Numerical Simulation of a Novel Microwave Plasma Source

Paolo Veronesi[1], Roberto Rosa[1], Cristina Leonelli[1], and M. Garuti[2]

[1]Department of Materials and Environmental Engineering, University of Modena and Reggio Emilia,
Modena, Italy
[2]Alter s.r.l, Reggio Emilia, Italy

Introduction

Microwave induced plasmas possess some important benefits, in particular a high efficiency in generating chemically active species, a relatively high electron density [1], the possibility of having nearly contamination-free processes and the capability of operating in a wide pressure range [2].

However, in order to maximize process efficiency, a proper impedance matching is required, in order to compensate the impedance variations of the load, due to even small changes in the plasma characteristics. Load variations can be easily compensated by existing automatic impedance matching devices, but this would mean practically increasing the installation costs. Moreover, it must be always remembered that a well matched system is not necessarily a synonym of an homogenous electromagnetic field distribution. Thus, the designer must pay a particular attention since minimising the reflected power could happen at the cost of plasma homogeneity.

The development of a novel plasma source, dedicated to Plasma Enhanced Chemical Deposition (PECVD) processes, moreover, has to fulfil other requirements, in primis the size compatibility with existing deposition chambers. For this reason, usually the design is constrained by size, and the reliability of the process usually leads to the need of minimizing moving parts.

Numerical simulation is a powerful tool to test potential alternative designs without the need of building a real prototype, provided the model is effectively representative of the real operating conditions. Moreover, most of the available numerical simulation tools offer optimizing modules which can maximize or minimize an objective function, like energy efficiency or parameters connected to the homogeneity of the electromagnetic field distribution in a certain region.

The present work is aimed at designing and optimizing a novel microwave plasma source, by means of numerical simulation. The optimised design lead to the construction of a prototype used to validate the model and currently transferred to a market product.

Experimental Setup

The software COMSOL 3.3 was used to simulate the electromagnetic field distribution inside a one-feed microwave applicator operating at 2.45 GHz, depicted in Fig. 1. The model consists of a feeding WR340 waveguide, connected to a curved rectangular waveguide closing on itself. On the curved waveguide, a single slot allows coupling to a second cylindrical cavity, placed at the bottom of the waveguide, separated by a quartz pressure window. In this second cavity, vacuum will be applied and the plasma is expected to be formed in that region. The plasma constitutes the load in the applicator and it can be described in terms of its complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$, according to [2]:

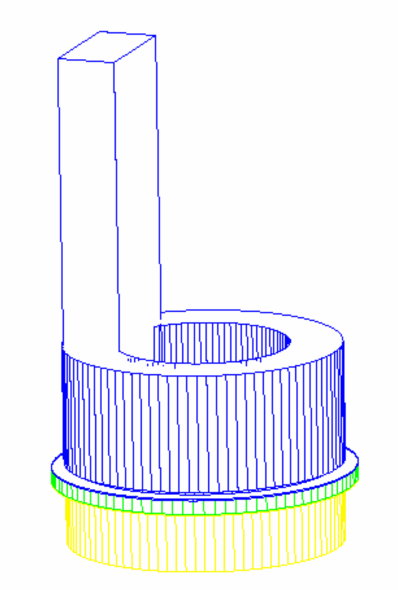


Fig. 1. Model geometry (from the top): the WR340 waveguide, the curved waveguide, connected with a single slot (not shown) to the underlying cylindrical cavity (bottom), trough a quarts pressure window.

$$\varepsilon^{*}=1-\frac{\left(\varpi_{p}/\varpi\right)^{2}}{1+\left(\nu/\varpi\right)^{2}}-j\,\nu/\varpi\,\frac{\left(\varpi_{p}/\varpi\right)^{2}}{1+\left(\nu/\varpi\right)^{2}}=1-\frac{\frac{n_{e}e^{2}}{\varepsilon_{0}m_{e}}\left(1+j\frac{\nu}{\varpi}\right)}{\varpi^{2}+\nu^{2}} \qquad (1)$$

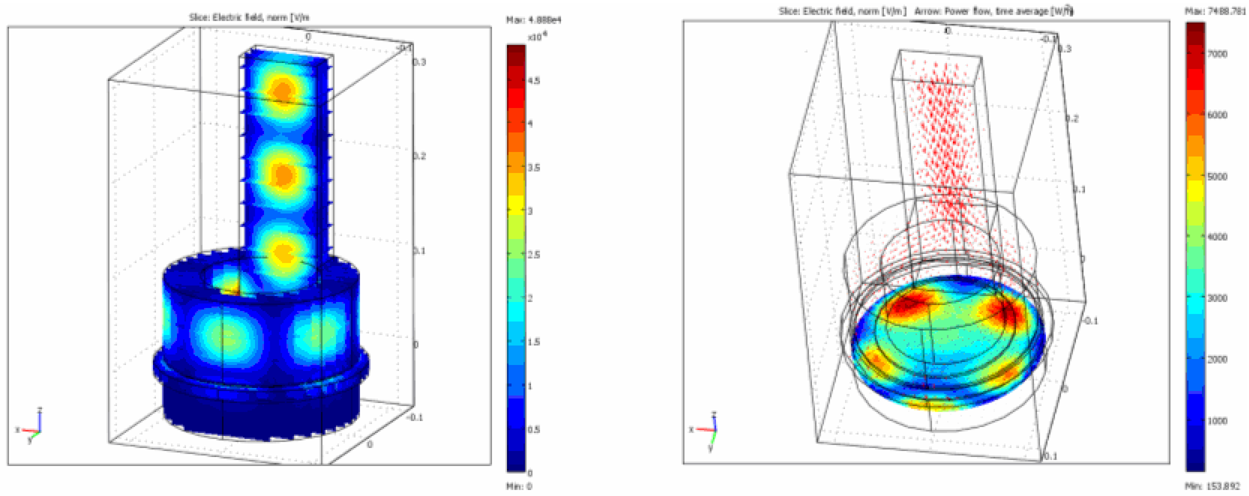
where n_e is electron number density, e is elementary charge, m_e is electron rest mass, ϖ is the excitation frequency, ϖ_p is the plasma frequency and ν is the collision frequency between electrons and neutrals, which is a function of the pressure, the gas nature, the gas temperature and the electron temperature [2].

Any change in one of these variables induces a change in the plasma equivalent permittivity, and thus in the load impedance, which needs to be adjusted by a proper impedance matching device.

A first set of simulations was run on the empty applicator using a parametric solver, aimed at minimizing power losses and maximizing electric field spatial distribution in the cylindrical cavity as a function of the curved waveguide section dimensions and size, shape and position of the slot.

Two indicators have been chosen: the reflection coefficient $|S_{11}|$ and the standard deviation of the electric field intensity calculated in the cells placed in the top, mid and bottom section of the pre-chamber. The standard deviation is intended to provide information on the homogeneity of the electric field distribution in the region where plasma will be generated. The maximization of homogeneity is considered more important than achieving high energy efficiency, at this stage of simulation.

A second set of simulation was run in order to investigate the impedance matching capabilities offered by a moving plunger placed on one arm of a T-junction placed along the feeding waveguide. This second set of simulations was conducted on the loaded applicator,



(a) (b)

Fig. 2. Electric field intensity in the empty applicator, 2.45 GHz excitation at the port (a); electric field intensity in the upper part of the cylindrical cavity of the loaded applicator (b).

varying its equivalent permittivity according to (1), in the range of equivalent imaginary part (ε'') [0.0127; 1.27]. Results of the second set of simulations are omitted in this paper.

Based on the numerical simulation results, a microwave plasma source prototype was built and tested, with respect to the effective homogeneity of the electric field distribution inside the cylindrical cavity. Heating of the upper part of the quartz pressure window can be considered representative of the distribution of the electric field at the top of the cylindrical cavity, thus temperature measurements were performed using non perturbing optical fibres connected to a Neoptix Reflex system.

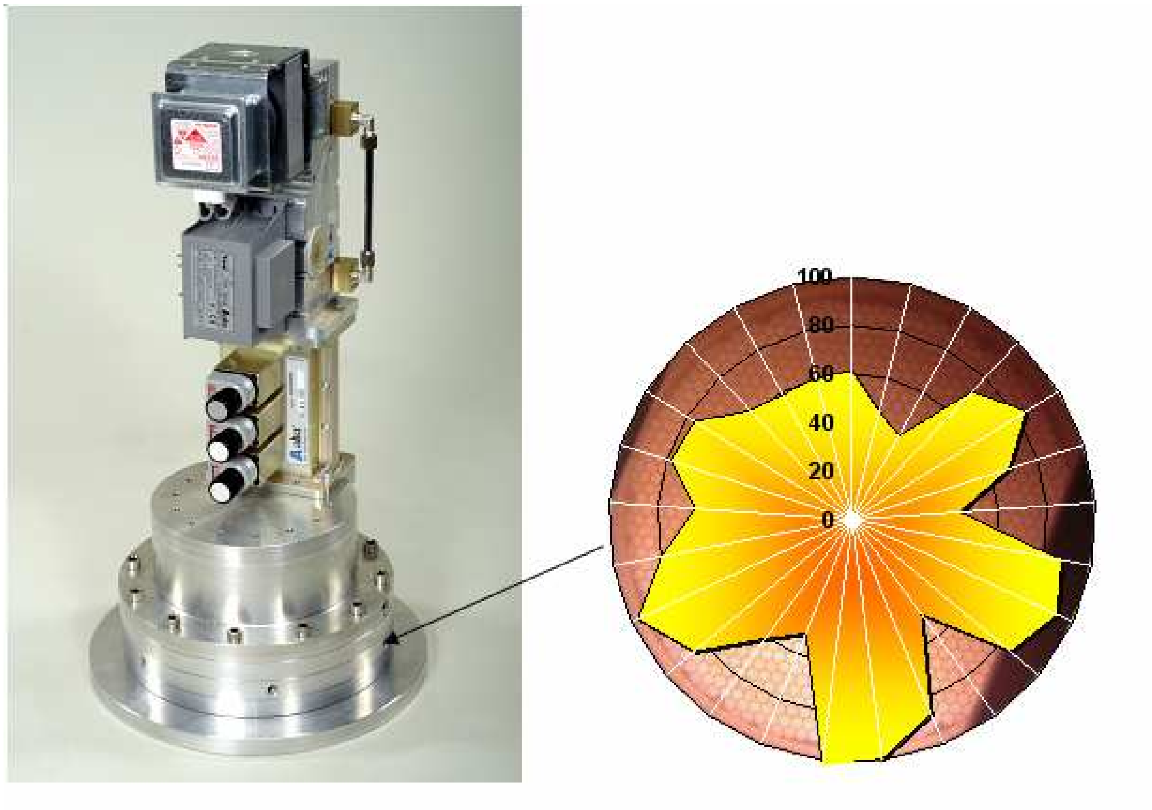
Results and Discussion

The results obtained from the numerical simulation of the empty applicator indicated that the maximum homogeneity with relatively low $|S_{11}|$ could be obtained using a single curved slot [3] whose width progressively varies from the region corresponding to the feeding waveguide (minimum slot width) to the region diametrically opposite (maximum slot width).

Numerical simulation results showed that an exponential increase of the slot width provides essentially the same electric field pattern obtainable using a slot obtained by two non coaxial circles, which is much easier to manufacture and assemble. The slot can be seen in Fig. 2(b). Fig. 2(a) shows the calculated electric field distribution in the applicator, for an input power of 1000 W.

In case of plasma generation, the applicator has to be considered "loaded", and the shape and position of the "load" depend on the electric field intensity. Considering a simplified loading conditions where the load is initially composed of a cylindrical slab half filling the upper part of the cylindrical applicator, the electric field distribution on the top of the load is depicted in Fig. 2(b), in case of plasma equivalent imaginary part $\varepsilon'' = 0.127$.

The electric field distribution in the plasma region is satisfactorily homogenous, and it is recognizable a 5-lobes pattern, with maxima on the sides of the cylindrical cavity.



(a) (b)

Fig. 3. Prototype microwave plasma source (courtesy of Alter s.r.l) (a); measured temperature (°C) during operation with argon taken on the upper side of the quartz pressure window (b).

The results of the first set of simulations showed that the optimum applicator for extremely different loading conditions (different plasma equivalent permittivity) should have presented relatively high $|S_{11}|$ values, above 0.7. Instead, considering each loading condition, and the presence of the T-junction terminated with a movable short circuit or a 3-stub tuner, a much lower $|S_{11}|$ could be achieved by small variation of the impedance matching device components.

Based on the results of the two sets of simulations, a first prototype of the plasma source [4] has been built by Alter Srl (Italy) and it is depicted in the left part of Fig. 3(a). In order to facilitate plasma ignition and sustaining, a pulsed microwave source, operating at 2.45 GHz, was used. Quartz cooling was required due to the pronounced heat generation in the plasma region, and it was accomplished by forced air convection on the upper side of the quartz, as well as using water cooling of the aluminium housing of the pressure window.

Argon and nitrogen plasma have been generated in the prototype and the temperature on the upper part of the quartz window was measured, to confirm the existence of the five lobes distribution.

Temperature measurement results are reported in the graph of Fig. 3(b), superimposed to a real picture taken from the bottom observation port of the applicator. It is confirmed the existence of the five lobes distribution, but the relative intensities do not exactly match the simulation results depicted in Fig. 2(b). This could be ascribed to the presence of the cooling air inlets, which impinge not homogenously on the quartz surface (cooling is more pronounced in the region near the feeding waveguide inlet) as well as to the difficulties in reaching the quartz region below the feeding waveguide. As shown in Fig. 3(a), measuring holes are drilled on the top of the applicator, but they are not present in the area where the feeding waveguide enters the curved one.

Conclusions

Electromagnetic simulation software has been used to design and optimise a new microwave plasma source. Optimization was performed on the basis of maximizing energy efficiency and maximizing electric field distribution homogeneity. The basic assumption in modelling loaded applicators (where plasma is ignited) was to represent plasma as an equivalent dielectric load, whose characteristics, position and shape are a function of the electromagnetic field distribution inside the microwave applicator. A completely new compact plasma source presenting a toroidal waveguide and an innovative coupling slot has been numerically simulated, designed and built.

In order to feed the new microwave plasma source, an innovative solid state pulsed power supply unit was developed, including a 3-port isolator, able to power a standard magnetron to reach up to 8 kW pulse at 2.45 GHz. The unit is compact and easy to control (peak amplitude, frequency, duty cycle) and the high intensity electric field peaks allow for easily igniting nitrogen as well as argon and most of process gases. Preliminary tests conducted on the microwave plasma source mounted on an existing deposition chamber confirmed the existence of the rather homogenous 5-lobes electromagnetic field distribution, which emerged from the numerical simulation and optimisation.

References

[1] W. Petasch, E. Rauchle, J. Weichart, H. Bickmann, *Surf. Coat. Technol.* 74-75 (1995), 200-205.
[2] A. Muller, M. Emme, D. Korzec, J. Engemann, *Surf. Coat. Technol.* 116-119 (1999), 674-678.
[3] P. Veronesi, C. Leonelli, M. Garuti, “Plasma generator with a slot antenna”, EP1739717
[4] P. Veronesi, C. Leonelli, M. Garuti, “Plasma generator”, EP1718135