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Experimental Comparison of Wideband and Narrowband Plasma-based Microstrip Power Limiters

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Abstract—This article presents the experimental work performed as part of the use of the non linear plasma-wave interactions in planar circuits to design microwave power limiters. A first non-resonant plasma-based microwave power limiter composed of a pre-ionized plasma discharge integrated into a $50\ \Omega$ microstrip line has been experimentally characterized with steady-state and transient measurements. These results have been then confronted at each step to a resonant one using the same plasma discharge. This study highlights the effect of the resonance on the non linear plasma-wave interactions and its consequences on the behaviour and the performances of a plasma-based microwave power limiter.

Index Terms—plasma devices, gas discharge devices, low temperature plasma, microwave breakdown, nonlinear wave propagation.

I. INTRODUCTION

When a high power microwave (HPM) threat impinges on typical receiver systems, they can be strongly deteriorated [1]. Microwave power limiters are commonly involved to protect them from these threats. For low HPM signals, active lumped elements such as PIN diodes or MEMS are used to design limiting functions [2], [3]. However, these integrated components remain, for most of them, fragile when the incident microwave power becomes more important.

Beyond a few tens of watts, the use of plasma discharges has proved its effectiveness in achieving microwave power limitation. In plasma-based microwave power limiters, plasma discharge arises when the induced electric field by the HPM is sufficiently intense to cause gas breakdown. The resulting plasma then interacts with the incident wave which leads to the limitation of the output power. This mechanism has been widely used in T/R (Transmit/Receive) tubes in order to protect RADAR receivers from high power microwave signals [4]. However, T/R tubes can not be easily integrated into compact planar circuits.

Several studies have then focused on the integration of plasma discharges into planar circuits for power limitation [5]. However, the high limiting threshold power was really challenging to design operational systems. Consequently, resonant circuits [6], pre-ionization techniques, or both [7]–[9] were used to lower and/or control this threshold.

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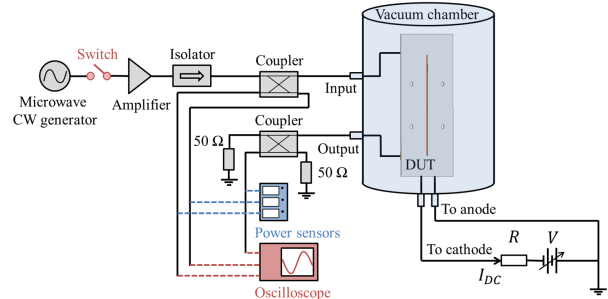


Fig. 1. Experimental setup for steady-state (blue configuration) and transient (red configuration) high-power microwave measurements.

In this paper, we experimentally compare the behaviour and performance between non-resonant and resonant, that is to say wideband and narrowband, plasma-based microstrip power limiters.

II. EXPERIMENTAL SETUP

A dedicated experimental setup has been developed to perform steady-state and transient power measurements as shown in Fig.1. A microwave unit allows to set up a power ramp and measure the input, output, and reflected powers by means of power sensors for the steady-state measurements. Regarding the transient measurements, a microwave switch is first inserted between the microwave generator and the power amplifier. Then, power sensors are replaced by a 4-channels fast oscilloscope. The microwave switch and the oscilloscope are synchronized with a control signal which pulse width and repetition frequency are equal to 1 ms and 100 Hz, respectively. Moreover, the experimental setup includes additional units that control the type of gas, its pressure, and the DC voltage and current for the pre-ionization of the microwave power limiter.

III. CIRCUITS DESIGN

A. Non-resonant microstrip power limiter

Firstly, a non-resonant microwave power limiter has been designed according to the schematic presented in Fig. 2. It consists of a $50\ \Omega$ microstrip transmission line printed on a 1.524 mm thick Rogers RO4003C substrate with $\epsilon_r = 3.55$

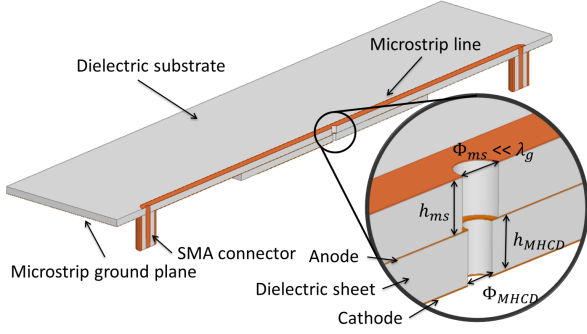


Fig. 2. Cut view of the non-resonant 50 Ω microstrip line combined with a pre-ionization system.

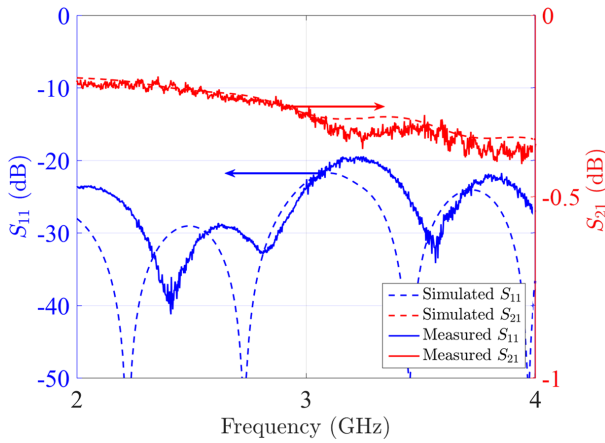


Fig. 3. Simulated and measured small-signal S -parameters of the non-resonant transmission line without pre-ionization.

and $\tan \delta = 0.0021$. This line is drilled in its center with a $\Phi_{ms} = 1.5$ mm diameter hole and connected to 50 Ω coaxial straight connectors at both ends. This microwave circuit is combined with a pre-ionization system using a DC plasma discharge [7]. The pre-ionization of the microstrip hole is done by a micro-hollow cathode discharge (MHCD) located under the ground plane. It has been optimized to work at a pressure of 10 Torr (i.e., 1333 Pa) in argon that is to say $h_{MHCD} = \Phi_{MHCD} = 1.5$ mm. Fig. 3 presents the magnitude of the simulated and measured small-signal S -parameters without pre-ionization as a function of the frequency.

B. Resonant microstrip power limiter

A similar resonant microwave power limiter has been designed. As shown in Fig. 4, it consists of an electromagnetically coupled annular ring resonator in microstrip technology printed on the same substrate. The microstrip width and the hole diameter are the same as previously. Note that the hole has been drilled on the location where the electric field is maximum at the resonant frequency (i.e., $\varphi = 0^\circ$ in Fig. 4). The ring radius r is equal to 11.7 mm while the stub length L_s is 15.75 mm. Fig. 5 presents the magnitude of the simulated and measured small-signal S -parameters without

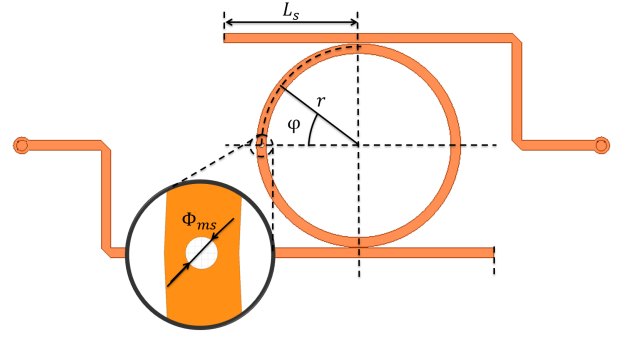


Fig. 4. Front view of the 50 Ω characteristic impedance ring resonator in microstrip technology.

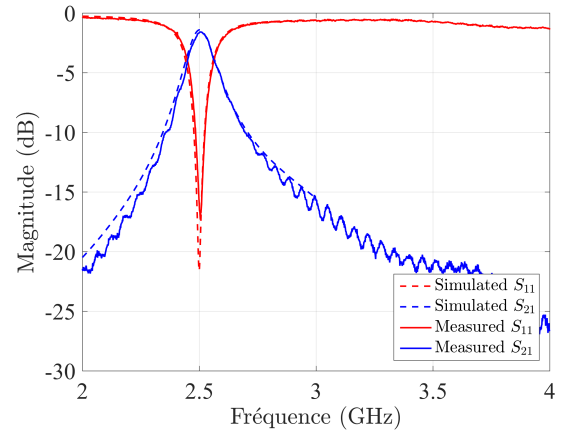


Fig. 5. Simulated and measured small-signal S -parameters of the resonant ring resonator without pre-ionization.

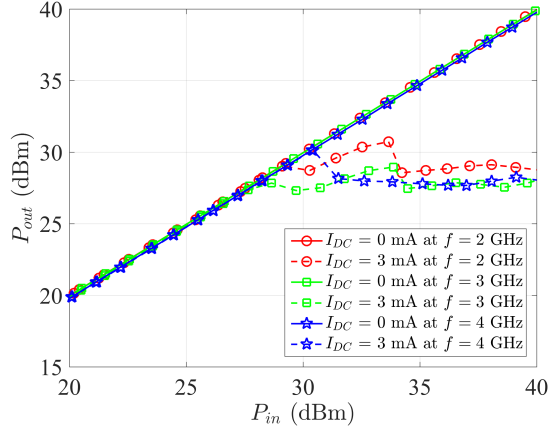
pre-ionization as a function of the frequency. The resonant frequency of the ring resonator is equal to 2.5 GHz.

IV. EXPERIMENTAL RESULTS

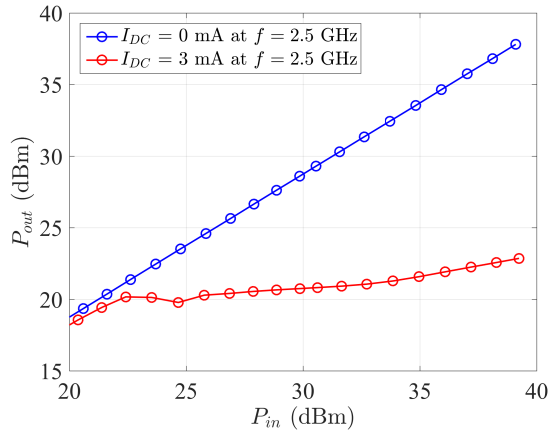
A. Steady-state measurements

Measurements using a VNA have shown that the additional insertion loss due to pre-ionization remains below 0.05 dB for both circuits when the pre-ionization current I_{DC} is under 5 mA. Consequently, a pre-ionization current of 3 mA is considered here. Such limiting devices then exhibit almost no insertion loss.

Fig. 6a presents the measured output power P_{out} as a function of the input power P_{in} at 2, 3, and 4 GHz for the non-resonant circuit. It should be noted that without pre-ionization ($I_{DC} = 0$ mA) no non-linear interaction is observed for the considered power range, that is to say up to 40 dBm. With a pre-ionization ($I_{DC} = 3$ mA), a breakdown occurs and a non-linear behaviour is then observed. The pre-ionization system thus generates an initial electron density in the upper hole of the DUT which drastically decreases the required microwave electric field for gas breakdown [10]. The measured breakdown threshold, defined here as the 1 dB compression point, are equal to 29.9, 28.9, and 30.7 dBm at 2, 3, and 4 GHz, respectively. Almost no dependence with frequency



(a) Microstrip transmission line.



(b) Ring resonator.

Fig. 6. Measured output power P_{out} as a function of the input power P_{in} for (a) the microstrip transmission line and (b) the ring resonator.

is noticed here since for such a reduced frequency range, the breakdown electric field does not vary substantially at 10 Torr in argon [11]. These measurements have been repeated varying the current flowing through the DC plasma discharge from 3 to 40 mA without any noticeable change in the limiting threshold power or dynamic range.

Fig. 6b presents the measured output power P_{out} as a function of the input power P_{in} at 2.5 GHz for the resonant case. As previously, with a DC pre-ionization current of 3 mA, a microwave breakdown occurs in the hole and the output power is then reduced. One can observe that the limiting threshold of 22.8 dBm is lower than the non-resonant case. Due to the microwave resonance of the ring resonator, the electric field is locally increased in the hole which lead to higher electric field for the same input power. Thus, the gas breakdown that happens for a given electric field value can occur for lower input power. Numerical simulations using Ansys HFSS has shown that the steady-state maximum electric field in the hole is 2.1 times larger for the resonant circuit than for the simple transmission line considering the same input power. Thus, the power must be multiplied by 4.2, or 6.2 dB larger, in the non-resonant circuit to obtain the same electric

field as in the resonant circuit. This theoretical result is very close to the observed difference between the measured limiting thresholds.

To understand the interaction between the HPM signal and the plasma discharge, it is also interesting to observe the reflected, output, and dissipated power rates relative to the input power that are denoted R_{refl} , R_{out} , and R_{dis} , respectively. The dissipated power is expressed as $P_{dis} = P_{in} - P_{out} - P_{refl}$.

Fig. 7a presents the measured power rates as a function of the input power at 3 GHz for the microstrip line. It is observed that the decrease of the output power rate R_{out} is mostly due to the dissipation of the input power by the plasma. Considering for instance $P_{in} = 40$ dBm, the measured output power rate R_{out} is then reduced to 6.6 % while the reflected and dissipated power rates reach 18 % and 75.4 %, respectively.

Contrary to the non-resonant power limiter, the output power of the ring resonator is mainly reduced due to reflection as shown in Fig. 7b. One can observe that for P_{in} between 22.8 dBm and 28 dBm the plasma dissipates most of the incoming power, but for P_{in} larger than 28 dBm the reflected power rate increases until reaching 58 % at 40 dBm while the dissipated and output power rates decrease to 39.7 % and 2.3 %, respectively. The plasma, here, acts as a disruptive impedance that tends to mismatch the microstrip device [6].

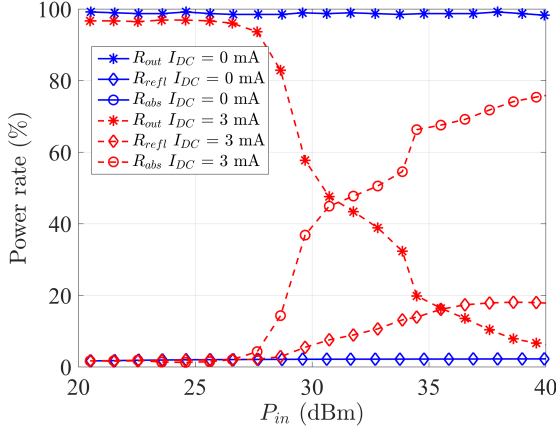
B. Transient measurements

Transient high power measurements of both circuits have also been conducted. Fig. 8a shows the measured envelope of the input, reflected, and output microwave signals considering a modulated pulse of 3 GHz with a power of 36 dBm with $I_{DC} = 3$ mA for the microstrip line. No significant change has been observed on the time response when varying I_{DC} from 3 to 40 mA or the modulation frequency from 2 to 4 GHz. However, the response time of the power limiter clearly depends on the input power of the microwave pulse. The higher the input power, the faster the device responds, thus reacting in 87 μ s at 36 dBm and 8.6 μ s at 45 dBm for example. This response time has been defined as the time needed for the output voltage to reach to within 5 % of its final steady-state value.

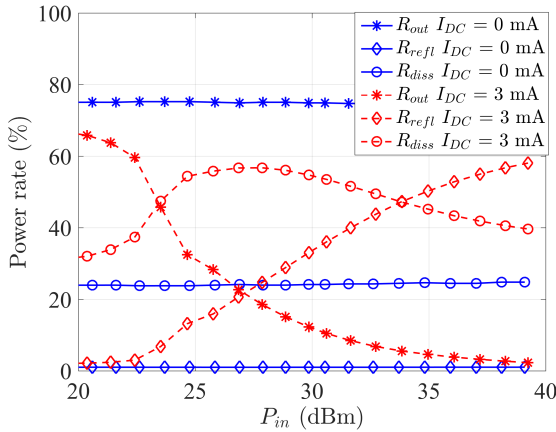
Regarding the transient analysis of the resonant circuit, Fig. 8b shows the measured envelope of the input, reflected, and output microwave signals considering a modulated pulse of 2.5 GHz with a power of 36 dBm and $I_{DC} = 3$ mA. Here, a 1 μ s response time is measured which is 87 times lower than the non-resonant case with the same input power. Actually, the higher electric field due to the resonance leads to lower response time [12].

V. CONCLUSION

In this article, we experimentally compared the behaviour of non-resonant and resonant plasma-based microstrip power limiters. Between 2 and 4 GHz, the non-resonant power limiter dissipates most of the incoming power from around 30 dBm and exhibits response times in the order of tens of



(a) Microstrip transmission line.



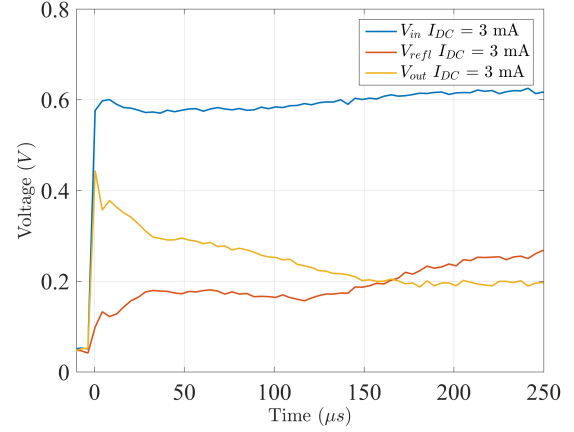
(b) Ring resonator.

Fig. 7. Output R_{out} , reflected R_{refl} and dissipated R_{diss} power rates as a function of the input power P_{in} for (a) the microstrip transmission line at 3 GHz and (b) the ring resonator at 2.5 GHz.

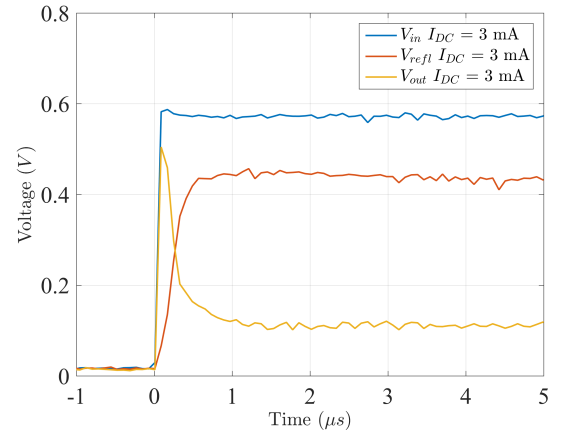
μ s. The comparison with the resonant power limiter clearly highlights the impact of the microwave resonance on the power limitation. Thus, the resonant microwave power limiter has a lower limiting threshold of 22.8 dBm, reflects most of the incoming power, and reacts 87 times faster compared to the non-resonant case with the same input power. Such a study may be promising to understand the non linear plasma-wave interaction and design optimized plasma-based microwave power limiters depending on the electromagnetic environment.

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(a) Microstrip transmission line.



(b) Ring resonator.

Fig. 8. Measured envelope of the input V_{in} , reflected V_{refl} and output V_{out} microwave signal as a function of the time with a $P_{in} = 36$ dBm input power pulse modulated respectively at 3 GHz and 2.5 GHz for (a) the microstrip transmission line and (b) the ring resonator.

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