Low insertion loss microplasma-based limiter integrated into a microstrip bandpass filter

R. Pascaud✉, F. Pizarro, T. Callegari, L. Liard, O. Pigaglio and O. Pascal

The use of microplasma discharges as power-induced limiter elements in microstrip devices is proposed to protect receivers against high-power microwave threats. A microstrip bandpass filter integrating such a microplasma-based active microwave power limiter has been designed and measured. Power limitation is observed when the input power exceeds 19 dBm with a leakage power of 14 dBm. Due to the gaseous properties of the active medium, the proposed structure exhibits a very low additional insertion loss of 0.06 dB.

Introduction: Front-door coupling due to receiving antennas makes microwave (MW) receivers highly vulnerable to high-power microwave (HPM) threats [1]. If out-of-band HPM signals can be countered by the use of filtering, the protection of sensitive components against in-band HPM threats usually involves MW power limiters [2]. However, the use of a MW power limiter generally leads to additional insertion loss in the receiver that increases its noise figure and reduces its dynamic range.

There exist different technologies to make MW power limiters, which include Schottky or diodes [3, 4], III-nitride varactors [5], high-temperature superconductor thin films [6], vanadium-dioxide thin films [7] or plasma discharges [8–10]. Among these solutions, specific implementations have been proposed to provide compact and low-loss protection solutions by directly integrating the power-limiting functionality into usual receiver MW components, namely low-noise amplifiers [3], antennas [9] or filters [6, 10].

In this Letter, we report on a microstrip bandpass filter integrating an original active MW power limiter. Its principle relies on the nonlinear interaction between an incident MW signal and a gaseous microplasma discharge. The proposed microplasma integration almost suppresses the insertion loss of the limiter.

Microplasma integration: Few modifications of a microstrip circuit are needed to integrate the microplasma-based MW power limiter. As shown in Fig. 1*a*, a layered structure made up of a cathode and a dielectric sheet is added under the microstrip ground plane, and a cylindrical hole is drilled over the height of the whole structure with different diameters through the layers. This cylindrical hole is hosting the microplasma discharge. Its position corresponds to a region where the magnitude of the MW electric field is maximum in order to reduce the threshold power of the limiter. The hole diameter $\Phi_{\text{microstrip}}$ in the microstrip circuit section (see Fig. 1*b*) is kept small compared with the wavelength so that its presence does not change the initial behaviour of the microstrip circuit. The dimensions of the hole in the lower part (i.e. h_{MHCD} and Φ_{MHCD} in Fig. 1*b*) are driven by plasma considerations that will be explained in the following Section. Finally, this device requires an environment where the pressure and gas type are optimal. The encapsulation problems, however, are not addressed in this Letter, which focuses on the MW power-limiter performance.

Basic principle: The operation of the suggested MW power limiter requires the prior generation of a microplasma discharge under the microstrip ground plane; that is to say, in the hole with a diameter Φ_{MHCD}. We refer to this step as the pre-ionisation step. This microplasma discharge is obtained by applying a DC voltage between the cathode and the microstrip ground plane that is higher than the breakdown voltage V_b of the gas. The thickness of the dielectric sheet h_{MHCD} and the hole diameter Φ_{MHCD} (see Fig. 1*b*) are chosen according to Paschen's law in order to stabilise the discharge and to keep V_b as low as possible for a given gas pressure [11]. This plasma configuration is also known as a micro-hollow cathode discharge (MHCD) [12]. At relatively low DC, the MHCD remains confined in the hole under the ground plane so that it does not modify the microstrip circuit properties. Note that the actual MW power limiter is of the active type since the pre-ionisation step requires DC power.

We now consider that an MW signal is propagating along the microstrip circuit. At low MW power, the MW electric field generated between the ground plane and the microstrip in the cylindrical hole is not sufficient to interact effectively with the pre-ionisation microplasma discharge. The latter then remains located under the microstrip ground plane and the limiter is still in the 'off' state. In that configuration, the MW power limiter has very low additional insertion loss. However, if the power of the incident MW signal exceeds a turn-on threshold (e.g. in the case of an HPM threat), it pulls upwardly the pre-ionisation microplasma discharge. The complex permittivity of the medium inside the microstrip cylindrical hole then varies, resulting in the detuning of the circuit and the introduction of losses. The limiter is then in the 'on' state. Finally, when the HPM incident signal is over, the upper part of the discharge disappears and the microstrip circuit goes back to its initial 'off' state.

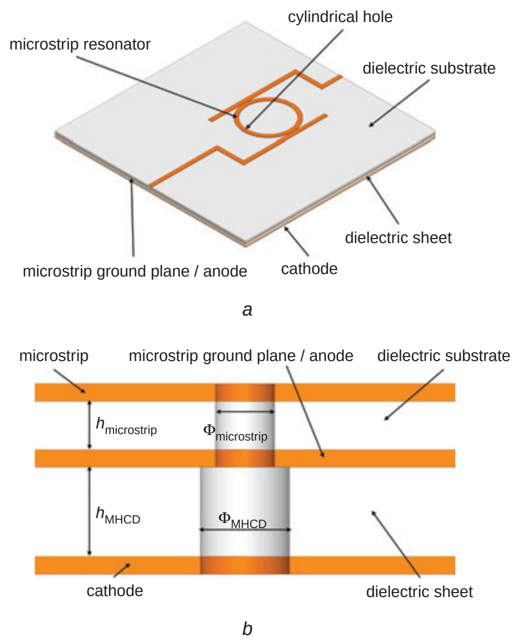

Fig. 1 *Schematic of microstrip circuit integrating active MW power limiter based on microplasma discharge*

a General layout
b Cut view of region hosting the microplasma (i.e. cylindrical holes)

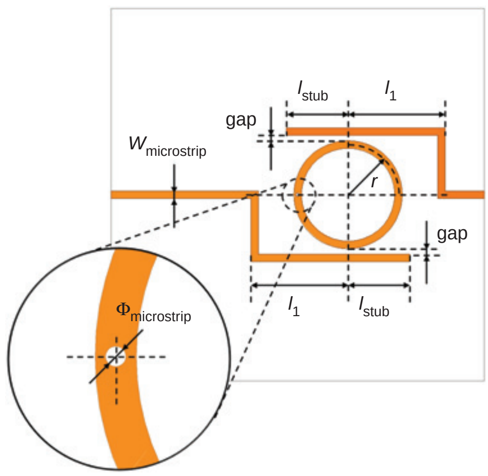

Fig. 2 *Dimensions of microstrip ring filter integrating microplasma-based active microwave power limiter*

Circuit design: A microstrip bandpass filter has been designed to experimentally verify the power-limiting capabilities of the proposed solution. Fig. 2 shows the design of the microstrip circuit that has been printed on a Rogers RO4003 substrate with a dielectric constant $\varepsilon_r = 3.65$ and a thickness $h_{\text{microstrip}} = 0.813$ mm. It consists of two 50 Ω microstrip transmission lines electromagnetically coupled to an annular ring resonator. Its dimensions have been optimised to obtain a resonance at 2.45 GHz, which means: $W_{\text{microstrip}} = 1.8$ mm, gap = 0.2 mm, $l_{\text{stub}} = 15.6$ mm, $r = 11.7$ mm and $l_1 = 27.2$ mm. As shown in

Fig. 2, the hole that is supposed to host the microplasma discharge when the limiter is in the 'on' state is drilled in the microstrip ring resonator and it has a diameter $\Phi_{microstrip}$ equal to 1 mm. Its position is chosen so that it corresponds to a region where the MW electric field is enhanced at the resonant frequency, that is to say an open-circuit plane.

Concerning the added copper cathode and dielectric sheet, they have a thickness of 0.035 and 1.525 mm, respectively. The hole diameter Φ_{MHCD} is equal to 1.5 mm and it is aligned with the hole in the microstrip circuit. Measurements of Paschen's law have shown that these dimensions are optimal for a pressure close to 10 Torr (i.e. 1.33 kPa) for argon. The associated breakdown voltage V_b of the MHCD is then equal to 335 V.

Results and discussion: The simulated and measured *S*-parameters of this microstrip ring filter without pre-ionisation of the microplasma discharge are shown in Fig. 3. The measured resonant frequency of this bandpass filter is equal to 2.462 GHz and its fractional bandwidth is 3%. Its insertion loss is equal to −2 dB at the resonant frequency.

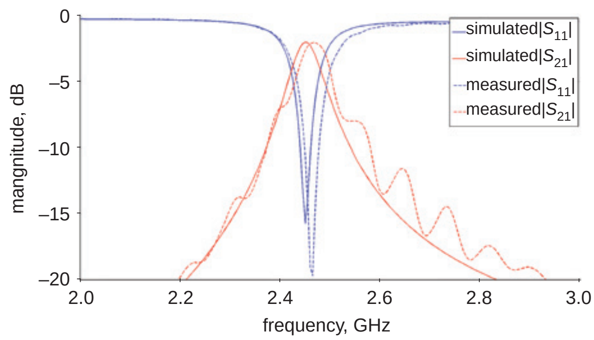

Fig. 3 *Simulated and measured S-parameters for microstrip ring filter without DC pre-ionisation of microplasma discharge*

This microstrip ring filter has been characterised using a dedicated experimental setup that allows MW power measurements while controlling the type of gas, its pressure and the DC power injected into the pre-ionisation microplasma discharge. Fig. 4 presents the measured output and reflected powers (i.e. P_{out} and P_{ref}, respectively) at 2.462 GHz against input power P_{in} for the microstrip ring filter for argon at 10 Torr.

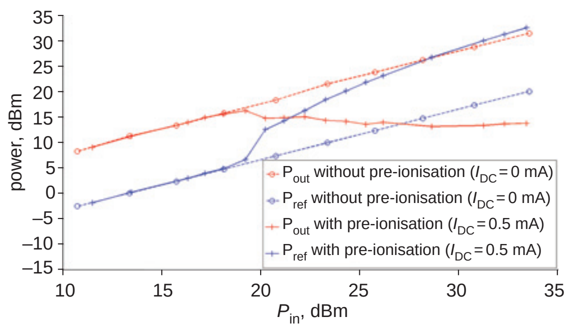

Fig. 4 *Measured output and reflected powers at 2.462 GHz against input power for microstrip ring filter without and with DC pre-ionisation of microplasma discharge for argon at 10 Torr*

Without pre-ionisation (i.e. $I_{DC} = 0$ mA), and in the considered input power range, we note a typical linear dependence between the output and reflected powers and the input power of the microstrip circuit in Fig. 4.

The case with pre-ionisation considers a DC current equal to 0.5 mA. Note that once the pre-ionisation microplasma discharge has been turned on, the voltage between the cathode and the anode must be equal to 260 V to maintain it. It means that the DC power consumption of the pre-ionisation step is equal to 130 mW when $I_{DC} = 0.5$ mA. As shown in Fig. 4, a linear behaviour is also observed for P_{out} and P_{ref} when P_{in} is lower than 19 dBm. The limiter is there in the 'off' state. The additional insertion loss due to the pre-ionisation microplasma discharge is then equal to 0.06 dB. Practically, this additional insertion loss increases for larger DC currents due to the volume expansion of the pre-ionisation microplasma discharge. When P_{in} exceeds 19 dBm, we note however that the microstrip ring filter behaves as an active reflective MW power limiter with 14 dBm leakage power. In that case, the microplasma discharge is pulled upwardly and the limiter is in the 'on' state. The compression and saturation that are observed on P_{out} when P_{in} increases can be explained by the modification of the plasma conductivity according to P_{in}. However, we assume that this limiter region should change to an attenuator region for larger input power. This result cannot be proved with our experimental setup.

Conclusion: The feasibility of self-power-limiting microstrip bandpass filters using microplasma discharges has been experimentally investigated to protect MW receivers against HPM threats. Thanks to the original microplasma topology, such a limiter exhibits a reduced power threshold combined with very low insertion loss.

Work is ongoing to determine the influence of different parameters (e.g. the microstrip filter *Q* factor, the type of gas, its pressure, the pre-ionisation DC current etc.) on the limiters performance.

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