The Performance Enhancement of Triple-band Vivaldi Antenna using SIW Structure for IIoT applications

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ABSTRACT The Industrial Internet of Things (IIoT) is a domain between IoT and Industry 4.0 that brings an evolution in automation and data exchange. Multiband and the wideband antenna are an important part to support high-rate IoT/IIoT communication through the wireless systems. In this study, we optimized a Vivaldi antenna for triple-band operation at well-known IIoT bands without adding any slot or extra structure. The antenna gets a large bandwidth of over 8%, 12%, and 19% at 2.4GHz, 4GHz, and 5.6GHz resonant frequencies, respectively. To improve several antenna characteristics such as impedance matching, gain, and radiation efficiency, an L shape symmetric Substrate Integrated Waveguide (SIW) structure is proposed. At the 5.6 GHz band, the SIW antenna achieves over 25% increase in radiation efficiency that reaches 99% although FR4 substrate is chosen to design the antenna. The proposed Vivaldi antenna is analyzed using CST simulation and measured using VNA equipment with an agree well result. Besides, we also set up a reality wireless system to test the antenna at two important IIoT bands: 2.4GHz and 5GHz.

INDEX TERMS SIW, Vivaldi, Triple-band, IIoT.

I. INTRODUCTION

THE development of modern wireless technologies such as WiFi 5, WiFi 6, 4G LTE, and 5G have brought innovations and benefits to the industry through a novel paradigm called Industrial Internet of things termed IIoT [1]. The IIoT can improve the industrial systems' performance with various types of services by collecting, analyzing, and transferring huge data. Multiband and the wideband antenna is one of the significant parts in powerful IIoT systems that support high data rate as well as flexible ability in bandwidth using [2]. As detailed in the Industry standards such as Wireless HART and ISA.100.11a, the well-known IIoT band is 2.4GHz. In addition, other popular bands for instance 3.5GHz, 4GHz, and 5GHz are used for IIoT [1], [3].

Vivaldi antenna is a type of planar antenna with easy integration, large band, constant beam width, and high gain that is a promising candidate for IoT/ IIoT equipment. Recently, there are many kinds of antennae for both consumption and Industrial IoT applications which have been researched [4] - [12]. In that, a lot of the studies use the Vivaldi structure [7]-[12]. Some of them need the filters to separate the operating bands [8], [9], [11] due to the broadband characteristic of Vivaldi antenna while another does not get enough wideband [10].

To improve the Vivaldi antenna's performance, several of methods have been used such as the Defected Ground Structure (DGS) [12], adding passive elements, or etching the slots [8], [10]. Substrate Integrated Waveguide (SIW) is a technique that can enhance significantly antenna performance [13]-[15], especially for the end-fire antenna which be like Vivaldi [16]-[20]. Arvind Kumar *et al.* [17] propose a dual-band antenna using SIW surrounded patch. The antenna gets wide bandwidth at the higher band and good gain for both operating frequencies. However, the total dimension is not compact much. It is $0.86\lambda_0 \times 1.3\lambda_0 \times 0.05\lambda_0$. Jing-Ya Deng *et al.* [18] use vertical SIW lines along their antenna to improve bandwidth, but the gain that is from 2.15dB to 5.75dBi is not quite good in the millimeter-wave band. Sara Salem Hesariand Jens Bornemann [19] and Amruta Sarvajeet Dixit *et al.* [20] achieve high gain at the millimeter-wave band, but both designs use array structure with 1x3 and 1x4 elements, respectively. In addition, all the above designs use Roger substrate RT5880 or RT6002 with a very low loss tangent to get high radiation efficiency.

In this paper, a Vivaldi antenna is optimized to achieve desired triple resonant frequencies without adding any extra slot and/ or special structure. The operating bands are 2.4GHz, 4.2GHz, and 5GHz which cover the well-known band of IIoT. Besides, two L shape of SIW structure are etched to improve antenna performance. Although based on FR4 substrate with low loss tangent of 0.02, the simulation radiation efficiency of the proposed antenna reaches 99%.

The rest of this paper is organized as follows. Part II presents the draft calculation and optimization to achieve a triple-band antenna. The performance enhancement using the SIW structure of the proposed antenna is detailed in Part III while the practical results in the reality wireless system are studied in Part IV.

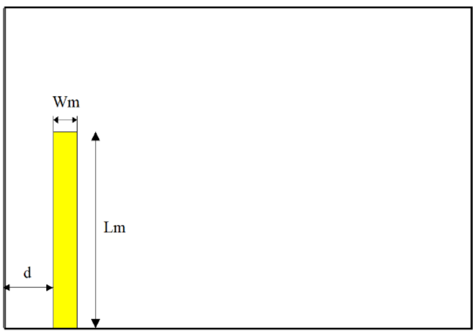
II. OPTIMIZING TRIPLE BAND VIVALDI ANTENNA

To fabricate easily and reduce the parameters to optimize, the conventional planar Vivaldi is chosen. The antenna includes two parts: one is a microstrip line on the patch plane and the other is an orthogonal slot that has an exponentially tapped shape on the ground plane.

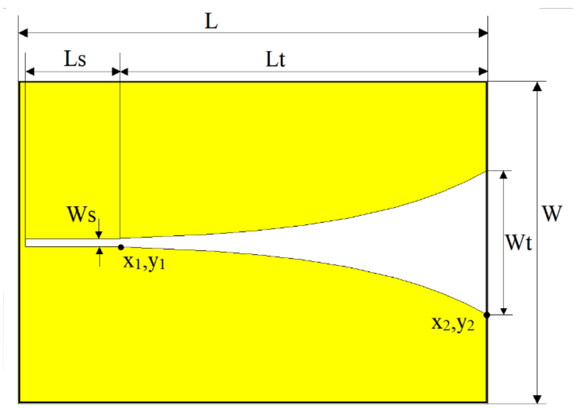
A. DRAFT CALCULATION

The FR4 substrate with 1.6mm height, 4.4 relative permittivity, and 0.02 loss tangent is chosen to design the proposed antenna because of its low cost and easy fabrication. The conventional antenna dimensions are calculated to determine the form and size as illustrated in Figure 1.

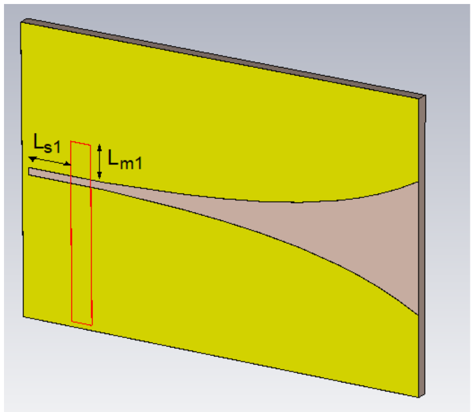
Firstly, two well-known IIoT bands which are 2.4GHz and 5GHz are chosen to calculate wavelengths at the minimum and maximum frequencies: λ_{min} and λ_{max}. Then the center frequency f_0 of the proposed antenna is chosen by another popular IIoT that is 4GHz. The length L is calculated from the length at the resonant frequency. Due to the compact size of IIoT devices, the highest resonant frequency is chosen, f_{max} = 5GHz.



(a) Top view



(b) Bottom view



(c) 3D

FIGURE 1. The Vivaldi antenna geometry.

The open microstrip L_{m1} and uniform slot line L_{s1} are calculated approximately by $\lambda_0/4$ where λ_0 is the wavelength at the center frequency f_0 [21]. The exponential taper can be determined by [22]:

$$y = C_1 e^{Rx} + C_2 \quad (1)$$

$$C_1 = \frac{y_2 - y_1}{e^{Rx2} - e^{Rx1}} \quad (2)$$

$$C_2 = \frac{y_2 e^{Rx2} - y_1 e^{Rx1}}{e^{Rx2} - e^{Rx1}} \quad (3)$$

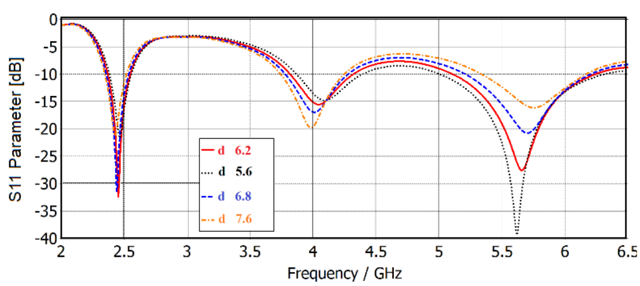
where y is the half separation of the slot and x is the position across the length of the antenna. R is the opening rate, (x_1, y_1), and (x_2, y_2) are coordinates of the start and end of the tapered slot. The opening width W_s is calculated by a double of the C_1 and depended on the highest frequency. The value of the aperture width W_t is calculated by the below equation [21]:

$$W_t < \frac{c}{2 f_1 \sqrt{\varepsilon_r}} \quad (4)$$

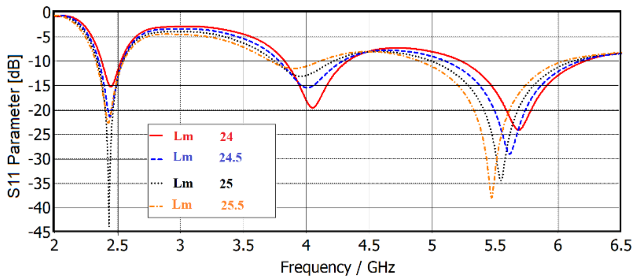
where c is the speed of the light, ε_r is the relative permittivity of used the substrate FR4, f_l is the lowest cut-off frequency.

B. OPTIMIZING THE ANTENNA DIMENSION

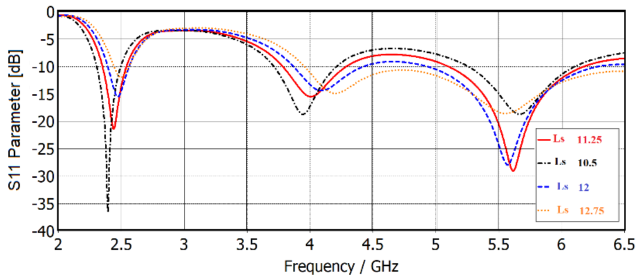
From the draft dimensions that achieved from Part II.A, the conventional planar Vivaldi antenna is designed and optimized by using CST MWS as shown in Figure 2.



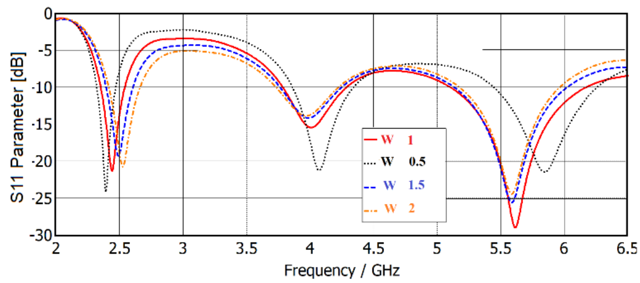
(a) The position of the microstrip line (d)



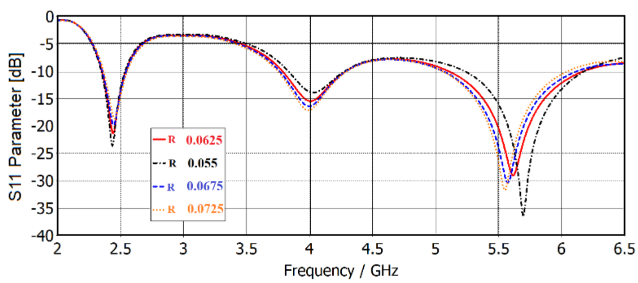
(b) The length of the microstrip line (Lm)



(c) The length of the slot line (Ls)



(d) The width of the slot (Ws)



(e) The opening of the tapered slot (R)

FIGURE 2. Optimizing the antenna dimensions.

It can be seen that the position and length of the microstrip line as shown in Fig. 2(a) and Fig.2 (b) affect the impedance matching point so that drifting these dimensions will achieve the three desired resonances. As calculated in Part II.A, the second resonant frequency is influenced by the length of the slot Ls. Thus it will obtain by optimizing this dimension as illustrated in Fig. 2(c). In addition, it needs to adjust in the 1/4λ range to ensure radiation efficiency. As shown in Fig.2 (d), the width of the slot (Ws) affects significantly not only the highest resonant frequency but also the lowest one. Thus, after setting right this parameter for the lowest bands, the highest one can be achieved by modifying the opening rate of the tapered slot R as seen in Fig. 2(e).

C. RESULTS AND ANALYZING

After designing and optimizing, the antenna that is based on an FR-4 substrate with a thickness of 1.6mm gets a total size of 40*58.5*1.6mm^3. The detailed dimensions of the proposed antenna structure are obtained and shown in Table 1.

TABLE 1. DIMENSIONS OF THE PROPOSED ANTENNA

Parameter	Size (mm)	Parameter	Size (mm)
L	58.5	:Ls	11.25
W	40	Ws	1
Lt	46.25	Lm	24.5
Wt	18	Wm	3
R	0.0625	d	6.2

Figure 3 presents the comparison between measurement and simulation of reflection coefficient result (S11). It can be seen that the Vivaldi antenna can operate at three frequencies which are 2.44GHz, 4GHz, and 5.6GHz with wide bandwidths of 189MHz, 500MHz, and 1GHz, respectively. These bands cover the bands of Wireless HART, ISA.100.11a, 802.11ac, and 5G which are well-known bands for IIoT devices.

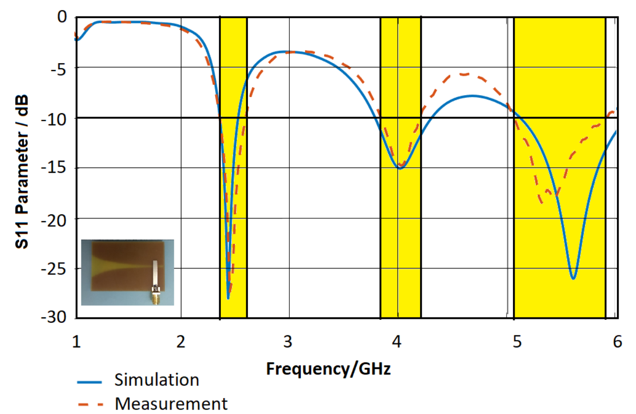
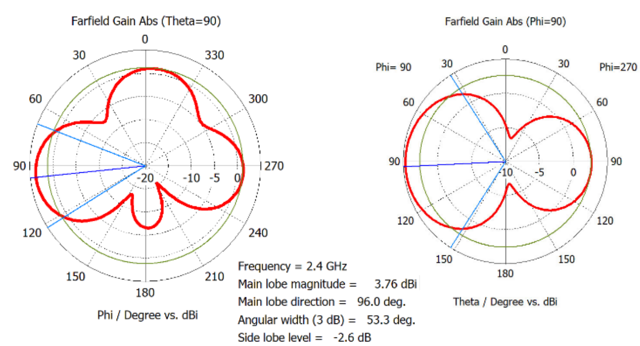
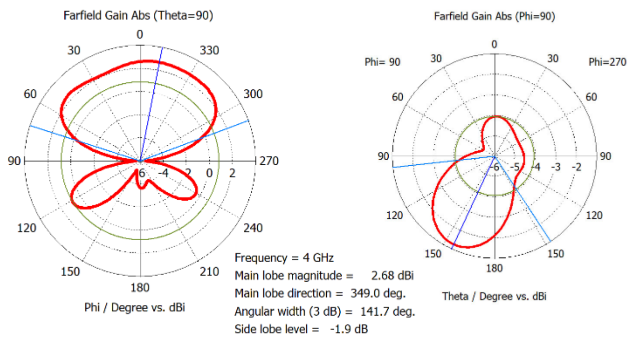


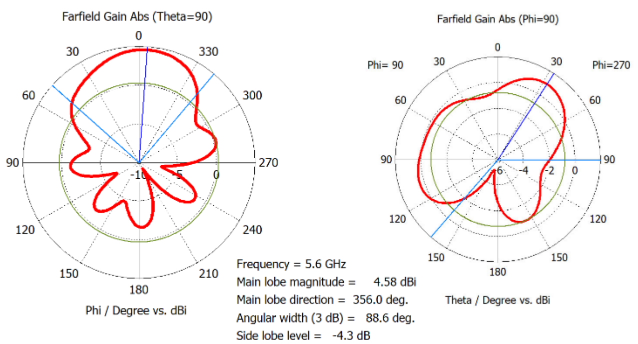
FIGURE 3. The simulation and measurement reflection coefficient of the proposed Vivaldi antenna.



(a) At 2.4GHz



(b) At 4GHz



(c) At 5.6GHz

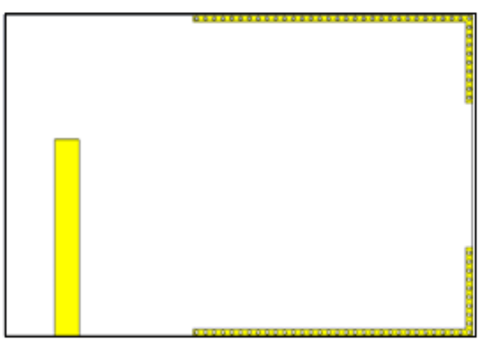
FIGURE 4. 2D radiation of the Vivaldi antenna.

The 2D radiation patterns of the proposed antenna at the E plane (on the left) and H plane (on the right) are presented in Figure 4. The antenna gets a good gain of 3.76dB, 2.67dB, and 4.58dB at 2.4GHz, 4GHz, and 5.6GHz, respectively. The simulation radiation efficiency of the antenna has achieved a rather high value of over 74% at 2.4GHz, nearly 80% at 4GHz, and 76% at 5.6GHz.

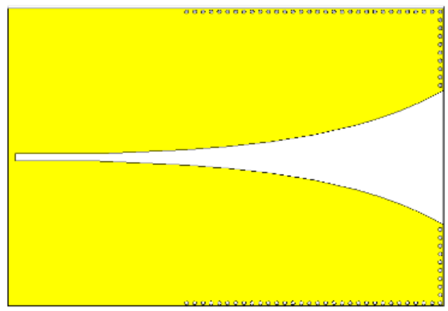
III. PERFORMANCE ENHANCEMENT USING SIW

A. VIVALDI ANTENNA USING SIW

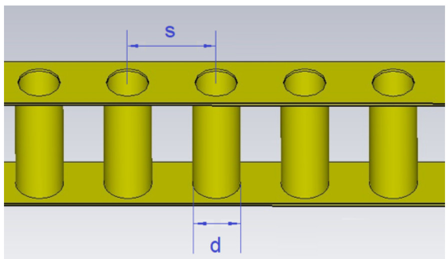
A parametric study [21] shows that to achieve optimal antenna performance, the length L has to be greater than one length at the lowest frequency. However, it is rather big that is difficult to apply for an IIoT device. Thus, to get a compact size while improving performance, the proposed Vivaldi antenna etches a SIW structure as shown in Figure 5.



(a) Top view



(b) Bottom view



(c) SIW structure

FIGURE 5. Vivaldi antenna using SIW structure.

Several previous public research [14] have shown that the SIW structure that their vias are around the patch or ground could achieve better enhancement. Depending on the Vivaldi design, we etched an L shape symmetric SIW that the first end is blocked by the opening of the tapped slot while the second end is limited by the feeding line. These limitations could decrease optimizing time significantly while ensuring the radiation pattern of the proposed antenna.

The transverse spacing between two SIW lines is nearly the antenna width W and is defined as the following [23]:

$$W = W_{FW} + \frac{d^2}{0.95s} \tag{5}$$

while W_{FW} is the transverse spacing in case of SIW wavelength is filled, d is via diameter and s is the distance between the vias from center to center.

$$W_{FW} = \frac{c}{2f_c\sqrt{\varepsilon_r}} \tag{6}$$

where f_c is the cut-off frequency.

Radiation efficiency is a significant antenna parameter. To achieve a reasonable value, s/d needs under 2.5 and it is recommended to equal 2 [13]. After optimizing by using CST software, the proposed SIW Vivaldi gets the s is 11mm and d is 6mm. Thus s/d=1.8(3).

B. RESULTS AND ANALYZING

The symmetric L shape SIW structure improves several performance parameters of the Vivaldi antenna. Firstly, it is impedance matching. From Figure 6, it can be seen that at two of three resonant frequencies, the S11 values decrease from -27.84dB and -25.48dB down to -49dB and -45dB, respectively. It means that the SIW-Vivaldi antenna gets the impedance matching is rather better than the Vivaldi antenna.

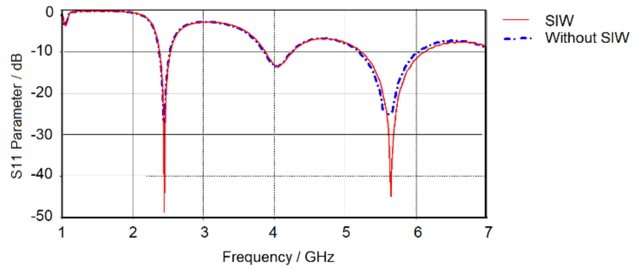
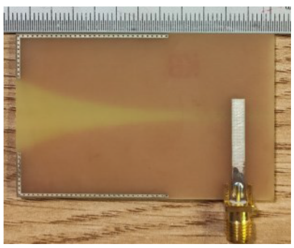
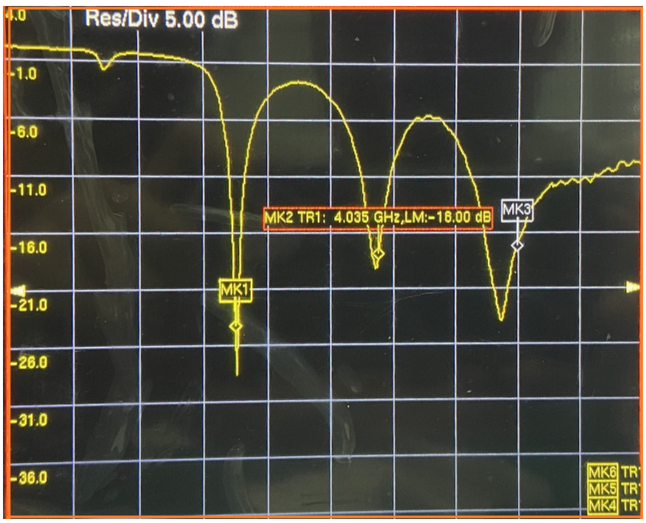


FIGURE 6. S11 Parameter of Vivaldi antenna with and without SIW structure.



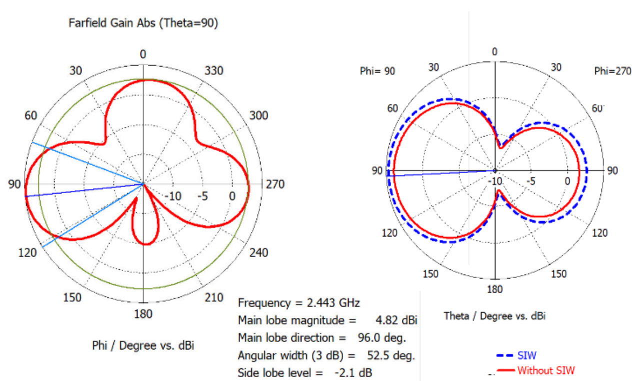
(a) Top plane

(b) Bottom plane

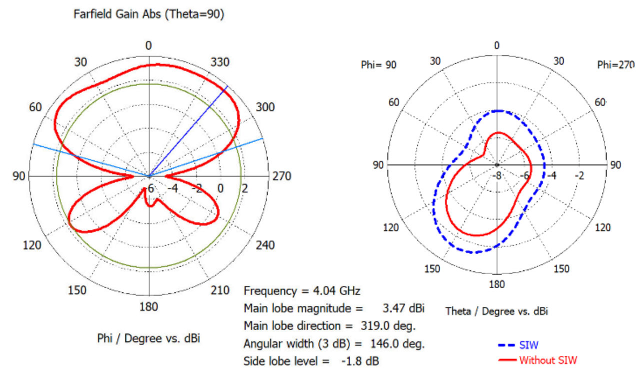


(c) Measurement S11 Parameter on based on VNA equipment

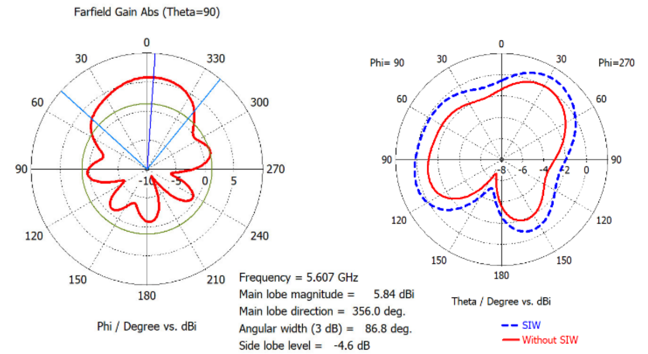
FIGURE 7. The fabricated SIW-Vivaldi antenna.



(a) At 2.4GHz



(b) At 4GHz



(c) At 5.6GHz

FIGURE 8. 2D radiation of the SIW-Vivaldi antenna.

The fabricated antenna based on FR4 is measured as shown in Figure 7. The measurement S11 result which is got from VNA equipment is also proven for impedance-matching enhancement. Besides, it also can be seen that the bandwidth at all bands is still the same to ensure the wide-band antenna for the IoT/ IIoT application.

Secondly, the gain is another parameter that achieves the enhancement as illustrated in Figure 8. It is seen that the SIW-Vivaldi antenna gets the same radiation shape which compared with the Vivaldi antenna. In addition, the gain is improved significantly at three operating bands.

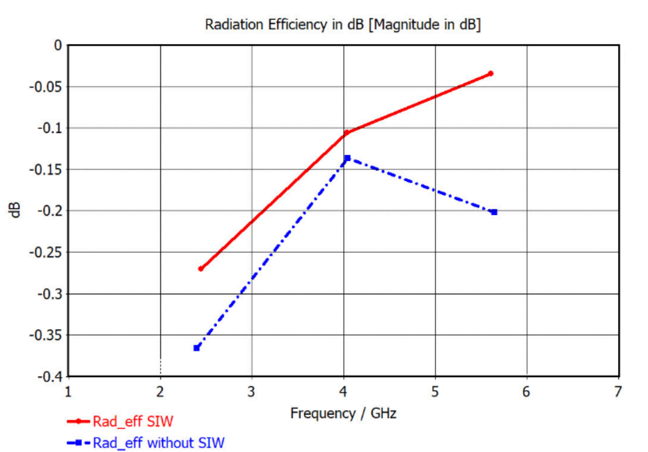


FIGURE 9. S11 Parameter of Vivaldi antenna with and without SIW structure.

The best for last is the simulation radiation efficiency which is an important parameter for the antenna based on the FR4 substrate. The radiation-efficiency comparison between the Vivaldi antenna with and without SIW structure is present in Figure 9. The SIW structure has improved significantly radiation efficiency. The SIW-Vivaldi antenna achieves simulation radiation efficiency of 93.24%, 97.56%, and 99.05% at 2.4GHz, 4GHz, and 5.6GHz, respectively. The enhancement of the gain and radiation efficiency parameters of the proposed antenna using SIW structure is presented in Table 2. It can be seen that, at all three operating bands, gain and radiation efficiency parameters are improved. It increases significantly at 5.6 GHz resonant frequency.

TABLE 2. THE ENHANCEMENT OF THE PROPOSED ANTENNA PARAMETERS

f (GHz)	Gain (dB)			Radiation efficiency (%)		
	No SIW	SIW	Enhancement	No SIW	SIW	Enhancement
2.4	2.54	3.02	0.48	79.12	93.24	14.12
4	1.82	2.24	0.42	79.04	97.56	18.52
5.6	2.88	3.91	1.08	76.64	99.05	22.41

The simulation comparative study with the state of artwork is presented in Table 3. With the same number of operating bands, their substrate type, resonant frequency, dimensions at the lowest band, ratio gain of resonant frequency, bandwidth, and radiation efficiency are compared. It can be observed that our design gets the most compact and has a wide band for all three bands while achieving very high radiation efficiency. It is a significant one based on the FR4 substrate.

TABLE 3. THE SIMULATION STUDY WITH TRIPLE BAND ANTENNAS USING SIW

Ref	Sub	f (GHz)	Dimension at the lowest band (λ*λ)	Gain (dB) per resonant freq (GHz)	B (%)	η (%)
[24]	RT5880	5.7	0.79^0.78	1.1	0.75	-
		6		0.98	1	-
		6.4		0.81	1.23	-
[25]	FR4	4,23	0.56*0.56	1.72	53.7	84
		13.63		0.37	2.79	80
		17.05		0.31	2.64	80.3
[26]	RT5880	10.07	1.29*1..2	0.65	1.29	80
		10.85		0.63	0.49	78
		11.82		0.65	1.6	81
[27]	RT5880	28	2.8*1.38	-	3.7	-
		33		-	2.3	-
		38		-	3.1	-
This work	FR4	2.4	0.32*0.468	1.26	8	93.24
		4		0.56	12	97.56
		5.6		0.7	19	99.05

IV. EXPERIMENTAL ON THE REALITY WIRELESS SYSTEM

A. TEST SET UP

The performance of both Vivaldi antenna with and without SIW structure antenna are verified in a real environment at 2.4GHz and 5GHz bands in different weather.

1) TEST CONFIGURATION

The test configuration is shown in Figure 10. It includes:

- A wireless router dual band D-Link Dir-809 that has two operating bands which are 2.4GHz and 5.8 GHz to establish the connections to IIoT devices. It includes three antennae with 5dBi gain. The receiver sensitivity gets -71dBi at both bands if using the 802.11n standard.
- A USB Wi-Fi Adapter AC for PC/ Laptop. It contains a USB 2.0 adapter and a dual-band dipole antenna. The Adapter can operate at 2.4GHz and 5.8GHz bands. The dual-band dipole has a receiver sensitivity from -110dBm to -40dBm and 2dBi gain.
- The proposed SIW-Vivaldi and Vivaldi antenna connect to the Laptop via USB Adapter AC600 using an SMA transform set.
- A Laptop has installed Wi-Fi Analyzer Application.

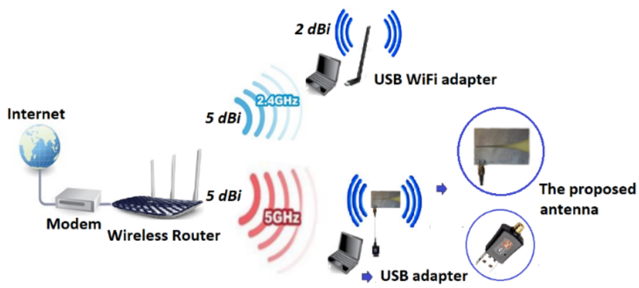
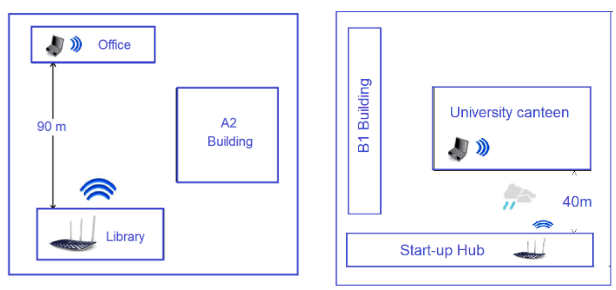


FIGURE 10. Test configuration

2) TEST ENVIROMENT



(a) In dry and hot weather (b) In rainy weather

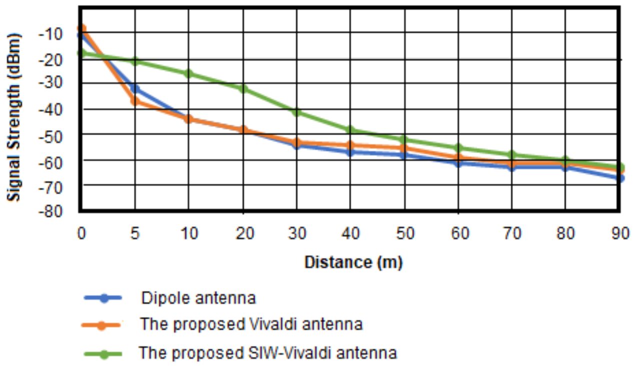
FIGURE 11. S11 Parameter of Vivaldi antenna with and without SIW structure.

The antenna performance is measured in two weather cases. The first one is dry and hot weather. The obstacles have a low height. The maximum distance between transmitter and receiver is 90 m. The second one is performed in heavy rain conditions. The maximum distance between transmitter and receiver is 40 m. The plot of both cases are presented in Figure 11.

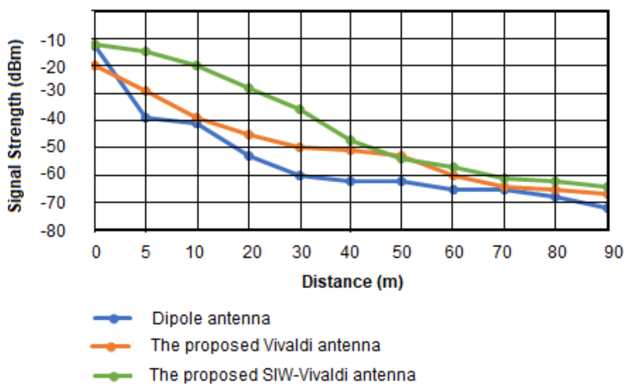
B. EXPERIMENTAL RESULTS

1) IN DRY AND HOT WEATHER

Figure 12 shows the comparison receiver's signal strength among the consumption dipole antenna, the proposed Vivaldi antenna, and the SIW-Vivaldi antenna in the dry and hot weather at both bands: 2.4GHz and 5.6GHz. It can be seen that the SIW-Vivaldi achieves the highest signal strength at both bands. At the 2.4GHz band, the signal strength of the Vivaldi antenna is the same as the dipole one while it is rather better at 5.6GHz.



(a) At 2.4GHz

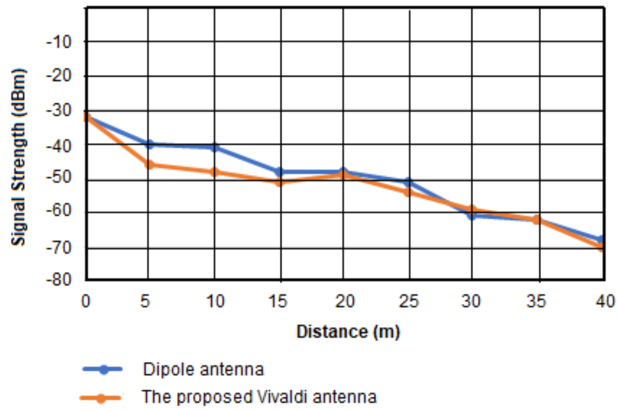


(b) At 5.6GHz

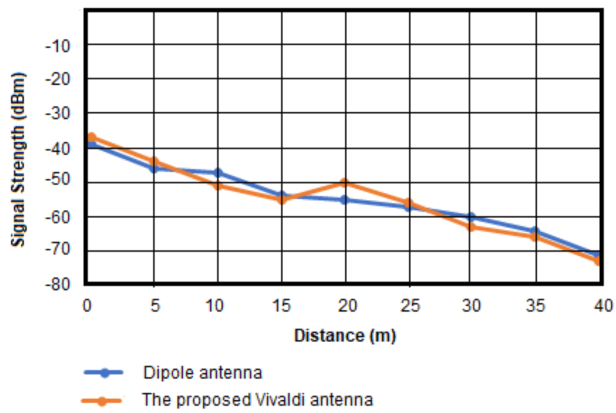
FIGURE 12. The signal strength comparison among dipole antenna and the proposed antenna with and without SIW structure in dry and hot weather.

2) IN HEAVY RAINY WEATHER

Figure 13 shows the comparison receiver's signal strength among the consumption dipole antenna and the proposed Vivaldi antenna in heavy rainy weather at both bands: 2.4GHz and 5.6GHz. It can be seen that the signal strength at both bands decreases significantly for both antennas. At the 5.6GHz band, the signal strength of the Vivaldi antenna is the same as the dipole one while it is a bit worse at 2.4GHz.



(a) At 2.4GHz



(b) At 5.6GHz

FIGURE 13. The signal strength comparison among dipole antenna and the proposed antenna with and without SIW structure in rainy weather.

V. CONCLUSION

A triple-band Vivaldi antenna is proposed with SIW structure on purpose to increase higher gain and radiating efficiency. By using CST, the tapered slot and size of SIW are optimized to achieve three well-known bands for IIoT applications. With the function of the Vivaldi antenna, wideband width is achieved, and the antenna can apply for wideband equipment to support high transmission speed, and stable connection.

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