Resonant rf network antennas for inductively-coupled plasma sources

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Resonant rf networks are new and versatile plasma sources with numerous potential applications in plasma processing [1]. They consist of parallel arrangements of ***L***, ***C*** elementary meshes with a set of resonant frequencies corresponding to the normal modes for the current/voltage distributions. At each resonant frequency, very high currents are generated within the antenna structure which can therefore be used as a source for inductively-coupled plasma (ICP).

Large area plasma processing is expanding worldwide for applications such as thin film silicon deposition for photovoltaic solar cells, flat panel display manufacture, packaging, etc. Actual plasma sources suffer from physical and technical difficulties (non-uniformity, low plasma density, excessive voltages and currents in the power transmission line, engineering complexity, etc), and improved concepts are urgently needed. Resonant rf network plasma sources present a real alternative to conventional capacitively-coupled and inductively-coupled devices for large area plasma processing. This work gives examples of an open network as a planar source and a closed network as a cylindrical source, as shown in Figure 1, with their equivalent circuits in Figure 2. The closed antenna (birdcage coil) is well known from nuclear magnetic resonance applications where the rf field is used to excite the nuclear spins in a sample. Other arrangements of the ***L***, ***C*** elementary meshes could be envisaged to form complex rf antennas adapted to specific applications.

PRINCIPLES OF THE HELYSSEN PLANAR ANTENNA

The present section describes briefly the principles of the Helyssen planar antenna [1]. Its structure and operating principles are similar to the closed cylindrical birdcage antenna previously described [2] but it has been unwrapped to form an open and planar structure as shown in Figure 1. The planar antenna is suited for large area surface treatment, whereas the cylindrical version is adapted to plasma processes requiring a volume plasma source. In both cases, the ***N*** parallel legs of the antenna are made of copper tubes which act essentially as inductive elements of inductance $\boldsymbol{L}$. High Q capacitors of capacitance $\boldsymbol{C}$ link the legs together and present also a small inductance $\boldsymbol{M}$ formed by the metal connectors. In the framework of a lumped elements analysis, and considering the ideal non-dissipative case, the impedance of the legs, and the impedance of segments containing a capacitor are purely imaginary. Solving the Kirchhoff equations over the antenna with the open boundary conditions of the planar structure gives $\boldsymbol{m} = [1, 2, ..., \boldsymbol{N}\textbf{-1}]$ resonant modes that arise from the parallel assembly of $\boldsymbol{L}$ and $\boldsymbol{C}$ components [2,3]. Each of these modes is characterized by a specific current distribution and a resonance frequency $\boldsymbol{f_m}$ given by:

$$f_m = \frac{1}{2\pi}[C(M - 2L\sin^2\{\frac{m\pi}{2N}\})]^{-1/2}$$

although mutual impedances between all the antenna elements must be accounted for to correctly reproduce the frequencies measured with a network analyser. The antenna can be represented by a simple equivalent circuit for each mode, which consists of a $\boldsymbol{R}$, $\boldsymbol{L}$, $\boldsymbol{C}$ parallel resonance circuit [3].

The plasmas produced by the resonant networks show an *E-H* transition similar to ICP devices using solenoids or spiral coils [4]. Resonant rf networks used as large area or large volume plasma sources have particular advantages because their dominantly real impedance near resonance avoids high reactive voltages or currents, regardless of the network dimensions. Also, the resonant currents are spatially distributed according to the chosen mode structure, which is better suited for uniform plasma sources than a single coil ICP, for example.

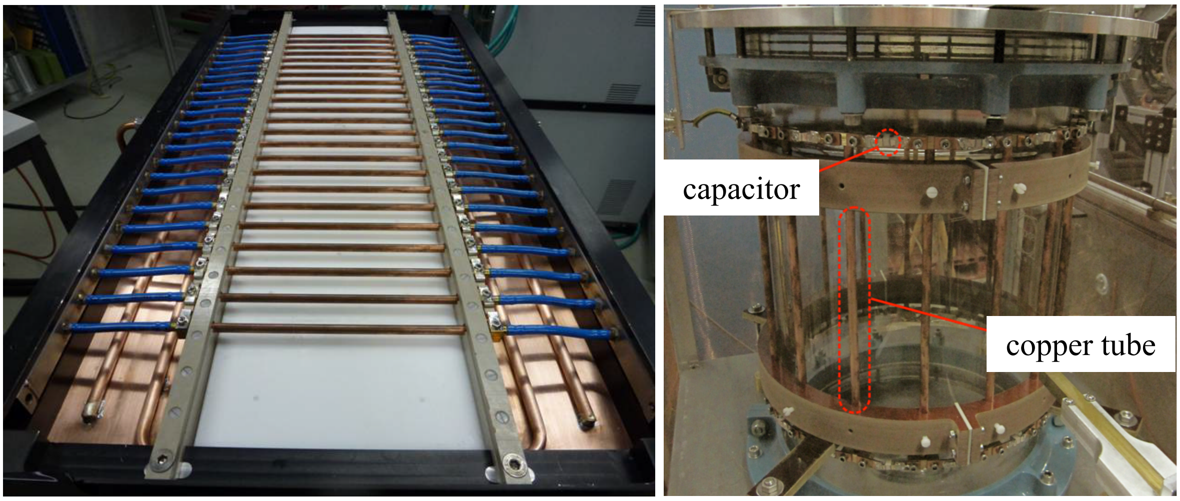

Figure 1. Left: Photograph of a 23-leg planar resonant network before it is embedded in a dielectric and placed inside a vacuum chamber. Right: Photograph of a 16-leg cylindrical (birdcage) resonant antenna. The vacuum vessel is a glass cylinder closed at the top and bottom by grounded metal plates.

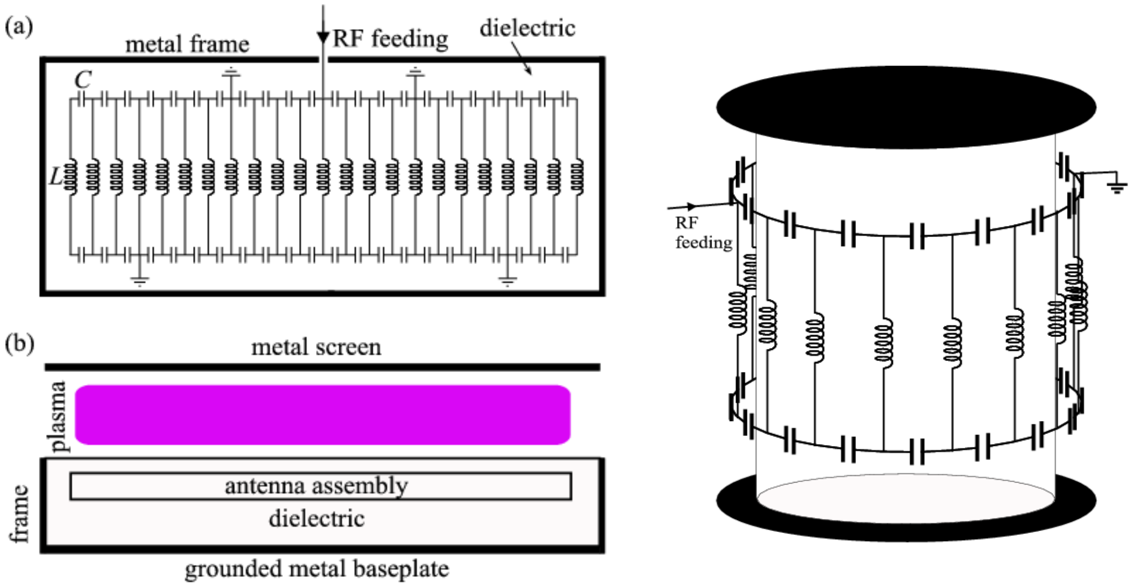

Figure 2. Left: Schematic and electrical circuit of a 23-leg planar rf network antenna. (*a*) Top view showing the rf feeding point and four ground connections. (*b*) Side view showing the metal screen used to confine the plasma above the antenna. Right: Schematic of a 16-leg cylindrical (birdcage) rf antenna, showing the electrical circuit and opposite points of rf feeding and grounding.

Another point concerns the standing wave effect that currently occurs in large area systems. By introducing an electromagnetic model for the antenna conductors instead of the conventional lumped elements analysis, Kirchhoff's equations can be solved taking into account the amplitude variations of the voltages and currents along the conductors. The first important result of this model is that no relevant standing wave effect is to be expected in the direction perpendicular to the antenna legs. This is due to the fact that the relevant scale length for the standing waves in this direction is not the full antenna length but rather the width of one elementary mesh containing a capacitor, which is always much smaller than the potential/current wavelength at rf operating frequencies. Standing waves are therefore expected to appear only along the antenna legs. However, this effect can easily be minimized by introducing a capacitor in the middle of the legs. The voltage standing wave is then divided, with no severe reduction of the mean current amplitude.

Protoypes of Helyssen antennas operating at 13.56 MHz have been tested up to 2 kW rf power and are currently under industrial pilot tests for barrier layer coatings in packaging, and for micro-crystalline silicon thin film deposition for photovoltaic solar cells.

WHISTLER-WAVE HEATED DISCHARGES USING A PLANAR ANTENNA

By adding a static magnetic field, resonant networks also open the way to novel, wave-excited plasma sources, comparable to helicon sources but without the constraint of a cylindrical geometry. With a static magnetic field perpendicular to the source plane above a given threshold, wave heated regimes are obtained, characterized by the formation of a plasma beam extending from the source up to the end of the vacuum chamber. The measured propagating wave presents all the characteristics expected for whistler waves; for example, the transverse magnetic field has a helical structure due to an elliptic polarization modulated by the propagation away from the antenna. The high efficiency of planar resonant rf networks for launching whistler-wave heated discharges [5] means that plasma generation is therefore not limited to a small skin-depth region, in contrast to ICP sources.

CONCLUSIONS

These results show the proof of principle of a novel generic type of plasma source which overcomes many of the physical and technical limitations of conventional large-area capacitive and inductive plasma sources. The general principle of resonant networks for plasma sources opens up a rich field of study for the plasma physics community. Many new permutations of plasma source physics could potentially evolve from this concept.

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