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The striplastron: a new circular stripline microwave launcher for plasma generation in capillary tubes

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Abstract

Up to now, microwave plasmas could be ignited in small capillary tubes (inner diameter less than 1 mm) by generating surface waves propagating along their dielectric surfaces, using mainly surfatron launchers, or stripline based launchers such as "split ring resonators". This work presents a novel launcher, which is called "striplastron", because it is half way between surfatrons and stripline launchers. It is a circular stripline directly excited by a microcoaxial cable. Compared to the surfatron, it is smaller and the part of the plasma hidden by the launcher is limited to its thickness ($\sim 1-2$ cm). Moreover its frequency response presents an intense and large resonance. Eventually its geometry could allow the simultaneous ignition of several microplasmas in capillaries arranged in parallel, which could be very interesting for applications, such as the use of multi-tubes microplasmas as metamaterials.

Keywords: microplasma, microwave, launcher, striplastron, capillary tube, surface wave

1. Introduction

For about two decades, there has been a growing interest in plasma physics within very small gas discharges, commonly called microplasmas. A microplasma is a small plasma, with at least one dimension less than a millimeter or, depending on the reference, ranging from tens to thousands of micrometers.

One characteristic that is common to almost all microplasmas and glow discharges is that the electrons are not in equilibrium with the heavy particles (ions and atoms). This means that while the electrons are sufficiently energetic to sustain ionization processes ($T_e > 1$ eV), the gas temperature is less than 0.2 eV (< 2000 K). The non-equilibrium nature of the microplasma sets it apart from arcs for which electrons and neutral gas temperatures are nearly equilibrated.

There are several excellent reviews of microplasmas that address the new physics presented by small gas discharges that primarily focus on direct current (dc), alternating current (ac), and pulsed input energy sources [1–6].

Our work is focused on sources able to generate a surface wave microwave microplasma in small dielectric tubes, i.e. capillaries or even hollow core fibers [7]. The advantages of microwave are the absence of electrodes (and thus absence of possible metallic pollution of the plasma), the large spectrum of operating conditions (pressure range, gas flow, microwave power...), and being able to operate continuously [8]. With capillary diameters down to 100 μm , large power density plasmas (up to 0.1 MW cm⁻³) can be generated by these microwave surface wave plasmas in gases that ranges from mbar to atmospheric pressures [9]. Thus, these plasmas can produce high quantities of charged species (ions, electrons), photons and active species, which gives them a high potential of applications in fields such as nano-material synthesis, micro-propulsion, photonics, plasma-assisted combustion, chemical analysis and conversion, environmental, agriculture, and biomedical applications. As an example, 10¹⁵ cm⁻³ electron densities can be obtained in pure argon in capillary tubes with inner diameter of a few hundred of μm [9].

Due to the wave nature of the input signal, microwave energy is commonly guided in coaxial cables, waveguides, or microstrip transmission lines. The latter, which is a sandwich made of a narrow metallic strip separated from a large ground metallic plane by a dielectric substrate, will be illustrated in figure 1.

Conception of a plasma launcher requires defining its geometry, generally by using electromagnetic simulation, so that the microwave generator power emission spectrum overlaps the system resonance (reflection coefficient as a function of frequency). Experimentally, the former can be measured by a spectrum analyser whereas the latter can be obtained using a network analyser. It can be noted that the more the system resonance is large, the easier it is to overlap the microwave power generator emission spectrum, and the higher is its amplitude, the less power it will require to ignite a plasma. Moreover, after the plasma is ignited, a system can be considered good if the ratio between reflected and incident powers is less than 10%. In this case, the addition of an impedance matching system is not required, even if it enables to minimize the reflected power.

Plasmas have been generated in dielectric tubes classically since the 1970s using surfatrons, which were jointly developed by P. Leprince and M. Moisan [10,11]. The surfatron is a re-entrant cavity, with two concentric metallic cylinders, the inner one being a little shorter than outer one, creating a zone of strong localized electric field called the "gap". This excitation device allows the propagation of a surface wave azimuthally ($m=0$ mode) along the tube, accompanied by the generation of a plasma inside the tube as soon as the latter is filled with flowing gas. Surfatrons are currently marketed for example by the company SAIREM [12]. It should be noted that they are optimized for the passage of tubes with external diameters of 5, 6 or 8 mm. Igniting a plasma in capillaries of small external diameter is possible with these surfatrons, but they generate large microwave leakage, since the external diameter of a capillary tube is small compared to the diameter of the orifice that allows the capillary to pass through the surfatron. Note that the use of a capillary with a small internal diameter (< 1 mm) and a large external diameter (> 5 mm) does not allow plasma ignition because the dielectric wall of the tube (> 2 mm thick) attenuates too much the waves that escape through the gap. It has been possible to modify the dimensions of the commercial surfatrons using 3D electromagnetic simulations and to build "home-made" surfatrons that are optimized to generate plasmas in capillaries of small external diameter (< 1.5 mm) [9,13].

Another type of launcher, the "split ring resonator" was proposed in the literature and optimized for microplasma generation [14]. It is composed of a linear microstrip ending in an opened circular microstrip. To avoid zero impedance, the opened part (gap) has to be a slot located so that its position on the ring is at $180^\circ \pm x^\circ$ from the linear microstrip ending location [15]. x cannot be 0° and is typically around 10° .

Several patents are dedicated to the generation of plasmas using a split-ring resonator. A first patent [16] describes the use of a microstrip type resonator at microwave frequencies for the production of "non-thermal" plasmas in a "gap" located in the same plane as the resonator. In this case, the plasma is directly ignited in the gap located within the gap. Another patent [17] describes the generation of a plasma with a split ring resonator and an element configured to circulate a gas through the gap of the split ring resonator. This evolution has been exploited to generate surface wave argon microplasmas inside the $127 \mu\text{m}$ diameter core of a Kagome hollow-core photonic crystal fiber [18].

This paper focuses on the development of a novel microwave-driven microplasma launcher, here called striplastron, dedicated to plasma generation in small dielectric tubes (capillaries or hollow core fibers). The goal is to get rid of the drawbacks of existing launchers, i.e.: the large volume of the surfatron, leading to a large part of the plasma which is optically hidden, which prevents performing optical diagnostics along a large part of the plasma column, the electromagnetic radiation losses of the split ring resonator, which reduces the power coupling to the plasma, and the thin resonance peak of both launchers, which requires a lot of optimization to obtain the best matching with the generator emission profile.

2. Development of a circular microstrip based excitator

The first step leading to the birth of the striplastron has been the development of a circular microstrip with "direct" excitation. A microstrip transmission line has a set of two conductors: a microstrip, separated from a wide ground plane by a dielectric substrate, as seen on figure 1. Its operating resonance frequency varies according to the permittivity ϵ of the dielectric and its dimensions: the width W and the height T of the microstrip, and the height H of the dielectric. Evolution of the linear microstrip towards a circular microstrip is

presented on figure 2 (a) 3D view, and b) 2D view). Note that the microstrip becomes a ring, introducing a new parameter, which is r_c , the "central" radius of the ring. Thus the ring extends radially from $r_c - W/2$ to $r_c + W/2$.

To obtain the desired resonance frequency f , classically 2.45 GHz for microwave excitation, the central radius of the ring r_c should fulfill $2\pi r_c = \lambda = c / (f \times \epsilon^{1/2})$, where c is the speed of light and ϵ is the permittivity of the dielectric material. Other dimensions can be adapted using electromagnetic simulation in order to obtain the desired resonance frequency. The dimensions chosen for the results presented throughout this article are the following: $W=10$ mm, $H=3.6$ mm, $T=5$ mm, and $r_c=16$ mm. Moreover the chosen dielectric material for the launcher is Teflon, which has a permittivity $\epsilon=2.1$, and the capillary, which has an internal diameter of $690 \mu\text{m}$ and an external diameter of $1375 \mu\text{m}$, is made of fused silica, having a permittivity equal to 3.8.

The "direct" excitation is performed via a microcoaxial cable which crosses the ground metallic plane and whose inner metallic conductor comes in contact with the ring. Dimensions of the microcoaxial are the following: inner conductor radius equal to 0.51 mm, dielectric external radius equal to 1.7 mm, and outer conductor radius equal to 2.2 mm.

An advantage of this launcher is that the capillary can pass through a slot as through a hole and that the position and the size of this passage do not change the launcher response.

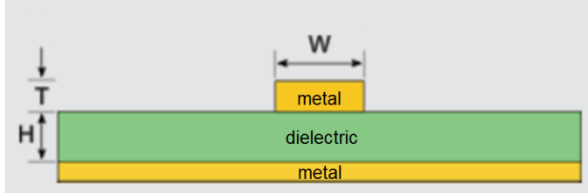


Figure 1: vertical cross-section of a linear microstrip

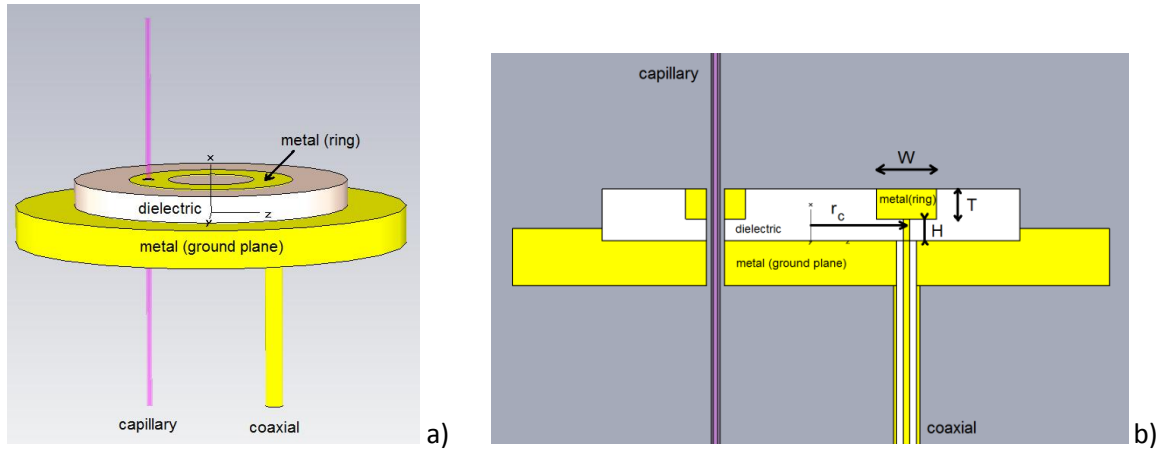


Figure 2: a) 3D view of the evolution of a linear microstrip towards a circular microstrip, b) 2D vertical cross section of the circular microstrip

This can be demonstrated both with experiments and calculations. A network analyser was used to measure the responses (reflection coefficient as a function of frequency) of a launcher without a slit, and of launchers having slits with widths going from 200 up to $1500 \mu\text{m}$. All the resonances are very similar: same width, same frequency for the resonance maximum intensity, and a decrease of 15% in maximum intensity when going from no slit to a $1500 \mu\text{m}$ slit. Moreover electromagnetic simulation using CST Microwave Studio [19] were performed to obtain the electric field configuration presented on figure 3 for an input power of 1 Watt. This calculation shows that the electric field presents a maximum around the microcoaxial location and another maximum at 180° from the latter. Several simulations have confirmed that this result is unchanged when performing a slit or a hole to let the capillary pass through the launcher, and that this result remains the same whatever the size (widths or diameters going from 200 up to $1500 \mu\text{m}$ have been tested) of the aperture and whatever its localization, i.e. the angle α between the aperture and the diameter passing through the microcoaxial cable ($0 < \alpha < 40^\circ$ have been tested). Of course, in order to enable leakage of microwave power as a surface wave

along the dielectric capillary tube, locating the slit or hole in the ring of the circular microstrip to let the capillary tube passage is better in zones where the electric field is not too low, which excludes zones around $\alpha = \pm 90^\circ$.

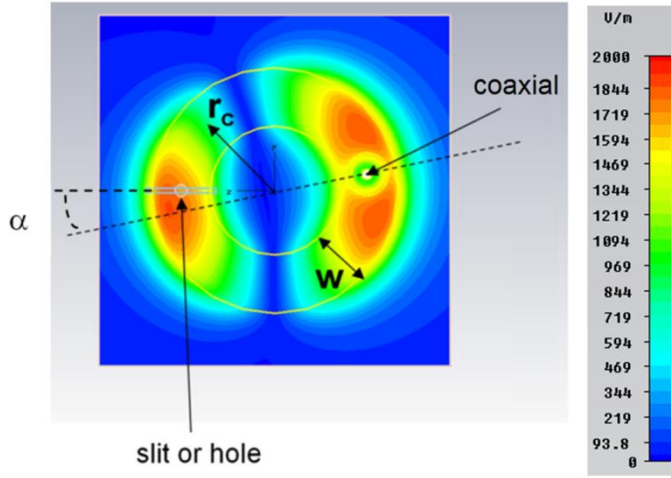


Figure 3: Simulated electric field obtained at 2.45 GHz either with a hole or a slit in a horizontal plane at half height of the circular microstrip.

Comparing the results obtained with this launcher with those obtained with a home-made surfatron optimized for plasma ignition into capillaries [9], the plasma obtained in pure argon at identical incident microwave power was longer with the surfatron than with the circular microstrip (see figure 4). The difference is not due to a different reflected power (which is around 10% in both cases) but is probably due to the fact that a part of the coupled power is lost by electromagnetic radiation, as suggested by the electric field simulation presented in a vertical cutting plane of the launcher on figure 5 (for an input power of 1 Watt).

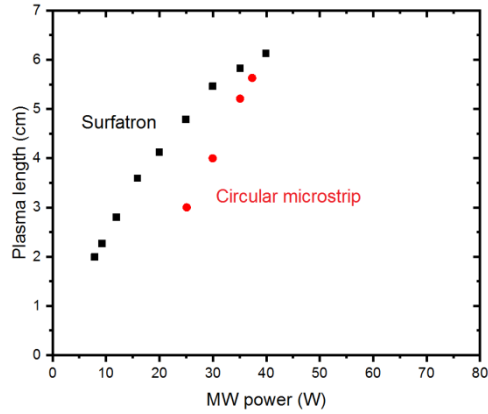


Figure 4: Comparison of plasma length as a function of incident microwave power obtained for circular microstrip (red circles) and surfatron (black squares) in a 690 μm inner diameter (1375 μm outer diameter) fused silica capillary filled with pure argon at a flow rate of 10 ml/min.

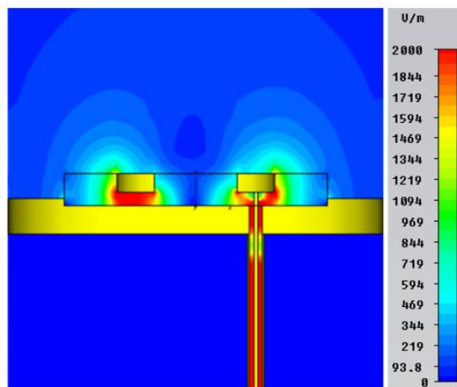


Figure 5: Electromagnetic field simulation in a vertical cutting plane of the circular microstrip launcher.

3. Development of a circular stripline based excitator: birth of the striplastron

In order to minimize possible electromagnetic leakage, it was decided to switch from a microstrip to a stripline, which consists of a symmetrization of the microstrip (see a schematic cross-section of a linear microstrip and a linear stripline in Figure 6).

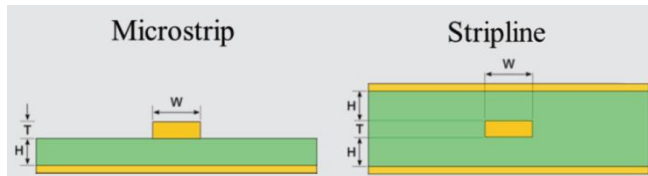


Figure 6: Schematic cutting view of linear microstrip and stripline

In the circular version with direct excitation, the transition from circular microstrip to striplastron is as shown in Figure 7 a) (with the capillary - in pink - passing through the structure at 180° from the microcoaxial - in yellow -). Figure 7 b) presents a 2D vertical cross-section of the striplastron.

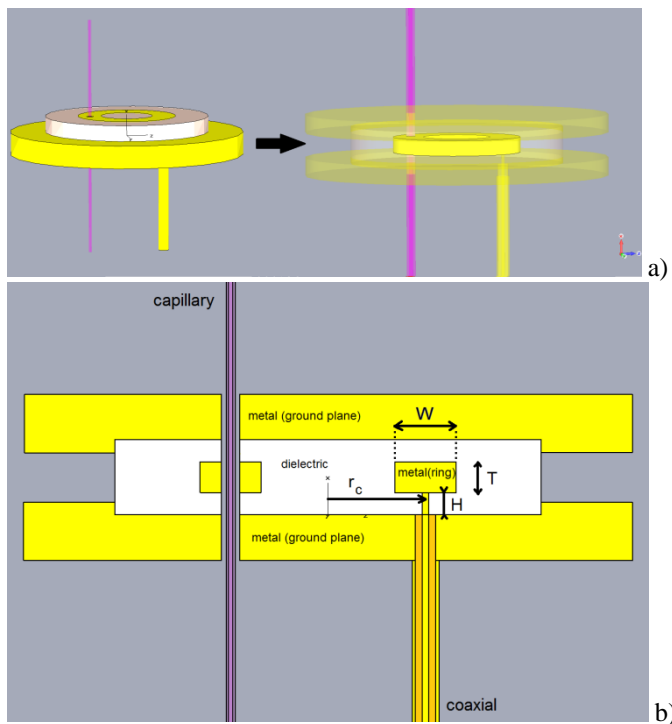


Figure 7: a) Schematic transition in 3D from circular microstrip to striplastron. b) 2D vertical cross-section of the striplastron.

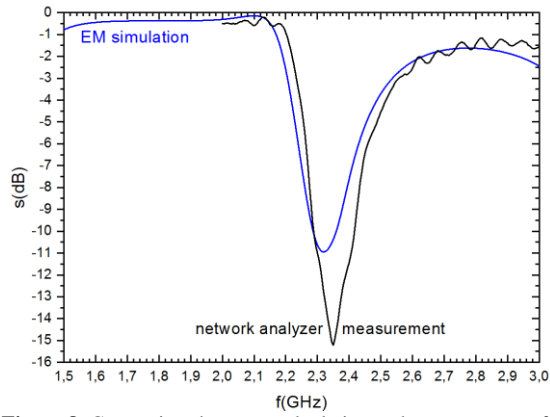


Figure 8: Comparison between calculation and measurement of the striplastron response (reflection coefficient as a function of frequency).

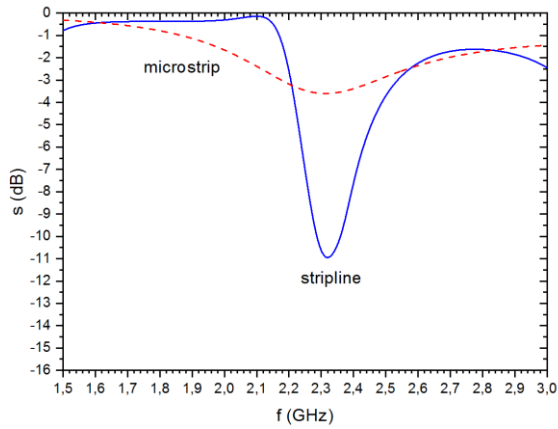


Figure 9: Comparison between circular microstrip and striplastron responses (reflection coefficients as a function of frequency) calculated by electromagnetic simulation.

Figure 8 shows that the striplastron structure calculated by electromagnetic simulation is validated by measuring the response (reflection coefficients as a function of frequency) of its home-made version with a network analyzer. The small differences in frequency and intensity of the resonance may be attributed to the not perfect dimensions and surfaces of the home-made striplastron. It is further shown in figure 9, by comparing the calculated responses of the striplastron and the circular microstrip, that the striplastron is more resonant than the circular microstrip (higher and thinner resonance peak).

Comparing the plasma lengths obtained in pure argon as a function of the incident microwave power (see figure 10), it can be noted that the striplastron structure is as optimized as the surfatron, except when tending towards high powers.

The small difference is due to the low possibility of "lateral" leakage by electromagnetic radiation that remains with this structure, which is confirmed by an electric field simulation performed in figure 11 for an input power of 1 Watt.

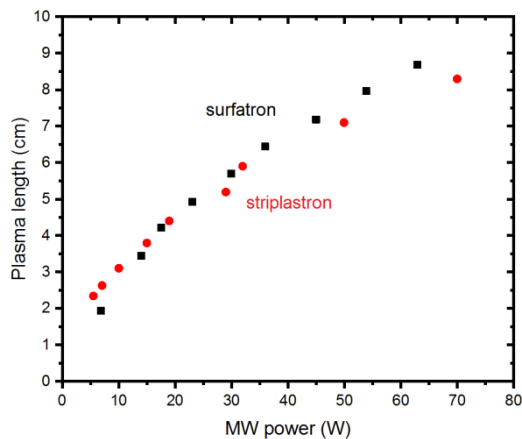


Figure 10: Comparison between plasma lengths obtained as a function of incident microwave power for the surfatron (black squares) and the striplastron (red circles) in a 690 μm inner diameter (1375 μm outer diameter) fused silica capillary filled with pure argon at a flow rate of 10 ml/mn.

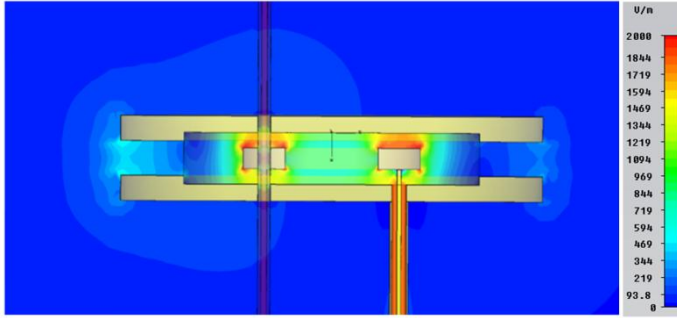


Figure 11: Simulated electric fields in the striplastron with demonstration of the possibility of low lateral microwave leakage.

In order to avoid these electromagnetic leaks, two solutions can be proposed. Both consists in closing the structure laterally. The first option is to add metal laterally, for example by using copper adhesive tape (see stripline S2 on figure 12). A second option is to laterally add an electromagnetic wave shield cloth [20] (see stripline S3 on figure 12).

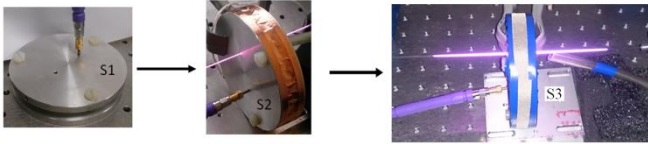


Figure 12: Example of lateral closure of the initial laterally opened striplastron launcher (S1) with metal (S2) and with electromagnetic wave shield cloth (S3).

Adding metal (S2) or electromagnetic wave shield cloth (S3) laterally reduces respectively by a factor 10 and 5 the resonance intensity (reflection coefficient measured by a network analyzer) of the basic striplastron structure S1. It should be emphasized that the decrease of the resonance intensity does not prevent plasma ignition.

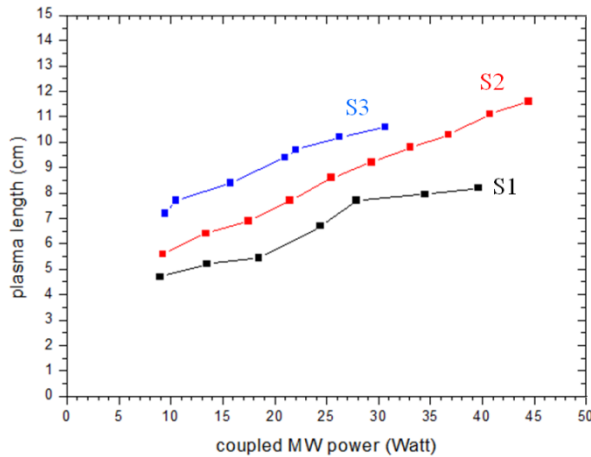


Figure 13: Comparison of the plasma lengths obtained for striplastrons S1 (black curve), S2 (red curve), and S3 (blue curve) as a function of coupled microwave power in a 690 μm inner diameter / 1375 μm outer diameter fused silica capillary filled with pure argon at a flow rate of 10 ml/mn..

Measurements of plasma length obtained as a function of coupled microwave power (incident power less reflected power) have been performed in pure argon at a flow rate of 10 ml/mn in a 690 μm inner diameter / 1375 μm outer diameter fused silica capillary (see figure 13). Results show that under similar conditions (gas, flow, pressure) the highest plasma lengths are respectively obtained with the S3, S2 and S1 structures at any given coupled microwave power.

Compared to the S1 structure, the addition of metal laterally in the case of the S2 structure has transformed the striplastron into a cavity and therefore the fraction of the waves which would have been lost as lateral

electromagnetic radiation can be either trapped as standing waves in the launcher (and finally lost by heat transfer) or give additional leak from the launcher as a surface wave to ignite and sustain the plasma. In the case of S3, the anti-radiation cloth absorbs a part of the waves which would have been lost by lateral electromagnetic leaks but also reflects a part of them which can give additional leak from the launcher as a surface wave to ignite and sustain the plasma.

4. Multiple ways to use the striplastron

First, the striplastron can be used to ignite in a dielectric capillary tube a plasma, whose length depends on the operating conditions, i.e. the microwave power, the gas used, the gas flow and thus the local pressure, and the internal diameter of the capillary. In this case, the capillary is placed between a high pressure chamber upstream and a low pressure chamber linked to a pump downstream.

The second possible configuration consists of a micro-torch. In this case, the downstream chamber is removed and the striplastron is placed near the open-end of a dielectric capillary so that increasing the microwave power leads to an increase of the plasma length, which can exit as a plasma jet. The jet can exit either directly into the air at ambient pressure or into a low pressure pumped chamber. In this case, the shape of the striplastron, especially its low thickness (less than 2 cm), is interesting because it can be encapsulated in a vacuum transition.

Note that several striplastrons can be placed in serie to generate several microplasmas at the same time along the same capillary. As the electron density profile of a plasma generated by a single launcher presents a maximum at the launcher gap location, with a decrease upstream and downstream of the gap position (as shown in the case of a surfatron in [9]), generating multiple plasmas and overlapping them could generate a long and axially homogeneous plasma (see the principle on figure 14).

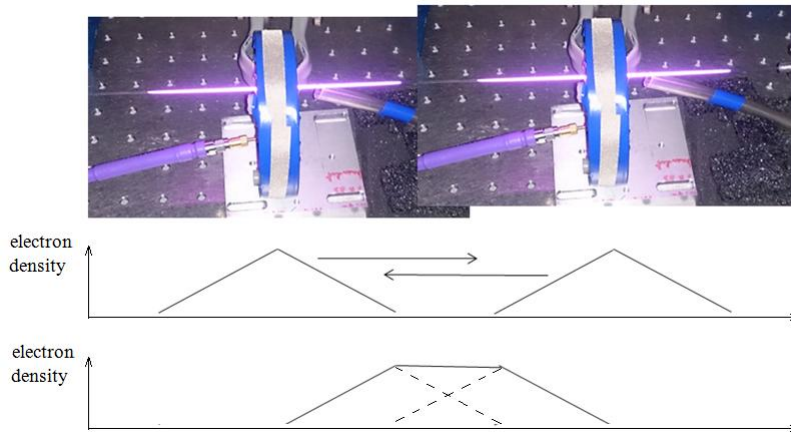


Figure 14: principle of generation of an axially homogeneous plasma by overlapping two plasmas generated by two striplastrons placed in serie along a single capillary.

Another great advantage of the striplastron is the possibility to use it to generate microwave microplasmas simultaneously in several capillaries placed in parallel. Such multi-tubes surface-wave discharges have been made in literature with larger diameter tubes [21, 22]. Performing this with capillary tubes would be a very interesting feature which could open a new way to generate arrays of microplasmas. The latter can be a functional device to control complex numbers expressed as amplitude and phase of microwaves, which is a unique aspect of metamaterials composed of microplasmas, as demonstrated in literature [23,24].

5. Conclusion

A new microwave excitator, called striplastron, has been developed. It is dedicated to the ignition of surface wave microwave plasmas in dielectric capillaries. It turns out to be a good alternative to the previously known microwave launchers, which are the surfatron and the split-ring resonator. The striplastron is a circular microstrip directly excited by a microcoaxial cable. Compared to the surfatron, it is smaller and the part of the plasma hidden by the launcher is limited to its thickness ($\sim 1-2$ cm). Moreover its frequency response presents an intense and large resonance. Last but not least, several striplastrons could be used to ignite several microplasmas if they are placed in serie along a same capillary and a single striplastron could ignite several microplasmas in capillaries placed in parallel. The latter points, which could turn out to be very interesting for applications, will be investigated in future works.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- [1] K. H. Becker, K. H. Schoenbach and J. G. Eden, Microplasmas and applications, J. Phys. D: Appl. Phys., Vol. 39, Number 3, 55 (2006)
- [2] R. Foest, M. Schmidt and K. H. Becker, Microplasmas, an emerging field of low-temperature plasma science and technology, International Journal of Mass Spectrometry 248, 87 (2006)
- [3] U. Kogelschatz, Applications of Microplasmas and Microreactor Technology, Volume 47, Issue 1-2, Special Issue: 3rd International Workshop on Microplasmas, 80 (2007)
- [4] A. P. Papadakis, S. Rossides and A. C. Metaxas, Microplasmas: A Review, The Open Applied Physics Journal, 4, 45 (2011)
- [5] K. H. Schoenbach and K. H. Becker, 20 years of microplasma research: a status report, Eur. Phys. J. D 70, 29 (2016)
- [6] K. H. Becker, W. Zhu, and J. L. Lopez, Microplasmas: Environmental and Biological Applications, Encyclopedia of Plasma Technology (2017)
- [7] B. Debord, L. L. Alves, F. Gérôme, R. Jamier, O. Leroy, C. Boisse-Laporte, P. Leprince and F. Benabid, Microwave-driven plasmas in hollow-core photonic crystal fibres Plasma Sources Sci. Technol. 23, 015022 (2014)
- [8] J. Hopwood, A.R. Hoskinson and J. Gregorio, "Microplasmas ignited and sustained by microwaves", Plasma Sources Sci. Technol. 23, 064002 (2014)
- [9] S. Dap, O. Leroy, J. Andrieu, C. Boisse-Laporte, P. Leprince, G. D. Stancu and T. Minea, Hydrodynamic and thermal effects of continuous microwaves sustained plasma in capillary tubes, Plasma Sources Sci. & Technol. 24, 065007 (2015)
- [10] M. Moisan, P. Leprince, C. Beaudry, and E. Bloyet, Perfectionnements apportés aux dispositifs d'excitation, par des ondes HF, d'une colonne de gaz enfermée dans une enveloppe, Brevet (Patent), France 74.36378 (1974)
- [11] M. Moisan, Z. Zakrzewski and R. Pantel, The theory and characteristics of an efficient surface wave launcher (surfatron) producing long plasma columns, J. Phys. D : Appl. Phys 12, 219 (1979)
- [12] www.sairem.fr
- [13] G. D. Stancu, O. Leroy, P. Coche, K. Gadonna, T. Minea, V. Guerra and L. L. Alves, Microwave air plasmas in capillaries at low pressure II. Experimental investigation, J. Phys. D: Appl. Phys. 49, 435202 (2016)
- [14] J. A. Hopwood, U.S. Pat. No. 6,917,165 (2005)
- [15] F. Iza and J. A. Hopwood, Split-ring resonator microplasma: microwave model, plasma impedance and power efficiency, Plasma Sources Sci. Technol. 14, 397 (2005)
- [16] F. Iza and J. A. Hopwood, Low-Power Microwave Plasma Source Based on a Microstrip Split-Ring Resonator, IEEE Transactions on Plasma Science, Vol. 31, Issue 4, 782 (2003)
- [17] Dutton et al., U.S. Patent Application Publication 2007/0170995 (2007)
- [18] F. Vial, K. Gadonna, B. Debord, F. Delahaye, F. Amrani, O. Leroy, F. Gerome and F. Benabid, Optics Letters, vol 41, no 10, 2286 (2016)
- [19] www.3ds.com/products-services/simulia/products/cst-studio-suite/
- [20] www.mwa.co.jp/en/product/pro03_01.html
- [21] J. Pollak, M. Moisan and Z. Zakrzewski, "Long and uniform plasma columns generated by linear field-applicators based on stripline technology", Plasma Sources Sci. Technol. 16, 310 (2007)

- [22] M. Moisan, Z. Zakrzewski, R. Etemadi, and J. C. Rostaing, "Multitube surface-wave discharges for increased gas throughput at atmospheric pressure", J. Appl. Phys. 83, 5691 (1998)
- [23] O. Sakai, T. Naito, T. Shimomura, and K. Tachibana, "Microplasma array with metamaterial effects", Thin Solid Films, Volume 518, Issue 13, 3444 (2010)
- [24] O. Sakai and K. Tachibana, "Plasmas as metamaterials: a review", Plasma Sources Science and Technology, Volume 21, Number 1, 013001 (2012)