MICROSTRIP AND WAVEGUIDE PASSIVE POWER LIMITERS WITH SIMPLIFIED CONSTRUCTION

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Abstract

There is a permanent interest in solid-state control devices for applications in different RF and microwave systems. Passive power limiters are one of them. These devices are the self-controlled elements and they serve to protect receivers from potentially damaging levels of input RF or microwave power. Design of the limiters with simple construction having high reliability, repeatability and suitable for the advance technologies is very actual problem. This paper describes several novel waveguide and microstrip solid-state passive power limiters with simple construction, small sizes and good electrical parameters.

1. Introduction

Solid-state passive power limiters (PPL) have been the devices of choice for the protection of sensitive microwave elements in most cases [1]. The most widely used microwave and RF semiconductor components for these are PIN diodes, detector diodes and MESFETs [1…3]. There are many circuit solutions for solid-state PPL design using above mentioned semiconductor components and their combinations. Different transmission lines are used for these purposes, also a great number of electrodynamics resonance and non-resonance systems are used. Nevertheless, fast development of different RF and microwave systems, rapid progress in technological area demand new requirements to all microwave devices and to control devices, in particular. Modern devices must have simple construction with high reliability and repeatability and be suitable for the advance technologies. So, the problem of solid-state PPL design with simple construction, providing high reliability and repeatability and low-cost is very actual.

2. Design approach

The simplest solid-state PPL (Fig.1) consists of thin PIN diode shunted transmission line and additional elements providing the DC short-circuit path or return path. In Fig.1 they reflect as
decoupling choke. This return path is important part of any solid-state PPL, because it is necessary to provide the close circuit for the rectifying DC current $I_0$ produced by diode under input RF or microwave power $P_{in}$. Otherwise diode can not change its impedance with input power increase or decrease, i.e. it loses «limiting» ability.

The return path of PPL must provide a short circuit for the DC current, but on the other hand it must be the open circuit for the RF current to prevent its leakage. In most cases such a path is made using standard decoupling elements: inductances, impedance transformers, etc. Constructions of waveguide PPL get complicated by use of these elements. It increases a number of additional elements and grounds in case of microstrip PPL. Also, it decreases the operating frequency band and increases cost. So it is very attractive to find solutions for PPL design where return path is provided only using the elements of RF circuit without any additional DC circuits or details. Several such solid-state waveguide and microstrip PPL will be described below.

![decoupling choke](image)

**Fig.1 Simplest solid-state PPL equivalent circuit**

3. Waveguide cross-section two-diode limiter

3.1 Design

Waveguide cross-section PPL [4,5] consists of a thin dielectric substrate with printed circuit and two diodes (Fig.2). The substrate is inserted in the waveguide cross-section. The printed circuit contains vertical metal strip and tuning inductive iris. There is a horizontal gap in the middle of this strip. Schottky and PIN diodes are incorporated into this strip across the slot connected by opposite electrodes. Also it is possible to use two thin PIN diodes (so-called limiter diodes) or two detector diodes. There are no any additional elements for return path.

In low-power regime diodes are in high-impedance state. Parallel type resonance between metal strip and high-impedance diodes from the one side and inductive iris from the other one provides low insertion loss, i.e. input RF or microwave signal passes the device with small attenuation. If the input power exceeds the limiter threshold the detector diode begins to generate direct current. It flows through the PIN-diode too and the impedances of the diodes fall. In this case the resonance of series resonant circuit formed by vertical metal strip and low-impedance diodes provides strong reflection of the input signal and a good isolation is achieved.
3.2 Equivalent circuit

The equivalent circuit of the passive power limiter is presented in Fig. 3. Vertical metal strip is represented as the total strip inductance $L$ and two edge capacitances $C$ between strip and nearest wide waveguide sheath. The inductance $L_{\text{iris}}$ reflects the inductive iris. The PIN diode is represented as the junction capacitance $C_{\text{PIN}}$, in parallel with the variable resistance $R_{\text{PIN}}$. Also, the lead inductance $L_{s\text{PIN}}$ and the resistance of ohmic contacts and passive regions $R_{s\text{PIN}}$ are added in series. The detector diode has the similar equivalent circuit: it consists of the junction capacitance $C_{\text{det}}$, the variable resistance $R_{\text{det}}$, the lead inductance $L_{s\text{det}}$ and the the resistance of ohmic contacts and passive regions $R_{s\text{det}}$. The edge capacitance of the gap is unimportant compared with the diodes capacitances. Diodes and printed circuit form an electronically self-controlled resonator with variable electrical parameters.

To simplify main equations, we first neglect the diode resistance in its low-impedance state. Therefore, in high-power regime the equivalent circuits of the diodes may be approximated as its lead inductances $L_{s\text{PIN}}$ and $L_{s\text{det}}$, respectively. In this case the series resonant circuit formed by vertical metal strip and low-impedance diodes provides the isolation regime. Maximum reflection is achieved at the central frequency $f_0$:

$$f_0 = \frac{1}{2\pi\sqrt{L_{\Sigma}C/2}}$$

(1)

where,

$$L_{\Sigma} = L + \frac{L_{s\text{PIN}}L_{s\text{det}}}{L_{s\text{PIN}} + L_{s\text{det}}}$$

Fig. 2 Two-diode waveguide cross-section passive power limiter.
Fig. 3 Equivalent circuit of the limiter

The isolation bandwidth is defined by loaded $Q_{\text{isol}}$. Taking into account the presence of matched load and matched oscillator, we obtain for total inductance $L_\Sigma$ of series resonant circuit:

$$L_\Sigma = \frac{Z_c Q_{\text{isol}}}{4\pi f_0}$$  \hspace{1cm} (2)

where, $f_0$ - central operating frequency in GHz, $Z_c$ - characteristic impedance in Ohm, $L_\Sigma$ is in nH. Lead inductances $L_{s\text{PIN}}$ and $L_{s\text{det}}$ are presented; the inductance $L$ may then be written as:

$$L = \frac{Z_c Q_{\text{isol}}}{4\pi f_0} - \frac{L_{s\text{PIN}} L_{s\text{det}}}{L_{s\text{PIN}} + L_{s\text{det}}}$$  \hspace{1cm} (3)

The capacitance $C$ is:

$$C = \frac{2 \times 10^3}{\pi f_0 Z_c Q_{\text{isol}}}$$  \hspace{1cm} (4)

where $C$ is in pF.

In high-impedance state (low-power regime) diodes are presented as capacitances $C_{\text{PIN}}$ and $C_{\text{det}}$, respectively. Then parallel resonant circuit provides in this case low insertion loss. Minimum reflection is achieved at the same central frequency $f_0$

$$f_0 = \frac{1}{2\pi \sqrt{(L_\Sigma + L_{\text{iris}})C_\Sigma}}$$  \hspace{1cm} (5)

where,

$$C_\Sigma = \frac{C / 2 (C_{\text{PIN}} + C_{\text{det}})}{C / 2 + C_{\text{PIN}} + C_{\text{det}}}$$
Combining (1) and (5) we obtain the inductance \( L_{\text{iris}} \) value

\[
L_{\text{iris}} = \frac{C/2}{C_{\text{PIN}} + C_{\text{det}}} L_{\text{C}}
\]  

(6)

Equations (1) - (6) allow to obtain main circuit parameters of the passive power limiter. Further computer frequency and amplitude analysis based on these equations and transmission lines theory was used to model this device.

3.3 Experimental and simulation results.

Several examples of the two-diode waveguide passive power limiter for the X-band were made. They have been fabricated on an 1 mm thick duroide substrate with \( \varepsilon_r = 2.2 \) using HMIC technology. PIN-diode and detector diode with capacitances 0.12 pF and 0.1 pF, respectively, were used. The substrate was inserted into the waveguide flange. Measured insertion loss and isolation are shown in Fig.4. The insertion loss of less than 1 dB and the Isolation of at least 15 dB were achieved at the 10\% bandwidth (0.6 dB of insertion loss and 24 dB of isolation were achieved at the central frequency). At the same figure one can see the comparison of computed results and measured insertion loss and isolation. The computer analysis includes the effects of diode parasitics, dispersion and power dissipation in waveguide.

![Fig.4 Low-power waveguide cross-section two-diode passive power limiter](image-url)
Figure 5 shows measured and predicted output power plotted as a function of the input power for this device. The experimental data were measured at the operating frequency 7.5 GHz for 3.5 µs microwave pulse and repetition frequency 1 KHz. The power threshold is low as 25 mW. Isolation is near 13 dB at about 1 W. Comparing this value to the maximum isolation in Fig.4 indicates that diodes are not completely turned on with an input power of about 1 W.

![Graph showing measured and predicted output power](image)

Fig.5 Computed and measured high-power characteristics of waveguide cross-section two-diode PPL.

4. Waveguide E-plane two-diode passive power limiter

4.1 Design

This type of PPL [6] consists of a thin, low permittivity dielectric substrate that is mounted in rectangular waveguide in the plane of the E-field (Fig.6). The circular or elliptical conductor pattern, which forms the resonant element, is defined on one side of the substrate and processed using standard photolithography techniques. Detector and PIN diodes are incorporated into metal configuration in the tops located on a main axis of ellipse (or circle). There are no any additional elements for return path in this case again. Diodes and metal configuration form an electronically self-controlled resonant system.

Due to metal configuration geometry in low-power regime diodes are in high-impedance state and electrodynamics system has non-resonant character. It provides low insertion loss.

In high-power regime direct current generated by detector diode causes the diodes impedances fall. In this case diodes and circular or elliptical conductor pattern forms resonator in
the plane of E-field. For this type of resonator the main mode is $H_{11\delta}$. Resonator provides a series resonance type and it leads to high isolation. The relation between resonance frequency $f_0$ and diameter of circular resonator $D$, located on the thin low-permittivity dielectric substrate, may be written as:

$$\pi f_0 D \sqrt{\varepsilon_{\text{eff}}} = 300,$$

where, $\varepsilon_{\text{eff}}$ is effective dielectric constant, $f_0$ is in GHz and $D$ is in mm.

4.2 Equivalent circuit

Equivalent circuit, shown in Fig.7, reflects in the first approach all frequency properties of this device. Resonator is represented as series resonance circuit with inductance $L$ and capacitance $C$. Their values are expressed through the loaded $Q_{\text{isol}}$ in isolation regime:

$$L = \frac{Q_{\text{isol}} Z_c}{4\pi f_0},$$

$$C = \frac{4 \times 10^3 \times L}{Z_c^2 Q_{\text{isol}}^2},$$

where, $Z_c$ - characteristic impedance in Ohm, $L$ is in nH, $C$ is in pF.

Impedances of the diodes are reflected as was mentioned in paragraph 3.2.
4.3 Experimental and simulation results

Waveguide E-plane two-diode passive power limiters have been designed for the X-band. They have been fabricated on an 1 mm thick duroide substrate with $\varepsilon_r = 2.2$ using HMIC technology. This substrate was inserted into $28.5 \times 12.6 \text{ mm}^2$ waveguide. The circular type of metal pattern was used. Its inner diameter was 9 mm. The width of metal pattern was 1 mm. The operating frequency was equivalent to 7.8 GHz. PIN-diode with capacitance 0.03 pF and detector diode with capacitance 0.3 pF were used in this case. Measured and computed insertion loss and isolation are shown in Fig.8.

The insertion loss of less than 0.5 dB and the isolation of at least 10 dB were achieved at the 6% bandwidth (17 dB of isolation were achieved at the central frequency). Its calculated and experimental limiting characteristics are shown in Fig.9. The measurements were taken on a 5 µs microwave pulse and repetition frequency 1 kHz at 7.7 GHz. The power threshold is low as 75 mW. The limiting characteristic of series two-diode chain with detector and PIN diodes typically has the bistability region [7]. This limiter reflects this interesting property.
Fig. 8 Computed and measured low-power insertion loss and isolation vs. frequency for the E-plane PPL.

Fig. 9 Computed and measured high-power characteristics of waveguide E-plane two-diode PPL.
5. Microstrip passive power limiter based on rectangle resonator

5.1 Design

The passive power limiter based on rectangle resonator was under our consideration [8]. It consists of microstrip input and output main lines coupled with a rectangle resonator with inserted two diodes. Conventional limiter diodes or detector diodes with Schottky barrier or a combination of a detector diode and a PIN-diode for the power handling capability increase are available. The diodes and the printed circuit form a self-controlled resonator with variable electrical length. There are no any additional elements for DC return path in this case (Fig.10). This device combined the principles of the self-feeding limiters, the switchable filters with external DC control and the filters using parallel-coupled lines.

When the input RF power is low, the equivalent electrical length of the rectangle resonator circuit including the diodes is equal to 180° at the operating frequency and limiter provides low insertion loss in a narrow band. When the input power exceeds the limiter threshold the detector diode begins to generate direct current and the impedances of diodes fall. It causes the strong decrease of the resonance frequency and the major part of the input RF power is reflected. So a good isolation is achieved in a very wide frequency range. The electrical lengths $l_1$ and $l_2$ of the rectangle resonator are defined from the solving of the two equations describing the total electrical length in both regimes [9].

![Fig.10 Microstrip PPL configuration.](image)

5.2 Equivalent circuit

The self-controlled resonator, to the first order, might be considered as a series resonant circuit. Two diodes with variable impedances are connected in series with it (Fig.11). The input and output lines are coupled with resonator by means of distributed capacitances expressed using pi-circuit. Capacitances $C_{ap}$ and $C_g$ formed this one [10]. The diodes equivalent circuit is represented as the junction capacitance in parallel with variable resistance. Also, the lead inductance and the ohmic contacts and passive regions resistance are added in series.
Inductance $L$ and capacitance $C$ were estimated as:

$$L = \frac{Q_{\text{ins}} Z_c}{4\pi f_0},$$

$$C = \frac{C_0 C_{\Sigma}}{C_{\Sigma} - C_0},$$

with

$$C_o = \frac{4 \times 10^4 \times L}{Z_c^2 Q_{\text{isol}}},$$

and

$$C_{\Sigma} = -\frac{160}{f_0 (X_{\text{PIN0}} + X_{\text{det0}})}.$$

where, $Q_{\text{ins}}$ – loaded $Q$ in insertion loss regime, $f_0$ - central operating frequency in GHz, $Z_c$ - characteristic impedance in Ohm, $L$ is in nH, $X_{\text{PIN0}}$ and $X_{\text{det0}}$ are reactances of the diodes in high-impedance state.

### 5.3 Experimental and simulation results

The two-diode passive power limiters based on rectangle resonator have been designed for the S-band. It has been fabricated using hybrid microwave integrated circuit (HMIC) technology on a 1 mm thick duroide substrate with permittivity 2.6. Input and output microstrip lines were 50 Ohm. The lines forming resonators had the same characteristic impedance. The distance between coupling lines and resonator is the compromise between low insertion loss and isolation. Detector diodes and PIN-diodes have capacitances 0.2 pF and 0.15 pF, respectively.

Low-power measurements of the limiter are presented in Fig.12. The insertion loss of less than 0.8 dB were achieved at the operation frequency. The isolation of at least 20 dB were obtained from 2.2 to 5 GHz. Fig.13 shows an experimental limiter characteristic at operating frequency 3.6 GHz. The power threshold is as low as 1 mW in CW mode.
Fig. 12 Insertion loss and isolation versus frequency for microstrip PPL.

Fig. 13 Limiting characteristic of microstrip PPL.
6. Microstrip closed-loop passive power limiter

6.1 Design

The next type of microstrip PPL [11] is based on a closed-loop configuration. It consists of two line paths with respective electrical length of 180° and 360° at the operating frequency (Fig.14). Transmission lines, forming PPL, may have different characteristic impedances, but one of them is equal to the characteristic impedance of main transmission line. A pair of diodes (PIN-diode and detector diode, two detector diodes or two limiter diodes) is used. They are connected by opposite sites and so, again, additional decoupling chokes or grounds are not required.

Both diodes are closed and they have high impedance when the input RF power is low. The path with the diodes is off and only the 50 Ohm path is on. The insertion loss are low in a wide frequency range, although the parasitic insertion loss resonances may occur in this case caused by the off path influence. The ways to overcome this inconvenience are shown in [11].

If the input RF power exceeds the limiter threshold the detector diode (in case of detector and PIN diode use) begins to generate direct current. It flows through the PIN diode too and the impedances of both diodes fall. The input RF signal begins to propagate threw both lines. The electrical length difference between them is 180°, the two signals are out of phase. There is no RF signal in the device output. It provides strong isolation in the wide frequency band. The parasitic diode inductance sometimes caused the isolation maximum displacement down the frequency range. Situation may be improved by reduce the 360° channel length by a few percents.

\[ P_{\text{in}} \quad 180^\circ \quad P_{\text{out}} \]

\[ \text{detector} \quad \text{PIN} \]

\[ l_0 \]

\[ 360^\circ \]

Fig.14 Microstrip closed-loop PPL configuration.

6.2 Equivalent circuit

Fig.15 represents the equivalent circuit of the limiter. It consists of pair of transmission lines with electrical lengths \( l_1 \) and \( l_2 \) and characteristic impedances \( Z_{c1} \) and \( Z_{c2} \), respectively. Also the pair of diodes are presented. PIN-diode and detector diode have the standard representation.
6.3 Experimental and simulation results

The computer simulation of this microstrip passive power limiter low-power and high-power characteristics was developed based on the ABCD-matrix and the special method for the power limiter analysis.

The two-diode closed-loop microwave PPL has been designed for the X-band. It has been fabricated on a 0.5 mm thick duroid substrate. The HMIC technology was used for the device fabrication.

PIN-diode and detector diode with capacitances of 0.03 pF and 0.15 pF, respectively, were used. Two lines have electrical lengths $l_2 = \lambda_{bo}/2 \ (180^\circ)$ and $l_1 = 0.94\lambda_{bo} \ (340^\circ)$, where $\lambda_{bo}$ – operating wavelength. Both transmission lines had the equal characteristic impedances – 50 Ohm. Over bandwidth of 2 GHz the insertion loss of less than 0.8 dB and the isolation of at least 12 dB were obtained (see Fig.16). The insertion loss parasitic peak is less than 0.8 dB. The same figure reflects the computed low-power characteristics. Non-optimal combination of the characteristic impedances $Z_{c1}$ and $Z_{c2}$ caused the non-highest isolation at the operating frequency band compared with calculated results presented in [11].

The experimental passive power two-diode microstrip limiter amplitude characteristic is given in Fig.17. It was obtained at the operating frequency 7.4 GHz for 5 µs microwave pulse and repetition frequency 1 KHz. The power threshold is as low as 25 mW. The computed amplitude characteristic is shown here. There is a good agreement between computed and measured results.
Fig. 16 Computed and measured low-power insertion loss and isolation vs. frequency for the closed-loop PPL.

Fig. 17 High-power computed and measured amplitude characteristics.
7. Conclusion

Four different waveguide and microstrip solid-state passive power limiters were described. The use of diode incorporation to different electrodynamics systems allowed avoiding the use of any additional elements (inductances, impedance transformers, groundings, etc.) for the return path. It strongly simplified its constructions and allowed increasing its reliability and repeatability.

References