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Analysis of Plasma Dipole Antenna Using Equivalent Circuit Model

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Abstract: Plasma antenna is an emerging technology that utilizes ionized gas as a conducting medium instead of metal. It is often convenient to represent the input impedance of the antenna by a lumped-element-equivalent circuit. Input impedance of the plasma dipole antenna is deduced using finite integration technique. A five-lumped-element equivalent circuit for the plasma dipole antenna variation with plasma frequency is investigated and optimized using the genetic algorithm (GA).The effect of plasma frequency of the ionized gas on input impedance variations of the plasma dipole antenna is studied with the help of the equivalent circuit model. This numerical investigation estimates the relation between the resonant frequency as well as the plasma frequency of the plasma antenna. The resonant height decreases by the plasma frequency. The numerical modeling shows that there is a specific band of plasma frequency for which the rate of variations of input impedance versus plasma frequency is minimal.

Keywords: Genetic algorithm (GA), lumped-element equivalent circuit, Plasma dipole antenna .Input impedance.

I. Introduction

Recently, the importance of using plasma technology in wireless communication has been developed due to its potential and innovativeness. Ionized plasma functions as an RF element for transmitting and receiving electromagnetic wave. This application is desirable for its ability to be on and off, in order to avoid interference and unwanted effects in the RF network. Thus, plasma antenna technology is in accordance with current and near future requirements. Plasma antenna is a type of antenna in which the metal conducting elements of a conventional antenna are replaced by plasma. Antenna made by plasma works like conventional metal antenna, in fact, it has been reported that the performance of plasma is better than performance of metal antenna in terms of resonance frequency, radiation pattern and gain [11] For antenna applications, the antenna must be maintained in precise spatial distributions such as filaments, columns, or sheets. The plasma volume can be contained in an enclosure (tube) or suspended in free space [3]. Plasma antennas use plasma elements instead of metal conductors. Such antennas are constructed from insulating tubes filled with low pressure gases. Plasma elements have a number of potential advantages over conventional metal elements for antenna design as they permit electrical, rather than mechanical control of their characteristics. In particular, for military applications, an unenergized plasma element can be difficult to detect by hostile radar if its tube is properly designed .Moreover, antenna arrays can be rapidly reconfigured without suffering perturbation from unused plasma elements. Finally, the effective length of the antenna can be changed by controlling the applied power, allowing its resonance frequency to be varied and therefore the useful bandwidth to be increased. Thus the plasma antennas have attracted many attentions all the time. For the last decade, practical unipole plasma antenna [11] and loop plasma antenna [2] have been made and reported to have similar property with metal one. In this paper, we set up a model of the dipole plasma antenna and investigate the relationship between the plasma parameters

In antenna, input impedance can be represented by an equivalent lumped-element impedance. The equivalent impedance is replacing the original antenna across the two terminals that are used to connect the antenna to a transmitter or a receiver. The input impedance at the feeding terminals depends on many factors, including the operating frequency, the method of excitation, its geometry, and its proximity to the surrounding objects [2]. Most dipole antennas are designed to operate at or near their first resonance frequency (minimum $S11$, dipole length close to $\lambda/2$). A plasma antenna consists of a glass tube, or any similar dielectric, filled with a low-pressure noble gas like argon, neon, or xenon. The radiation characteristics of a plasma antenna are electrically controlled by the applied ionizing voltage as well as the dimensions of the plasma column. The radiation characteristics of a plasma antenna are similar to a copper antenna when the signal is transmitted or received [3]. When a plasma antenna is turned OFF (the gas is not ionized), it becomes transparent and allowing other adjacent antennas to transmit or receive without interference [4]. Plasma antennas are highly reconfigurable (i.e., rapid reconfiguration of the resonant length). Plasma can be generated by dc discharge, RF discharge, or laser excitation. The input impedance of a plasma dipole antenna in free space can be accurately represented by lumped-element equivalent circuit. The literature has many articles dealing with antenna equivalent circuits [5]. The input impedance of a plasma dipole determines the efficiency of the antenna and facilitates the design of a matching network to the feed line.

The simple equivalent circuit is just a series resonant circuit (to deal with the first resonance of the antenna) connected in series with a parallel resonant circuit (to deal with the first anti resonance of the antenna). The elements of the compound circuit can be adjusted to produce the same behavior of the antenna input impedance in the considered range of frequency. A resistance Rp is added to cope with the radiation [6].Equivalent circuit can be used in many ways to: 1) replace an antenna with its equivalent dummy load for measurement purposes; 2) determine the antenna matching circuit; and 3) understand the antenna operation. The disadvantage of the lumped-element model is that the representation of each additional overtone response requires another circuit branch. Antennas, normally, have overtone responses, but lumped element circuits do not [7].

In this paper, an equivalent lumped-element circuit model is proposed for representing the plasma dipole antenna. It demonstrates the effect of changing the component values of the equivalent circuit model in comparison with the plasma frequency and collision frequency of the simulated plasma dipole. Different optimization techniques can be used for estimating the values of the lumped-element equivalent circuit of the antenna over its frequency band [9]. A genetic algorithm (GA) technique is used to optimize the equivalent circuit of the plasma dipole antenna. GA is very easy to understand and can be employed for a wide variety of optimization problems. It performs very well for large scale problems that may be very difficult or impossible to solve by other traditional methods. The antenna is simulated using the finite integration technique (FIT) as a full wave numerical modeling tool and the results are compared with the results obtained from the equivalent lumped-element circuits. The use of a GA [10] is demonstrated to optimize a conventional lumped-components antenna equivalent circuit model for the best impedance fidelity over the considered frequency band. Another circuit model is presented using a rational function of reasonable order. The GA is utilized to determine the optimum values of the elements of the equivalent circuit with the help of model-based parameter estimation (MBPE) technique.

II. Principle of Plasma Antenna

Plasma is a dispersive medium. The reflective index of uniform plasma under low electron-neutral collision rate assumption is as follow:

$$n^2 = \epsilon_r = 1 + \frac{\omega_p^2}{\omega(j\nu-\omega)} = 1 - \frac{\omega_p^2}{\omega^2+\nu^2} - j\frac{\nu}{\omega}\,\frac{\omega_p^2}{\omega^2+\nu^2} \tag{1}$$

where

ϵ_r is complex relative permittivity of plasma [F/m],
ω is the frequency [rad/s], ν is the electron-neutral
collision frequency(Hz). ω_p is the plasma frequency given [rad/s] by

$$\omega_p = (n_0\, e^2 / m_e\, e^2)^{1/2} \tag{2}$$

n_0 is the electron density [m^{-3}], me is the electron mass [*kg*]
e is the charge of the electron [C].
The collision frequency is given by [13]

$$\nu p = ne\, k(Te) \tag{3}$$

where k is Boltzmann’s constant and T_e is the free electrons temperature within the plasma (the measure of kinetic energy of free electrons). When the plasma electron density is large enough, the plasma shows good electrical conductivity, which can effectively act as an antenna radiating elements. The conductivity of plasma can be expressed as follows:

$$\sigma = \epsilon_0 \frac{\omega_p^2}{\nu} \tag{4}$$

From Eq.(4), we find that the conductivity σ depends on ω_p and ν in the plasma. If ω_p or ν varies, σ will be changed, which results in different characteristic of the electromagnetic wave .Following the analysis of [8], the plasma density is found from a power balance in which the power absorbed per unit length by the plasma from the surface wave the plasma column is balanced by the power per unit length lost to the walls from the plasma by the migration of electron-ion pairs at the Bohm velocity. According to this relationship, the availability of plasma density 0 *n* and effective length of the antenna *h* are expressed as follows:

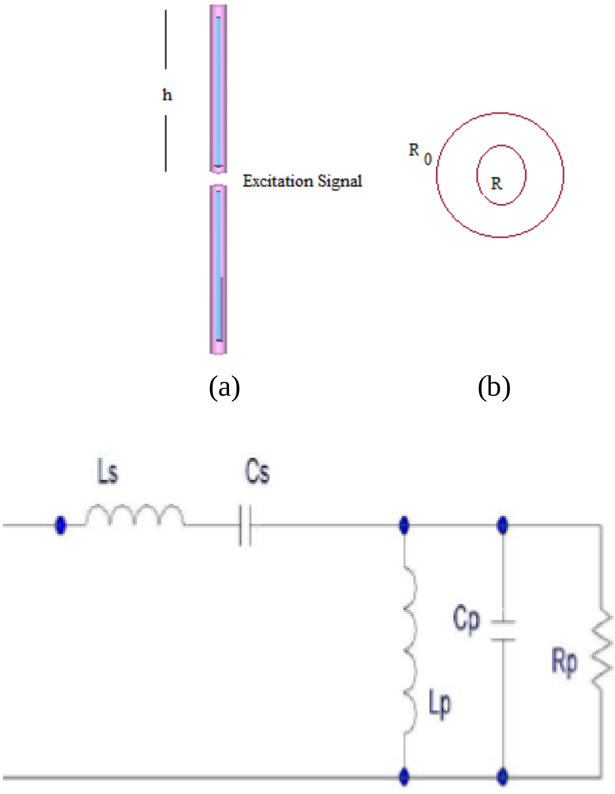
$$n_0 = A(P)\sqrt{P_0} \qquad (5)$$

$$h_0 \approx B\,(\,P\,)\sqrt{P_0} \qquad (6)$$

Where P is filling press, *P*0 is input power. Equation (5) and Equation (6) show that for a given pressure, plasma density and effective length of the antenna should increase as the square root of the applied power. Hence, given a transmitting frequency, it should be possible to produce the correct plasma density and effective length of the antenna for a dipole antenna by controlling the applied power. However. since the plasma density and conductivity of the antenna varies along its length, the physical length of the plasma column is not necessarily the same as the electrical length of the antenna.

III. Genetic Optimization

GA technique is quite suitable to optimize the equivalent circuit models of plasma dipole antenna. GAs are powerful and widely applicable search and optimization methods. GAs are applying the principle of the survival of the fittest [10]. It is started with a set of solutions represented by species known as chromosomes. This number of chromosomes in a certain step is usually called a population.



(a) (b)

(c)

Fig. 1. Detailed structure of the plasma dipole antenna. (a) Side view (b) Top view. c) Lumped-element equivalent circuit

Solutions from one population are taken and used to form a new population for a better one. Solutions that are selected to form a new population are selected according to their fitness. Comparison with a suitable objective function *G* identifies the best performance chromosomes of each generation; the objective function is given by [15]

$$G = \sum_{n=1}^{N_f} [(R_e^{FIT}(F_n) - (R_e^{GA}(F_n))^2 + (I_m^{FIT}(F_n) - I_m^{GA}(F_n))^2]$$

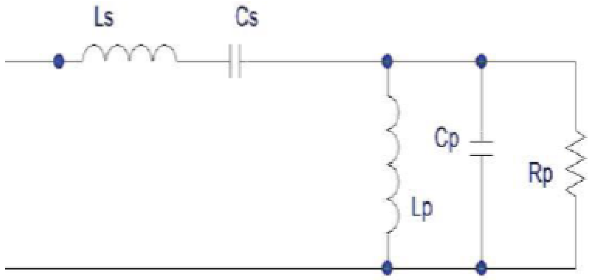
where N_f is the number of frequency points within the considered range of frequencies with those points are usually selected to be uniformly spaced. R_e^{FIT} (F_n) and $I_m^{FIT}(F_n)$ are the real and imaginary parts of the impedance of the lumped element circuit resulting from applying the FIT, respectively. $R_e^{GA}(F_n)$ and $I_m^{GA}(F_n)$ are the real and imaginary components of the equivalent circuit model worked out by the GA.

IV. Numerical Result Analysis

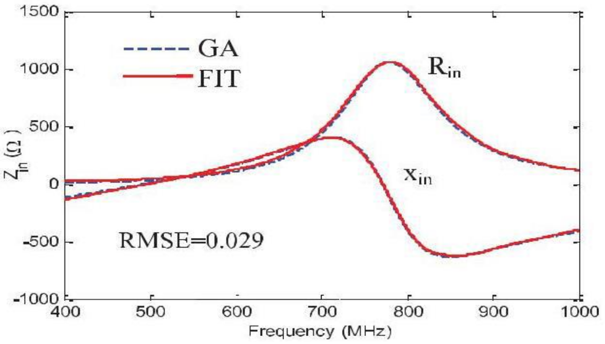
A. Plasma Dipole Antenna:

The construction of a plasma dipole antenna is shown in Fig. 1(a). The plasma dipole antenna consists of a hollow cylindrical dielectric tube with a dielectric constant $\varepsilon r = 3.4$,

an outer radius $Ro = 2.5$ mm, an inner radius $Ri = 2$ mm,and a length $h = 110$ mm filled with argon gas with plasma parameters $f\ p = 28.7$ GHz and $\upsilon p = 200$ kHz.The equivalent circuit model of plasma dipole antenna ,its parameters extraction,and validation of circuit model is shown in fig 1(c). The proposed equivalent circuit model of a dipole antenna operating in its first resonant region.the circuit model consists of Z_s (L_s in series with C_s) in series with a parallel RLC network (L_P, C_P , R_P) designated as Z_P..The series section represents the antenna's first resonant at input terminals while the parallel resonator section represents the first anti resonance of the dipole antenna. Thus, investigation is done only at the first resonance and the first antiresonance for the dipole. The plasma dipole antenna is designed and simulated using FIT,and then the input impedance data are fitted to the equivalent lumped-element circuit model using the GA to calculate the values of the five lumped elements *Ls* , *Cs* , *L p*, *Cp*, and *Rp*. Good agreement between the two input impedance variation is depicted as shown in Fig. 2



LS=8.03nH, CS=1.384 Pf, LP=39.60nH, CP=1.07pF, RP= 1.15KΩ



(b)

Fig. 2. (a) Lumped-element equivalent circuit for plasma dipole antenna (b) Variation of the input impedance versus frequency for the plasma dipole antenna with $h = 110$ mm, $f\ p = 28.7$ GHz, and $\upsilon p = 200$ kHz.

B. Effect of Plasma Frequency:

The effects of the plasma frequency on different elements of the equivalent circuit model and the resonant frequency of the plasma dipole antenna are presented in this section. The collision frequency of and ν_P = 200 kHz and the antenna length and radius of *h* = 110 mm and an outer radius *Ro* = 2.5 mm, an inner radius *R* = 2 mm are used for numerical simulations. The results reveal that increasing the plasma frequency shifts up the antenna input impedance curves to higher frequencies. In order to study the effect of changing the plasma frequency on the elements of the equivalent circuit model, the values of the lumped element equivalent circuit are extracted from the simulated input impedance. By increasing the plasma frequency f_P, the resonant frequency shifts up to a higher frequency and the impedance matching is varied due to the change of the effective length of the plasma dipole antenna and the change of plasma conductivity as shown in Fig. 3.This boundary frequency depends on the antenna dimension, physical characteristics of plasma and the operating frequency. It is known that the electrical conductivity is a major factor which plays a dominant role in altering the resonant frequency of a dipole antenna. The conductivity of ionized plasma is a function of operating, plasma and collision frequencies. The operating frequency is kept constant at *f* = 499 MHz for the results given in Fig. 3. From (4), as ω_P goes higher, the conductivity σ' goes higher.

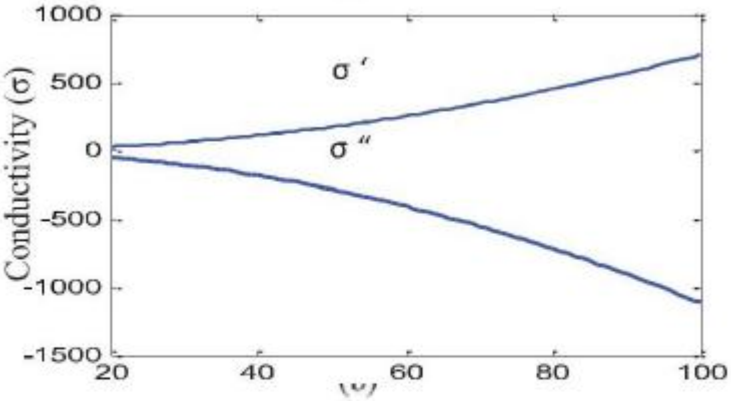


Fig. 3. Variation of conductivity versus plasma frequency.

As the plasma frequency is increased, the maximum resistance is decreased and shifts up to a higher frequency. The GA is used to fit the simulated input impedance data to the lumped-element equivalent circuit to end up with the values of the equivalent circuit elements given in Table I.

Table I :Values Of Circuit Element For Plasma Dipole Antenna For Different Plasma Frequencies

Components			Frequency f_P (GHz)			
28.8	33.8	38.8	43.8	50.3		100
LS (nH)	8.03	7.80	7.74	7.71	5.70	5.50
CS(pF)	1.384	1.38	1.35	1.37	1.35	1.36
RP(Ω)	1150	918	866.60	820.1	797	692
CP(pF)	1.07	1.20	1.148	1.27	1.07	1.16
LP(nH)	39.60	36.89	37.03	32.61	37.1	32.2

A comparison between the input impedance determined using FIT and that determined from the equivalent circuit model for different plasma frequencies is shown in Figs. 4

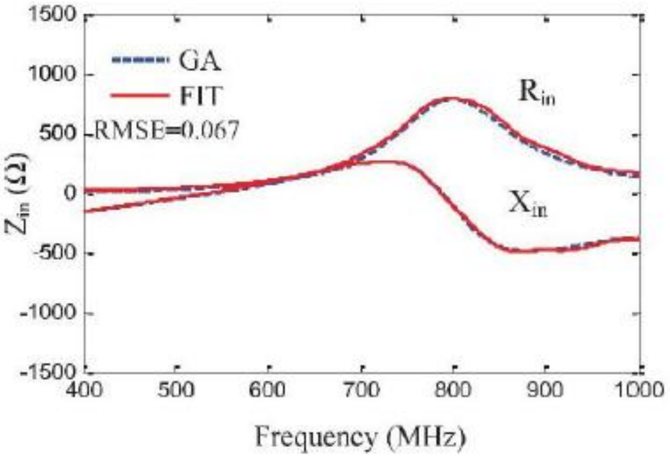
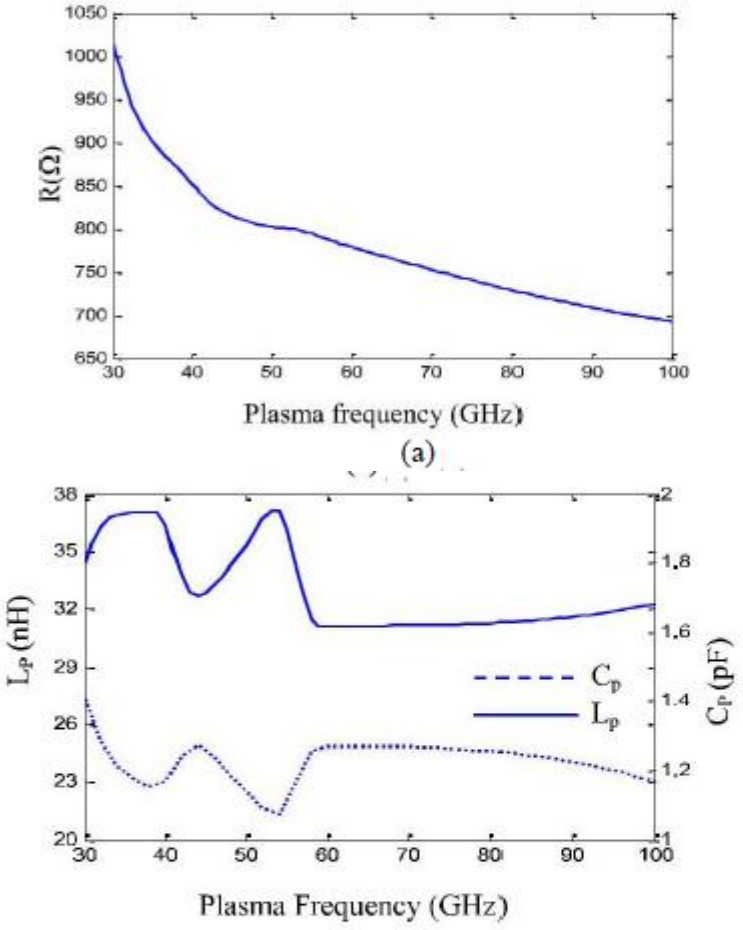
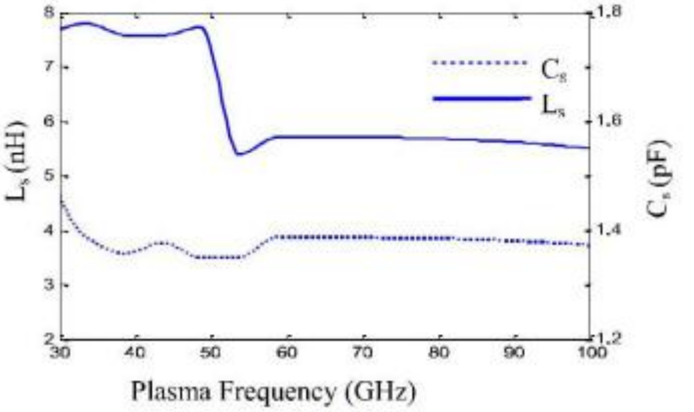


Fig. 4. Variation of the input impedance of dipole versus frequency for different plasma frequencies at v_P 200 kHz. *And* f p = 100 GHz.

The resistance R_p is decreased by increasing the plasma frequency, while the inductors (L_s , L_p) have an opposite behavior with capacitors (C_s , C_p), respectively, up to plasma frequency f_P and the response is approximately fixed for higher plasma frequency. The frequency range selected for operation is far lower than the plasma frequency, and by increasing the plasma frequency, the conductivity will increase to reach the case of a good electric conductor. The relations between the elements of the lumped circuit and the plasma frequency are shown in Fig. 5.



(b)



(c)

Fig. 5. (a) Variation of R_P of lumped-element equivalent circuit versus plasma frequency. (b) Variation of L_P and C_P of lumped-element equivalent circuit versus plasma frequency. (c) Variation of L_S and C_S of lumped-element equivalent circuit versus plasma frequency.

V. Conclusion

Numerical analysis of Effect of plasma frequency on input impedance variations of the plasma dipole antenna is studied. A GA technique is used to optimize two equivalent circuits for the plasma dipole antenna.A lumped element circuit has been proposed as an equivalent circuit model for the plasma dipole antenna which consists of a series *LsC*s circuit connected to the parallel *RpLpCp*. The series elements represent the first resonance of the dipole, and the parallel circuit represents the first antiresonance effect of the dipole length. By increasing the plasma frequency fP, the antiresonance frequency shifts up to a higher frequency and the impedance matching is varied due to the change in the conductivity of the plasma, the resonant frequency and the antenna input impedance almost are not affected.It affects the equivalent lumped element circuit values in a nearly constant rate. Variation of the components of the equivalent lumped circuit model with changing the plasma frequency is also studied. It has been shown that the dependency of the equivalent circuit to the plasma frequency creates two different regions: fast and slow impedance variation regions. In the slow impedance variation region, variations of the plasma frequency have small effects on the components of the equivalent circuit.

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