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Experimental Study of Microwave Power Limitation in a Microstrip Transmission Line Using a DC Plasma Discharge for Preionization

Antoine Simon, Romain Pascaud, Thierry Callegari, Laurent Liard, and Olivier Pascal

Abstract—Plasma-based microwave power limitation is experimentally investigated in a microstrip transmission line integrating a direct current (dc) plasma discharge for preionization. Steady state and transient high-power microwave measurements demonstrate that the preionization by the dc plasma discharge helps in reducing limiting power thresholds and time responses to about 30 dBm and tens to few microsecond, respectively. Besides, optical diagnostics also exhibit interesting behaviors of the plasma discharge such as diffusion and parasitic breakdowns. Finally, the effect of plasma confinement is discussed, and it is shown that reducing the volume devoted to plasma expansion leads to a decrease in the dynamic range of the microwave power limitation.

Index Terms—Electromagnetic propagation in plasma media, microwave limiters, nonlinear wave propagation, plasma applications, plasma devices.

I. INTRODUCTION

HIGH-POWER microwave (HPM) can be a serious threat for microwave receiver systems [1], [2]. Consequently, microwave power limiters are usually introduced before the sensitive components to avoid their permanent damage [3]. They should ideally exhibit almost zero loss below a specific threshold power value to avoid degradation of the receiver performance. However, when the input power exceeds that threshold, they should quickly reduce their output power to a safe value.

Microwave power limiters are mostly based on diodes [4]–[6], microelectromechanical systems [7], or other nonlinear devices or materials [8]–[10]. In addition, plasma discharges have been investigated as limiting elements because of their high-power handling capability. In plasma-based microwave power limiters, the incoming HPM signal leads to gas breakdown and plasma formation. This microwave-driven plasma finally reduces the output power of the limiter by absorbing and/or reflecting the incoming power.

Transmit–receive (TR) tubes precisely rely on this nonlinear interaction between HPM and plasma discharges. They are usually involved in microwave duplexer for high-power pulsed radar systems [11]. However, TR tubes remain bulky and heavy solutions limited to waveguide technology.

Lighter and smaller plasma-based microwave power limiters have, therefore, been investigated. For instance, Patel et al. [12] have developed an operational plasma limiter using a suspended microstrip transmission line. Nevertheless, its limiting threshold power was higher than 47 dBm. Since then, lower limiting thresholds have been obtained in compact plasma limiters, mainly using resonant microwave devices with or without preionization [13]–[20]. Thus, plasma-shells have been integrated into microwave bandpass filters [13]. The intense microwave electric field obtained at resonance generates self-activation of plasma-shells and power limitation with a threshold value of 28 dBm. A similar concept has been proposed in [14]–[16] where a direct current (dc) plasma discharge is inserted into resonant microstrip devices for preionization. The measured limiting threshold in S-band was 19 dBm with a leakage power of 14 dBm. Semnani et al. [17], [18] have also developed microwave power limiters that consist of plasma-loaded evanescent-mode (EVA) cavity resonators. The combination of the high quality factor of the EVA cavity resonator and the preionization of the discharge area helps reducing, and even tuning, the limiting threshold level from 41.2 to 25.7 dBm. More recently, similar limiting behavior has also been demonstrated in the X- and V-bands using 2-D photonic crystals (PhCs) [19], [20]. In that case, a vacancy-type defect in the PhC acts as a resonant cavity where the electric field is strongly enhanced. This large electric field leads to gas breakdown at the defect location, thus detuning the PhC and limiting its output power.

This paper presents an experimental study of microwave power limitation in a 50 Ω microstrip transmission line integrating a dc plasma discharge for preionization. The use of a nonresonant microwave circuit leads to a wideband and low-loss device under test (DUT) which differs from the
solutions already proposed in [14]–[16]. Steady state and transient HPM measurements clearly show that the incoming HPM signal is predominantly dissipated by the plasma discharge in the proposed DUT, while it is mostly reflected in resonant topologies [15], [19]. It is also demonstrated that the preionization by the dc plasma discharge helps in reducing limiting power thresholds. Besides, optical analyzes of the DUT during the time of the HPM threat exhibit specific behaviors of the plasma discharge such as diffusion and parasitic breakdowns. Finally, the effect of plasma confinement is discussed. It is clearly shown that reducing the volume devoted to plasma expansion leads to a decrease in the dynamic range of the microwave power limitation.

The proposed DUT and its dedicated experimental setup are first described in Section II. Then, its small-signal behavior, continuous wave (CW) limiting characteristics, and transient analysis are exposed in Section III. Finally, the effects of the volume confinement of the plasma discharge are discussed in Section IV followed by conclusions in Section V.

II. DEVICE AND EXPERIMENTAL SETUP

A. Basic Principle

The proposed device to study plasma-based microwave power limitation in a microstrip circuit is described in Fig. 1. It is a multilayer structure surrounded by gas and made up of a microstrip transmission line and a dc circuit. Its basic principle has already been exposed in [14] and [15]. It is here briefly recalled.

Plasma-based microwave power limitation operates using the nonlinear interaction between an incoming HPM signal and the surrounding gas. In practice, microwave signals are propagating along the microstrip transmission line that has a small hole in its center as illustrated in Fig. 1(b). When the incoming HPM signal is large enough, the induced electric field ignites gas breakdown and plasma formation in this hole. The shunting action of the microwave-driven plasma finally leads to a reduction of the output power by absorbing and/or reflecting the incoming microwave threat.

In order to reduce the microwave breakdown threshold, preionization is implemented by generating an initial electron density inside the hole of the microstrip transmission line [14]. As shown in Fig. 1(a), a cathode, a dielectric sheet, and an anode are thus added under the microstrip circuit. This dc circuit is similar to a microhollow cathode discharge (MHCD) with its opening hole in the center [21]. Note that in Fig. 1(b), the holes in the dc and microwave circuits are perfectly aligned. Once ignited, the MHCD then acts as a source of free electrons that preionizes the upper part of the hole as in microcathode sustained discharges [22]. It is important to notice that this dc plasma discharge is created below the microstrip circuit. The preionization is, therefore, due to the diffusion of free electrons in the hole of the microstrip transmission line.

B. Device Under Test

In this paper, the DUT is based on a 50 Ω microstrip transmission line. A similar circuit has been briefly studied in [14] without an in-depth analysis. Indeed, our previous works have mainly considered resonant microwave circuits with narrowband responses such as microstrip annular ring resonators [14]–[16]. The whole microwave circuit is $W_{\text{ms}} = 100$ mm wide and $L_{\text{ms}} = 200$ mm long. The microstrip transmission line has been printed on a $h_{\text{ms}} = 1.524$ mm thick Rogers RO4003C substrate with $\varepsilon_r = 3.55$ and $\tan \delta = 0.0021$, and connected to 50 Ω coaxial straight connectors at both ends. Its length $L_{\text{line}}$ is equal to 140 mm, whereas its width $W_{\text{line}}$ is 3.316 mm to obtain a 50 Ω characteristic impedance. The diameter of the hole in the microstrip circuit results from a tradeoff between the transmission line characteristics and the ability to ignite microwave breakdown for power limitation. Thus, it must be small compared to the wavelength so that its presence does not change the initial behavior of the microstrip circuit, but large enough to allow breakdown in our gas conditions (10 Torr in argon). Finally, this cylindrical hole has a $\Phi_{\text{ms}} = 1.5$ mm diameter, i.e., to say $\lambda_0/50$ at 4 GHz.

The dimensions of the dc circuit are $W_{\text{dc}} = L_{\text{dc}} = 100$ mm while the circular cathode has a diameter of $\Phi_{\text{cathode}} = 80$ mm. Note that the cathode is reduced in size to avoid parasitic breakdowns at its ends during the MHCD ignition. The dimensions of the MHCD hole are chosen to obtain a low breakdown voltage and a stable plasma discharge at 10 Torr.
in argon, i.e., to say \( h_{\text{MHCD}} = \Phi_{\text{MHCD}} = 1.5 \text{ mm} \). For the considered dc currents \( I_{\text{dc}} \) flowing through the MHCD, namely, from 3 to 40 mA, the MHCD is in a normal glow regime until 10 mA and then turns to an abnormal glow regime for higher currents [23]. In the normal glow regime, the gas voltage is constant whatever the dc current, and in our case, it is equal to 224 V. Therefore, the power consumption for preionization is, for example, equal to 762 mW when \( I_{\text{dc}} = 3 \text{ mA} \), 672 mW consumed by the dc plasma discharge and 90 mW by the 10 k\( \Omega \) series resistance used to limit the dc current.

C. Experimental Setup

As shown in Fig. 2, the DUT is placed in a quartz vacuum chamber that is pumped to \( 10^{-5} \text{ Torr} \) and then backfilled at 10 Torr with an argon flow at around 0.1 L/min. Thus, the circuit is totally immersed in a large volume of argon. The problem of encapsulation of the circuit is partly discussed in Section IV.

The dc plasma discharge for preionization is ignited and sustained by a Technix SR2KV-2KW high-voltage generator connected to the MHCD electrodes through a dc vacuum feedthrough. A series resistor \( R = 10 \text{ k}\Omega \) is also used to limit the current \( I_{\text{dc}} \) flowing through the discharge.

The HPM measurement setup is detailed in Fig. 2. It concerns both steady state and transient analyzes. The different components and instruments are connected to the DUT using 50 \( \Omega \) coaxial vacuum feedthroughs.

The steady-state measurement setup uses the components in Fig. 2 (blue). A CW generated by an Anapico APSIN20G microwave signal generator is fed into a MC2 Technologies HPA60W2-4G (2–4 GHz, 60 W) power amplifier (PA). The output HPM signal is then delivered to the DUT through an isolator (Quest Microwave NM2040C02) that protects the large volume of argon. A return loss larger than 20 dB and an insertion loss lower than 0.5 dB are noticed for the bandwidth of the experimental setup, namely, 2–4 GHz.

III. EXPERIMENTAL RESULTS

A. Small-Signal S-Parameters

Prior to gas breakdown, the DUT behaves as a microstrip transmission line. The whole structure has been simulated using ANSYS HFSS software and measured with a VNA considering a low-power test signal of \( -10 \text{ dBm} \). As a result, all power measurements reported thereafter have been corrected so that they refer to DUT ports. Note that the frequency range is limited to 2–4 GHz due to the PA, isolator, and couplers characteristics, and the maximum power is 45 dBm because of coaxial feedthroughs power handling.

Regarding the transient analysis, slight modifications are made to the experimental setup [Fig. 2 (red components)]. A microwave switch (American Microwave Corporation SWM-DJV-1DT-2ATT) is first inserted between the microwave signal generator and the PA. The resulting test signal thus consists of a high-power modulated pulse. In order to analyze the input, reflected, and output signals in the time domain, the initial power sensors are replaced by a 4-channels Keysight MSO9254A oscilloscope with its inputs set to 50 \( \Omega \). Its 4-GHz bandwidth allows direct sampling of the studied signals. The experimental setup is completed by a PI-MAX-512 high-speed camera with an RB red-blue optimized GEN II intensifier placed right in front of the microstrip transmission line. The microwave switch, the oscilloscope, and the camera are synchronized with a control signal whose pulsewidth and repetition frequency are equal to 1 ms and 100 Hz, respectively. Contrary to power measurements, the measured voltages have not been corrected to take the power loss into account.
noted that without preionization \((I_{dc} = 0 \text{ mA})\) no power limitation is observed in this power range. The induced microwave electric field is not large enough to cause gas breakdown in that case. With a dc current \(I_{dc} = 3 \text{ mA}\), however, microwave power limitation is observed with a linear response at low input power and a saturation region once the limiting threshold power is exceeded. The preionization 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 [24]. The measured limiting threshold power, defined here as the 1 dB compression point, is equal to 29.9, 28.9, and 30.7 dBm at 2, 3, and 4 GHz, respectively. Almost no dependence with frequency is noticed here since for such a reduced frequency range, the breakdown electric field does not vary substantially at 10 Torr [25]. It is worth mentioning that these threshold values may change with the microstrip transmission line properties, such as substrate height \(h_{\text{ms}}\) and characteristic impedance \(Z_0\) [16]. Regarding the dynamic range, Fig. 5 shows that the output saturation is almost constant for an input power as large as 45 dBm.

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. It can be explained by the effect of preionization on microwave breakdown. As described in [24], when the initial electron density due to preionization exceeds about \(10^8 \text{ cm}^{-3}\) in neon, the electric field required for microwave breakdown greatly reduces and remains almost constant. In a MHCD configuration similar to ours (hole diameter of 300 \(\mu\text{m}\) and pressure of 37.5 Torr), Penache et al. [26] measured a peak electron density around \(10^{15} \text{ cm}^{-3}\) at 0.5 mA in argon, and Belostotskiy et al. [27] showed that the value at the exit of the anode is similar to the sheath edge. Using similarity laws, as a rough approximation, we can reasonably assume that in our case the initial electron density produced by the MHCD when \(I_{dc} = 3 \text{ mA}\) is higher than \(10^8 \text{ cm}^{-3}\). Therefore, increasing the dc current from 3 to 40 mA does not significantly change the limiting threshold power. One may expect to see modifications of this threshold for lower initial electron density, i.e., to say when \(I_{dc} < 3 \text{ mA}\). However, we were not able to perform accurate measurements at lower dc currents due to stability issues of the MHCD.

To understand the interaction between the microwave signal and the plasma discharge, it is also interesting to look at the reflected, output, and dissipated power rates relative to the input power that are denoted \(R_{\text{refl}}\), \(R_{\text{out}}\), and \(R_{\text{dis}}\), respectively. The dissipated power is expressed as \(P_{\text{dis}} = P_{\text{in}} - P_{\text{out}} - P_{\text{refl}}\). According to this definition, the dissipated power includes both the absorbed power by the plasma discharge and the possibly radiated power. However, measurements made with an exposure level meter have not revealed a change in the radiated electric field with or without the microwave-driven plasma discharge. Therefore, the dissipated power can reasonably be considered as mainly absorbed by the plasma discharge. Fig. 6 presents the measured power rates as a function of the input power at 4 GHz. It is observed that the decrease of the output power rate \(R_{\text{out}}\) in the limitation regime is mostly due to the dissipation of the input power by the plasma.

### B. Limiting Characteristics

The steady-state high-power measurement setup of Fig. 2 has been used to evaluate the device limiting characteristics. The microwave power at the input of the DUT has been swept from 15 to 45 dBm at different frequencies with and without preionization. These measurements, repeated 10 times, lead to the following average results with a standard deviation of \(\pm 0.5 \text{ dB}\) on the output power values.

Fig. 5 presents the measured output power \(P_{\text{out}}\) as a function of the input power \(P_{\text{in}}\) at 2, 3, and 4 GHz. First, it should be

![Fig. 4. Measured additional insertion loss due to preionization as a function of the current \(I_{dc}\) for three frequencies.](image)

![Fig. 5. Measured output power \(P_{\text{out}}\) as a function of input power \(P_{\text{in}}\) at 2, 3, and 4 GHz.](image)

Small-signal transmission coefficients, or \(S_{21}\) parameters, have also been measured when the dc plasma discharge is on. Fig. 4 shows the measured additional insertion loss due to the DUT preionization as a function of \(I_{dc}\) at 2, 3, and 4 GHz. It is observed that the losses in the microstrip transmission line increases with \(I_{dc}\) whatever the frequency. Although the MHCD is located under the microwave circuit, it still diffuses into the microstrip hole and slightly disturbs the microwave transmission. However, these losses still remain below 0.25 dB even for a large dc current of 40 mA.
Considering for instance $P_{\text{in}} = 44$ dBm, the measured output power rate $R_{\text{out}}$ is then reduced to 3% while the reflected and dissipated power rates reach 13% and 84%, respectively. Such microwave power limitation is, therefore, of the absorptive type. It differs from the behavior of plasma-based microwave power limiters exploiting resonant circuits [13]–[20]. In resonant topologies, the plasma discharge acts as a disruptive impedance that detunes the resonator resulting in a large reflected power [28]. Such solutions are known as reflective microwave power limiters.

As shown in Fig. 7, the observation of the microstrip circuit during the steady-state measurements also gives some additional information. Referring to the results exposed in Fig. 6 with $I_{\text{dc}} = 3$ mA, no plasma discharge is observed for very low input power except the MHCD [Fig. 7(a)]. When $P_{\text{in}}$ exceeds 30 dBm, however, a microwave plasma discharge is ignited as expected in the hole of the microstrip circuit [Fig 7(b)]. The increase in input power up to 36 dBm then results in the volume expansion of the discharge. When the input power reaches 37 dBm, the optical emission of the plasma discharge in the hole is reduced and an additional microwave plasma discharge appears above the input connector of the microstrip transmission line [Fig. 7(c)]. These different plasma regimes can also be seen in Fig. 6 where reflected and dissipated power rates undergo sudden variations at $P_{\text{in}} = 37$ dBm.

C. Response Time

The response time of the device has been studied using the transient experimental setup described in Fig. 2. All measurements have been conducted using a high-power modulated pulse at 3 GHz with and without DUT preionization. Again, no significant change has been observed when varying $I_{\text{dc}}$ from 3 to 40 mA, and therefore, a 3-mA dc current has been considered. All optical measurements, in this section, have been performed using a 200-ms exposure time and 20-ns gate time, and the results have been plotted with a 0.8% contrast.

Fig. 8(a) shows the measured envelope of the input, reflected, and output microwave signals considering a modulated pulse with a moderate power of 32 dBm. It can be noted that the reflected voltage increases with time while the
output voltage decreases when preionization is considered. After around 105 μs the output voltage has reached to within 5% of its final steady-state value. It corresponds to a time after which the output power is below 29.5 dBm, i.e., to say an uncorrected output voltage $V_{\text{out}} = 0.29$ V. Such measurements have been repeated and no modification of the time response have been observed. In fact, the time to breakdown depends on two components, namely, the statistical delay, which is the time spent waiting for initial free electrons to appear in the gas, and the avalanche formation time [29]. The statistical delay may be long depending on the initial electron density and gas pressure [30]. But the use of a seed electron source, like the preionization circuit in our case, can totally eliminate it so that the response of the DUT is only governed by the avalanche formation time. In a sense, the MHCD in Fig. 1 is similar to keep-alive dc electrodes in TR tubes [31].

As illustrated in Fig. 8(b), the voltage measurements have been completed with optical snapshots at 0, 25, 50, and 800 μs of the top view of the microstrip transmission line. The white trace represents the input branch and the hole of the microstrip circuit. For a moderate input power of 32 dBm, it is clearly seen that the plasma discharge is ignited and sustained in the hole of the microstrip transmission line as observed in Fig. 7(b) in steady state.

These transient measurements have been repeated for a pulse power of 36 dBm. As shown in Fig. 9(a), the output voltage gradually decreases as before. However, ripples now appear on the reflected voltage. It can be explained by looking at the optical snapshots presented in Fig. 9(b). If the plasma still ignites in the hole, it quickly leaves to diffuse along the microstrip transmission line toward the input coaxial straight connector, i.e., to say the microwave power source. From the circuit point of view, the plasma can be viewed as a mismatched load moving along the transmission line. As a result the time period of the ripples on the reflected voltage in Fig. 9(a) is directly linked to the plasma diffusion rate. The particular behavior of the plasma discharge, and thus the voltage curves, makes it difficult to evaluate correctly the response time contrary to the previous case. As a consequence, it has been defined as the time required for the output voltage to remain below 0.29 V. In that case, it is equal to 87 μs.

Finally, Fig. 10 presents the transient measurements for a pulse power of 45 dBm. Optical snapshots at 0, 0.5, 1.1, 4, and 20 μs show that the plasma discharge first ignites and expands in the microstrip hole as previously, but another microwave gas breakdown appears rapidly on the input port without any diffusion mechanism. This particular behavior could be explained by either the formation of a large stationary wave due to the presence of the plasma in the hole and the high input power, or the discontinuity due to the coaxial to microstrip transition, both resulting in a local enhancement of the microwave electric field. However, as observed...
in Figs. 8(b), 9(b), and 10(b), the initial microwave breakdown always happens in the microstrip hole. As a result, we can reasonably assume that the limiting threshold power does not depend on the connector assembly. Regarding the response time, the same definition as previously has been used, and it leads to a value of 8.6 μs. One can observe that this time generally decreases with the increase of the input power $P_{\text{in}}$. It is interesting to mention that it could also be reduced by using different gas mixtures and pressure [32].

D. Recovery Time

In addition to the response time, the recovery time is also an important feature regarding microwave power limitation. It defines the time required by the device to come back to its low-loss mode once the HPM threat is over. Its measurement involves a low-power CW test signal that is added to the HPM signal thanks to a power combiner. The recovery time has been defined as the time required by the low-power CW test signal to recover 90% of its final value. During the measurements, the low-power signal has been selected with a frequency of 2.45 GHz and a CW power of 15 dBm. Concerning the HPM signal, its frequency has been set to 3 GHz and its power has been varied from 32 to 45 dBm.

The measured recovery time is equal to 36.9, 65.7, and 252.6 μs for a HPM signal power of 32, 36, and 45 dBm, respectively. Note that, contrary to the response time, the recovery time increases with the input power. The increase of the recovery time with the HPM power is associated with an increase of the electron density, both in size and peak value. At 10 Torr, the plasma extinction is mainly due to ambipolar diffusion that does not depend on the electron density. Thus, the higher the initial electron density is once the HPM signal is OFF, the longer it takes for this electron density to decrease under a threshold value at which the afterglow discharge acts as vacuum for the low-power CW test signal.

IV. DISCUSSION ON THE EFFECT OF PLASMA CONFINEMENT

The time-domain analysis of the DUT has shown that the interaction between the HPM and the plasma discharge mostly rely on the volume expansion of the plasma discharge on top of the microstrip circuit. However, a realistic implementation of such a microstrip power limiter would require the encapsulation of the whole device. The device described in Fig. 1 has thus been modified to study the effect of the plasma confinement on its behavior.

Thus, an additional thick dielectric layer, also called superstrate, has been added on top of the microstrip transmission line. As shown in Fig. 11, a cylindrical hole has been drilled in the center of the superstrate with a $\Phi_{\text{sup}}$ diameter. This hole is supposed to be representative of the packaging by limiting the available volume for the plasma discharge in the upper part of the microstrip circuit. No cover has been used to allow optical diagnostic of the microwave-driven plasma. However, the large thickness of the superstrate strongly reduces the microwave electric field above its upper face, and thus prevents from diffusion and gas breakdown elsewhere than in the hole.

![Fig. 11. Cut view of the DUT with a superstrate to study plasma confinement.](image)

Fig. 11. Cut view of the DUT with a superstrate to study plasma confinement.

Practically, several superstrates have been considered with a $h_{\text{sup}} = 3.048$ mm thick Rogers RO4003C substrate ($\varepsilon_r = 3.55$ and $\tan(\delta) = 0.0021$) and different values for $\Phi_{\text{sup}}$. If the addition of these superstrates slightly changes the S-parameters of the microstrip transmission line, the return loss remains higher than 15 dB and the insertion loss lower than 0.6 dB from 2 to 4 GHz in the worst case, i.e., to say $\Phi_{\text{sup}} = 0$ mm.

The steady-state high-power measurement setup of Fig. 2 has been used to assess the resulting limiting characteristics. Fig. 12 presents the measured output power $P_{\text{out}}$ as a function of input power $P_{\text{in}}$ at 3 GHz with $I_{\text{dc}} = 3$ mA and different diameters $\Phi_{\text{sup}}$ for the hole in the superstrate.

![Fig. 12. Measured output power $P_{\text{out}}$ as a function of input power $P_{\text{in}}$ at 3 GHz with $I_{\text{dc}} = 3$ mA and different diameters $\Phi_{\text{sup}}$ for the hole in the superstrate.](image)

Fig. 12. Measured output power $P_{\text{out}}$ as a function of input power $P_{\text{in}}$ at 3 GHz with $I_{\text{dc}} = 3$ mA and different diameters $\Phi_{\text{sup}}$ for the hole in the superstrate.
Finally, the effects of the plasma encapsulation have also been experimentally investigated. It has been shown that reducing the volume devoted to plasma expansion leads to a decrease of the limiter dynamic range.

These experimental results show that microwave power limitation with low limiting power threshold and high-power handling capability is possible in nonresonant microstrip circuits. However, the long response time of the microwave-driven plasma discharge can lead to the leakage of the incident HPM. As a result, an interesting approach would be to design wideband microwave power limiters in microstrip technology by cascading semiconductor diodes to respond quickly to low power pulses and plasma discharges to reach high-power handling capability.

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