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Research paper

Design and Fabrication of Coaxial Plasma Waveguide Filter with the Ability to Reconfigure the Frequency Band

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Abstract

Background and Objectives: This study aims to present a new structure based on coaxial waveguide, which can change the bandwidth, return losses, and input impedance by changing the plasma parameters of the coaxial waveguide. This structure consists of a metal body and a gas tube inside it, which uses a high voltage alternating current converter, can change the plasma parameters and, consequently the waveguide parameters. The input and output of the waveguide are also designed using the indirect capacitive coupling method.

Methods: In the Field of plasma research and related emerging technologies, recently, it has achieved a special place in various industries such as radar and Aerospace industries. The creation of telecommunication structures such as antennas and Waveguides with plasma, has given features such as adaptability, the ability to reconfigure the characteristics of the structure, and improve the sensitivity of this type of structure.

Results: By applying and changing the plasma excitation parameters, a change in the bandwidth was observed in the frequency band range of 0.5-4 GHz and a maximum of 1.38 GHz. Also, increasing the intensity of the excitation current improved the return losses in the resonance frequencies and, on the other hand, increased the band ripple.

Conclusion: According to the results, the change of Plasma parameters depends on the change of plasma excitation frequency, and the value of Excitation current applied. As the Value of excitation current increases, the matching to the resonance frequencies improves, but on the other hand, the passband ripple of the plasma waveguide filter increases. As the plasma excitation pulse frequency increases, the bandwidth and resonance frequencies change to higher frequencies, and the matching to the resonance frequencies improves. But on the other hand, the passband ripple increases. This new waveguide filter can be used in cognitive/ adaptive telecommunication systems due to the constant change of frequency band.

Introduction

With the idea of using Plasma as a substitute for metal in telecommunication structures [1], researchers have made great efforts make the most of this material with its special properties. In recent years, various researches have been conducted in the field of plasma structures in radio frequencies, including plasma waveguides [2], plasma antennas [3]-[4]. and, frequency selective Surfaces [5]-[6]. Plasma is a highly ionized gas whose number of free electrons is approximately equal to the number of its positive ions and is commonly referred to as the fourth state of matter [7]. The existence of plasma was first proven by Sirviliam Crooks in 1879.

Plasma can be generated by a variety of methods, some of which include: AC and DC excitation [8]-[9], radio frequency (RF) excitation [10], high power pulsed laser [11], and high-energy (nuclear) methods [12]. Meanwhile, the high plasma ionization capability has made it possible to use it as a substitute for metal in microwave conducting structures [13]. In metal, free electrons move and radiate along the metal conductor, causing electromagnetic fields to pass through or radiate. in Plasma, electrons released from positive ions formed during the ionization process [14]. They pass or radiate electromagnetic fields. The difference between metal and plasma RF structures does not end here. For example, plasma waveguides, unlike metal waveguides, have a reconfiguration property [15] and can be changed and controlled by plasma parameters such as plasma frequency, collision frequency, and plasma density, waveguide parameters from Sentences change the frequency bandwidth, Reflection coefficient of the passing band, ripple of the passing band and input impedance, a new generation of controllable and flexible waveguides. Certainly, the nanosecond rate of change of plasma parameters is remarkable compared to the speed of mechanical change of metal structures and the many advantages of Plasma. Waveguides are used in telecommunication systems to transmit a wave from the generating part to the antenna and vice versa or to transmit a wave between different parts of a RF system [16]. Waveguides have different dimensions, shapes, and types depending on the application and transmission wave parameters [17].

Due to the dependence of their parameters on their physics, waveguides also have different filtering capabilities and, consequently, have their frequency bandwidth [18]. In some telecommunication systems, such as some meteorological and monitoring radars, depending on transmitter/receiver system, it is sometimes necessary to change the frequency of the wave transmitted from the generator and then transmit it to the antenna [19]. In this case, the use of broadband waveguides will be used. Broadband waveguides have their advantages and disadvantages as power limitation, ripple bandwidth, and fixed input impedance, and high manufacturing costs [20].

In the field of adaptive/ cognitive radars, continuous and instantaneous frequency band change is very important [21]-[22]. Therefore, various filters have been designed and manufactured for this purpose. Configurable filters are usually microstrip, which is pass frequency band controlled by MEMS devices or PIN Diode. The most important disadvantage of these structures is the low power and step change(Discontinuity in change) of bandwidth [23]-[24].

The system proposed in this paper is a reconfigurable coaxial plasma filter waveguide in terms of the frequency band, ripple bandwidth, and input impedance. The system follows a coaxial waveguide-based plasma structure consisting of a plasma tube, body, capacitive couplers, and alternating high voltage excitation circuit. The proposed system will be able to change the plasma parameters such as plasma frequency and collision frequency by changing the output frequency or input current of the excitation circuit. By changing the plasma parameters, the waveguide parameters can be configured and controlled. Weakpoints of the proposed structure are sensitivity to temperature stresses, need for independent high voltage excitation circuit, and more passband ripple than conventional filters. Section 2 deals with the theory and parameters of Plasma. Section 3 deals with the results of coaxial plasma waveguide simulation, and Section 4 describes the laboratory method of coaxial plasma waveguide test with the proposed Excitation. Section 5 deals with the results of applying Excitation current waveforms at variable frequencies to coaxial waveguide parameters. Finally, the conclusion will be made.

Theory and Parameters of Plasma

The fourth state of matter is called Plasma. Plasma is a quasi-neutralized ionized gas that has lost all or a significant portion of its atoms to one or more electrons and become positive ions. This highly ionized gas equals the number of free ions in its positive electrons. The degree of ionization can vary from 100% (fully ionized gases) to low degrees (partially ionized) [25]. Plasma can be created by electric and magnetic fields, radiated heating, and laser excitation. The electric method itself is divided into two sections: alternating current and direct current. In the field of plasma antennas, it should always be noted that the plasma frequency (ω_p) is quite different from the frequency of the RF Structure (ω) and must be distinguished. The plasma frequency is the measure of plasma ionization, while the frequency of the plasma antenna is the frequency at which the plasma antenna transmits and receives. The plasma frequency of a metal antenna in the X-ray range of the stabilized electromagnetic spectrum means that it has a plasma frequency equal to 30 PetaHertz(3×10^{16}) up to 30 ExaHertz(3×10^{19}). Still, the plasma frequency of the plasma antenna can vary. Plasma, an environment that contains free charge, generates natural oscillations due to thermal and electrical disturbances. Because of these coordinate oscillations, the density of electrons can oscillate around the angular frequency (ω_p) [26].

Because the Plasma is a dispersive material, it has its own electrical and magnetic properties, which occur at different excitations, each depending on the type of Excitation. As mentioned, the plasma environment is homogeneous, nonlinear, and dispersive in terms of electromagnetic properties. Therefore, its electrical and magnetic parameters can vary depending on the frequency and other factors, and consequently the Plasma is an environment with special properties. Thus, the Plasma behaves differently against the electromagnetic waves emitted at each specific frequency and different degrees of ionization. Electromagnetic waves are transmitted, scattered, or transmitted by radiation to the Plasma [27]-[28].

The relation between the electrons and the electric field in the excitation state with alternating current is as follows [10]:

$$F = eE = eE_0 e^{-j\omega t} = \frac{d}{dt}(mv) \tag{1}$$

$$\frac{d}{dt}(mv) = m\frac{dv}{dt} + mv\upsilon_c \tag{2}$$

$$v = \left(\frac{e}{m}\right)\frac{1}{\upsilon_c - j\omega}E \tag{3}$$

where F is the electric force, υ_c is the plasma collision frequency, v is the velocity of the electron under the field E, e is the electron charge, and m is the mass of the electron. These interpretations, plasma inner surface current, are defined by (4):

$$J = n_e ev = \left(\frac{n_e e^2}{m}\right)\frac{1}{\upsilon_c - j\omega}E \tag{4}$$

where n_e is the density of free electrons per cubic meter. Plasma discharge power can be written as (5), and Plasma electrical permeability is also described by (6):

$$P = J.E = \left(\frac{n_e e^2}{m}\right)\frac{E^2 e^{-2j\omega t}}{\upsilon_c - j\omega} \tag{5}$$

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega(\omega - j\Upsilon)} = 1 - \frac{\omega_p^2}{\omega^2 + \Upsilon^2} - \frac{j\Upsilon}{\omega}\frac{\omega_p^2}{\omega^2 + \Upsilon^2} \tag{6}$$

$$\omega_p = \left(\frac{n_e e^2}{m_e \varepsilon_0}\right)^{\frac{1}{2}} \tag{7}$$

$$f_p = \frac{\omega_p}{2\pi} \approx 9000\sqrt{n_e} \quad (Hz) \tag{8}$$

$$\gamma = \alpha + j\beta = jk_0\sqrt{\mu_r \varepsilon_r} \tag{9}$$

where ω_p is the plasma frequency, and ϒ is the natural collision frequency of the electron. The Plasma in this experiment has low temperature and is unbalanced. In other words, the temperature of the electrons is higher than the temperature of the ions [29]. As a result, the plasma frequency is calculated according to (7). By placing the values of the charge and mass of the electron on (7), (8) will result. According to (6), if the wave frequency delivered to the plasma surface is greater than the plasma frequency, that is, $\omega > \omega_p$, in this case, the propagation constant (γ) is imaginary (9), and the Plasma is found for the wave as a transparent medium, and the wave from It passes. However, if the frequency of the wave delivered to the plasma is lower than the plasma frequency, that is $< \omega_p$, in this case, the wave propagation constant is real, the wave does not pass through the Plasma, and the Plasma acts as a metal [27].

Simulation of Coaxial Plasma Waveguide Filter

Initially, to evaluate the proper functioning of the coaxial plasma waveguide filter, it was simulated with CST software. This software, which is one of the most powerful software in the field of antenna and microwave simulation, can simulate Dispersive environments with special properties such as plasma. The model used in this software for plasma simulation is called the Drude model. to create the structure of Plasma, this model requires two main parameters of Plasma, namely collision frequency, and plasma frequency. Fig. 1 and Fig. 2 show the simulation scheme of a coaxial plasma waveguide filter.

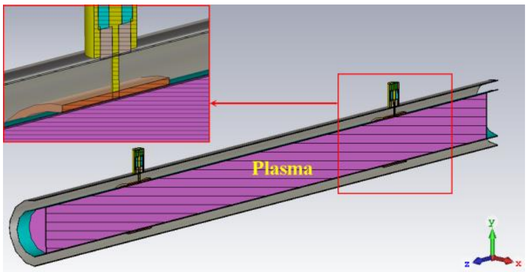

Fig. 1: Capacitive coupler view with connector and cut view of coaxial plasma waveguide filter.

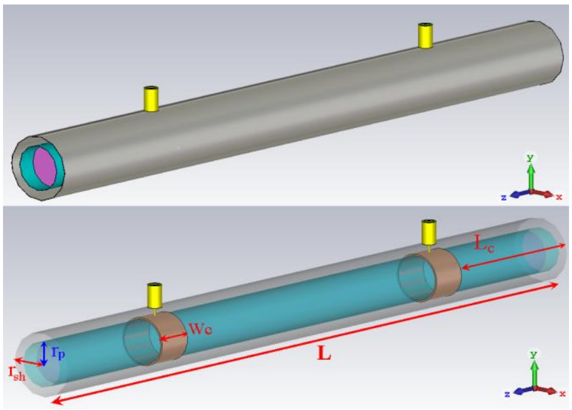

Fig. 2: Full and transparent view from inside the structure of coaxial plasma waveguide filter with details and parameters.

physical parameters of waveguide filter, including waveguide length, tube glass radius, Shield radius, coupler width, and capacitive coupler distance from the end of the waveguide.It is presented in Table 1. It should be noted that the values of these parameters are defined based on the actual values of the 9-watt linear fluorescent lamp.

Table 1: Physical parameters of simulated plasma waveguide filter

Size (mm)	parameter of the waveguide
200	waveguide length(L)
7	tube glass radius(r_p)
20	Shield radius (r_{sh})
10	coupler width(W_c)
30	capacitive coupler distance from the end of the waveguide(L_c)

Then, by calculating these two parameters using the above relations and in different excitation frequency values, the plasma frequency value (ω_p) is 3.6×10^{11}, 2.6×10^{11}, and 1.6×10^{11}, and the collision frequency (υ_c) is defined in all three cases 4×10^8. Fig. 3 shows the S-parameter for different plasma frequencies.

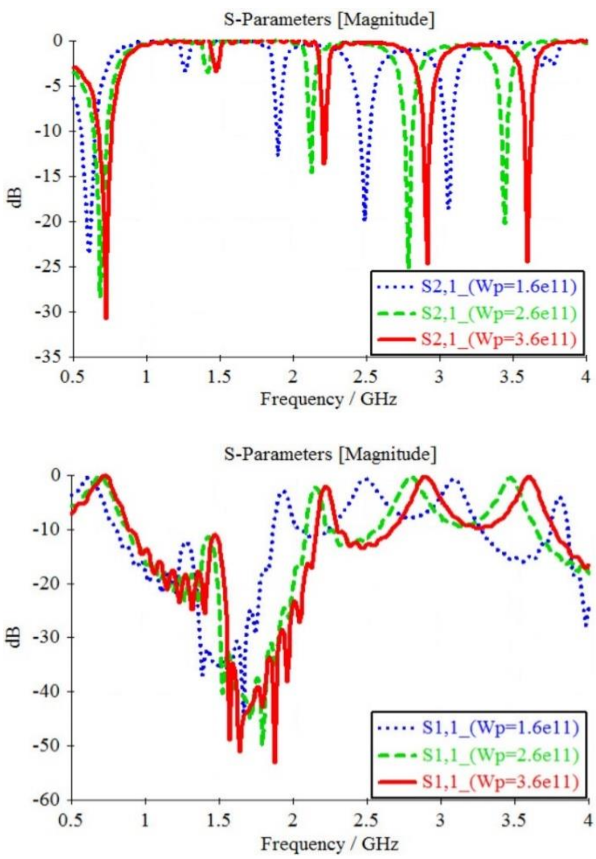

Fig. 3: S-parameter of simulated coaxial plasma waveguide filter at different plasma frequencies.

As you can see, the waveguide with plasma frequency transmits the wave in the bands 1-2, 2.2-2.8, and 3-3.5 GHz, which with the change of the plasma frequency (ω_p), the values of the resonance frequencies and the bandwidths decrease. On the other hand, by reducing the plasma frequency, the matching in the resonance frequencies decreases, which can be compensated by increasing the collision frequency (υ_c).

The simulation results of the matching reduction compensation at low plasma frequencies with increasing collision frequency (υ_c) are shown in Fig. 4. In plasma frequency 1.6×10^{11}, the value of collision frequency is increased from 4×10^8 to the value of 1.4×10^9, and the results are recorded. As can be seen, the matching to the resonance frequencies is improved, but on the other hand, the ripple bandwidth is increased, which is not desirable. For Coaxial Plasma Waveguide Filter operation at higher pass frequencies, It is necessary that Increase the plasma frequency($\omega < \omega_p$). On the other, the plasma frequency will not increase to a certain extent, because it depends on the density and material of the gas used, the value of excitation voltage and current, and the size of the gas tube. By changing the mentioned parameters (in order to increase the plasma frequency), the dimensions of the structure will increase and the pass frequency band of Plasma Waveguide Filter will decrease. Also, in this structure, due to its special design (coaxial waveguide) at higher frequencies, high-order modes are excited and the structure will not be a TEM transmission line [30].

In the following, the laboratory equipment and how to change the plasma parameters to change and improve the plasma coaxial waveguide parameters are discussed.

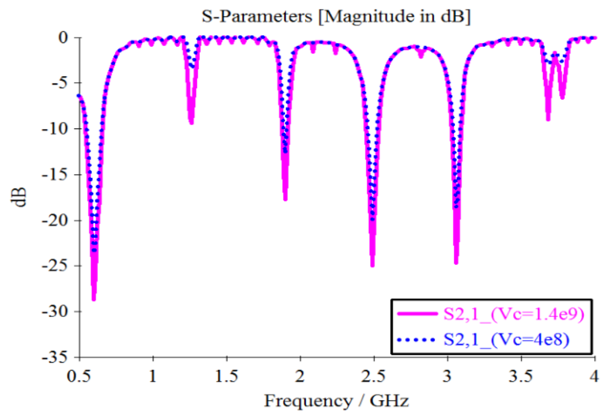

Fig. 4: S-parameter of coaxial plasma waveguide filter with constant plasma frequency and increase of collision frequency to compensate for the reduction of matching.

Implementation of Coaxial Plasma Waveguide Filter and Excitation Circuits

In this section, According to the simulation results, the construction and design the coaxial plasma waveguide filter and its most important part, the excitation circuit, are discussed. To implement the structure of the plasma tube, a 9-watt linear fluorescent lamp is used, which has an effective length of 20 cm. Since the designed waveguide is of coaxial type and needs a metal body (shield), an aluminum tube with a thickness of 0.5 mm and a length of 20 cm has been used as a metal body. The whole set of excitation circuits is embedded in one box. Fig. 5 shows a general schematic of the laboratory equipment.

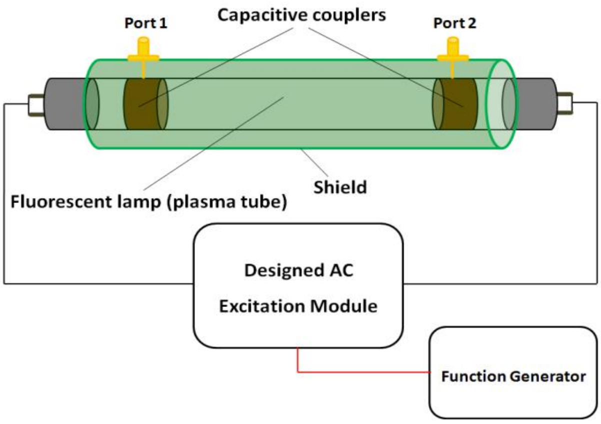

Fig. 5: Schematic of laboratory equipment to test plasma coaxial waveguide filter.

Fig. 6 shows the view of the plasma coaxial waveguide filter. It should be noted, however, that it is not possible to measure the parameters of the Drude model, plasma frequency, and collision frequency without access to the Plasma inside the tube (by Langmuir probe), so the exact Value of these parameters varies in different stimuli. And so far, there is no clear method for measuring or calculating them. Therefore, in the measurements section of this article, the exact Value can not be calculated for them, and only the waveguide parameters are considered.

Fig. 6: Real view of plasma coaxial waveguide filter.

Plasma Excitation Circuits

Since the change of plasma parameters to change and improve the waveguide parameters depends on the excitation circuits, the excitation circuit was designed with several capabilities [31]. The circuit in Fig. 7 can generate pulses from 500 Hz to 40 kHz using an internal stable multi-vibrator circuit. But since we want to test the excitation current with different waveforms, we have a wider frequency and, at the same time, change the excitation voltage and current by the function generator. Using the key embedded in the surge box, we will be able to change the excitation circuit state by applying an internal excitation waveform (stable multi-vibrator) to an external excitation waveform (function generator). The transistor used acts as a buffer to provide more excitation current.

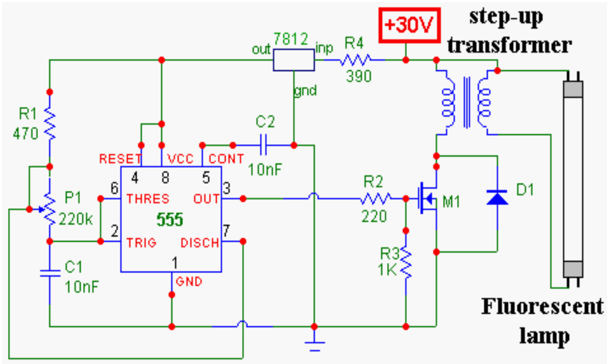

Fig. 7: Plasma AC excitation circuit with the ability to apply adjustable internal and external excitation waveforms.

The function generator device is used to apply the external excitation waveforms and adjust the frequency and amplitude of the wave. Depending on the supply voltage and the amplitude of the applied waveform, this circuit can generate an output voltage of 500 to 20,000 volts. The output current is also 0.1 to 1 amp, depending on the input values.

Signal Coupler

Because there is no direct access to the Plasma inside the tube to send or receive radio signals, as with conventional metal waveguides, we have to use a signal coupler. This coupler consists of a conductive copper strip with a thickness of 0.1 mm and a width of 1 cm, which is wrapped around the two ends of the lamp at a distance of 4 cm from the ends of the fluorescent lamp. The SMA connector core is connected to this coupler, and its body is connected to a metal body (Shield). Fig. 8 shows how the capacitive couplers of the signal are positioned around the two ends of the fluorescent tube and a view of the coaxial waveguide.

Fig. 8: Connecting the capacitive signal coupler to the fluorescent tube.

Plasma Coaxial Waveguide Test

To test the plasma coaxial waveguide with different excitation frequencies and its effect on plasma parameters and compare it with the simulation results of a function generator device manufactured by EZ-Digital with model FG-7005C and to Plasma waveguide, S-parameter was measured using an Agilent network vector analyzer (VNA) model E5071C. After applying the Excitation to the fluorescent lamp and keeping the input current to the module constant, as well as the amplitude of the external Excitation waveform, the measurement parameter and its results were recorded Fig. 9.

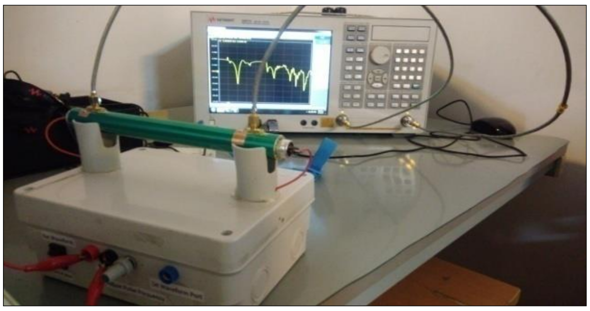

Fig. 9: Measurement of waveguide filter parameter with VNA.

Fig. 10 shows an example of parameter measurement using a VNA device. In the following, the results obtained from measuring and changing the input current and excitation frequency are discussed.

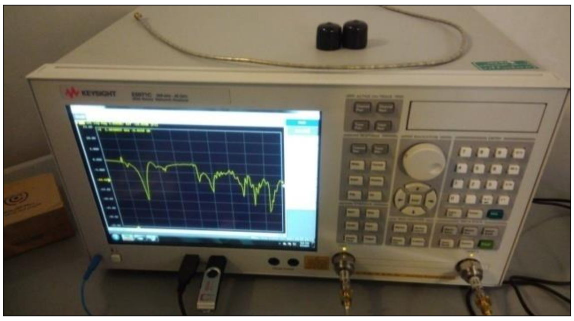

Fig. 10: Example of S_{21} parameter measurement with VNA.

Experimental Results and Discussion

First, AC excitation is investigated. After the connections and calibration of the VNA device, by keeping the applied wave amplitude constant, the pulse frequency was changed, and the effect of the excitation pulse frequency on the plasma waveguide parameters was measured step by step. The general results can be seen in Table 2.

Due to the ample space of the results in the table, some intermediate values have been removed. Then, without changing the excitation connections and their parameters and by keeping the excitation frequency constant at 30 kHz, the excitation input current applied to the Plasma Waveguide from 0.45(A) to 1.05(A) with steps 0.1(A) increased, and the effect of increasing the excitation input current on the ripple passband and improving the matching at resonance frequencies was observed. The general results can be seen in Table 3.

Table 2: Results of square wave excitation method (pulse)

Max, Min Pass Band Ripple (dB)	Waveguide Pass Bandwidth (GHz)	Excitation Current (A)	Excitation Frequency (KHz)
(0), (-1.1)	0.76 – 2.01 = 1.25 2.19 – 2.71 = 0.52 2.84 – 3.14 = 0.3	0.55	5.00
(0), (-1.2)	0.8 – 2.1 = 1.3 2.2 – 2.75 = 0.55 2.9 – 3.18 = 0.28	0.52	10.00
(0), (-2.1)	0.9 – 2.22 = 1.32 2.36 – 2.94 = 0.58 3.13 – 3.41 =0.28	0.50	15.00
(0), (-3.1)	0.95 – 2.29 = 1.34 2.4 – 3 = 0.6 3.2 – 3.46 =0.26	0.48	20.00
(0), (-4.4)	0.97 – 2.32 = 1.35 2.44 – 3.05 = 0.61 3.25 – 3.50 = 0.25	0.45	25.00
(0), (-5.9)	1 – 2.38 = 1.38 2.5 – 3.11 = 0.61 3.3 – 3.55 = 0.25	0.44	30.00
The results were the same with the 30 kHz excitation frequency.		0.43	35.00

Table 3: Results of increasing the excitation current on the passband ripple and improving the Matching at the resonance frequencies

Max, Min Reflection Losses (dB)	Min, Max Pass Band Ripple (dB)	Excitation Current (A)	Excitation Frequency (KHz)
(-2.98), (-34.9)	(0), (-5.75)	0.45	30.00
(-3.0), (-35.5)	(-0.21), (-6.10)	0.55	30.00
(3.40), (-36.8)	(-0.43), (-6.50)	0.65	30.00
(-3.98), (-37.1)	(-0.71), (-7.10)	0.75	30.00
(-4.30), (-38.3)	(-1.20), (-7.69)	0.85	30.00
(-4.60), (-39.1)	(-1.51), (-8.11)	0.95	30.00
(-4.80), (-39.8)	(-1.94), (-8.65)	1.05	30.00

In excitation alternating current with a square wave (pulse), excitation frequencies below 5 kHz cause the transistor temperature to rise and heat loss to be high. According to the measured values in Table 2, the maximum Value of Excitation current frequency was measured to be about 30 kHz. From this frequency onwards, no change was observed in the passband ripple and the bandwidth frequency range. Increasing the excitation input current, as recorded in Table 3, improved the matching of the resonance frequencies and, on the other hand, increased the passband ripple, which is not desirable. In the diagram of Fig. 11, we can see the trend of changes in the passband ripple in opposition to the excitation input current.

It should be noted that the excitation current and frequency are actually the plasma excitation current and frequency and is different from the Excitation of the input and output signal ports of the waveguide.

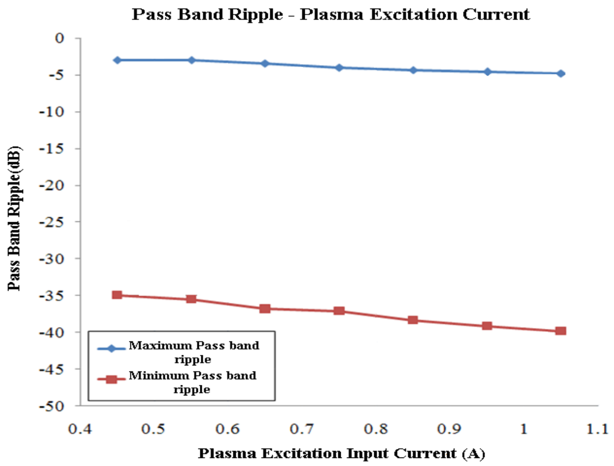

Fig. 11: Pass Band Ripple - Plasma Excitation Current.

In the diagram of Fig. 12, you can see an example of the parameters measured at different excitation frequencies. In Fig. 13, the excitation frequency is stabilized at 30 kHz, and the plasma excitation input current is increased.

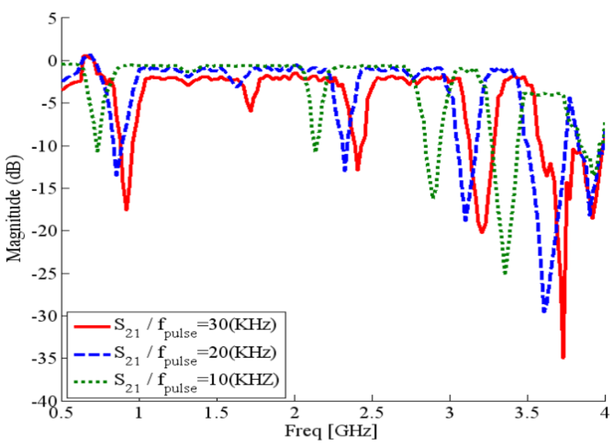

Fig. 12: S_{21} Parameter measured with different excitation frequencies

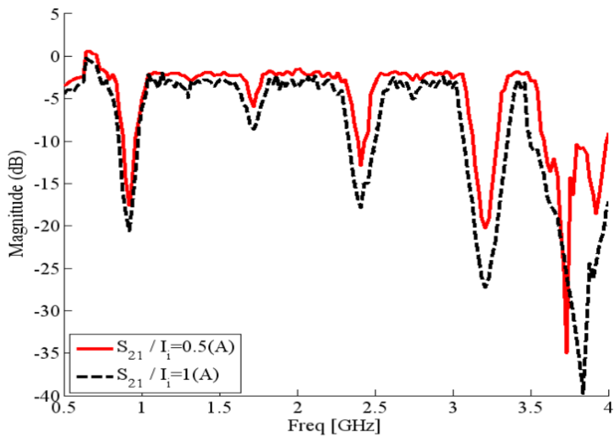

Fig. 13: S_{21} Parameter measurement at 30 kHz with increasing plasma excitation input current.

Fig. 14 shows the degree of conformity of the S_{21} parameter in both simulated and measured modes. In the simulated mode the rate ω_{p} is equal to its maximum rate of 3.6×10^{11} Rad/s, and in the measured mode, the plasma excitation frequency is assumed to be equal to its maximum Value of 30 kHz. The maximum value is when the value has not changed significantly in the simulated or measured results.

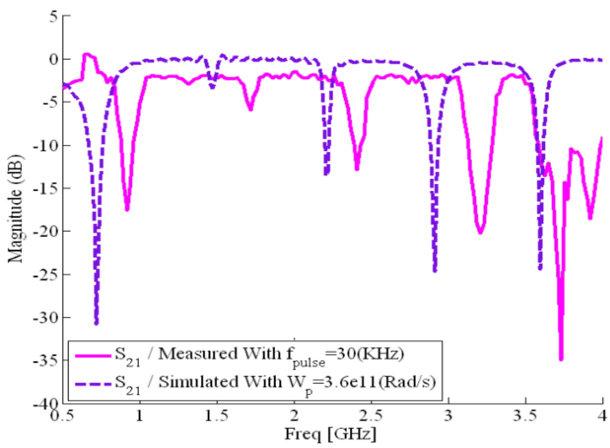

Fig. 14: The degree of conformity of the S_{21} parameter in both simulated and measured modes.

As can be seen from the parameter diagram of Fig. 12, with increasing the frequency of the plasma excitation pulse, the plasma frequency increases. Consequently, the frequency range of the Passband and its resonance frequencies also increase. Also, by increasing the excitation Frequency and transmission Passband of the waveguide filter, the passband ripple and matching at the resonance frequencies also increase. In other words, at lower frequency ranges, the waveguide filter passband will have fewer ripples. It should be noted, however, that low-frequency plasma excitation pulses cause several resonance frequencies to be lost. According to the S_{21} parameter diagram of Fig. 13, with increasing the plasma excitation input current, the Matching to the resonance frequencies is improved. Still, on the other hand, the passband ripple is also increased, which will not be desirable.

As shown in Fig. 14, the simulation results slightly disagree with the practical results. The reasons for this can be 1- The new type of excitation used and the different frequencies of plasma Excitation, 2- Inability to measure plasma parameters in natural state, and 3- an ideal the simulation environment. On the other hand, as mentioned earlier, Plasma is a complex environment (nonlinear and Dispersive), and it isn't easy to match the simulation and Experimental results. For example, the ripples in the S21 parameter measured in Fig. 12 and Fig. 13 are due to the alternation of the plasma excitation signal, which is practically impossible to create such a thing using the Drude model in the simulation software.

Conclusion

During the article, the complete steps of designing a coaxial plasma waveguide filter with the ability to adjust the frequency range of the passband were followed, which are: simulation with CST software, implementation of plasma waveguide, excitation circuits, coupling design, and finally plasma coaxial waveguide test, the results of which were presented. The main focus of this paper was to reconfigure waveguide characteristics using altering and controlling plasma parameters through AC excitation. As mentioned, Plasma has two main parameters called collision frequency and plasma frequency. By changing them, the properties of plasma material and, consequently, without changing the physical structure, the parameters of plasma waveguide change.

According to the results, the change of these two parameters depends on the change of plasma excitation current frequency, and the value of excitation current applied. As the value of Excitation current increases, the matching to the resonance frequencies improves, but on the other hand, the passband ripple of the plasma waveguide filter increases. As the plasma excitation pulse frequency increases, the bandwidth and resonance frequencies change to higher frequencies, and the Matching to the resonance frequencies improves. But on the other hand, the passband ripple increases. This new type of waveguide filter can be used in cognitive/ adaptive telecommunication systems due to the constant change of frequency band.

Author Contributions

This paper is the result of M. Tohidlo's Research project which is supervised and advised by S. H. Mohseni armaki and M. Kazerooni, respectively. M. Tohidlo did the Simulations, Design and fabrication of Coaxial Plasma Waveguide Filter and wrote the manuscript. M. Tohidlo and S. H. Mohseni Armaki presented a new Reconfigurable Coaxial Plasma Waveguide Filter. S. H. Mohseni armaki interpreted the results and edited the manuscript. M. Kazerooni reviewed the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

ω_p	Plasma frequency
υ_c	Plasma collision frequency
ω	Waveguide frequency
F	Electric force
v	Electron velocity
e	electron charge
m	Mass of the electron
n_e	density of free electrons
J	plasma inner surface current
P	Plasma discharge power
Υ	Electron natural collision frequency
γ	Propagation constant
L	Waveguide length
r_p	Tube glass radius
r_{sh}	Shield radius
W_c	Coupler width
L_c	Capacitive coupler distance from the end of the waveguide

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