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# Static and Dynamic Control of Limiting Threshold in Plasma-based Microstrip Microwave Power Limiter

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**Abstract**—Static and dynamic control of the limiting threshold in a very low-loss plasma-based microstrip power limiter is investigated in order to prevent receivers from being threatened by high-power microwave (HPM). An analytic model of the microstrip circuit is proposed to derive the influence of its design on the limiting threshold of the microwave power limiter. Experimental results are in good agreement with those expected. Finally, an original approach to allow discrete limiting threshold tunability is presented and validated experimentally.

**Index Terms**—microwave limiters, radio frequency (RF) tunability, plasma devices, gas discharge devices.

## I. INTRODUCTION

Current receiver systems can be highly vulnerable to high-power microwave (HPM) [1]. To protect them from these threats, microwave power limiters are commonly involved. They usually rely on PIN diodes, MEMS, and other non-linear devices [2], [3]. However, when the threat becomes important these components deteriorate and lose their power limiting properties. Recently, limiters based on plasma discharges have been proposed to handle very high-power threats.

In microwave power limiters, plasma discharges arise when the incoming HPM is sufficient to ionize an inert gas. The non-linear interaction between the incident electromagnetic wave and the ionized gas is finally used for power limitation. Plasma discharges have been widely used in T/R (Transmit/Receive) tubes in order to protect RADAR receivers [4]. If T/R tubes are fully compatible with waveguide technology, they can not be easily integrated into compact microstrip circuits.

Several works have thus studied the integration of plasma discharges into planar microwave power limiters. The first proposed solution was to integrate a plasma discharge into a microstrip line [5]. The measured limiting threshold of this device was above 50 W which remains important. In order to reduce the limiting threshold, recent works have considered resonant circuits [6], pre-ionization techniques [7], or both [8], [9]. Using such techniques, the limiting threshold has been reduced from tens of watts to hundreds of milliwatts. However, no design guidelines have been provided to tune the limiting threshold.

In this paper, we study both theoretically and experimentally the control of the limiting threshold of a plasma-based microwave power limiter by using several geometrical parameters of the microstrip circuit. Besides, an original, simple, and low-loss technique is presented to provide tunable limiting threshold.

## II. BASIC PRINCIPLE

In plasma-based power limiters, the limiting capability is achieved when the gas breakdown happens. It practically corresponds to a critical value of incident microwave electric field  $|E_B|$  that only depends on plasma parameters related to ionization processes such as the type of gas, the electrode material, or pre-ionization. However, from a circuit point of view, the electric field magnitude at any point is directly linked to the incident microwave power, but also to the microwave circuit properties.

In order to illustrate the influence of the microwave circuit design on the limiting threshold, we here consider a microstrip annular ring resonator. Nevertheless, the proposed analysis remains valid for any microwave circuit. According to [10], the input impedance of a low-loss unloaded microstrip ring resonator at the resonant frequency of its first mode is:

$$Z_{in} \simeq \frac{Z_0 Q_{unloaded}}{2\pi} \quad (1)$$

Considering the  $\cos(\varphi)$  angular dependence of the electric field for the fundamental mode, and since the voltage at the feeding point is  $V_{in} = \sqrt{2P_{in}Z_{in}}$ , we can show that the magnitude of the electric field along the ring resonator may be written as:

$$|E| = \frac{1}{h_{ms}} \sqrt{\frac{Z_0 Q_{unloaded}}{\pi}} \sqrt{P_{in}} |\cos(\varphi)| \quad (2)$$

with  $h_{ms}$  the substrate thickness,  $Z_0$  the characteristic impedance of the ring resonator,  $Q_{unloaded}$  its unloaded quality factor,  $P_{in}$  the input power, and  $\varphi$  the angle around the ring. Equation (2) shows that modifying  $h_{ms}$ ,  $Z_0$ , or  $\varphi$  can theoretically change the required input power to reach  $|E_B|$  and thus control the limiting threshold of a plasma-based microwave power limiter.

## III. DEVICES AND EXPERIMENTAL SETUP

In order to experimentally verify the control of the limiting threshold, several plasma-based microwave power limiters have been designed according to the schematic presented in Fig.1a. It consists of an electromagnetically coupled annular ring resonator in microstrip technology combined with a plasma pre-ionization system [9]. The pre-ionization is ensured by a micro hollow cathode discharge (MHCD) that has been optimized to work at a pressure of 10 Torr (i.e., 1333 Pa) in argon that is to say  $h_{MHCD} = d_{MHCD} = 1.5$  mm.

Here, the proposed annular ring resonator is loaded at its input and output. This is obviously different from the case

considered in Section II but if the loading and the coupling modify the electric field magnitude in the ring, it can still be assumed that this electric field has the same dependency on  $h_{ms}$ ,  $Z_0$ , and  $\varphi$  as stated in (2).

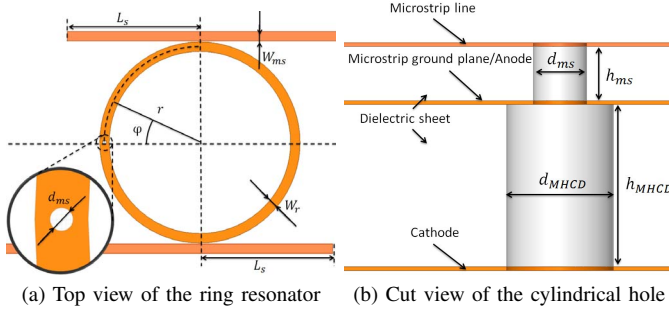


Fig. 1. Integration of a plasma discharge in a microstrip circuit

A dedicated experimental setup has been developed to perform a power budget for different configurations. A microwave unit allows to set up a power ramp and measure the input and output power at the resonant frequency of each resonator. Moreover, the experimental setup includes additional units that control the type of gas, its pressure, and the DC pre-ionization.

#### IV. STATIC CONTROL OF LIMITING THRESHOLD BY CIRCUIT DESIGN

##### A. Circuits design

In order to illustrate the static control of the limiting threshold, three ring resonators have been designed using full-wave simulations. Each ring resonator has been realized on a Rogers RO4003C substrate ( $\epsilon_r = 3.55$ ) and optimized to have a resonant frequency equal to 2.5 GHz. A reference ring resonator (Resonator 1) has been printed on a 0.508 mm thick substrate with a  $50 \Omega$  characteristic impedance for the ring resonator and a hole located at  $\varphi_d = 0^\circ$  (see Fig.1a), where the magnitude of the electric field reaches a maximum at resonance. Then two additional ring resonators with each a different parameter compared to Resonator 1 have been designed. The first one has a  $25 \Omega$  characteristic impedance for the ring (Resonator 2), while the other one has a 1.524 mm substrate thickness (Resonator 3). Table I summarizes the dimensions of each microstrip circuit. Note that in each case the coupled microstrip lines have a  $50 \Omega$  characteristic impedance.

Fig. 2 presents the simulated and measured S-parameters for each resonator. One can distinguish a slight frequency shift between numerical simulations and measurements mainly due to the manufacturing tolerances. These simulations were performed with ANSYS HFSS.

##### B. Experimental results and discussion

Fig. 3 presents the output power versus the input power for each resonator at the resonant frequency with or without pre-ionization. Measurements using a VNA have shown that the additional insertion loss due to pre-ionization remains below

TABLE I  
RING RESONATORS DIMENSIONS

	$h_{ms}$ (mm)	$W_r$ (mm)	$W_{ms}$ (mm)	$\varphi$ ( $^\circ$ )
Resonator 1	0.508	1.15	1.15	0
Resonator 2	0.508	3	1.15	0
Resonator 3	1.524	3.25	3.25	0

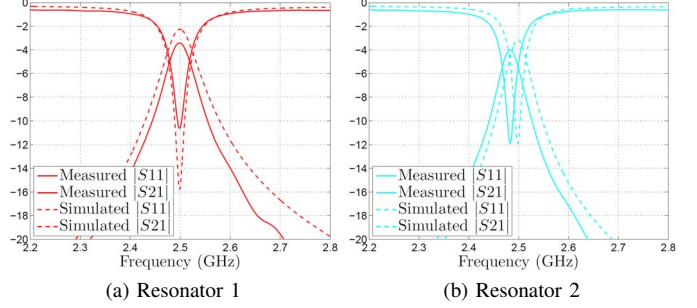


Fig. 2. Simulated and measured S parameters of each resonator

0.1 dB when the pre-ionization current  $I_{DC}$  is under 2 mA. Consequently, a pre-ionization current of 0.5 mA is considered here leading to almost no additional insertion loss.

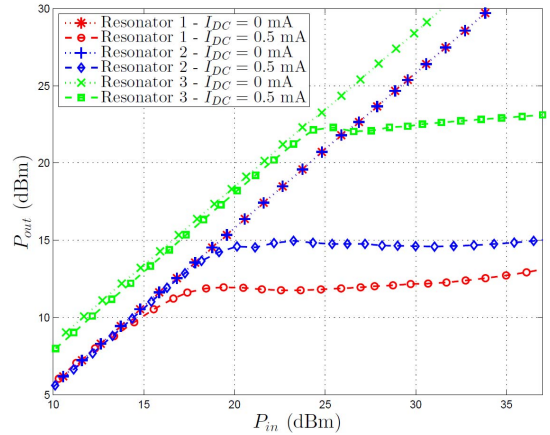


Fig. 3. Measured output power versus input power for the three microstrip ring resonators

As shown in Fig. 3, without pre-ionization, the three resonators remain in a linear regime. This microwave breakdown happens for an input power larger than 40 dBm. With pre-ionization, the limiting threshold values are well lowered, and

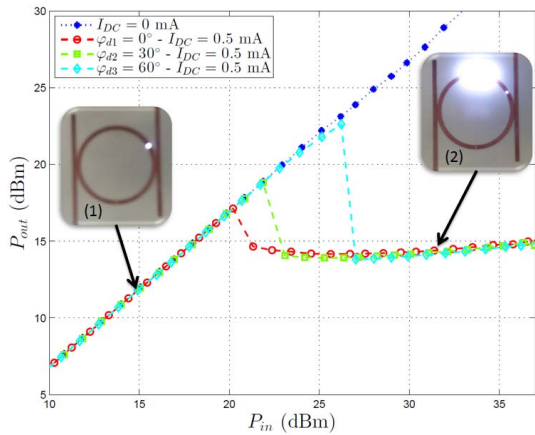


Fig. 4. Measured output power versus input power of the microstrip resonator with different plasma discharge positions.

the typical response of a power limiter is observed with a linear regime at low input power and a saturated behaviour at high input power.

The limiting threshold is defined as the 1 dB compression point. Resonators 1, 2, and 3 have a measured limiting threshold of 16.2 dBm, 19.6 dBm, and 24.8 dBm, respectively. Considering (2), and assuming that the required breakdown electric field is constant in each case, the theoretical differences between the limiting thresholds taking Resonator 1 as a reference are 3 dB for Resonator 2, and 9.5 dB for Resonator 3. The comparison of the relative limiting thresholds with the experimental results shows an accuracy of 1 dB. This difference is mainly attributed to the measurements accuracy and the different assumptions that have been made to establish the theoretical model. However, these results clearly exhibit the capability of having a static control of the limiting threshold for a given power limiter.

## V. DYNAMIC CONTROL OF LIMITING THRESHOLD WITH MULTIPLE PLASMA DISCHARGES

### A. Circuit design

If  $h_{ms}$  and  $Z_0$  are fixed once the circuit has been realized, one can easily use multiple holes in the microstrip circuit in order to dynamically control the position of the discharge  $\varphi_d$ . Such a property paves the way of discrete limiting threshold tunability. Thus, an additional ring resonator including three holes drilled at  $\varphi_{d1} = 0^\circ$ ,  $\varphi_{d2} = 30^\circ$ , and  $\varphi_{d3} = 60^\circ$  has been printed on a 0.508 mm thick Rogers RO4003C substrate. The dimensions of this resonator are similar to those of the Resonator 1 (see Table I). In order to control independently the pre-ionization of each plasma hole, a new MHCD circuit was printed on a 1.524 mm thick Rogers RO4003C including three cathodes at positions  $\varphi_{d1}$ ,  $\varphi_{d2}$ , and  $\varphi_{d3}$ .

### B. Experimental results and discussion

This microstrip ring resonator has been characterized at its resonant frequency by pre-ionizing independently each MHCD. Fig. 4 presents the output power versus the input

power at the resonant frequency with or without pre-ionization. Again, a current of 0.5 mA is considered here. In this case, we can observe that the transition between the linear and the non-linear behaviour is abrupt for the  $\varphi_{d2} = 30^\circ$  and  $\varphi_{d3} = 60^\circ$  positions contrary to the smooth transitions seen in Fig. 3. This can be due to the observed shift of the plasma discharge from the  $\varphi_{d2,3}$  positions (Picture 1) to the  $\varphi_{d1}$  position (Picture 2). It can be explained by the fact that the microwave plasma discharge, once ignited, goes where the microwave electric field is maximum. Regarding the  $\varphi_{d1}$  case, it should not however have this abrupt behaviour. We suppose that there were some issues with the MHCD and microstrip holes alignment within the manufacturing process.

Fig. 4 shows that the limiter turns on when the input power exceeds 20.5 dBm for  $\varphi_{d1}$ , 22.1 dBm for  $\varphi_{d2}$ , and 26.3 dBm for  $\varphi_{d3}$ . Considering (2), and assuming again that the required breakdown electric field is constant in each case, the theoretical differences between the limiting thresholds taking the  $\varphi_{d1}$  case as a reference are 1.2 dB for  $\varphi_{d2}$  and 6 dB for  $\varphi_{d3}$ . The measured thresholds show a difference compliant with the theoretical results and prove that this method can be considered as accurate to enable dynamic control of the limiting threshold by pre-ionizing the appropriate hole.

## VI. CONCLUSION

Static and dynamic control for microstrip power limiters have been theoretically and experimentally investigated. The theoretical method used in this paper exhibits a good accuracy that can be employed to design any microstrip plasma-based power limiter. Besides, an original approach to obtain discrete limiting threshold tunability has been proposed and experimentally validated. Such a low-loss solution may be very promising to tune the level of receiver protection depending on the electromagnetic environment.

## VII. ACKNOWLEDGEMENT

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