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Mode filtering based on ponderomotive force nonlinearity in a plasma filled rectangular waveguide

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Abstract

Here a new scheme for mode filtering is proposed. Based on the ponderomotive force effect, propagation of the microwave dual-mode through a plasma-filled metallic rectangular waveguide is investigated. To excite the TE_{20} mode in a rectangular waveguide, the existence of fundamental modes is unavoidable. To filter the destructive mode (TE_{10}), the waveguide is filled with a collisional plasma. Based on the coupling effect, the energy of this destructive TE_{10} mode is transferred to the TE_{20} mode. The proposed structure acts like a mode convertor. The TE_{10} mode become more attenuated and instead the TE_{20} mode is amplified. The plasma filled rectangular waveguide acts as a mode filtering tool.

Keywords: mode filtering, mode convertor, collisional plasma, ponderomotive force

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent progression in wireless communication systems has created a need for tools such as the microwave (MW) multiplexers, waveguide filters and RF circuits, which have reduced the production cost and compact size [1–4]. Waveguides are usually constructed so that only one mode propagates, while sometimes the existence of other modes is unavoidable. In rectangular waveguide, the TE_{10} mode is the dominant mode. To provoke the TE_{20} mode, the wave frequency is greater than its cutoff frequency, so the existence of fundamental modes is unavoidable. The existence of TE_{10} mode is modified in the electron density distribution. To have a higher order mode (such as TE_{20} mode) without the destructive mode (such as TE_{10} mode) a some research has been investigated. Recently, a substrate integrated waveguide (SIW) slot array antenna with a TE_{20} mode to realize boresight radiation was proposed [5]. Also, the excitation of two wideband TE_{20} mode is surveyed by a novel SIW structure [6]. In other methods, a mode converter has been proposed [7]. In this converter, the energy of this destructive TE_{10} mode is used to amplify the TE_{20} mode. Furthermore, by using a nonlinear plasma and choosing the suitable initial conditions, a method to convert Hypergeometric-Gaussian subfamily mode to one or more mode components of Laguerre-Gaussian modes has been demonstrated [8]. Here we proposed that to filter destructive mode, the waveguide can be filled with a nonlinear plasma. Based on this proposed structure, the energy of this destructive TE_{10} mode is transferred to the TE_{20} mode. By the ponderomotive force nonlinearity, the TE_{10} mode is attenuated and instead the TE_{20} mode is amplified, therefore our structure is a mode convertor. On the other hand, due to filter the destructive mode, a mode filtering occurred in the our plasma waveguide structure. Recently, a waveguide structure based on embedding a graphene film for spatial-mode-filtering applications has been proposed [9]. In other work, the ability of periodic subwavelength grating waveguides to use for mode filtering is investigated [10]. The utility of the plasma for filtering has been applied in other research. A photonic crystal doped by

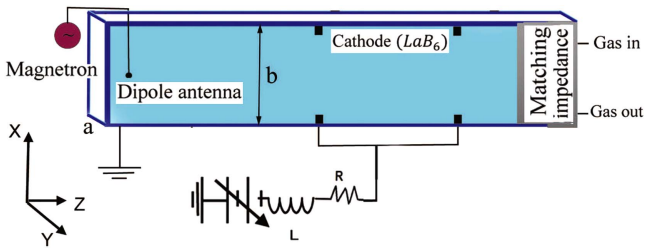

Figure 1. The TE_{10} and TE_{20} modes of the evacuated metallic waveguide, with the width $a = 2$ cm and height $b = 1$ cm, are provoked by a magnetron through a dipole antenna. By employing an electric discharge between LaB_6 cathode and the waveguide grounded surfaces, the plasma is produced in the right-hand waveguide [26].

plasma has been surveyed to filter the defect mode of the TE wave [11]. Wave-plasma interaction leads to many interesting phenomena, such as resonance absorption [12–14], wave generation [15–19], frequency shift [20] and modication of electron density distribution [8]. Such types of interaction are active fields of research due to their broad range of applications in the areas like MW refelectometry, stellarators, controlled fusion, RF-based plasma thrusters and plasma production [21–25]. One of the important nonlinear occurrences in the high MW propagation in plasma is the ponderomotive force effect. In the presence of ponderomotive force, the charged particles, such as electrons, are expelled from regions of high field strength. The electron density modication in the plasma by the ponderomotive force of strong-power MW has been investigated [26]. Propagating high power MW in a plasma-filled metallic waveguide has been surveyed [23, 27].

In section 2, propagating high-power MW dual-mode in an evacuated waveguide that provokes a plasma filled in a similar and co-axis waveguide is investigated. The effect of coupling on each modes via the ponderomotive force through a collisional plasma is surveyed. Section 3 is devoted to study the propagation and evolution of TE_{10} and TE_{10} modes in rectangular waveguide. Finally, the conclusion is presented in section 4.

2. Device modeling and analysis

In this section, a mode filtering tool based on the plasma filled rectangular waveguide is demonstrated. A scheme of an evacuated rectangular waveguide, which is connected coaxially to an plasma filled waveguide, is presented in figure 1. The waveguides have similar sizes (1 cm × 2 cm). A dipole antenna provokes the TE_{10} and TE_{20} modes in the evacuated metallic waveguide [28]. To produce plasma in the second waveguide, we employed an electric discharge between LaB_6 cathodes [13] and the waveguide grounded surfaces. Here, the effects of plasma and LaB_6 cathodes on the modes is ignored. By choosing the wave frequency greater than the TE_{20} cutoff frequency, the TE_{20} mode excites in the rectangular waveguide. The cutoff frequency of TE_{20} mode is higher than that of TE_{10}, so the fundamental modes is provoked. When the excited TE_{10} and TE_{20} modes encounter plasma, the characteristics of the modes are varied. The cutoff frequency of the modes in the plasma waveguide is greater than that of the evacuated waveguide. Thus the modes propagate with larger wavelength into the plasma filled waveguide. The existence of TE_{10} mode modified the plasma, which varied the propagating characteristic of TE_{20} mode. The incidence of a strong MW on the plasma is supposed perpendicularly. Recently, the governing equations of the MW field propagation through the plasma-filled rectangular waveguide has been demonstrated [26].

The permittivity of the collisional plasma can be expresed as $\epsilon_0' + \mathrm{i}\epsilon_i' + \Phi(\mathbf{E}\cdot\mathbf{E}^*)$, where $\epsilon_0'(z) = 1 - \frac{\omega_\mathrm{p}^2(z)}{\omega^2+\nu_\mathrm{ei}^2}$, $\epsilon_i'(z) = \frac{\nu_\mathrm{ei}}{\omega}\frac{\omega_\mathrm{p}^2(z)}{\omega^2+\nu_\mathrm{ei}^2}$, Φ is the nonlinear effect, which created by the ponderomotive force, ω is the MW frequency and ν_ei is the electron-ion collision frequency [29–31]. Also, $\omega_\mathrm{p} = \left(\frac{e^2 n_0}{\epsilon_0 m_\mathrm{e}}\right)^{1/2}$ is the plasma frequency where n_0, ϵ_0, m_e and e are the equilibrium electron density, vacuum permittivity, electron mass and electron charge, respectively. Here, $\mathbf{E}$ is the sum of electric fields of TE_{10} and TE_{20} modes. Due to obsorbation in collisional plasma, the wavenumber is imaginary as $k(z) = k_r(z) + \mathrm{i}k_i(z) = \frac{\omega}{c}[\epsilon_0'(z) + \mathrm{i}\epsilon_i'(z)]^{1/2}$, where c is the velocity of light, $k_r(z)$ is the wavenumber of MW beam, and $k_i(z)$ is related to the MW energy damping rate. By propagating the MW in plasma, the ponderomotive force accelerates the electron, which creates a lower electron density. The ponderomotive force exerted on the ions is ignored. It is assumed that the plasma pressure gradient force is lower than the pondeomotive force. Therefore, the nonlinearity term is expressed as $\Phi(\mathbf{E}\cdot\mathbf{E}^*) = \frac{\omega_\mathrm{p}^2}{\omega^2+\nu_\mathrm{ei}^2}(1 - \mathrm{e}^{-\eta\mathbf{E}\cdot\mathbf{E}^*})$, where $\eta = e^2/(8m_\mathrm{e}\omega^2 k_\mathrm{B} T_0)$, T_0 and k_B are the equilibrium temperature of plasma and Boltzmann constant, respectively [27, 31]. The electron density, modified by the ponderomotive force, may be written as $n_0 = n_{00}\,\mathrm{e}^{-\eta EE^*}$, where n_{00} and n_0 are the electron density in the absence and presence of the MW electric field, respectively [8, 27]. The dielectric permittivity varies as a function of the sum of electric fields of TE_{10} and TE_{20} modes, which is considered as $E_{1y}(x, y, z) = E_{10}(z)\sin(\pi x/a)\mathrm{e}^{\mathrm{i}(\int k(z)\mathrm{d}z-\omega t)}$ and $E_{2y}(x, y, z) = E_{20}(z)\sin(2\pi x/a)\mathrm{e}^{\mathrm{i}(\int k(z)\mathrm{d}z-\omega t)}$. The electric fields of modes separate out as $E_{10}(z) = A_r(z) + \mathrm{i}A_i(z)$ and $E_{20}(z) = B_r(z) + \mathrm{i}B_i(z)$. The separated amplitudes are substituted in the MW field propagation equation through the plasma-filled rectangular waveguide (which is demonstrated in [27]). Then the real and imaginary parts of the MW field propagation equation are separated for each mode and some mathematical manipulations are employed. By multiplying both sides of the MW field propagation equation by $\sin(n\pi x/a)$ and integrating over x (0 to a), the variation of separated amplitudes are written as

$$\frac{\partial^2 A_r}{\partial z^2} - 2k_i\frac{\partial A_i}{\partial z} + 2k_r\frac{\partial A_r}{\partial z} - \frac{\partial k_i}{\partial z}A_i + \frac{\partial k_r}{\partial z}A_r - \left(\frac{\pi}{a}\right)^2 A_r + \frac{\omega^2}{c^2}\Phi(\mathbf{E}\cdot\mathbf{E}^*)A_r = 0 \quad (1a)$$

$$\frac{\partial^2 A_i}{\partial z^2} + 2k_i\frac{\partial A_r}{\partial z} + 2k_r\frac{\partial A_i}{\partial z} + \frac{\partial k_i}{\partial z}A_r + \frac{\partial k_r}{\partial z}A_i - \left(\frac{\pi}{a}\right)^2 A_i + \frac{\omega^2}{c^2}\Phi(\mathbf{E}\cdot\mathbf{E}^*)A_i = 0 \quad (1b)$$

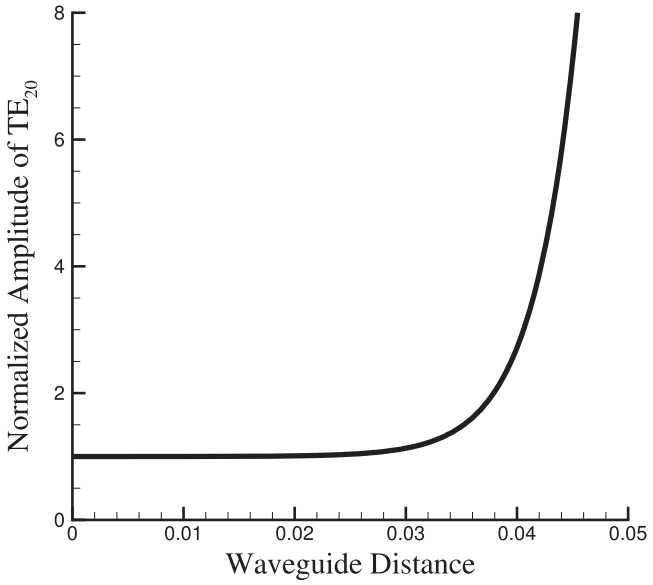

Figure 2. Normalized amplitude of TE_{20} mode verses the distance z (m) in the plasma-filled waveguide.

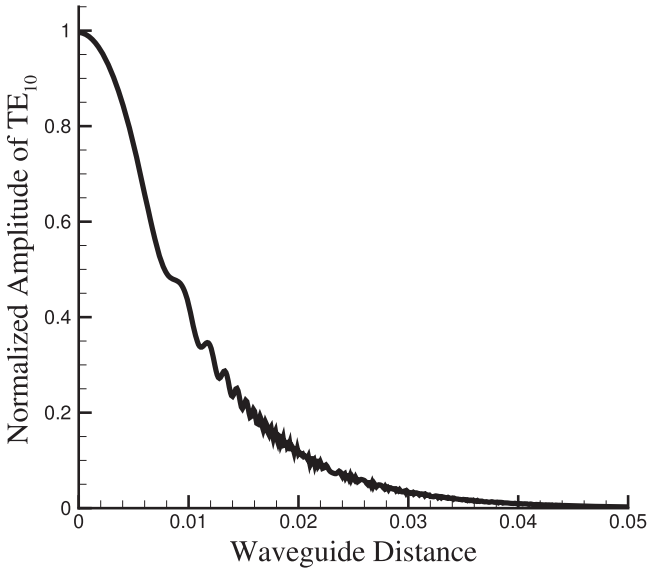

Figure 3. Normalized amplitude of TE_{10} mode versus the distance z (m) in the plasma-filled waveguide.

$$\frac{\partial^2 B_r}{\partial z^2} - 2k_i\frac{\partial B_i}{\partial z} + 2k_r\frac{\partial B_r}{\partial z} - \frac{\partial k_i}{\partial z}B_i + \frac{\partial k_r}{\partial z}B_r - \left(\frac{2\pi}{a}\right)^2 B_r + \frac{\omega^2}{c^2}\Phi(\mathbf{E}\cdot\mathbf{E}^*)B_r = 0 \quad (1c)$$

$$\frac{\partial^2 B_i}{\partial z^2} + 2k_i\frac{\partial B_r}{\partial z} + 2k_r\frac{\partial B_i}{\partial z} + \frac{\partial k_i}{\partial z}B_r + \frac{\partial k_r}{\partial z}B_i - \left(\frac{2\pi}{a}\right)^2 B_i + \frac{\omega^2}{c^2}\Phi(\mathbf{E}\cdot\mathbf{E}^*)B_i = 0. \quad (1d)$$

Equations (1*a*)–(1*d*) are coupled together. The coupling effect of modes is clear in the nonlinear term as $\mathbf{E} = E_{1y}\hat{j} + E_{2y}\hat{j}$, where $\hat{j}$ is the unit vector in the y-direction. Considering the boundary condition for metallic waveguide, the coupled equations (1*a*)–(1*d*) are solved numerically. When the energy relaxation time of electrons ($t \ll \tau_\epsilon = \frac{M}{2m_e\nu_{ei}}$), where M is the ion mass, is larger than the time duration of MW, the ponderomotive nonlinearity is dominant [29].

To derive equations (1*a*)–(1*d*), orthogonality relations between $\sin(\pi x/a)$ and $\sin(2\pi x/a)$ is employed. The orthogonality relations of $\sin(n\pi x/a)$ is written as

$$\int_0^a \sin(n\pi x/a)\sin(m\pi x/a)\mathrm{d}x = \frac{a}{2}\delta_{n,m}. \quad (2)$$

3. Results and discussion

Considering the boundary condition for the metallic waveguide, the spatial distribution of electric fields is varied as equations (1*a*)–(1*d*). The MW frequency should not be selected too close to the cutoff frequency, since the conductor losses are then large [28]. The MW frequency is 20 GHz, so the TE_{10} and TE_{20} modes can excite in the waveguide. Parameters are taken as $L = 0.05$ m, $\omega_p = 0.9$ GHz, $\nu_{ei} = 0.05\ \omega_p$ and the MW intensity $I = 2 \times 10^8$ W/m^2.

In figure 2, the normalized amplitude of electric field for TE_{20} mode ($\sqrt{B_r(z)^2 + B_i(z)^2}$) in collisional plasma is presented. As maintained above, the electrons are repulsed from high intensity regions by the ponderomotive force. Hence at the location of $a/2$ for the TE_{10} mode and $a/4$ & $3a/4$ for TE_{20} mode, the dielectric permittivity is raised. The outset of the propagation path at $a/2$ of the waveguide width, the TE_{10} mode has high intensity, so the ponderomotive force accelerates the electrons to a location of $a/4$ and $3a/4$. When the plasma frequency grows, the ponderomotive force nonlinearity increases. The plasma plays the role of a convex lens and converging the MW takes place. The normalized amplitude of TE_{20} mode is increased. However the plasma is collisional so the normalized amplitude of the TE_{20} mode is slowly attenuated. The growth of electric field amplitude due to the nonlinearity is challenged to the attenuation due to collisional absorption. Finally, the ponderomotive force nonlinearity is predominated and the normalized amplitude of electric field is increased.

Figure 3 illustrates the normalized amplitude of electric field for the TE_{10} mode ($\sqrt{A_r(z)^2 + A_i(z)^2}$) in the plasma waveguide. By rising the normalized amplitude of the TE_{20} mode, the electron density at a location of $a/2$ decreases and is larger near the waveguide walls. Plasma plays the role of a concave lens, so the effect of diffraction occurs and MW diverges. At a location of $a/2$, the plasma frequency and ponderomotive force nonlinearity decrease. Due to the collisional attenuation and diffraction effect, the normalized amplitude of TE_{10} attenuates. By selecting the higher collision frequency, the decreasing rate of the normalized amplitude takes place rapidly. So the collision frequency can be considered as a controlled parameter.

Furthermore, the observed result can be described by the energy conservation law. By propagating the TE_{10} and TE_{20} modes in the proposed waveguide, this structure acts like a

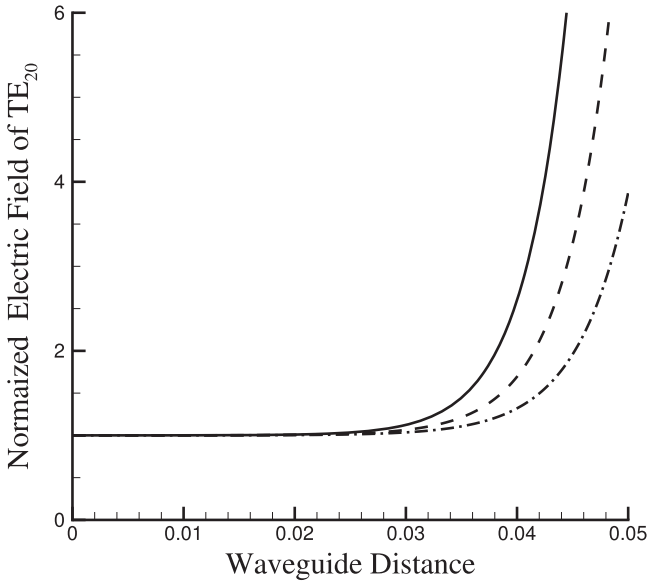

Figure 4. Normalized electric field of TE_{20} mode verses the distance z(m), when the collision frequency is $\nu_{ei} = 0$ (solid line), $0.05\omega_p$ (dashed line) and $0.1\omega_p$ (dash-dotted line) in the plasma-filled waveguide.

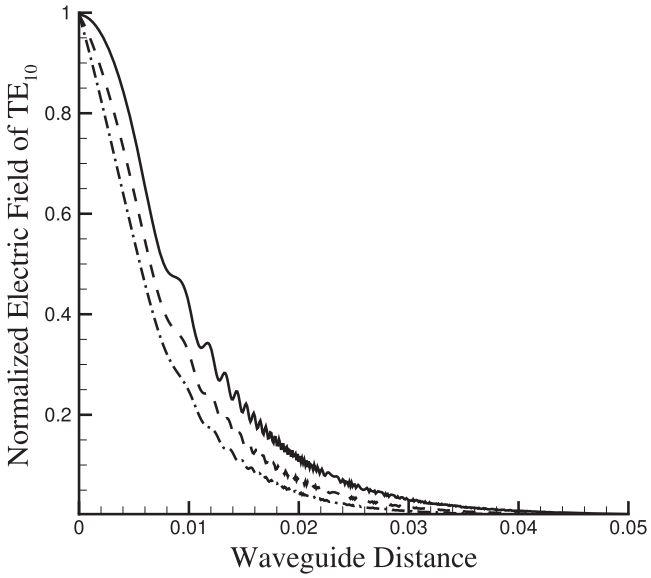

Figure 5. Normalized electric field of TE_{10} mode versus the distance z(m), when the collision frequency is $\nu_{ei}= 0$ (solid line), $0.05\omega_p$ (dashed line) and $0.1\omega_p$ (dash-dotted line) in the plasma-filled waveguide.

mode filtering tool. The TE_{20} mode is amplified and the TE_{10} mode is filtered. On the other hand, the energy transfers from the TE_{10} mode to the TE_{20} mode.

In the presence of the electron-ion collision, the electromagnetic energy of modes is absorbed via collision. To survey the collision effect in collisional plasma, the normalized electric field of TE_{20} mode ($\sqrt{B_r(z)^2 + B_i(z)^2}\ e^{-\int k_i(z)dz}$), which is attenuated by the collision effect for three different collision frequencies, is presented in figure 4. The more the collision frequency is selected, the lower amplification of the normalized electric field for the TE_{20} mode occurs. In figure 5, the normalized electric field of the TE_{10} mode ($\sqrt{A_r(z)^2 + A_i(z)^2}\ e^{-\int k_i(z)dz}$), which is attenuated by the collisional effect for three different collision frequencies, is pictured. As seen, the more the collision frequency is selected, the higher absorbtion of the normalized electric field takes place.

4. Conclusion

A method to filter the destructive mode on the basis of ponderomotive force nonlinearity is proposed. To suppress the fundamental mode, a collisional plasma-filled waveguide is designed. This aim is provided by surveying a mode filtering that is based on amplifying the TE_{20} mode and filtering the TE_{10} mode. Based on the 'coupling effect', the energy of this destructive TE_{10} mode is transferred to the TE_{20} mode. On the other hand, this proposed structure is a mode convertor. To clarify the collision effect in this structure, the effect of exchange in collision frequency on the electric field of modes is investigated. Finally, this structure is useful to many industrial and technological applications.

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