Compact microwave waveguide limiter

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\textbf{Abstract:} A novel waveguide passive X-band power limiter with a compact size and simple construction is designed and tested. The proposed limiter is made with the combined structure of a band pass filter and a limiter by incorporating a PIN diode in the narrow gap region of the H-shaped resonant aperture. Single- and two-stage limiters are designed and experimented with. In particular, for the two-stage limiter structure, a miniaturization method is proposed by using an inductor-type iris as a compact inverter, and the limiter length is reduced by about 67\%, compared to the conventional one.

\textbf{Keywords:} H-shaped resonant aperture, PIN diode waveguide limiter, band pass filter, two-stage

\textbf{Classification:} Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

There has been steady interest in microwave passive power limiters to protect receivers against damage from exposure to high levels of radio frequency signals for various microwave systems, such as radar, reflection altimeters, and communications systems, etc. Among the different kinds of power limiters, the circuit form is widely used because of its low insertion loss and moderate power handling capability [1].

In a waveguide limiter, packaged PIN diodes are incorporated into the port across the transverse coupling aperture of the waveguide in which limiting is desired. The design objective of a waveguide limiter is to compromise between insertion loss and isolation via appropriate design of its structure [2].

Recently, a lot of research has been done on the method [3] for increasing the transmission efficiency of the small coupling aperture [4] for nano-lithography, near-field optical-probe [5], and meta-material applications [6].

In the area of near-field optical microscope applications, C-shaped and H-shaped apertures have been widely used as an optical probe. On the other hand, in meta-material applications, a complementary split-ring resonator (CSRR) aperture has been widely studied as an element of the meta-material plane. These coupling apertures have the common feature of a transmission-resonant aperture, in the sense that under the transmission–resonance condition, the transmitted power through the aperture reaches maximum when the incident electric field has the component normal to the slot axis of the aperture center. The two types of resonant apertures have almost the same maximum transmitted power through the apertures under the transmission resonance condition [7, 8, 9]. When the condition is met, spatial confinement of the incident wave power is achieved for the above C-, H-shaped apertures and CSRR aperture. But the confinement can be made better with the H-shaped aperture. In other words, with an H-shaped aperture, most incident power is funneled through the aperture while the power is spatially confined mainly within the small region between the ridges. A few years ago, the capability of rectangular CSRR elements to design waveguide band pass filters [6] and a miniaturization method by using new compact inverter were suggested.

In this article, we consider a design method for two stages of a compact microwave waveguide limiter by employing a miniaturization scheme similar to that of Cho et al. [9] With a CSRR-type aperture, most incident power is trans-
mitted mainly through the horizontal slit region, whereas most incident power is mainly through the small region between the ridges for an H-shaped aperture. The remaining aperture region outside the main coupling region plays the role of impedance matching in the aperture. Therefore, an H-shaped aperture appears to be superior to the CSRR-type aperture for spatial confinement. For this reason, a PIN diode connection into the two terminals between the ridges of the H-shaped aperture is expected to give better isolation characteristics than connection into the center part of the slot in the CSRR structure. An H-shaped aperture has another advantage over the CSRR structure; that is, on the upper and lower conducting arms, a gap can be secured for another circuit element connection to lower the transmission–resonance frequency of the H-shaped aperture.

2 Proposed waveguide limiter configuration

Fig. 1(a) shows the transmission-resonant aperture in a rectangular waveguide for implementing the simple combined structure of the band pass filter and PIN diode limiter. The resonant aperture is implemented on a Taconic TLX-8 microstrip substrate ($\varepsilon_r = 2.55$) with the ground plane eliminated. The detailed structure of the resonant aperture is given in Fig. 1(b), where the dark region corresponds to the conducting regions.

If we connect the two conducting patches C and E and place an electrical shorting circuit between F and D, the resulting aperture shape reduces effectively to the H-shaped resonant aperture.

On the resonant aperture plane in Fig. 1, choke inductors are connected between the C-E and F-D regions, and the gap between E and F regions is connected via a PIN diode, as shown in Fig. 2. As choke inductors, there are two kinds. One is a lumped inductor, and the other is a meander type. However, from the viewpoint of reproducing the desired value for choke inductance, the meander type of inductor is much more favored.

Figs. 2(a) and 2(b) show the choke coil connection between C-E and F-D conducting patches through the via holes from the meander type of choke coils.
printed on the back of the microstrip substrate. The small circles indicate the locations of the four via holes. The detailed geometrical dimensions of the designed meander coil are given in Fig. 2(c). As shown in Fig. 2(a), the gap between E and F regions is connected via the PIN diode as above.

![Fig. 2. Detailed geometry of a single unit of the combined structure of band pass filter and PIN diode limiter. (a) H-shaped resonant aperture printed on the front of the thin microstrip substrate; (b) meander inductor printed on the rear of the substrate; and (c) the designed meander inductor.](image)

The PIN limiter diode functions as an incident-power–controlled variable resistor. Without a larger input signal, the impedance of the diode is at its maximum, resulting in insertion loss of typically less than 0.5 dB. Any large input signal temporarily forces the impedance of the diode to a much lower value, producing an impedance mismatch that reflects most of the input signal power back toward its source. So PIN-limiter diodes effectively protect receivers.

The design objective of a waveguide limiter is to compromise between insertion loss and isolation through appropriate design of its structure. According to the desired compromises, the waveguide limiter may consist of a single stage or multiple stages.

In this article, we are going to deal with a single stage of the combined structure of the band pass filter and the PIN diode limiter as an element, and the two-stage structure is a simple example of the multiple-stage structure.

3 Simulation and experimental results

In order to check the band pass filter response of the structure, as seen in Fig. 1(a), we carried out a numerical simulation using the CST Microwave Studio software on the reflection (S11) and transmission (S21) properties when \(a = 1\) mm, \(b = 8\) mm, \(x = 5\) mm, \(y = 3.5\) mm, \(x_1 = 6\) mm, and \(y_1 = 0.5\) mm. Fig. 3(a) shows the reflection (S11) and transmission (S21) characteristics curves versus frequencies with no PIN diode connected between E-F patches. Fig. 3(b) shows a comparison between the simulation and the experiment when the incident power on the limiter is low, so that the PIN diode is off when the PIN diode is connected. We can see that the transmission bandwidth with the PIN diode connected is reduced, compared to when no PIN diode is connected.

When higher power than the threshold is incident upon the PIN diode limiter, so that the PIN diode is on, we investigated the isolation characteristics of the limiter in the experimental set-up in Fig. 4.
The threshold power is 15 dBm for the CLA4606-219 PIN diode made by Skyworks [10]. To protect the receiving end circuit from damage due to high power, a 20 dB attenuator is connected to the back stage of the limiter. The input to the limiter is a pulse train where pulse width is 0.5 µs, duty is 1%, and the power level is 43 dBm.

The experimental result from limiter isolation was $-2.495$ dBm, as shown in Fig. 5, which corresponds to the power level after the input of 43 dBm passes the limiter and the 20 dB attenuator.

So, if we compensate for 20 dB attenuation, the limiter isolation is 25.495 dBm, from which the flat leakage is calculated to be 17.5 dBm. For comparison, the
isolation for the CLA4606 PIN diode is roughly 27 dBm for an incident power level of 43 dBm.

Next, we carried out the experiment on scattering parameters, $|S_{11}|$ and $|S_{21}|$, of the two-stage limiter with the spacing of a quarter waveguide length ($\lambda_g/4$), as shown in Fig. 6. Fig. 7 shows the frequency response of $|S_{11}|$ and $|S_{21}|$ when PIN diodes are off and when the PIN diodes are on.

Recall that the incident power level was 43 dBm, and a 16 dB attenuator was used for protection of the peak power meter. So the isolation was found to be 26.577 dB.

Fig. 6. Conventional two-stage limiter.

Fig. 7. Simulation and experimental results for the two-stage limiter: (a) when PIN diodes are off, and (b) when PIN diodes are on.

Fig. 8. Experimental result for conventional two-stage limiter isolation.

Fig. 8 shows the experimental result from the two-stage limiter isolation. In this case, limiter isolation was 0.423 dBm.
Comparison of Figs. 5 and 8 shows that the recovery time characteristic (14 ns) is significantly improved when the meander-type choke coil is used, compared to when the lumped choke coil is used.

4 Design of the inverter

To reduce the filter length where the length is a one-quarter waveguide length \((\lambda_g/4)\), it is necessary to design the inverter with a length smaller than \(\lambda_g/4\). This can be done by inserting an iris structure. By adjusting the iris hole \((k)\), the effective electrical length, \(\theta_e\) of the inverter is reduced considerably.

Fig. 9 shows the inverter configuration that will be used for miniaturization of the filter length.

![Iris configuration as inverter.](image)

Fig. 9. Iris configuration as inverter.

Fig. 10 shows the proposed limiter structure with the two-stage filter characteristics that uses an L-type iris as an inverter for miniaturization of the filter length. The overall length of the limiter is fixed at \(\lambda_g/12\) at 10 GHz.

![Proposed compact limiter having two-stage filter structures.](image)

Fig. 10. Proposed compact limiter having two-stage filter structures.

We compared the band pass filter characteristics of the proposed limiter against the two-stage limiter without an L-type inverter in Fig. 6. The results for \(|S11|\) and \(|S21|\) are given in Fig. 11.

In Fig. 11, the pass band shifts toward the higher frequency band when the miniaturization is done. So, to lower this pass band center to the desired 10 GHz, some compensation should be made by modifying the geometric parameters of the original filter iris, i.e., by changing the vertical iris width \(b\) from 8 mm to 7.5 mm, and the first horizontal strip width \(x\) from 5 mm to 6 mm.

Fig. 12 compares the results for \(|S11|\) and \(|S21|\) before compensation with those after compensation. We see that after some appropriate compensation, the desired pass band can be achieved.

Fig. 13 shows a comparison of the theory and experiment for \(|S11|\) and \(|S21|\).

Fig. 14 shows the isolation characteristics of the limiters for an incident power level of 43 dBm and 16 dB attenuation for the protection of the peak power meter.
In this case, isolation was 34.237 dB. Therefore, a 7.66 dB improvement in isolation is observed, compared to when the separation between the two limiters is kept at $\lambda_e/4$ without inclusion of the inductor-type iris.
5 Conclusion

A design for limiters with a simple construction and high reliability and repeatability has been proposed. We considered a novel waveguide limiter that is made with the combined structure of a band pass filter and a limiter by incorporating a PIN diode into the narrow gap region of an H-shaped resonant aperture for the band pass filter structure.

Single- and two-stage limiters were designed and experimented with. In particular, for the two-stage limiter structure, a miniaturization method was proposed by using an inductor type of iris as a compact inverter. In addition, as a choke inductor, the meander type (instead of the lumped type) was designed and used with a view to reproducibility of the desired value. The length of the proposed compact two-stage limiter structure was reduced by about 67% compared to a conventional one without the inverter. In addition, some enhancement in isolation was achieved. The utility of the proposed type of limiter was confirmed experimentally.

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