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Study of Miniaturized SIW and RWG Limiters for S-Band Receiver Protector Radar and Communication Applications

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Abstract—Limiter is a protective structure that is considered a vital device in microwave systems, especially radars. A limiter operates as a receiver protection against large input power for receiver microwave circuit component protection and allows the receiver to function normally when these large signals are not present. In this paper, the investigation and implementation of a miniaturized microwave substrate integrated waveguide power limiter (SIWL), approximately $43 \times 20.5 \times 135$ millimeters cubed, for low power receiver protection in military S-band portable radar applications are compared with a rectangular waveguide limiter (RWGL), approximately $72.14 \times 64.04 \times 178.05$ millimeters cubed, and analyzed using commercial software. The proposed limiter design configurations for receiver protection have been designed, analyzed, and compared with samples of other literature techniques. The proposed designs have been fabricated, and the microwave characteristics have been illustrated. The measured results of the proposed limiters have been analyzed, and the agreement between the measured and simulated results shows that the proposed limiters provide excellent protection and meet the needs of low power receiver portable radar and communication applications with a design that reduces SIWL size.

1. INTRODUCTION

Receiver protection has been used a lot in modern communication and radar systems to deal with interference threats and reflected power. Receiver protectors are used for many things, like fixed-wing, rotary-wing, missile seeker, military, meteorological, and portable radars [1–3]. When the transmitter and receiver of a radar system are tuned to the same operating frequency, limiters are used. The receiver circuits must be protected from strong reflected power, and the limiters must be able to pick up and process very weak reflected signals. Limiters can be divided into passive-type devices that is self-activate and active-type limiters that require an external control signal [4–6]. The self-activated limiter can serve as receiver protection without the help of external control signals or a power source. Compact size, ease of fabrication, and integration with other systems and devices are the main aims of microwave applications. Waveguides, particularly the rectangular shape (RWG), still have the benefit of being able to handle high power, but with the drawbacks of complex structures, high implementation costs, transitions requiring special components, devices, or flanges, and challenging microwave component integration in the high frequency range [6–8]. The devices based on microstrip technologies have several benefits, including being less expensive and simpler than other conventional receiver protectors to integrate with other devices and circuits, but they still have the drawbacks of low power and radiation loss due to their structure and materials compared to waveguide devices and components. Substrate integrated waveguide (SIW) technology, which is a metal-filled via-hole array

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in a substrate with grounded planes, provides a way to combine the benefits of both technologies while minimizing their drawbacks [1–3]. The benefits of SIW technologies include their low cost, small size, high quality, low radiation loss, and ease of integration with other parts and systems [9–13]. Radar applications, like the Blighter B202 Mk2 manportable radar for ground surveillance, Man-portable Surveillance and Target Acquisition Radar (MSTAR), are lightweight radar systems that are easy to use and move around without a vehicle. It is a low-power radar designed to bring radar to remote locations where using vehicles is impractical. Using commercial software and Rogers 4350 of varying thickness, the investigation, analysis, design, and implementation of a compact SIWL for low-power receiver protectors have been introduced. The proposed SIW and RWG limiter design configurations have both been assembled and examined. Simulated and measured results from both are compared to show how well SIWL size reduction compared with RWGL. The proposed design structures are also compared with the limiter design techniques described in the literature. To meet the protection requirements for low-power portable radar and 5G and 6G network applications, the measured results of the proposed structure can be analyzed to show that it has superior protection performance to RWGL at the frequency band of 2.5–3.2 GHz.

2. THE PROPOSED RWG AND SIW LIMITERS DESIGN CONFIGURATION

Short microwave pulses from the outside can affect radar receiver circuits. This can add to the high level of unwanted microwave signals caused by leakage from the transmitter to the receiver. Microwave limiters can provide protection from these effects [1–3]. Because the timing of the transmitted signal is known, threats to the microwave are divided into predictable threats like transmitter leakages and unknown threats with unpredictable timing like outside signals. Its technical considerations have an impact on the microwave power limiter's design. On-state and off-state threshold values, response time, and recovery time are among these factors [4, 5]. The following subsections will go over the proposed SIWL and RWGL's design processes and associated details. Limiting voltage amplitude while applying limiters until the limiter's upper limit is one of the main mechanisms that makes limiters work. The clamping response, which refers to the amplitude of the pulse envelope being clipped and subsequently decreased to a safe level, limits the low impedance connection between the signal and ground [6–8]. A switching mechanism that is activated when power reaches a predetermined threshold is an additional key. When the limiter is engaged, the pulse is shorted to ground potential, leaving no RF voltage and only a maximum current. Switching techniques require more recovery time than clamping tools. Technical terms used in the proposed limiter design include threshold value, on-state, off-state, response time, and recovery time [5–8]. To shield receiver circuits from high power levels, a low threshold level is needed. The limiter should be a transmission line medium with the lowest possible insertion loss in the off state. When the limiter is turned on, it protects delicate systems or components from overloading by either sending high power to the ground or absorbing it. The response time, which is the interval between when a pulse strikes the limiter and when the on-state is turned on, causing the pulse to be clamped, should be as brief as possible. The recovery time is the period after the input pulse level drops to zero before the limiter returns to approximately 3 dB of its previous off-state insertion loss values [1–5]. For the proposed limiters to meet the best specifications, multiple design phases were used. In these stages, which will be demonstrated and discussed in the following subsections, the design for each of the RWGL and SIWL is carried out sequentially and in parallel to illustrate and compare the design methodology and power reduction for each stage of them using the iris and post to limit power. This method of presentation will achieve logical and phased symmetry between the two design configuration methods, RWGL and SIWL, in addition to showing the design of each of them as complete and separate from the other.

2.1. The RWG and SIW Structures Design Methodology

With rows of conducting vias in the place of conducting walls, the SIW technology is regarded as a quasi-dielectric filled RWG. It is a brand-new technology for applications and compact, integrated microwave circuit systems. Where $(d < P)$ as $p < 4d$ and $p < \frac{\lambda_0}{2}\sqrt{\varepsilon_r}$ [9–14] are present, the via has a diameter d and a pitch p between each via. The TM mode is ineffective when SIW structures are used with

$TE_{n,0}$ mode $n = 1, 2, \ldots$ This is because the specific mode behavior at $n = 1, 2, \ldots$ in a SIW structure is dependent on the proposed structure's SIW physical dimensions. The dominant TE_{10} vertical electric current density mode on via rows has the highest handling power [15–17]. The physical dimensions of the guide, in which a_{WG}, b_{WG}, and L_{WG} are the width, height, and length of the RWG, respectively, and determine the cutoff frequency f_c of the propagating mode in the RWG, which can be calculated using equations in [6], where $f > f_c$. Also, the SIW width without a tapering transition and the guided wavelength based on the cutoff frequency, f_c as well as the widths of the dielectric-filled waveguide, a_d, and the SIW structure, a_s, can be calculated, as illustrated in [17–19]. To match the quasi-TEM mode of the microstrip transmission line with that TE_{10} of the SIW structure, a tapering transition has been used. The goal is to reduce the reflection coefficients for integrated planar circuits on the same substrate without using any mechanical assembly [11–13]. The typical microstrip line design formulas determine the dimensions W_{T1}, W_{T2}, $L_{T1} = \frac{\lambda_{gs}}{3}$, and $L_{T2} = \frac{\lambda_{gT}}{4}$ of the proposed feeding line and transition based on the SIW wave impedance, Z_{TE} and the ohmic resistance, Z_P for a nominal 50 ohm impedance, as illustrated in Eqs. (1) [20] and (2) [21–23].

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12h_R/w_{T1}}} \quad \text{and} \quad \lambda_{gT} = \left(3 \times 10^8/f\sqrt{\varepsilon_e}\right) \tag{1}$$

$$Z_{TE} = \sqrt{\frac{\mu}{\varepsilon}} \times \frac{\lambda_{gS}}{\lambda} \quad \text{and} \quad Z_P = Z_{TE}\frac{\pi^2 h_R}{8a_S} \tag{2}$$

Tables 1, 2, and 3 show the SIW and RWG's main dimensions, and Fig. 1 shows how the SIW structure changes as it gets smaller. According to the S-matrix of the RWG and SIW structures, shown in Eq. (3) and Fig. 2(a), the structures work well when the transmission coefficient across the whole frequency band is close to unity.

$$[S_{\text{SIW}}] = \begin{bmatrix} 0.0005 & 0.99 \\ 0.99 & 0.0007 \end{bmatrix} \quad \text{and} \quad [S_{\text{RW}}] = \begin{bmatrix} 0.00008 & 0.99 \\ 0.99 & 0.00008 \end{bmatrix} \tag{3}$$

Table 1. The SIW dimensions.

Parameter	ε_r	$\tan\delta$	h_R	λ_{gs}	W_S	$L_S = 1.5\lambda_{gs}$	a_S	p	d
Value (mm)	3.6	0.004	4.5	78	44	115	42	2	1

Table 2. The RWG dimensions.

Parameter	ε_r	λ_{WG}	a_{WG}	b_{WG}	$L_{WG} = 1.5\lambda_{WG}$
Value (mm)	1	118.7	72.14	34.04	178.05

Table 3. The microstrip tapering transition dimensions.

Parameter	λ_{gT}	W_{T1}	W_{T2}	L_{T1}	$L_{T2} = \frac{\lambda_{gT}}{2}$
Value (mm)	20	23.6	9	10	10

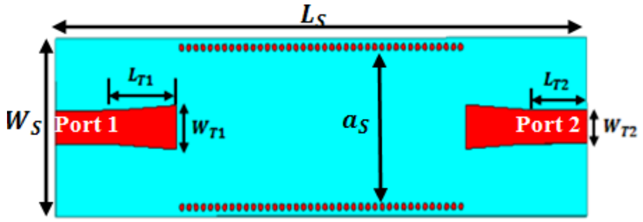
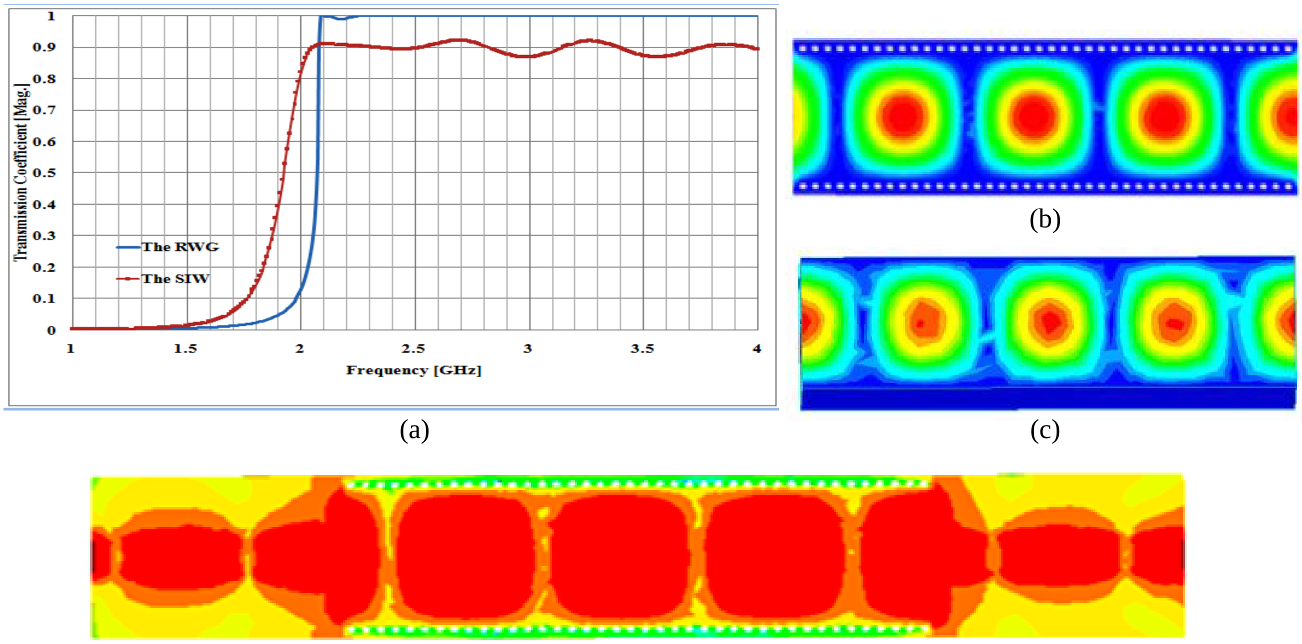


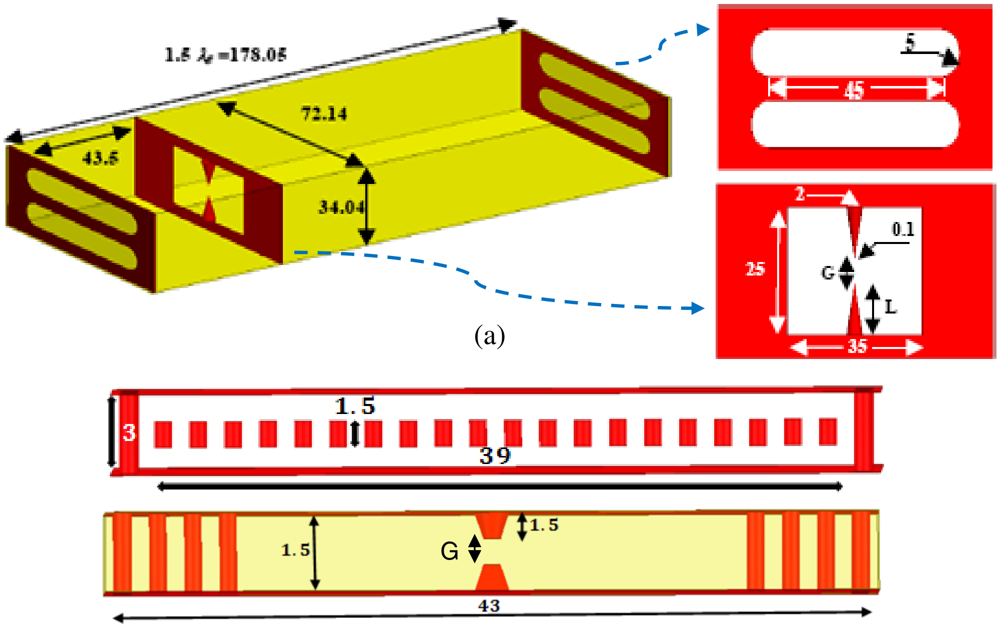
Figure 1. The SIW structure with tapering microstrip transition.



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

Figure 2. The RWG and SIW simulation results. (a) The S-parameters [dB]. (b) The SIW E-field [V/m]. (c) The RWG E-field [V/m]. (d) The SIW with tapering E-field [V/m].

In Fig. 2, the results of the simulation show how the SIW and RWG structures compare to each other. It suggests that both structures performed well, with SIW outperforming RWG. Benefits include simplicity in fabrication and ease of system integration, as well as cost reduction.



(a)

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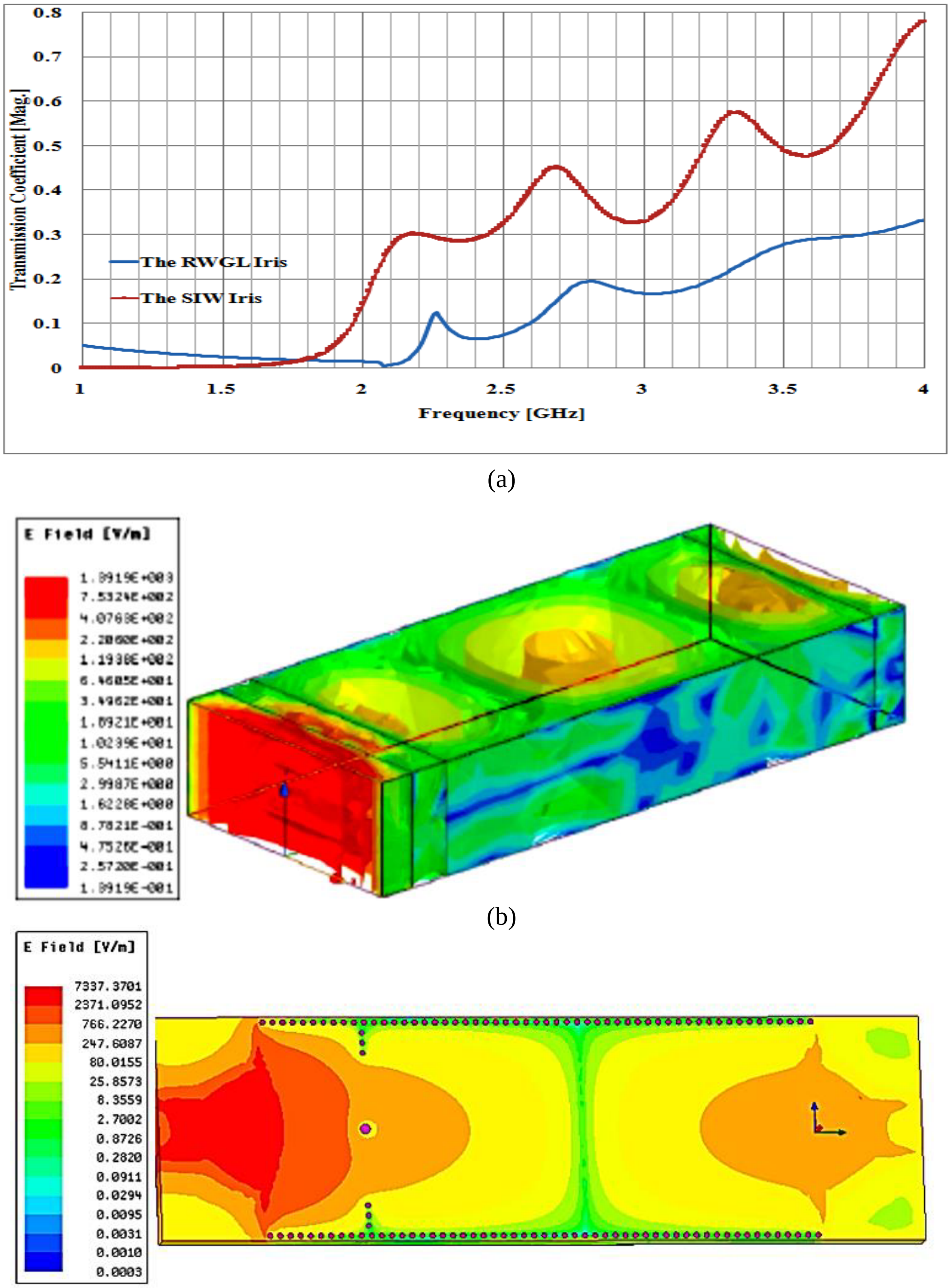
Figure 3. The iris dimensions [mm]. (a) RWGL, (b) SIWL.

2.2. The RWG and SIW Iris

Iris is a metal plate that is used in microwave limiters to add inductance, capacitance, or both. Microwave limiter can accept resonant, inductive, and capacitive iris. The magnetic and electric fields are each surrounded by an inductive and capacitive iris, respectively. Thus, by using a limiter iris, the handling power can be restricted [1–5]. A double symmetrical or resonant iris and an inductive iris



(a)

(b)

(c)

Figure 4. The RWG and SIW Iris simulation results. (a) The transmission coefficient magnitude, (b) RWGL E-field [V/m], (c) SIWL E-field [V/m].

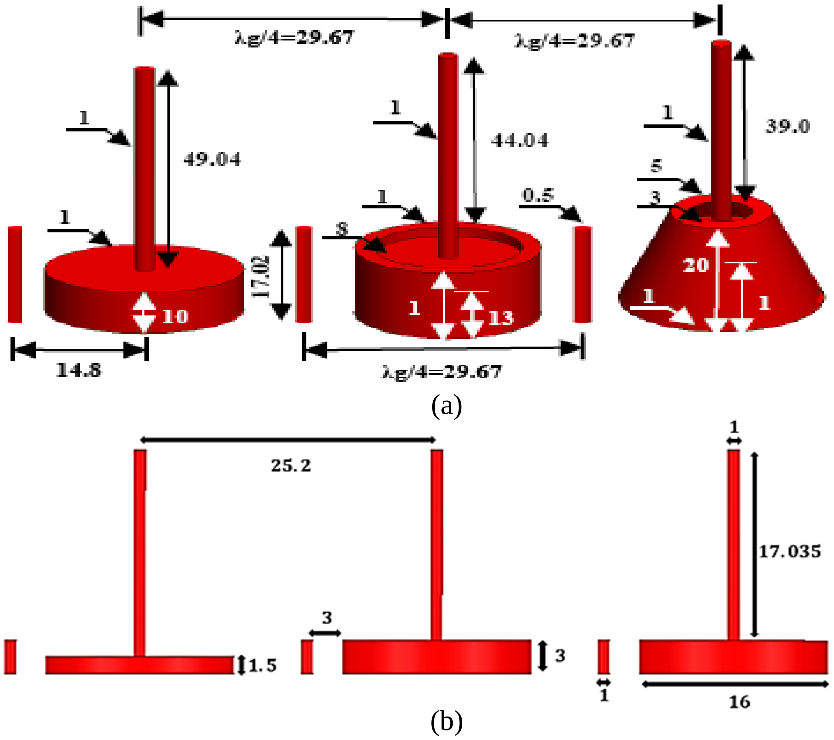
have been used to balance the limiter design in the proposed RWGL and SIWL [7, 8]. Fig. 3 depicts the design of the iris for the WG and SIW limiters in 3D, 2D, and side views, with all measurements in millimeters.

As the first step in the design process, a commercial simulator based on the finite element method (FEM), as shown in Fig. 4, was used to simulate the proposed RWGL and SIWL with iris. The proposed design's role in decreasing the output power compared to the input power for the proposed SIW structure, first by adding the irises and then to the full SIW design, is shown in Fig. 4, along with an intuitive observation of the proposed limiter total electric field distribution. The magnitude of the transmission coefficient of the RWGL simulation as compared to the proposed SIWL is shown in Fig. 4(a) as a function of frequency in GHz at off-state. Figs. 4(b) and (c) depict the S-band iris electric field distribution in V/m for both RWGL and SIWL.

The proposed design's role in decreasing the output power compared to the input power for the proposed SIW structure, first by adding the irises and then to the full SIW design, is shown in Fig. 4, along with an intuitive observation of the proposed limiter total electric field distribution. The magnitude of the transmission coefficient of the RWGL simulation as compared to the proposed SIWL is shown in Fig. 4(a) as a function of frequency in GHz at off-state. Figs. 4(b) and (c) depict the S-band iris electric field distribution in V/m for both RWGL and SIWL.

2.3. The RWG and SIW Posts

When the post is only partially inserted into the microwave limiter, it acts as a shunt capacitive reactance. When it is fully inserted, with connections on both sides of the waveguide wall, it creates an inductive reactance [1–5]. Fig. 5 depicts the layout of the posts for the RWGL and SIWL as well as their millimeter dimensions. Three different stages of shunt capacitive reactance in combination with instantaneous inductive reactance have been used [8–10] in the proposed SIWL and RWGL to achieve the desired protection following a robust study to obtain excellent performance based on technical considerations, as shown in Fig. 5.



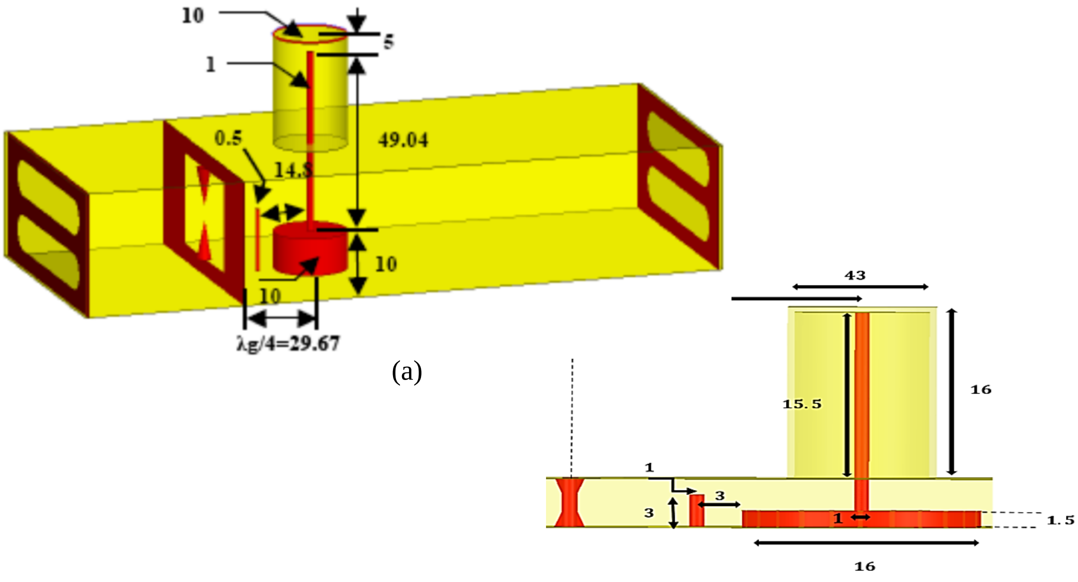
(a)

(b)

Figure 5. The posts dimensions [mm]. (a) RWGL, (b) SIWL.

2.4. The One Stage RWG and SIW Limiter Structure

This section introduces the one-stage RWGL and SIWL designs, as seen in Fig. 6. First, a one-stage presentation of the structure is made. Based on the design parameter analysis discussed in [1], Fig. 6 shows the proposed one-stage RWGL and SIWL structures with their full dimensions and fractional guided wavelength lengths. The proposed limiters' transmission characteristics simulation results were obtained and shown in Fig. 7.



(a)

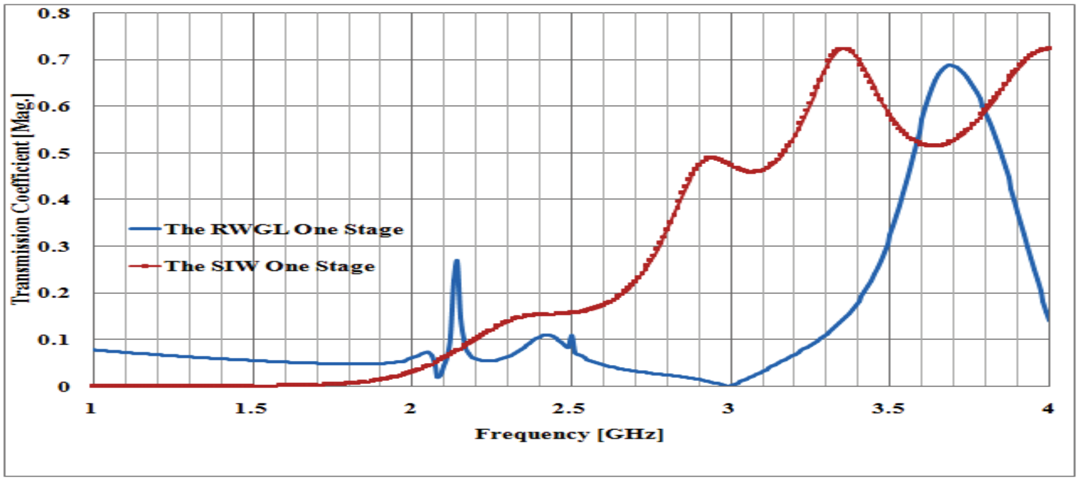
(b)

Figure 6. The one stage limiter design dimensions [mm]. (a) RWGL, (b) SIWL.

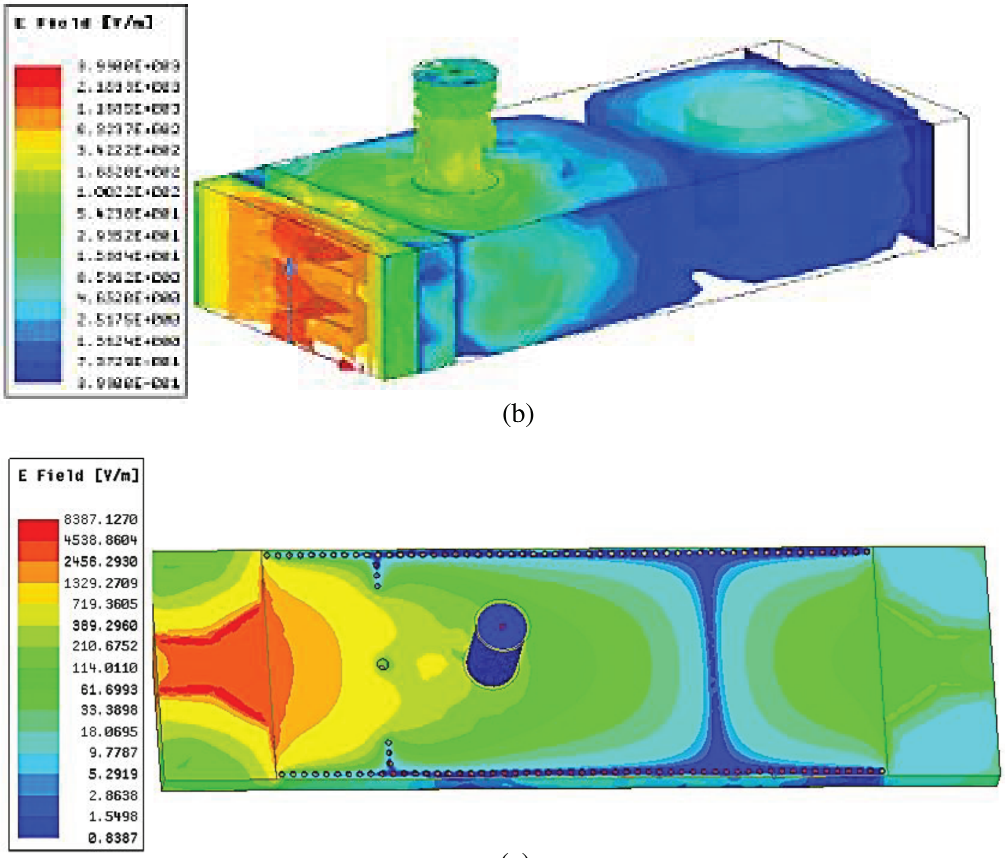
2.5. The Two Stages RWG and SIW Limiter Structure

The two stages, RWGL and SIWL, are introduced in this section. Fig. 8 shows the proposed limiter structure design for the two stages, which are made up of an iris and two stages of posts.

The simulation results, including the magnetite of the transmission coefficient and the electric field distribution of the structures in V/m, are shown in Fig. 9. It shows an intuitive difference according to the role of the proposed two-stage design in decreasing the output power compared to the input power.



(a)



(b)

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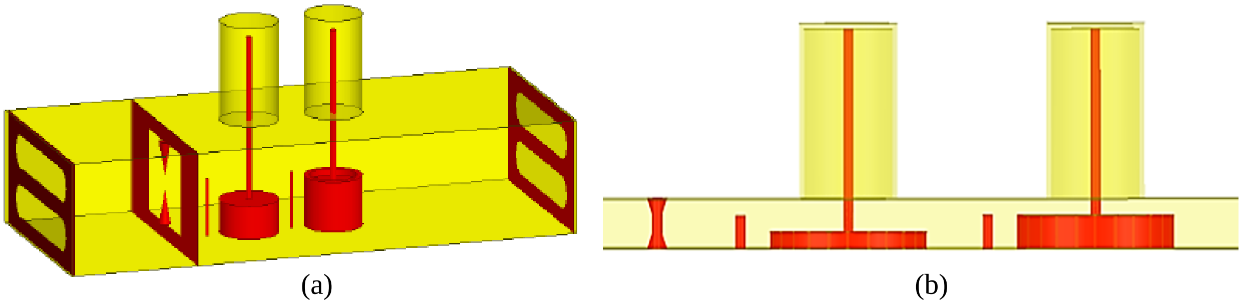
Figure 7. The proposed limiter one stage simulation results. (a) The RWGL and SIWL transmission coefficient [Mag.]. (b) The RWGL E-field [V/m]. (c) The SIWL E-field [V/m].



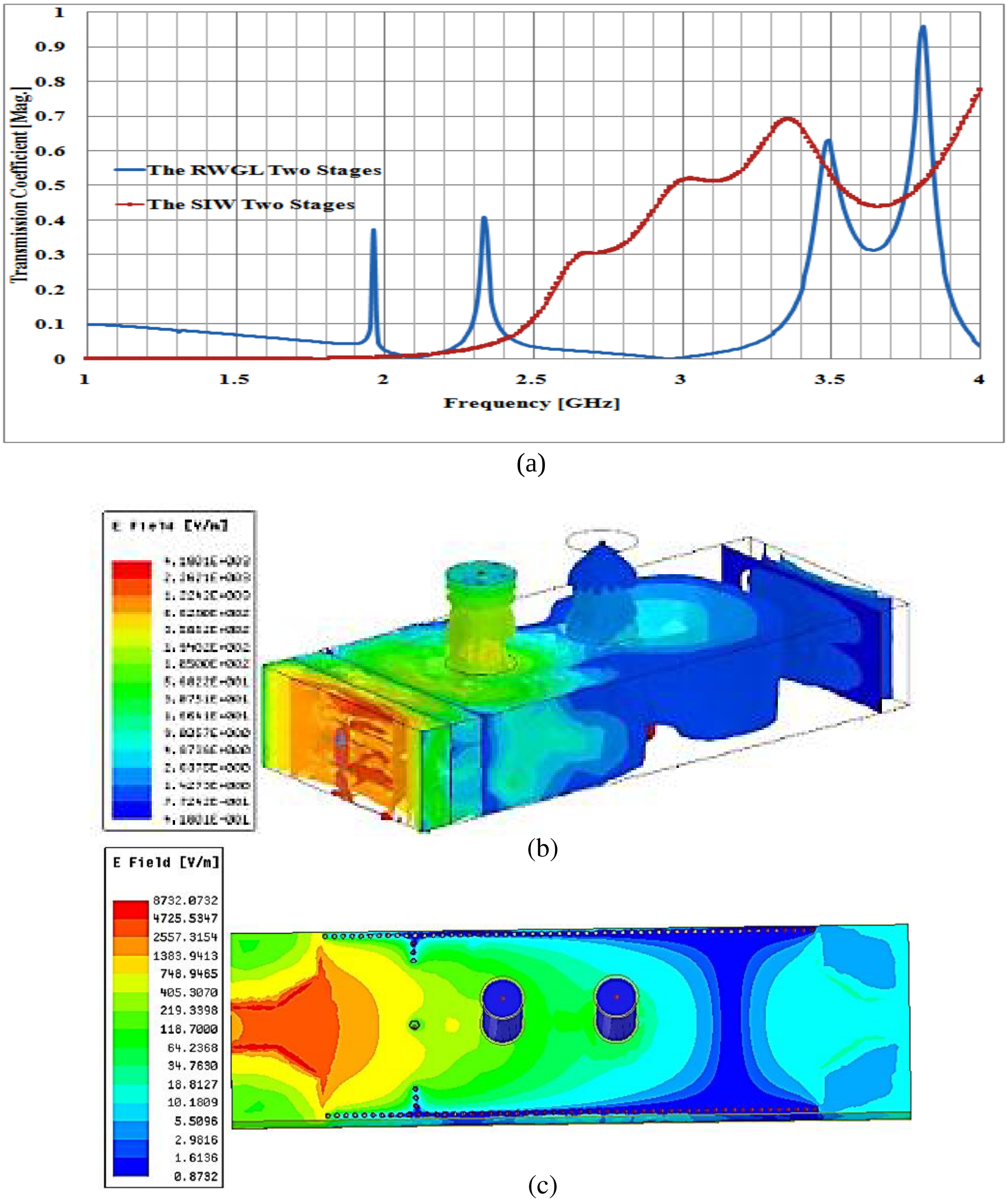
(a) (b)

Figure 8. The two stages limiter design structure. (a) RWGL, (b) SIWL.

2.6. The Final Proposed RWG and SIW Limiter Design

Finally, the three stages of the proposed RWGL and SIWL structures (final design) have been introduced in this section. The final limiter design is composed of iris structures and three stages of posts for the threshold of limiting power by the inert gas under specific temperature and pressure as a switching technique based on the high input power to be limited to a certain level.

The final RWGL and SIWL structures are illustrated in Fig. 10. The simulation results, such as the magnitude of the transmission coefficient and the electric field distribution in V/m of the structures, are shown in Fig. 11.



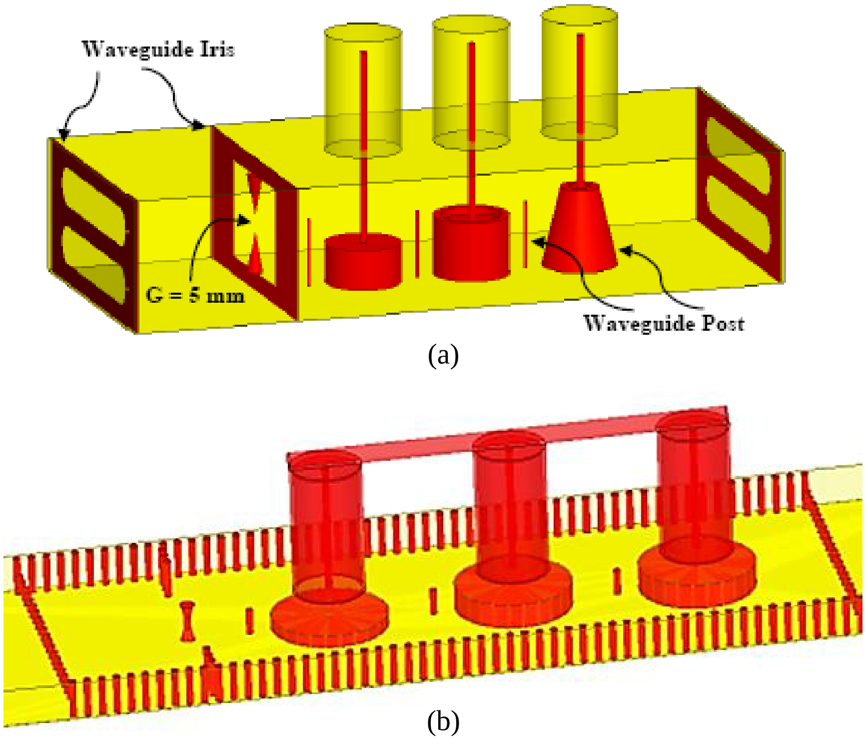
(a)

(b)

(c)

Figure 9. The proposed limiter two stages simulation results. (a) The RWGL and SIWL transmission coefficient [Mag.]. (b) The WGL *E*-field [V/m]. (c) The SIWL *E*-field [V/m].

Figure 11 shows how the proposed structures perform. It gives an intuitive look at the proposed RWGL and SIWL total electric field distribution and the role of the proposed design in reducing the output power compared to the input power by adding the iris and the three stages as a final structure to be built and tested in the lab. Table 4 compares the RWGL and SIWL. It lists the SIWL's advantages over the RWGL, such as its small size, low cost, ease of integration with other components, ability to be easily made, low conductor loss, and low radiation loss, as well as its disadvantages, which include low power and high dielectric loss.



(a)

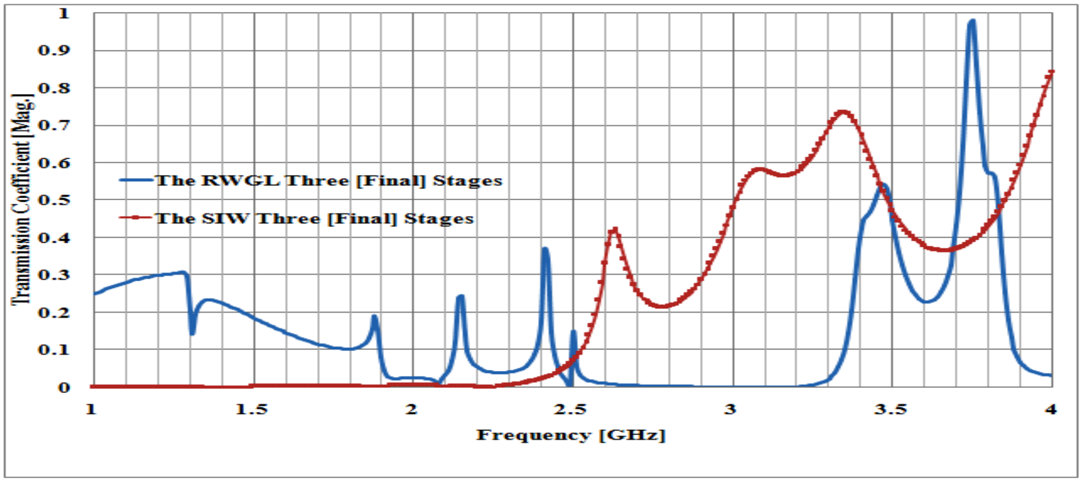
(b)

Figure 10. The 3D view the three stages [Final design]. (a) WGL, (b) SIWL.

3. THE INVESTIGATION OF THE PROPOSED RWG AND SIW LIMITER EXPERIMENTAL RESULTS

Photographs of the proposed RWGL and SIWL at the microwave laboratory is shown in Fig. 12. The measurement results of the proposed design structures are demonstrated in Fig. 13. It was discovered that power handling capacity was limited over a relatively wide frequency range while efficient performance was maintained. The measured result is differed from the simulated one because of the effect of the connector welding and practical design accuracy.

Many references indicate that a power limiter is the best way to lower the high power of the receiver input. To reduce receiver power input, a variety of limiting techniques are used to provide receiver



(a)

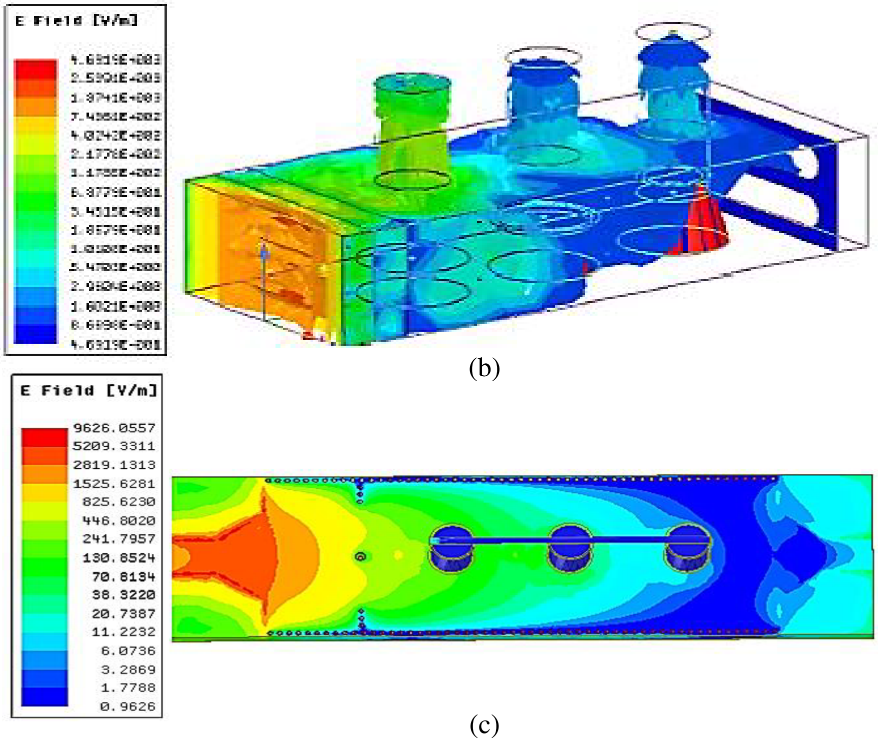


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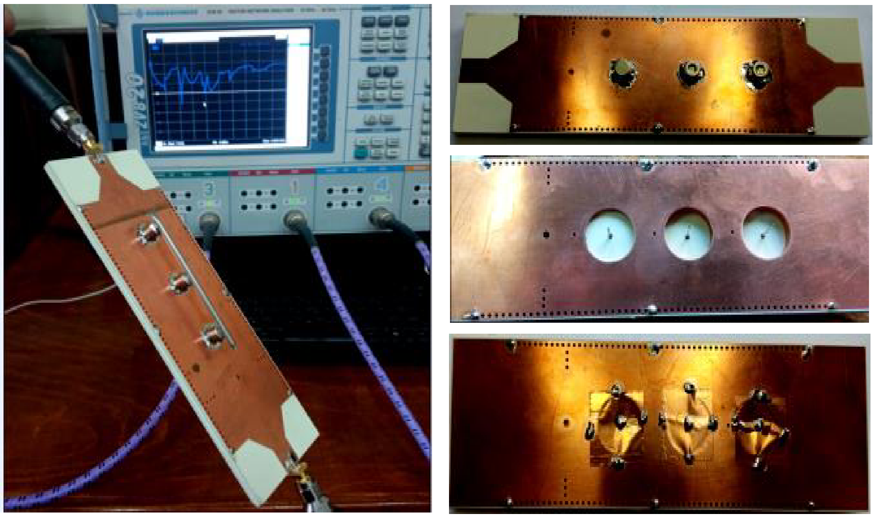
Figure 11. The limiter three stages [Final] simulation results. (a) The RWGL and SIWL transmission coefficient [Mag.]. (b) The RWGL E-field [V/m]. (c) The SIWL E-field [V/m].

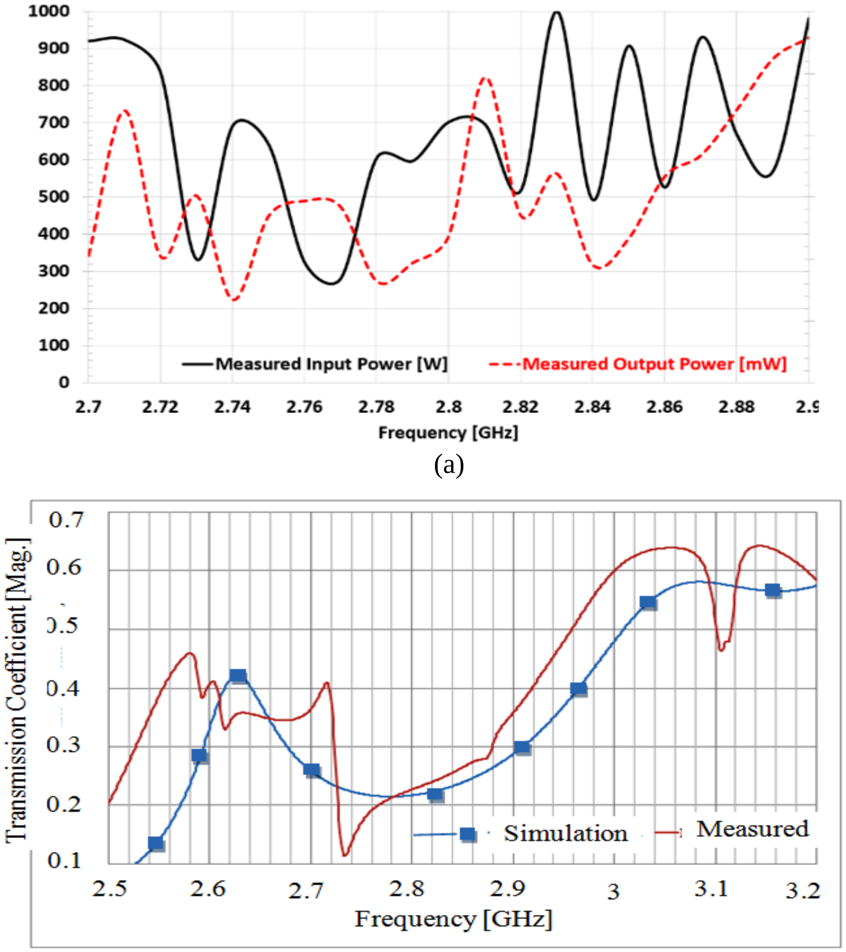
protection, for example those described in [1, 2, 24–29]. It is also noted that while some of the techniques have simple designs, others have complex ones with different input power levels. The proposed RWG and SIW specifiers are compared against a sample of literature techniques, and summaries of these comparisons are listed in Table 5.

(a)



(b)

Figure 12. The photographs of the measurement at the microwave laboratory. (a) RWGL, (b) SIWL.



(a)

(b)

Figure 13. The proposed limiter simulation and measurement results comparison. (a) RWGL, (b) SIWL.

Table 4. The comparison of the proposed SIWL and RWGL design structures.

Parameter/Ref. No.		**[1], [2]**	**This Paper**
Design Type		RWGL	SIWL
Size		Large	Compact
Cost		Expensive	Low
Connection		Difficult using flanges	Easy using tapering
Power		High	Low
Fabrication		Difficult	Easy
Integration		Difficult	Easy
Losses	**Conductor**	High	Low
	Dielectric	Low	High
	Radiation	Low	Low

Table 5. Comparison of sample literature techniques with the proposed limiters design.

Ref. No.	**Design Type**	**Analysis Type/Range**	**Design Size**		**Input Power Level**	**Input Power [W]**	**Output Power [mW]**	**Power Reduction %**
			Size	**Unit**				
[1] & [2]	RWGL	Freq. Domain/ 2.7–2.9 GHz	$72.14 \times 64.04 \times 178.05$	mm	High	1000	200	99.98
[24]	Multistage PIN-Diodes	Time Domain/ 0–1 sec.	-		Low	31.6	79.4	99.75
[25]	Multistage PIN-Diodes	Freq. Domain/ @ 1 GHz	-		Low	8	35.5	99.56
[26]	Multistage PIN-Diodes	Freq. Domain/ 8–10 GHz	$19 \times 16 \times 8$	mm	Very Low	0.05	1	98
[27]	RF-MEMS	Freq. Domain/ @ 10.24 GHz	$470 \times 400 \times 500$	µm	Very Low	0.525	24	95.43
[28]	pHemt GaAs	Freq. Domain/ 7–21 GHz	$1.4 \times 0.83 \times 0.075$	mm	Low	4	100	97.5
[29]	SPST Switch PIN-Diode	Freq. Domain/ 3.1–3.5 GHz	-		High	2×10^3	6.31×10^4	96.84
This Paper	SIWL	2.5–3.2	$43 \times 20.5 \times 135$	mm	Low	1	1	99.9

4. CONCLUSIONS

The RWGL and SIWL, as receiver protectors, are forced to deal with three different conditions. When the device is in the low-power state, the RWGL and SIWL are deactivated, and the goal is to match the limiter and transmission line for the echo signal to pass through and arrive at the receiver. In the second, high-power state, the RWGL and SIWL keep the receiver safe from high-power signals that are not wanted and could cause damage. The third is the recovery time state; the limiter is in the process of switching from the high-power state to the low-power state. In this paper, it is claimed that the RWGL and SIWL structures will be designed and built. They also show how the proposed limiters work. The RWGL works from 2.7 to 2.9 GHz, and the SIWL works from 2.5 to 3.2 GHz. The SIWL structures have the advantages of being small, cheaper, easier to integrate with other parts, and having low radiation loss. The simulation analysis and measured values show that the proposed SIWL has good protection performance. A few other techniques from the literature are compared to the proposed RWGL and SIWL to show how useful and effective the SIW limiter design proposed in this paper is and how it meets the protection requirements up to the stage of low-power intermediate frequency for receiver radar and communication applications.

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