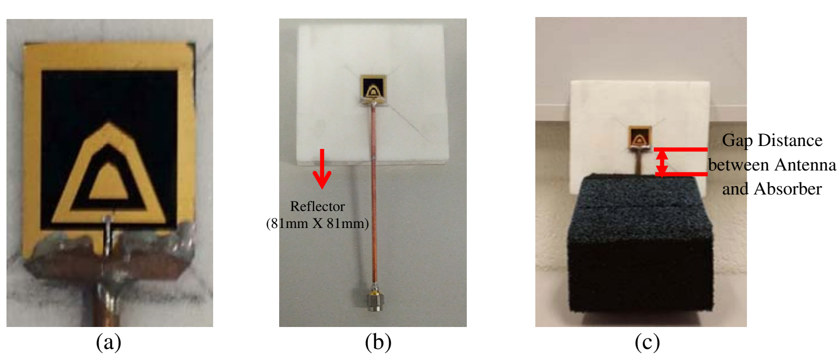

Figure 7. Measurement setup (a) for the miniature antenna, (b) with long coaxial cable, (c) covered by absorber.

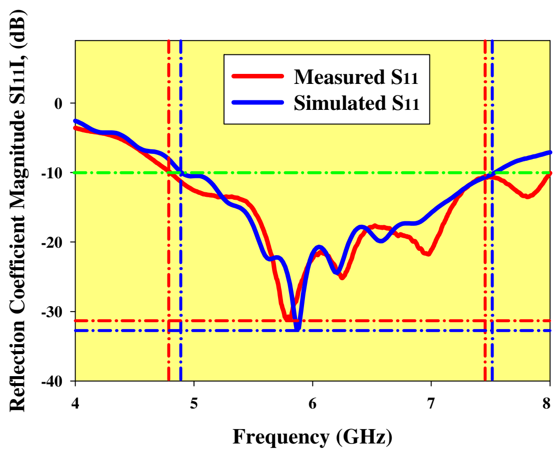

Figure 8. Simulated and measured $|S_{11}|$ of the proposed antenna with absorber.

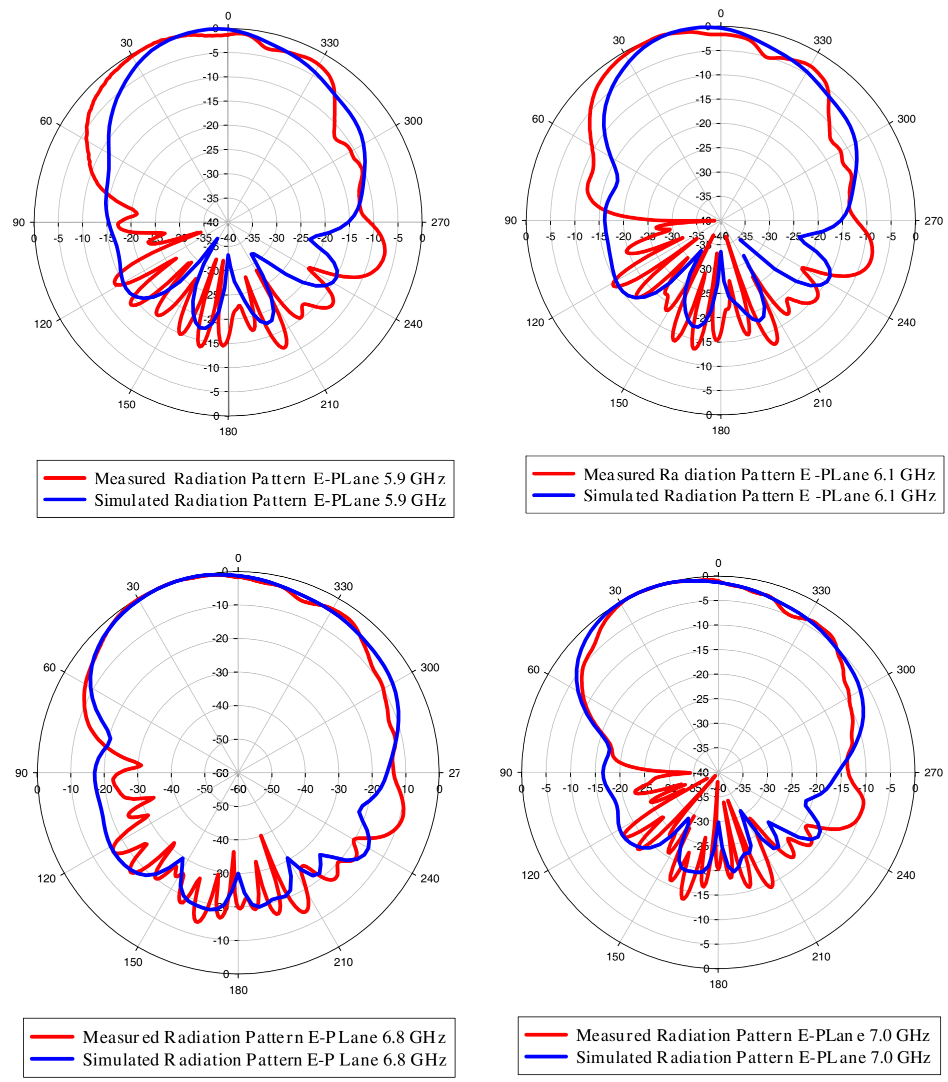

Figure 9. Simulated and measured radiation pattern E-plane of miniature antenna with absorber covered the cable at frequency 5.6 GHz, 5.9 GHz and 6.1 GHz.

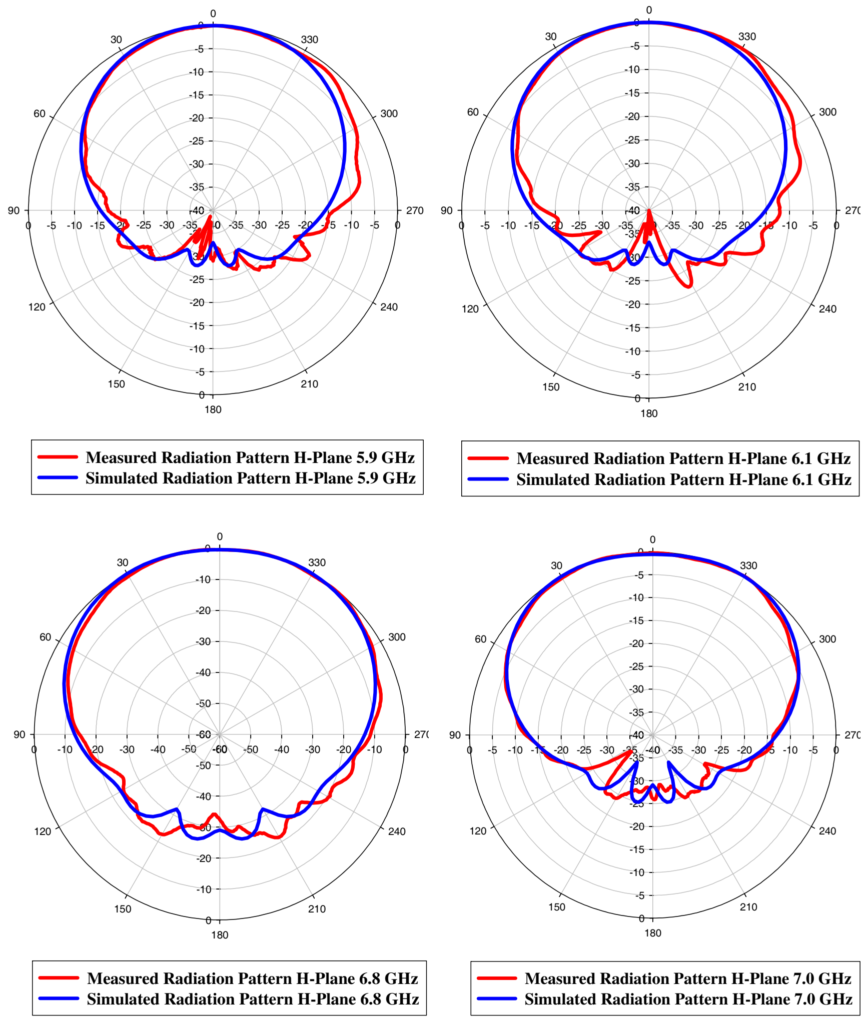

Figure 10. Simulated and measured radiation pattern H-plane of miniature antenna with absorber covered the cable at frequency 5.6 GHz, 5.9 GHz and 6.1 GHz.

coaxial cable will be removed, hence no need to use any absorber. The coaxial cable and absorber are simply used to analyse the antenna properties.

Figure 8 shows simulated and measured $|S_{11}|$ for the proposed antenna. The measured and simulated results are quite similar with a bandwidth of approximately 45%. The transition from coaxial to CPW (mostly junction capacitance) and the fabrication tolerance might cause small differences between measured and simulated results.

The radiation patterns of simulated and measured E and H planes for frequencies of 5.9 GHz, 6.1 GHz, 6.8 GHz and 7.0 GHz are shown in Figures 9 and 10, respectively. For the H-plane, a good agreement was obtained between the measured and simulated radiation patterns. However, for the E-plane, the ripples are slightly different between the measured and simulated results. This is mainly due to absorber, which had slightly lower absorption coefficient than that used for the simulation.

The simulated and measured gains of the proposed antenna at the frequencies range of 4.8 GHz–7.5 GHz are shown in Figure 11. The differences between measured and simulated gains are due to the resistivity of the silicon wafer. The actual wafer resistivity is varied from 9000 to 15,000 ohm·cm. In the simulation, a tangent loss of 0.03 was calculated based on the maximum resistivity from data sheet. However, as can be seen in Figure 11, the measured and simulated gains are similar at the lower frequencies, but measured gain decreases at the higher frequencies. This is due to dispersive characteristics of the material, which indicates that the tangent loss increases with the frequency.

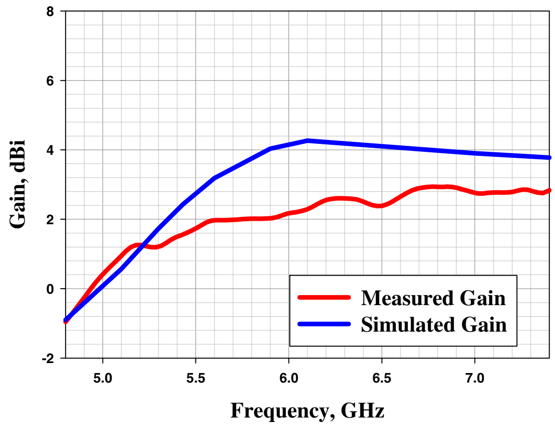

Figure 11. Simulated and measured gains over frequency range of 4.8 GHz to 7.4 GHz.

6. CONCLUSION

In this study, a small silicon antenna for the realization of a fully integrated GaN/Si TR module for SAR system front-end has been designed at C-band frequency. This technique has proved that double patches separated by a slot have decreased the size of the antenna. Parametric analysis has been carried out to determine the optimum size of the purpose antenna requirement which is 15.5 mm×13.7 mm×0.5 mm. It is observed that a 45% bandwidth with 20% size reduction over the frequency range of 4.8 GHz–7.5 GHz has been achieved. The antenna return loss is 10 dB or lower for frequency range of 4.8 GHz–7.5 GHz, and the antenna gain is 2.5 ± 0.5 dBi over the frequency range of 5.0 GHz to 7.4 GHz. Hence, this small antenna is suitable for full integration on the same silicon substrate.

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