A Microwave Limiter with Non-reciprocal Limiting Threshold

Jian Shen, Jibin Liu, Mingtuan Lin, Zhaofeng Wu, and Shixiong Deng

The College of Electronic Science, National University of Defense Technology, Changsha, China

Email: onlysj1994@163.com.

A novel microwave limiter with non-reciprocal limiting threshold is proposed in this paper to protect the transceiver switch or the transmitter. The directivity of the directional coupler is utilized to make the power of the received signal input to the detection circuit larger than that of the transmitted signal, thereby the detection circuit provides different DC bias voltage to the limiter circuit and changes the threshold level of the limiter diode. The test results show that this limiter has a threshold level of 35 dBm for the transmitted signal and 17 dBm for the received signal, which has a non-reciprocal limiting threshold for high-power signals input in both directions.

Introduction: With the continuous development of strong electromagnetic technology, the protection needs of the electronic information equipment are also increasing [1]. As a signal transmitting and receiving equipment, the active phased array radar is composed of hundreds of independent T/R modules, which use a large number of low-power solid-state power amplifiers. The peak output power of a single T/R module is usually between a few watts and tens of watts. In the T/R assembly, the transmit channel and the receive channel are connected to the transceiver antenna through the transceiver switch. If the strong electromagnetic signal coupled into the transceiver antenna is so energetic that the transceiver switch is destroyed, the strong electromagnetic signal will directly enter the transmit channel or receive channel and damage the transmit channel which is not electromagnetically protected [2]. Therefore, it is necessary to design a non-reciprocal limiter with one-way limiting function between the transceiver antenna and the transceiver switch, or in the front of the solid-state transmitter, so that it does not affect the normal passage of the transmitting signal, but can also limit the high-power receiving signal.

Conventional limiters, while offering good protection and proven technology, usually do not have non-reciprocal capabilities [3]. For a single-stage limiter, the limiter performance is basically the same when the signal is input in both directions. For multi-stage limiters, the limiter structure of the previous stage is usually optimized in order to improve the withstand power, and generally requires one-way input and one-way output. Literature [4] adopts a two-stage limiter structure when designing the limiter, in which a PIN diode is used in the front stage to withstand the input power, and a Schottky diode is used in the latter stage to reduce the recovery time. Literature [5,6] adopts a multi-level limiting structure. In order to improve the withstand power, the I-layer of the PIN diode used in the previous stage is large in thickness and large in number, while the I-layer of the PIN diode used in the latter stage is small in thickness and small in number in order to improve the response speed. Therefore, when using the existing limiter to protect the transmitter and the transceiver switch, the transmitted signal will be limited at the same time. At present, the commonly used non-reciprocal devices mainly use the characteristics of magnetic anisotropy of ferrite materials under the action of an external bias magnetic field, and are often used in circulators and phase shifters [7,8]. However, the requirement of external bias magnetic field is high, and it is still insufficient compared with the limiter in terms of protection performance such as miniaturization, wide frequency band and high power.

In order to solve the above problems, this paper designs a non-reciprocal limiter without external bias electric or magnetic field. In this paper, the principle of the non-reciprocal limiter is described first, and the influence of the DC bias voltage on the threshold level of the PIN diode, the S-parameter and the bidirectional power input and output curves of the non-reciprocal limiter are simulated and analyzed. To verify the effect of non-reciprocal limiting, a non-reciprocal limiter is fabricated and tested. The test results show that it has a small insertion loss for the transmitted high-power signal and a good limiting effect for the received high-power signal.

Principle of non-reciprocal limiting technology: The core device of the limiter is the PIN diode, which consists of a highly doped P-layer, a highly resistive I layer, and a highly doped N layer semiconductor. The internal resistance of the PIN diode is mainly determined by the I layer resistance, which is determined by (1) [9].

$$R_{\mathrm{I}} = \frac{W^2}{2\mu\tau I_0} \tag{1}$$

Where W is the thickness of I layer, μ is the effective average mobility of holes and electrons, τ is the carrier lifetime, and I_0 is the forward conduction current.

When the PIN diode is in forward bias, the applied electric field and the space charge field are in opposite directions and partially offset, the holes and electrons in the P layer and N layer move to the I layer respectively, the space charge area becomes narrower, the thickness of the I layer decreases, and the resistance of the I layer also decreases. When the PIN diode is in the reverse bias state, the applied electric field is in the same direction as the space charge field, the space charge area widens, the thickness of the I-layer increases, and the resistance of the I-layer also increases. Therefore, the resistance of the I-layer can be changed by varying the bias field [10].

The structure of the non-reciprocal limiter is shown in Fig. 1, and the main transmission path includes port 1, directional coupler, limiter circuit and port 2 connected in sequence. The detection circuit is connected between the directional coupler and the limiter circuit. Among them, the role of the directional coupler, in addition to drawing some energy from the main transmission path, is most importantly to use its directionality to distinguish the direction of the signal input. When the signal is input from the A direction, the signal power output from the directional coupler to the detection circuit is much larger than the signal power when the signal is input from the B direction [11]. The detection circuit can detect the input signal into a DC voltage, and within a certain range, the greater the signal power, the greater the detection voltage [12]. At the same time, the threshold level of the PIN diode decreases as the detector voltage increases.

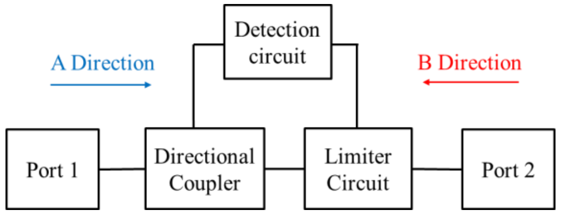

Fig. 1. *Structure schematic of non-reciprocal limiter*

Therefore, due to the directional nature of the directional coupler, when the signal is input from the A direction, the signal power input from the directional coupler to the detection circuit is higher, and the DC bias voltage from the detection circuit to the limiter circuit is also higher, and the threshold level of the limiter circuit is lower. At this time, the signal power through the limiter circuit is greater than or equal to its threshold level, the limiter circuit begins to limit the output level and limit the output level to within the tolerated power of the transmitter or transceiver switch to prevent damage to the transmitter or transceiver switch. On the contrary, when the signal is input from the B direction, the DC voltage obtained through the directional coupler and detection circuit is relatively small, and the threshold level of the limiter circuit is relatively high, and the signal can pass normally as long as the threshold level is made higher than the input power of the signal at this time. Moreover, within the design range, the threshold level when the signal is input from the A direction will be reduced if the coupling degree of the directional coupling degree only is increased. Increasing only the directionality of the directional coupling, the threshold level when the signal is input from the B direction will be raised.

Simulation analysis: In the simulation, we analyzed the effect of external DC bias voltage on the conduction capability of the PIN diode, designed the circuit structure of the non-reciprocal limiter, and analyzed the S-parameter and bidirectional input and output power curves.

Figure 2 shows the simulation results of the power input and output curves of the PIN diode at different bias voltages. As can be seen from the simulation, the small signal insertion loss is 0.2 dB. when the bias voltage is -0.4 V, the starting limit level is 15.8 dBm and the output power is 14.6 dBm. when the input power is 0 V, the starting limit level is 12.5 dBm and the output power is 11.3 dBm. when the bias voltage is 0.4 V, the starting limit level is 6.3 dBm and the output power is 5.1 dBm. Therefore, when the PIN diode is provided with a forward bias voltage, the on-state voltage of the PIN diode is lower compared to zero bias, and the higher the forward bias voltage, the lower the starting limit level before the PIN diode is fully on.

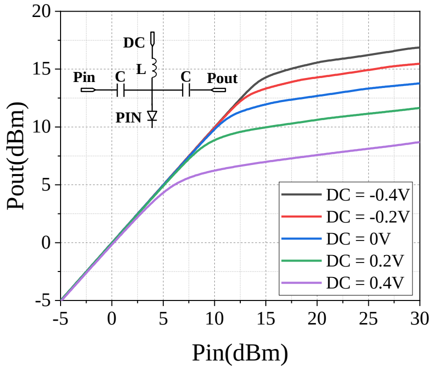

Fig. 2. *Power input and output curves at different DC bias voltages*

Figure 3 shows the circuit structure of the non-reciprocal limiter. For the simulation, the directional coupler is a parallel line coupler with a coupling degree of 10 dB and a directionality of 20 dB. The Schottky diode SBD detects the AC signal, capacitor C1 and resistor R1 form an integral circuit to further play the role of low-pass filtering, and provide voltage bias to the PIN diode through inductor L.

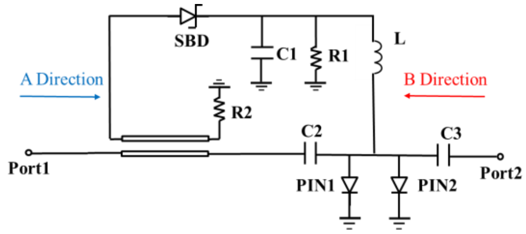

Fig. 3. *Circuit schematic of non-reciprocal limiter*

Figure 4 shows the S-parameter curves and bidirectional input-output power curves of the non-reciprocal limiter. From the simulation results, we can see that |S21|>-0.72 dB, |S11|<-14.75 dB, |S22|<-16.63 dB in 8~10 GHz band. When the signal is input from A direction, the threshold level of the limiter is about 9.2 dBm, and the output level is less than 8 dBm. When the signal is input from B direction, the threshold level of the limiter is about 14 dBm. The simulation shows that the non-reciprocal limiting can be achieved by taking the A direction as the signal receiving direction and the B direction as the signal transmitting direction.

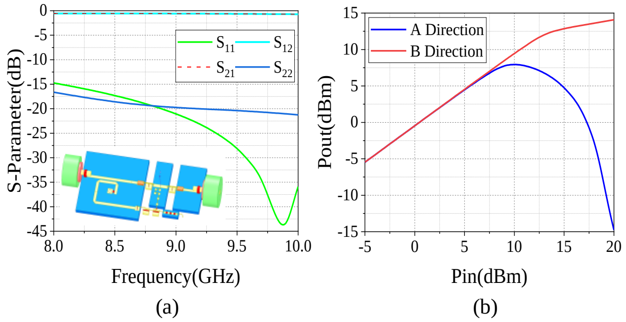

Fig. 4. Simulation Results (a) S-Parameter simulation curve (b) Bi-directional input and output power simulation curve

Since the MA4L-401 PIN diode selected for simulation has fewer parameters and data provided in the technical manual on the official website, considering that the PIN diode simulation model is not established accurately enough and has errors with the actual product, a physical object was made for verification and testing in order to illustrate the feasibility of the non-reciprocal limiting technique.

Experimental verification: The prototype of the proposed non-reciprocal limiter is fabricated by micro-nano process, in which sapphire is selected as substrate and gold wire is selected as electrical connection. The product size is only 19 mm × 16 mm × 8 mm, and the interior view of the non-reciprocal limiter is shown in the small image in Fig. 5. For the small signal test, the non-reciprocal limiter is connected to the calibrated vector network analyzer, and the test result is shown in Fig. 6(a). The test results show that the non-reciprocal limiter has |S11|<-14.0dB, |S22|<-14.1dB, |S12|>-1.17dB and |S21|>-1.2dB in the 8~10GHz band.

Fig. 5. *High power injection test scenarios for non-reciprocal limiters*

The large signal test scenario of non-reciprocal limiter is shown in Fig. 5, in which the signal generator, power amplifier, circulator, non-reciprocal limiter, and spectrum analyzer are connected in sequence. In order to verify its non-reciprocal effect, after the first round of testing is completed, the direction of the non-reciprocal limiter is changed for the second round of testing, and the data of the two rounds of testing are recorded. The large signal selected in the test is a square wave, the frequency is 8GHz, the pulse width is 5μs, and the duty cycle is 1%. The bidirectional power input and output test curve of the large signal is shown in Fig. 6(b).

As shown in Fig. 6(b), when the large signal input from the A direction, the threshold level of the non-reciprocal limiter is 17 dBm, the output power is less than 15 dBm, which can effectively prevent the received high-power signal damage to the transmitting channel. When the large signal input from the B direction, the non-reciprocal limiter starting limit level of 35 dBm, much higher than the threshold level when the signal is input from the A direction, to ensure that the normal passage of the transmit signal. Therefore, the non-reciprocal limiter can be realized by taking the A direction as the direction of signal reception of the non-reciprocal limiter and the B direction as the direction of signal transmission.

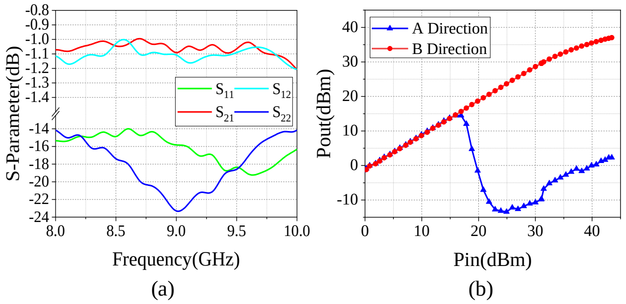

Fig. 6. Test Results (a) S-Parameter test curve (b) Bidirectional input and output power test curve

Conclusion: A novel non-reciprocal microwave limiter is proposed in this paper, which has a small insertion loss for the transmitted high-power signal, and has a good limiting effect for the received high-power signal. The test results show that the threshold level is 35 dBm for transmitted signal, and 17 dBm for received signal. The non-reciprocal limiter can be flexibly installed between antenna and transmitter or transceiver switch without external bias electric field or magnetic field, which can effectively solve the problem that traditional limiter cannot be applied to transmitting channel and improve the power resistance performance of transmitter or transceiver switch.

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