

## Why is impedance matching important:

In general sputtering or etching applications, power generators are used to transfer either DC, Medium Frequency (typically in the several kHz range) or RF (usually in the several MHz) power into a chamber where the sputtering or etching is to take place. With steady state DC power (no oscillations), there is no need for impedance matching. For Medium Frequency (MF), there is some need for impedance matching and usually deals with coupling of generator power to the load. For Radio Frequencies (RF), however, impedance matching is critically important – RF waves behave much differently than low frequency waves. Most Power generators available in the market are specified to transfer power into a 50 ohm load. This is analogous to an example shown in *figure 1*. As shown in the figure, the waves generated from the wave maker (in section A of the pool) are reflected back to the wave maker by the walls of pool A and only the waves that pass through the hole in wall are transferred into Pool B.

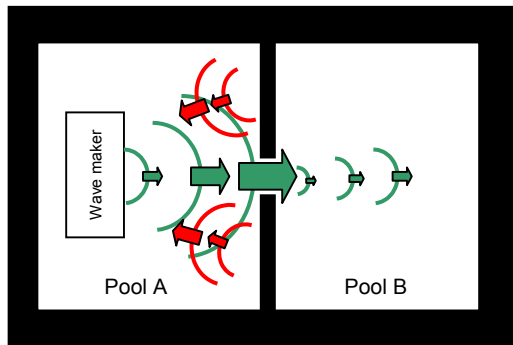


figure 1

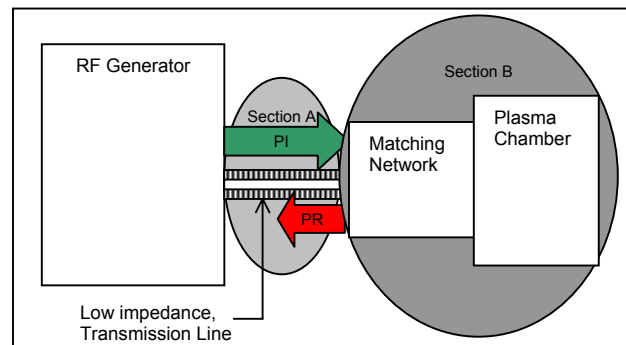


figure 2

Similarly, figure 2 shows this effect on RF systems. If, like the wave maker, the RF generator is delivering an output power of 2kW (called incident or forward power) and the matching network is not properly “tuned” (resulting, for instance, in 50% reflected power), then 1kW of power will be reflected back to the generator. This means that only 1kW is delivered to the load (plasma chamber). The combination of a high quality, low impedance, properly selected length transmission line with a properly sized (for current and impedance range) matching network can provide the best power transfer from generator to the plasma chamber. As shown in this figure, there are two sections of concern for a good power transfer. Section A – the transmission line (much like the water and surrounding walls in pool A) and Section B – the matching network and plasma chamber (similar to the wall between pool A and pool B).

## Transmission Line (Coaxial Cable):

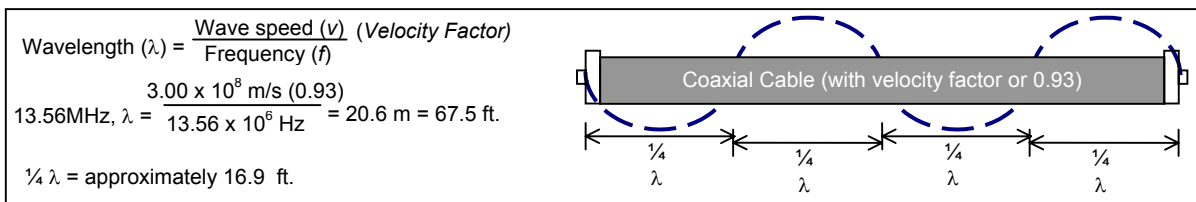


figure 3

The coaxial cable is the first section the power must transfer through before reaching the matching network. Because the matching network’s function is to “Match” the load (plasma chamber) to 50 ohm impedance – as seen from the generator, great care must be taken in selection of transmission line. The transmission line includes: coaxial cable as well as any adapters, 90 degree elbows or connectors. Each connector, each adapter and elbow adds impedance to the transmission line. For a transmission line with no adapters, the length is chosen by multiple of  $\frac{1}{4}$  wavelength size and is calculated as shown in *figure 3*. It is important to point out that wave speed (v) shown in *figure 3* is depends on the properties of the

transmission line. Wave speed can be calculated by multiplying velocity factor times speed of light ( $3 \times 10^8$  meters per second). The velocity factor of air is 1.0. Therefore, the wavelength of a 13.56MHz wave in air is calculated using formula in *figure 3* to be 22.12 meters. Not all transmission lines are alike: they each have their own velocity factors. This means that to calculate the proper RF cable length, we must first know the velocity factor of the cable.

Cable (Manufacturer specific)	Velocity Factor (13.56Mz)	Full wavelength ( $\lambda$ ) of 13.56MHz
7/8" Flexwell	0.93	20.6m (67.5')
RG 218	0.69	15.3m (50')

Transmission line lengths of non-quarter wavelengths can generate reflected power which the matchbox is unable to reduce. This is due to the reflected power being generated "upstream" from the matchbox. This effect can be called "Transmission line Reflected Power" and is illustrated by example in *figure 4*.

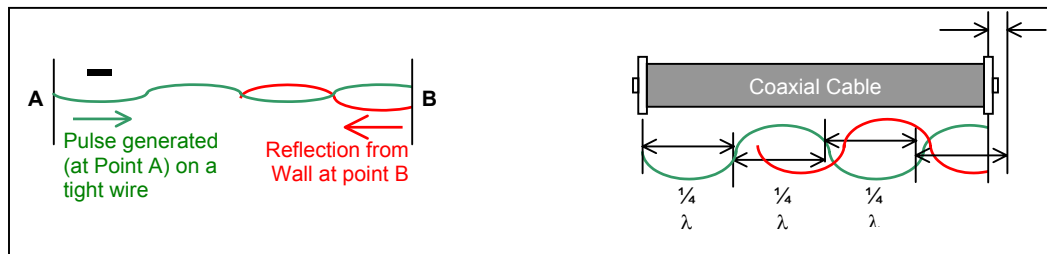


figure 4

The left picture in *figure 4* shows a pulse being generated by pushing down on a tight wire between point A and point B. If the oscillation is just right (wavelength being equal to distance between A and B) then the reflected wave is identical (in phase) to the standing wave. If the distance between A and B is shorter than the wavelength of the oscillation (as shown), then the reflected wave from point B is seen as opposite (out of phase) of the forward wave.

In addition, the attachment of adapters, connectors or elbows at the end of the coaxial cable not only adds to the wavelength of the transmission line, but can also add impedance in the form of inductance, resistance and/or capacitance. This additional impedance can also cause reflected power from matchbox to the generator that the matching network cannot reduce.

Effects of improperly sized transmission lines include:

- Presence of reflected power at the generator
- Localized heating of RF cable due to standing waves
- Harmonics present on RF cable due to presence of reflected frequencies other than 13.56MHz

## Matching Network:

There are many different designs of matching networks for different impedance and power levels. The sole purpose of the matching network is to convert the impedance of the chamber so that, viewing from the transmission line termination, the forward power sees an impedance of 50 ohms.

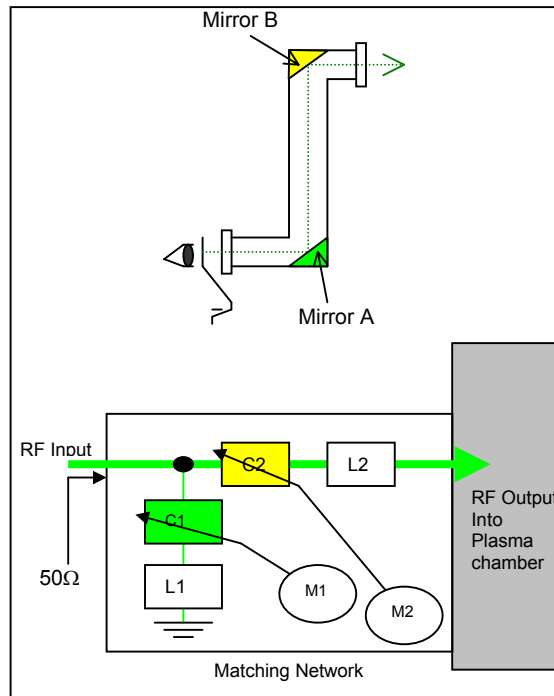


figure 5

In *figure 5*, the periscope has two mirrors (A and B). As the mirrors are aligned just so, the sight of the eye can reach to the top and outside. If the body of the periscope is made out of flexible pipe and is assumed to rotate at the corners at mirrors A and B, then the angles of the mirrors A and B would also have to move accordingly to allow the viewer see from one end through the other.

Bottom picture in *figure 5* shows an “L” type matching network. It is named “L” because the circuit consisting of C1, L1 and C2, L2 is shaped in the form of “L”. Other designs include “Pi” or “T” networks. Like the mirrors in the periscope, capacitors C1 and C2 in the matching network can be adjusted (via motors) to provide the proper settings so that the combination of the circuit with L1 and L2 can properly “tune” so that the power is transferred from Input to the plasma chamber. As with the flexible body of the periscope in above example, the Plasma Chamber is also very dynamic. Therefore, capacitors C1 and C2 should also dynamically adjust their positions to allow for continuous “tuning” of generator to load.

## The Plasma Chamber and its effects on impedance:

As discussed above, plasma chambers can have very dynamic impedance's consisting of all three components: capacitive, inductive and resistive. An example of capacitive component in a plasma chamber can arise from the close proximity of ground surface to the side walls of the target. This basically simulates the two walls of a capacitor separated by some distance. An inductance component is inherently present in any network that distributes power from matchbox to the target. In addition, as the plasma ignites, it creates its own complex impedance. An equivalent circuit for matching network, cathode, plasma and substrate can be characterized with the model in *figure 6*.

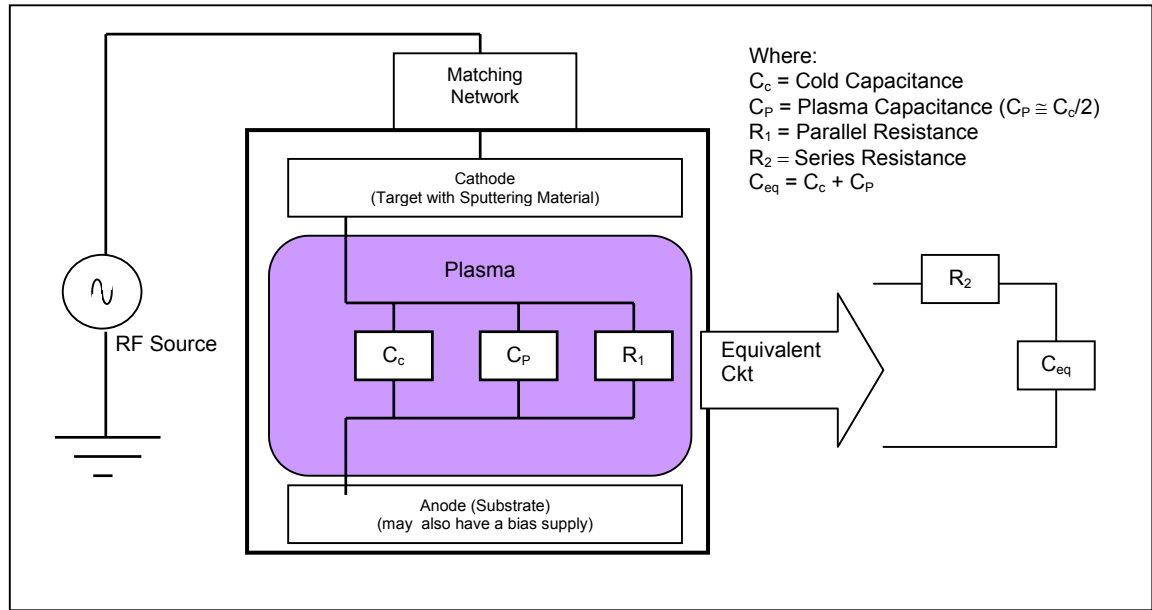


figure 6

Cold Capacitance ( $C_c$ ) can be measured with no plasma and Plasma Capacitance can be measured using a matching network and controller (i.e.: Huettinger's PFM matching network and PFC controller) that can display vector impedance coordinates of plasma chamber. The equivalent circuit on the right-hand side of figure 6 is shown to easily convert to reactance form to be later used on Smith Chart. Below are some useful formulas for converting capacitance and inductance to reactance (X with units of Ohms):

$$X_c \text{ (reactance of a capacitor)} = 1 / (2\pi fC)$$

$$X_L \text{ (reactance of an inductor)} = 2\pi fL$$

where:  $\pi = 3.1416$   
 $f$  = frequency (13.56MHz)  
 $C$  is capacitance in Farads  
 $L$  is inductance in Henrys

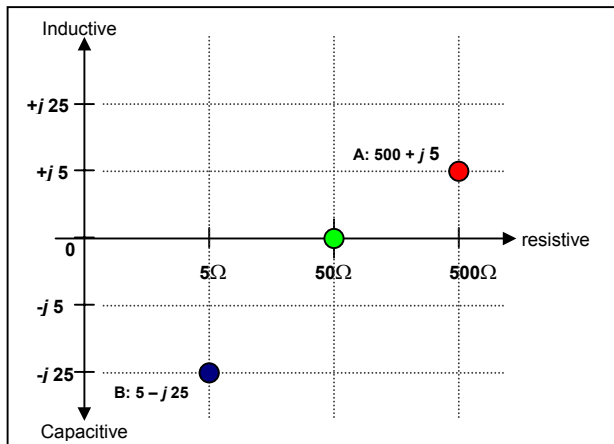


figure 7

As an example, a plasma chamber with  $C_{eq}$  of  $4.697 \times 10^{-10}$  F {or 469.7 Pico Farads} can be converted to have reactance of 25 Ohms (using the formula for  $X_c$ ) and the resistive part is assumed to be 5 ohms for this example. Therefore the total impedance,  $Z = [5 - j25]$  Ohms (resistive and reactive component).

This can be plotted in polar form with "real" (purely resistive) and "imaginary" (inductive or capacitive) axis charts. It is important to note that the reactance part above is annotated as  $-j25$  ohms using the  $-j$  sign. Capacitive reactance is noted as negative  $j$  and inductive reactance is noted with a positive  $j$ .

In figure 7, point A shows an example of chamber impedance of  $[500 + j5]$  – resistive component of 500 ohms and inductive reactance of  $+j5$  ohms. Point B is another example chamber impedance of  $[5 - j25]$  ohms -- resistive component of 5 Ohms and capacitive reactance of  $-j25$ .

As discussed earlier, purpose of the matching network is to add an additional circuit that will (looking from the generator side of the matchbox) resemble an equivalent of purely resistive 50 ohms  $[50 + j 0]$ . For this, the matchbox must successfully cancel out all inductive and capacitive reactance components of the chamber. This means, that for a plasma chamber with impedance of point **A** (in *figure 7*), the matching network would reduce the inductive reactance by 5 (or alternatively add capacitive reactance of 5) and reduce resistance of 450 ohms (500-50).

Alternatively, a chamber with impedance of point **B** (in *figure 7*), the matching network would need to reduce capacitive reactance by 25 Ohms (or add inductive reactance of 25) and increase resistance by 45 ohms (50-5) to bring resistance to 50 ohms without any reactive component.

For ease of readability, *figure 7* shows a much simpler version of a more complex chart (called the Smith Chart) used by designers of matching networks to calculate the required operating impedance range of the network. In matching network designs, it is very useful to measure and plot a normal operating impedance range of a particular plasma chamber design. By specifying a properly defined range of operating conditions, one can sometimes reduce the cost of expensive matching networks used to operate over a wider range of impedances. On the other hand, depending on the system design and process parameters, it is also conceivable that a matchbox may need to be able to handle a much wider (and possibly a specific) range of operating impedances. Because each mechanical component in the chamber influences overall impedance, it is important to remember that no two chambers will be identical and that proper care should be taken in defining operating impedance ranges.

## Plasma Impedance and Matching Network:

As discussed earlier, “cold impedance” of plasma chamber can be measured without a power supply attached to it. Although, this will change in value under the presence of gas, vacuum and ignited plasma, “cold impedance” gives the designer an indication of the chamber impedance. Typically, one can take a vector impedance meter to measure the value for either an inductive or capacitive reactance of a chamber. This value then can be plotted on an “impedance smith chart”. Then, using an “conductance smith chart” (which is basically inverse of the “impedance smith chart”), one can calculate the required impedance for the matching network. This can be quite complicated, but it is important to note that most adjustable matching networks are designed for a specific range of impedance. And, of course, fixed matching networks are designed for a particular value (with a only a slight deviation tolerance for variations in load conditions) of impedance condition. *Figure 8* shows a sample smith chart which can be used to help you determine the type of matching networks you require.

## Smith Chart:

The center horizontal line, highlighted by green, in the Smith Chart indicates “real” impedance or resistive part of the impedance. Arc lines originating from center right extending above the center line and to the left are inductive reactance lines. Arc lines extending below the center line are capacitive reactance lines. The circle highlighted in blue is the unit circle and is designated on the chart by resistance of 1.0 ohm.

Circles inside the unit circle represent constant resistance of higher than 1 ohm and logarithmically increase to infinity. Likewise, circles outside of the unit circle are resistance

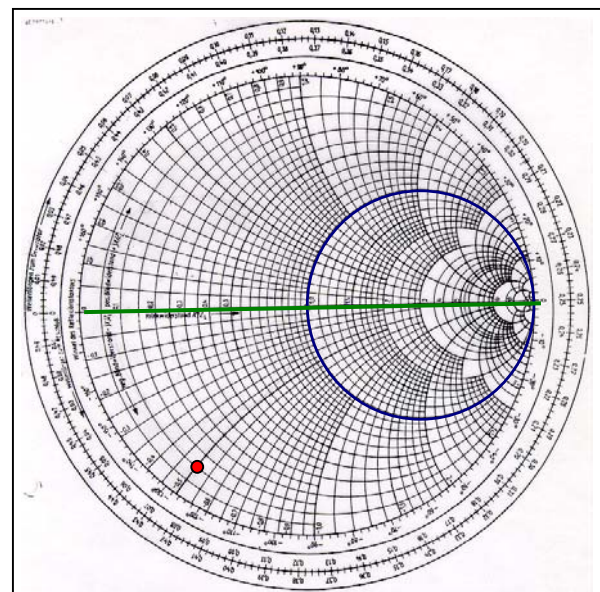


figure 8



values lower than 1 Ohm and decrease in value to 0 ohms (this is the outermost circle).

## Using the Smith Chart to calculate operating range of your plasma chamber:

“Cold impedance” is a good start to estimate the operating range of your chamber. For example, say that the impedance value you’ve measured is  $Z_{load} = 5 - j 25$  and that the RF generator is designed to match into a 50 Ohm impedance. In the previous example, we had a simple impedance chart that included resistive values of 5 ohms up to several hundred ohms. Unfortunately, the unit circle on a Smith Chart is labeled 1 Ohm and therefore, we need to convert  $Z_{load}$  to  $Z_{Smith\ Chart}$ . This can be done using the following formula:

$$Z_{Smith\ Chart} = (Z_{load}) / (50\ ohms) = (5 - j 25) / 50 = 0.1 - j 0.5$$

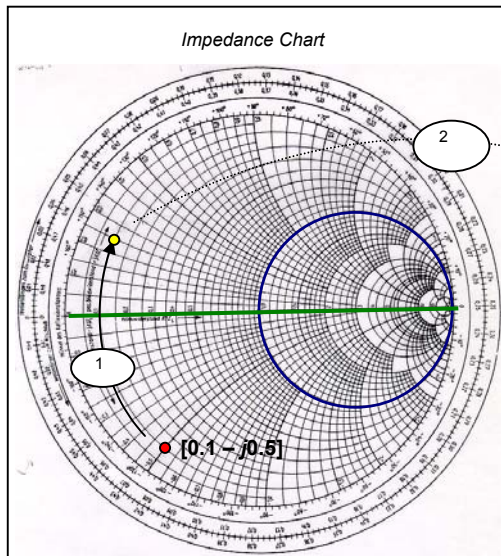


figure 9

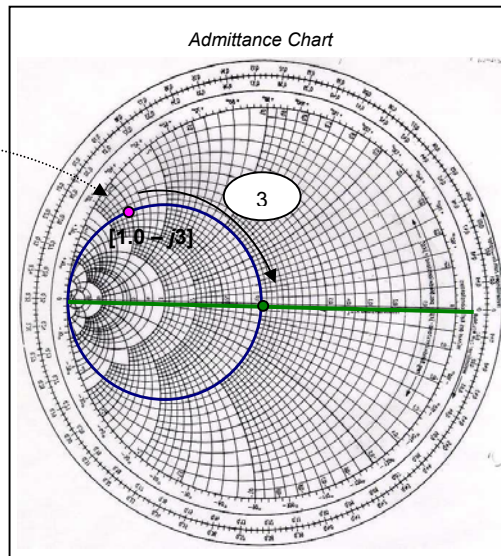


figure 10

First, this value is on the Smith Chart in *figure 9* (marked with a “red dot” at  $[0.1 - j0.5]$ ) at resistive circle of 0.1 and capacitive arc (denoted by  $-j$ ). This represents the chamber **impedance** on the Smith Chart. This is a very important characteristic of your vacuum chamber. Power requirements along with this value will determine the topology, circuitry and size of your matching network.

The matchbox is designed to bring this “red dot” in *figure 9* to the unit circle crossing with green line (resistive impedance with no reactive component). One way to do this is to follow the resistive circle line until they intersect an arc that will bring the “red dot” to the intersection of green line and unit circle (on the **admittance** chart – shown in *figure 10*). Required matching network values can be calculated using a **admittance** Smith Chart. For an **admittance** chart you would make a transparency of the original **impedance** Smith chart, flip it so that the unit circle is on the left and then line the two charts up as shown in *figure 9 and 10*.

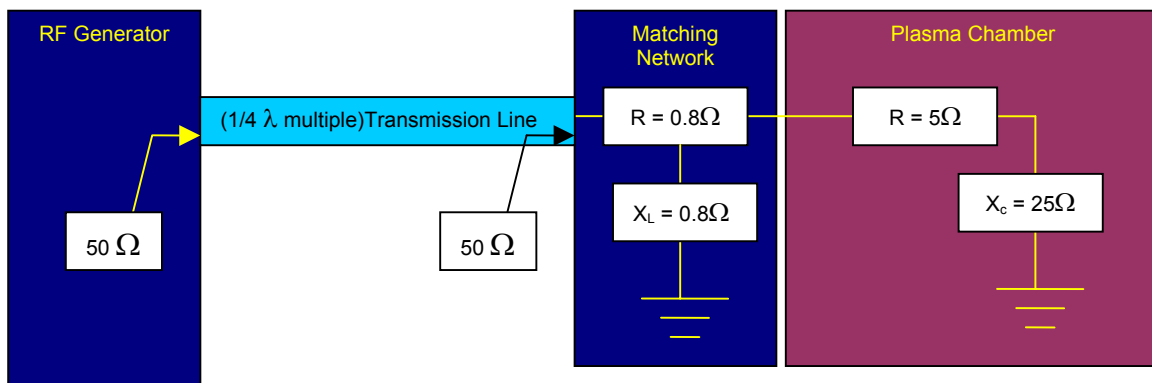
The first step is to place the transparency of admittance chart on the Impedance chart. Trace the red dot (towards the up arrow until it intersects the unit circle in upper half section of the **admittance** chart. This is shown as the “magenta dot” (in *figure 10*) on the **admittance** chart and a “yellow dot” (in *figure 9*). To get to the “yellow dot” on the **impedance** chart, the dot moved on resistive circle of 0.1 from  $-0.5$  (capacitive reactance) to  $+0.3$  (inductive reactance) on the **impedance** chart. The net move from  $-0.5$  to  $+0.3$  is **0.8 Ohms** – this is our required resistive value for the matching network.

The next step is to take the “magenta dot” on the **admittance** chart (*figure 10*) from  $-3$  to  $0$  reactance “green dot” on **admittance** chart. Resulting in a net move of **+3 admittance**.

Therefore, the matching network need to provide a **series resistance of 0.8 Ohms** and a **parallel admittance, Y, of 3.0 Mhos (or siemens)**. The admittance now must be converted to impedance and the unit circle (10hm) needs to be converted to 50 Ohms using the following set of formulas:

$Z_{\text{matching network}} = (Z_{\text{impedance}} / 50 \text{ Ohms})$	therefore, $Z_{\text{impedance}} = Z_{\text{matching network}} \times 50 \text{ Ohms}$
$1 / 50 \text{ Ohms} = 20 \text{ milli Mhos}$	$Y_{\text{matching network}} = Y / 20 \text{ milli Mhos}$
$Y = Y_{\text{matching network}} \times 20 \text{ milli Mhos}$	And $Z_{\text{matching network}} = (50 \text{ Ohms} / Y_{\text{matching network}})$
Therefore, $Z_{\text{matching network}} = (50 \text{ Ohms} / 3 \text{ Mhos}) = 16.67 \text{ Ohms}$	

This means that a matching network with an impedance,  $Z_{\text{matching network}}$  of  $[0.8 + j16.67]$  will transform the load impedance,  $Z_{\text{load impedance}}$  of  $[5 - j25]$  such that looking from the end of the transmission cable, generator will see a load impedance of 50 Ohms.



## Summary:

Because each chamber is different, there are slight changes in impedance from chamber to chamber. In addition, for similar chambers from the same production line operating under different conditions can have changes on their impedance. Varying vacuum pressure, gas type, gas purity, power level and especially moving mechanical components inside the chamber can also effect impedance to deviate from nominal operating condition. Because of this dynamic nature of plasma chambers, it is important to have the matching network compensate automatically while the process is running.

## Checklist of just some items to consider in evaluating your matching network requirements:

- ☐ Is the transmission line and its length appropriate for a particular configuration?
- ☐ Will the addition of mechanical components on the transmission line cause impedance problems?
- ☐ Does the chamber require a narrow or wide range of impedance matching capability?
- ☐ Which network design is the most cost effective for my application ("L", "π" or "T")?
- ☐ Are the tuning points of capacitors or inductors (inside the matching network) within a safe range to allow for permissible fluctuations on either side?
- ☐ Is the matching network rated for the proper current for my application?



## Application Note RF (13.56MHz) Impedance Matching

Huettinger's PFM series matching networks are built with intelligence of the algorithm to fully and AUTOMATICALLY adjust so that the impedance is continuously matched for a selected range of operating conditions. Huettinger's PFC series matching network controllers offer the following standard features:

- Impedance monitoring of  $|Z|$  and  $\angle \theta$
- RF Voltage and DC Bias
- Fiberoptic connection from matching network to controller
- AUTOMATIC or Manual mode of operating conditions

Contact your local representative to help you choose the type of matching network that your application requires.

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