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An Automatic Real Time Impedance Matching System for Use in an RF Electrostatics Accelerator Ion Source

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Abstract: This paper presents the design and construction of an apparatus in an RF ion source for automatic impedance matching between variable impedance environment (plasma) and fixed impedance system (an RF power generator) in order to transfer a maximum power to the plasma. The apparatus includes a matching box, a directional coupler and a balanced antenna associated with a transmission line transformer (TLT). The constructed automatic matching system is very simple and at the same time is capable of functioning under different conditions of the gas pressure to ensure a good performance. The matching network is mainly designed in order to be used in the first electrostatic accelerator designed and constructed in NSTIR, where the RF ion source is placed in the HV terminal, where there is no access to a manual matching box during the operation. The measured output current of the ion source is about 700μA with 200W RF power input in the working frequency of 70MHz. The output current of the previous ion source current could not exceed 200μA under the same condition (10^{-2} Torr) without employing the present matching system. The system is capable of reaching an optimum VSWR point of about 1.2 in the pressure range of 10^{-1} to 10^{-4} Torr. This can be realized in a short matching convergence time (i.e., couple of seconds).

Keywords: ***RF Ion Source, Impedance Matching, Accelerator, VSWR, Plasma, Power Amplifier***

1- Introduction

An RF ion source basically includes a plasma chamber, a low pressure gas filled enclosure, excited by an RF generator at different levels of power and frequencies (ie.13.56-125 MHz 50-400 W…).

Such plasma chambers are used in many processing operations such as RF based ion sputtering (etching or coating), glow discharge process, reactive ion etching, thin film industry, electrostatic accelerators etc.

The design of the RF generators of ion sources makes it sensitive to voltage standing wave ratio (VSWR) of the load.

Controlling the forward and reverse power as well as protection over a wide range of impedance is necessary for the optimal performance of the ion source.

The design and construction of a matching system to overcome these impedance matching problems are presented here.

2. Design and Construction Matching System Necessity

Basically in an RF system, the maximum RF power is transferred from the source to the load, if the output impedance of the source is complex conjugate of the load. Therefore, a matching network is necessary to be placed between the source and load to transfer the RF power with a minimum loss through power reflection, heat dissipation etc.

Unfortunately, the impedance of the plasma is a complex and highly variable function of many parameters and conditions such as the type of gas, gas dielectric constant, density, pressure, volume and also gas temperature. In other words, the impedance of the plasma will typically vary significantly throughout the running process and usually differ from one chamber to the other [1]. For this reason, it is necessary to have an automatic impedance matching system to match the output of RF amplifier instantly to the variable impedance of plasma in order to transfer the maximum possible energy to the plasma chamber. This will be resulted in increasing the degree of ionization and finally produces more output current.

The matching network also avoids high peak voltages and high peak currents associated with a high VSWR on the transmission line.

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High voltages and high currents could damage transmission line which could in turn change its characteristic impedance.

In addition to the impedance variation of the plasma, another aspect of the plasma chamber is to take care of matching filter with a rapid drop of plasma impedance from a high-value when it is off (not ignited) to a low-value during a full ignition state. The impedance variation is shown in Fig. 1. The impedance magnitude may vary between one ohm to 1 mega-ohm in these two states and its drop time usually is in the order of microseconds.

Once the plasma is ignited, its impedance remains approximately constant with a small fluctuation hence accordingly, the impedance matching control will be faster and easier [2]. Due to this reason the matching network must function in such a way that it should cover this gap of variation and ignite the ion source without any problem.

There are two main methods to construct automatic active matching filters for an RF ion source.

- Using variable elements such as air gap capacitors or variable inductors to tune the elements up to an optimum point in order to achieve the minimum VSWR [3 and 4].
- Designing a network of several fixed capacitors or inductors as a matching box and selecting the elements using a fast solid state switching system (i.e. pin diodes) to achieve the minimum VSWR [5 and 6].

However, some other methods such as 'stub tuning', 'Fixed RF matching' etc., have also been applied previously [7 and 8].

Here we present a real time automatic impedance matching system based on the second method.

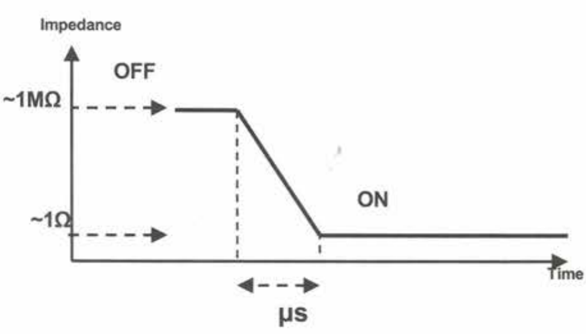

Fig. 1. Ion Source impedance variation.

2.1 Design Procedure

The general block diagram of the automatic matching system is shown in Fig. 2.

The system includes a sampling unit, a matching box, transmission line transformer (TLT) as a balun and a double solenoid antenna. A 200W solid state power amplifier is used as an RF source with the working frequency of 70MHz.

2.2 Prototype Matching Box Configuration

The matching box which is actually the most important part of the system consists of two main parts:

Matching filter and control unit.

2.3 Matching Filter

Finding the elements of the matching filter components for the aforementioned plasma behaviors has a high degree of importance.

The block diagram and setup of the matching box elements are shown in Fig. 3.

Plasma can be electrically represented as a resistor and a capacitor in parallel [9].

Considering this fact, some conventional configurations of filters (i.e. π or L) have been used. Microwave office software is used to find the best configuration of filter. By applying these filters consisting of variable components in the test fixture (set-up), and manually tuning on the basis of the minimum possible VSWR, an L type filter was established as the simplest and most favorable configuration.

The circuit simulation and also the diagram of S_{11} parameters of the system are shown in Figs. 4 and 5.

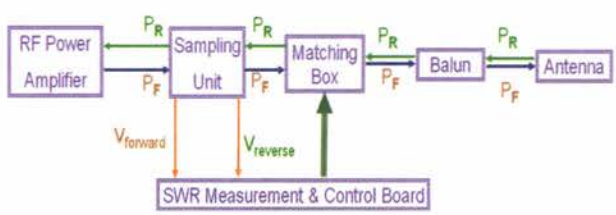

Fig. 2. RF ion Source impedance matching system block diagram.

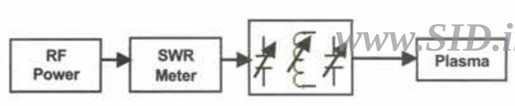

Fig. 3. Manual matching set up.

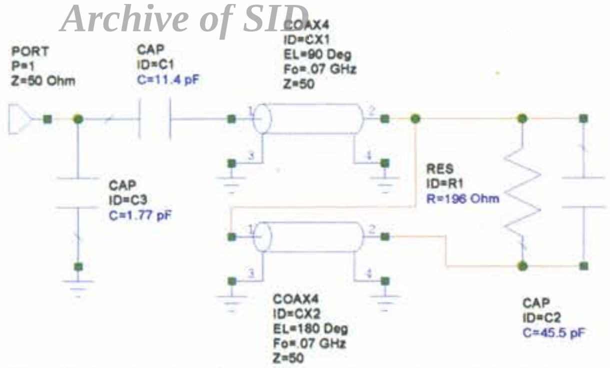

Fig. 4. The circuit of matching filter and model of plasma load.

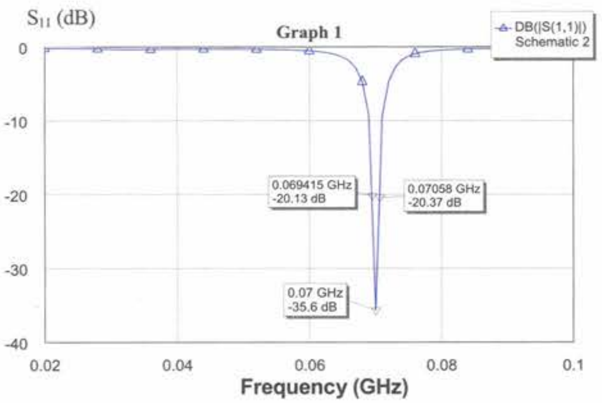

Fig. 5. S_{11} parameter graph of the circuit.

It should be noted that S parameters[(1)] represent, as they are generally known, transmission characteristics in a four-port circuit network.

These parameters are obtained when a high frequency signal is input to an input port and an output terminal of the four-port terminal circuit network is connected to a line having a characteristic impedance (ie:50Ω) [10].

Fig. 4 is the schema of the matching filter which includes two capacitors, the transmission line and the plasma load model.

The analysis of parameter S_{11} is shown in Fig. 5.

Generally, S_{11} of a four-port system represents the reflected RF power from the load. It is clear that the lower value of S_{11} corresponds to a better matching achievement.

Fig. 5 presents the parameter S_{11} of the whole circuit including the plasma load, the transmission line, the matching filter and the 50-Ω port that represents the output impedance of the RF power amplifier.

Measurement using the present matching methods shows that in the frequency range of 69-70MHz a good matching response of S_{11} (-20dB) could be achieved.

A parallel variable capacitor covering a capacitive range of 1-10 pF connected in series with a 1-20pF capacitor enables us to achieve a satisfactory matching condition in the pressure range of 10^{-1} to 10^{-4} Torr.

The pressure in the ion source varies in the range of 10^{-1} to 10^{-4} Torr. The tuning point of the filter is, however, set at a pressure of 5×10^{-2} Torr.

If a wide range for matching circuitry is selected, the matching convergence time increases in a large plasma density range or even the optimum matching gap and the ignition state may be lost.

Using an isolator before utilizing the matching fixture is necessary to protect the amplifier from unwanted reflected powers.

The capacitors and sampling unit should be isolated from the control unit and must be carefully shielded from the influence of RF emission on the control unit.

The test should also be performed at a power lower than the typical power of amplifier for safety considerations.

2.4 The Control Unit

After identifying the elements of the filter and their required values, variable capacitors were substituted with eight discrete capacitors with a capacity of 1-10pF for the parallel bank and 1-20pF for the series. The schematic diagram is shown in Fig. 6.

The control unit includes an AVR IC controller.

Each capacitor is incorporated in the circuit through a relay switch R1 to R8.

The controller receives two signals V_{ref} (reflected wave) and V_{for} (forward wave) from the sampling unit and calculates VSWR through the following equation:

$$SWR = \frac{V_{for} + V_{rev}}{V_{for} - V_{rev}}$$

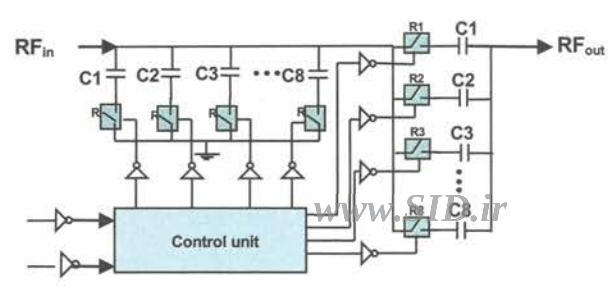

Fig. 6. Control unit schematic circuit diagram.

The capacitors and relay switches associated with it can make up to 256 different values of capacitors with a resolution of 2pF.

Two buffers are allocated for isolating the peak detectors of sampling units and the main IC controller.

The picture of the matching system is shown in Fig. 7.

2.5 Antenna Configuration

Basically, the RF power is transmitted to the gas enclosure in two different methods: inductively or capacitively. The source is called an inductively coupled RF ion source, and the RF power is connected inductively to the discharge volume if the discharge tube is placed into a solenoid. If the source is capacitively coupled, the RF power is connected to two clips placed around the discharge volume [11 and 12].

In the second type, the matching system sensitively depends on the distance of the two rings which can be modeled as a very small capacitor, as a result, the frequency response of the filter will be too quick, and the implementation of matching system will be rather difficult. Also in the transient time between the preignition and the full ignition, the matching convergence point can also be lost.

The first type, as shown in Fig. (8-a), was constructed of a simple solenoids.

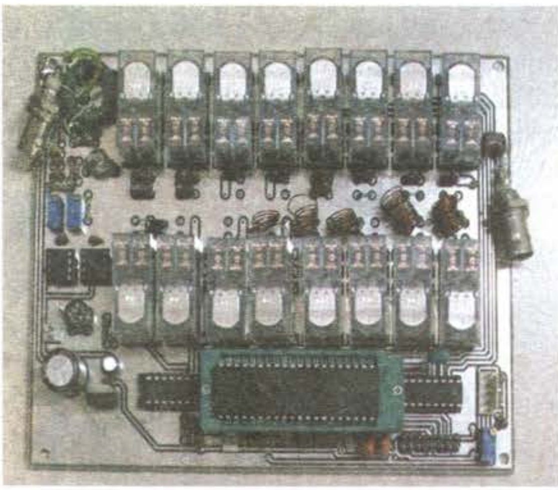

Fig. 7. The constructed prototype automatic matching system.

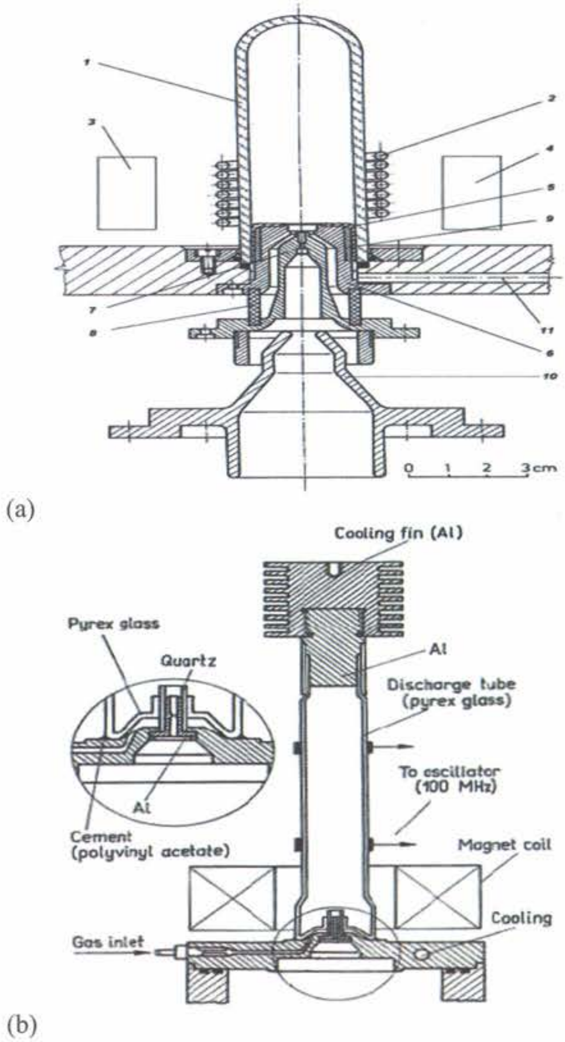

Fig. 8. Antenna models (a, b).

2.6 Sampling Unit

Traditionally, there are two main methods for sampling unit design:

- Detecting magnitude and phase on the RF line (PM detecting) [6].
- Detecting forward and reversed voltage [13].

The second method is more straightforward because it includes only one detection circuit. Several circuits based on the second technique were studied for possible use. The choices were narrowed down to two main types:

- Micro-strip directional coupler [14]
- VSWR bridges: Tandem match coupler and Bruene bridge [15].

Tandem coupler has some desirable features. Simplicity, excellent directivity, being scalable to other power levels and 50 Ohm load impedance on all ports.

The disadvantage of this kind is its low insertion loss or high VSWR.

Although the Bruene Bridge is more complex, requires adjustment and loses the 50 Ohm termination feature, its high return loss can compensate for its disadvantages for our usage with a reasonable compromise.

The constructed circuit of Bruene Bridge is shown in Fig. 9.

The voltage pick up is performed by a coiled ferrite core T_1 around the transmission line.

The pick up voltage decreases as T_1 turns decreases.

The RF voltage supplied by a transmitter is coactively coupled via C_1 to serve as a kind of reference against which the forward and reverse powers are measured.

The forward and reflected voltages are detected by the peak detector which includes a germanium or schottky diode. These diodes provide more detection accuracy for their low threshold voltages.

C_1 is a 1-20pF air variable trimmer capacitor. T_1 is 12 bifilar wound of #22 AWG enameled wire tightly and uniformly wound around a suitable ferrite core for this frequency and power (i.e. FT 37-43).

2.7 Transmission Line Transformer

Fig. 10 shows the transmission line transformer used in the system.

This is a voltage balun (balance to unbalance) constructed solely from transmission line.

The length of the first part is optional and the second half is $\lambda / 2$.

The extra half way section causes the voltage at its output to be equal and opposite of the voltage at the input. An RG-213 coaxial cable is used to construct the balun.

This balun also is an impedance transformer with the ratio of 1:4 [16].

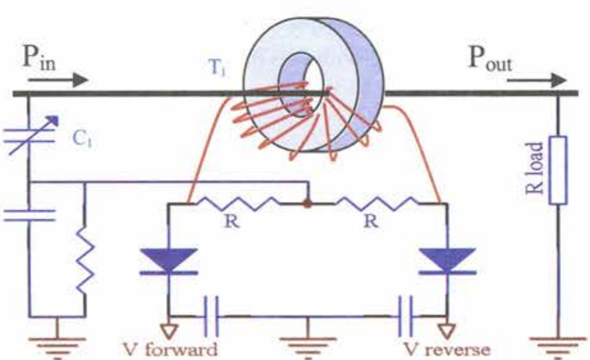

Fig. 9. Bruene bridge schematic.

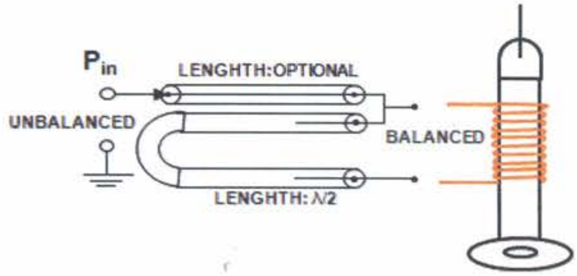

Fig. 10. Transmission line transformer.

3. The System Features

The presented automatic matching network may be applied in various fields such as manufacturing process using plasma, nuclear magnetic resonance (NMR) power supplies, ultrasonic power supply, broadband antenna and in many other applications where maximum power transfer is required to a variable impedance load.

A traditional method for auto-matching network was to use variable vacuum capacitors or inductors and controlling the elements with servo or step motors in order to achieve a system to reach a minimum VSWR.

But, this method suffers problems such as:

- It is bulky and furthermore, since it employs moving parts that consideres to be unreliable.
- Linear gear capacitors are not readily adapted for high speed operation or synchronous movement when multiple capacitors are required and may introduce significant delay in the process.
- It needs electrical contact through moving components such as bearings, bellows and the like.

In the presented method, however, all the above problems have been solved.

It is truly comparable in size, weight and cost to the traditional method.

Moreover, it has a high reliability compared to the vacuum capacitor controlling with a better accuracy. This device also has 250 memories for using at the start up, so if the user can estimate some suitable value for filters, and save them to the memory, it will quickly find the best matching network.

But it deserves to mention that usually this kind of auto-tuner is suitable only for a RF power bellow 200W. This automatic matching network is mainly designed for use in the first electrostatic accelerator designed and constructed in NSTIR, where the RF ion source is placed in the HV terminal, so the biggest advantage of this device is its low VSWR.

4. Application in an electrostatic Particle Accelerator

The present RF impedance matching system was used in an electrostatic accelerator to ensure high beam current.

The exprimental measurement showes that with Ø2mm exit channel a current of 450μA in a vacuum pressure of about 10^{-2} Torr can be extracted, while without any matching system at the most 200μA under the same condition is extracted.

In order to demonstrate the relation of the output current with the input RF power and also the diameter of the exit channel, the output beam current of ion source was measured as function of RF power for two different sizes of ion source exit channels.

The measurements show the direct relation between the beam current with the input RF power and exit channel size.

Fig. 11. Shows schematic diagram of the designed and constructed ion source for RF 200kV accelerator.

Fig. 12. clearly demonstrates the performance of the RF ion source.

The picture of the whole RF ion source and the solid state power amplifier is shown in Fig. 13 and 14, respectively.

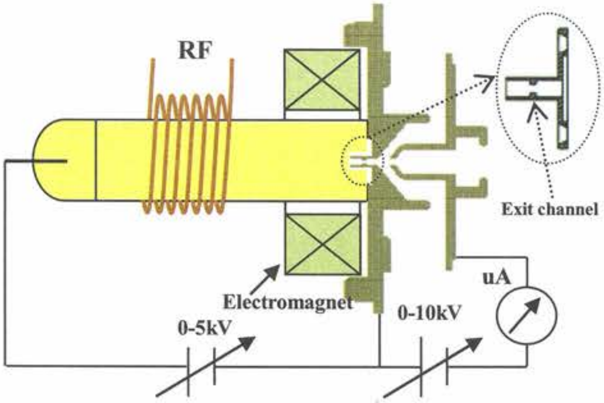

Fig. 11. Schematic diagram of the constructed ion source.

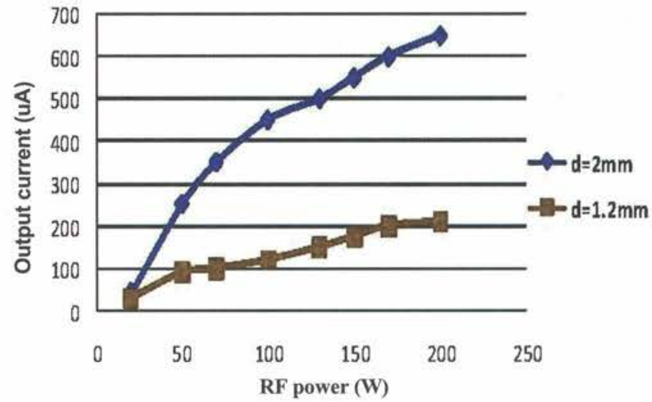

Fig. 12. Ion source output current versus input RF power at the pressure of .01 Torr.

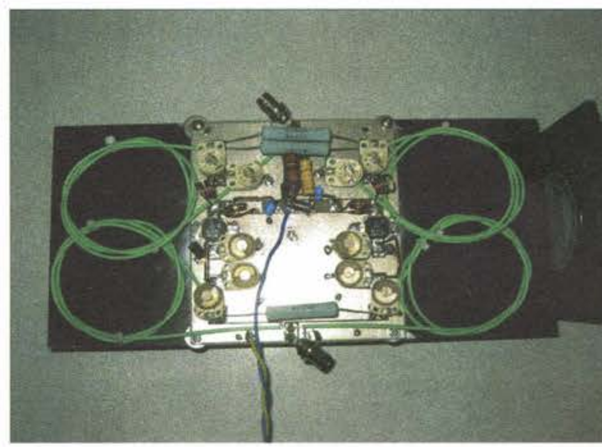

Fig. 13. Final 200W solid state power amplifier.

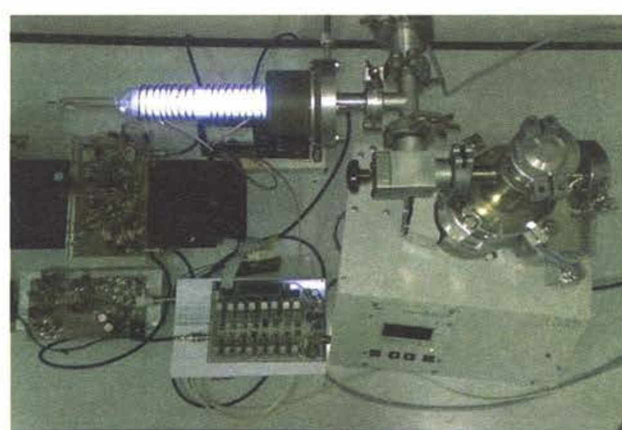

Fig. 14. RF ion source with 200W RF power at 10^{-2} Torr pressure.

Footnotes:

1. S_{11}: Input Side Voltage Reflection Coefficient
   S_{12}: Reverse Voltage Transmission Coefficient
   S_{21}: Forward Voltage Transmission Coefficient
   S_{22}: Output Side Voltage Reflection Coefficient

1. M. Spencer, S. Saddow. "An automatic RF tuner for RIE applications," Department of Electrical and Computer Engineering, Mississippi State University, January 24 (2000).

2. Carl A. Sorensen, Wandell blonigan, John white, United states patents, Patent No. 5815047, Sep. 29, "Fast transition RF impedance matching network for plasma reactor ignition," (1998).

3. David Armitag "Automatic impedance matching," United States patent, Patent No. 4356458, Oct. 26 (1982).

4. Daisuke Matsuno, "Impedance matching apparatus," United States patent, Publication No.: US2006/0151591 A1, (Jul.13, 2006).

5. Richard N. Arounly, "Solid state plasma chamber tuner," United States patent, Patent No. 5473291, (Dec. 5, 1995).

6. Antone Marretic, Andrew Ciszek, Joseph Stach, "Apparatus for matching available load impedance with an RF power generator impedance," United States Patent, Patent No. 5654679, (Aug. 5, 1997).

7. Pil Jae park, Cheon Soo Kim, Mum Yang Park, "Variable impedance matching circuit," United States Patent, Publication No.: US2004/0104785 A1, (Jun. 3, 2006).

8. Jun Zhao, Kennet Smyith, Wiliam Nikson Taylor, Gerald McNut, "Plasma chamber with fixed RF matching," United States Patent, Patent No. 5643364, (Jul. 1, 1997).

9. Advanced Energy Indusrties, Inc. Application note on Impedance matching, http: //www. advanced-energy.com/upload/File/White _papers/ EnG-WHITE18-270-02.pdf (2006).

10. Chris Bowick, "RF circuit design," Newnes Publication (1982).

11. A.J. Bayly, A.G. Ward: Can. J. Res. **26A**, 69 (1948).

12. C.D. Moak, H. Reese, Jr., W.M. Good: Nucleonics **9**, 21 (1951).

13. John D. Swank, "VSWR monitor and alarm," United States Patent, Publication No.: US2002/ 0113, 601, A1, (Aug. 22, 2002).

14. David M. Pozar, "Microwave Engineering," John Wily and Sons, Inc. (2005).

15. Dominique-f1frv, "All powers SWR bridge and power meter," (2006).

16. Chris Trask, "Transmission line transformers: theory, design and applications," Sonoran radio research. (January 2006) http: //www. highfrequencyelectronics. com/ Archives/ Jan06/ HFE0106_Traskpart2.pdf.