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Dispersion characteristics of dielectric tube waveguide loaded with plasma for leaky wave antenna application

Rasila R. Hirani [a,b,*], Surya K. Pathak [c], Shweta N. Shah [b], Dushyant K. Sharma [c]

[a] *Electronics & Communication Department, HJD Institute-Kutch, India*
[b] *Electronics Department, S.V.N.I.T., Surat, India*
[c] *Microwave and ECE Group, Institute for Plasma Research, Gandhinagar, India*

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ABSTRACT

The leaky mode dispersion characteristics $(\omega-\beta)$ of a Dielectric Tube Waveguide Loaded with Plasma (DTWLP) is analytically solved and numerically computed using Muller's complex root search algorithm with an aim to define its complex propagation constant behaviour. Consequently, complex leaky mode characteristics and its classification as guided mode, reactive mode and antenna mode have been investigated. These modal characteristics reveal wide fundamental antenna mode (TM01) with the variation in plasma density, which can find prospective application in high resolution radar and communication system where "re-tuning" of the antenna to a new frequency or making it electrically invisible is required. A computational cum simulation study is also performed using CST Microwave Studio software, which confirms our analytical findings.

1. Introduction

In recent years, the dielectric waveguide has attracted much attention over metallic waveguide for millimeter waves and light wave technology applications [1]. Dielectric slab waveguide [2,3], dielectric cylindrical column waveguide [4,5] and dielectric tube waveguide [6] are some of the simplest structures and their guided mode characteristics have been studied for a long time. One of the important features of dielectrics open waveguide is that it supports a leaky antenna mode, which finds application in Antenna Engineering. Working principle of a leaky-wave antenna resembles as a travelling wave antenna in which major radiation takes place in the axial direction due to guiding structure [7]. The complex dispersion diagram (ω-β diagram) of a waveguide defines the different mode regions such as reactive mode, antenna mode, improper and proper surface wave modes which are helpful in defining the behavior of leaky wave radiation [8]. Leaky mode characteristics for dielectric rod waveguide [9], printed circuit line [10] and rectangular multiple layer dielectric structure have already been extensively analyzed and reported.

The dielectric tube waveguide loaded with plasma (DTWLP) has an additional advantage that it can be used as an electrically reconfigurable waveguide structure. Change in plasma density changes the plasma frequency as well as the effective permittivity of the waveguide structure which in turn changes the modal characteristics of the waveguide along with the propagating frequency [11]. This unique property of the plasma changes the field distribution in the waveguide.

Over decades, many investigators have done theoretical and numerical analysis based research on plasma waveguide [12–16]. Khalil et al. [17] described the dispersion characteristics of plasma filled cylindrical waveguide with the different physical situations of plasma approximation (cold and warm), relativistic electron beam and magnetized plasma field configuration. This finds applications in microwave Gyrotron development for fusion plasma. Chatterton [18] investigated the behavior of the modes of the plasma-loaded Bragg waveguide and calculated the dispersion and loss characteristics by choosing the proper plasma refractive index for optical communication problems. Kim [9] analyzed leaky mode characteristics of isotropic and lossless plasma column waveguide using the Davidenko's method to solve complex propagation constant. The major limitation of plasma column waveguide is that it has a higher cut-off frequency of $\omega_p/\sqrt{2}$, which provides a limited frequency bandwidth for surface wave propagation due to the dispersive nature of plasma. However, leaky modes exist in wide spectral ranges. While the major disadvantage of a plasma

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* Corresponding author at: Electronics & Communication Department, HJD Institute-Kutch, India.

E-mail addresses: hirani.rasila@gmail.com, rasila05ec21@yahoo.com (R.R. Hirani), bhusurya@gmail.com (S.K. Pathak), snshah@eced.svnit.ac.in (S.N. Shah), dushyantsharma2@gmail.com (D.K. Sharma).

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column waveguide in free space is its experimental realization. One cannot produce a plasma column in free space or in other words, we need a cylindrical enclosure like a dielectric tube of the proper thickness within which we can create a plasma column for leaky mode antenna application.

Many researchers have made practical proto type of plasma antennae such as a monopole, dipole and array structure [19–22]. They have studied the radiation characteristics such as gain, directivity and bandwidth. Kallel et al. [23] have presented, experimentally, beam-scanning leaky-wave plasma antenna operating in the X-band wherein they have demonstrated plasma antenna at 11.14 GHz by means of electron density measurements.

However, to the best of our knowledge, leaky mode characteristics of DTWLP structure have not yet been investigated or reported. In this paper, we present the comprehensive complex mode analysis and characterization of DTWLP structure for lower order symmetric transverse modes (TM). This includes proper surface wave, improper surface wave, antenna mode and reactive mode as a function of plasma parameter, namely its density. Furthermore, these analytical findings are verified by computer simulation using commercially available CST Microwave Studio software. This is a completely new investigation for the DTWLP structure which clearly visualizes and distinguishes the surface wave and leaky wave antenna mode propagation behaviors.

2. Mathematical formulation of dielectric tube waveguide loaded with isotropic lossless plasma

The schematic diagram of DTWLP structure is shown in Fig. 1, where it has been profiled in three regions namely, the plasma medium as the core, the dielectric medium as the cladding and free space as the outermost region.

The complex permittivity of the plasma medium is expressed as [13,16]:

$$\begin{aligned}\varepsilon_p &= 1-\frac{\omega_p^2}{\omega(\omega+i\nu)}\\ &= 1-\frac{\omega_p^2}{\omega^2}\left(1+\frac{\nu^2}{\omega^2}\right)^{-1}+i\frac{\nu}{\omega}\frac{\omega_p^2}{\omega^2}\left(1+\frac{\nu^2}{\omega^2}\right)^{-1}\end{aligned} \tag{1}$$

where ν is the collision frequency and is associated with the momentum transfer and loss. Once the plasma is created having particular targeted density then plasma frequency and collision frequency remain almost constant. From Eq. (1) it is clear that at operating frequencies much higher than the collision frequency the effect of collisions may be ignored, typically at $\nu \sim 0.1\omega_p$ or less [12] and therefore the imaginary part of the plasma complex permittivity can be neglected for higher frequency analysis. Similarly, loss mechanism of radiative damping can be neglected [24], as plasma has less collisional damping. Landau damping is considered as another loss mechanism, where energy exchange takes place between wave and particle, and which occurs when phase velocity of electromagnetic wave is approximately equal to the particle velocity in the plasma. Usually, the particle velocity distribution is a Maxwellian with an average velocity which is much lower than the phase velocity of the leaky mode or fast wave mode of an antenna system and thus the landau damping can also be neglected [24,25]. Therefore, the permittivity of isotropic, homogeneous, and lossless plasma can be normalized using the factor (r_1^2/c^2) and the permittivity may now be expressed in terms of the normalized plasma frequency, $K_p r_1$ and normalized operating frequency, $K_0 r_1$ as:

$$\begin{aligned}\varepsilon_p &= 1-\frac{\omega_p^2}{\omega_0^2}\\ \varepsilon_p &= 1-\frac{\omega_p^2 r_1^2/c^2}{\omega_0^2 r_1^2/c^2} = 1-\frac{(K_p r_1)^2}{(K_0 r_1)^2}\end{aligned} \tag{2}$$

here, r_1 is the radius of the inner core plasma column, $K_p = \omega_p/c$ is the plasma wave number, $K_0 = \omega_0/c$ is the free space wave number, $\omega_p = \sqrt{\frac{Ne^2}{m\varepsilon_0}}$ is plasma angular frequency, N is plasma density, e and m are charge and mass of an electron respectively, ε_0 is the permittivity of the free space and c is the speed of light.

When $\omega > \omega_p$, electromagnetic wave propagates through plasma in guided mode, also called surface wave mode, which exists between interfaces of two different mediums (in our case dielectric-plasma boundary). This implies that there is no energy flow perpendicular to the plasma-dielectric boundary. This wave is also known as slow wave, where the phase velocity of propagating wave is less than the velocity of light. When such a plasma material is bounded by some dielectric medium, surface wave propagates with the evanescent field on both sides of the boundary [12]. For $\omega < \omega_p$ the plasma permittivity is negative. This does not happen in conventional dielectric medium. It is also possible to investigate the waves that oscillate in the transverse direction but are evanescent in plasma. These waves are known as fast waves or leaky waves with phase velocity greater than the velocity of light.

Plasma can be generated by filling ionized gas like neon and argon in a tube. Energizing the plasma can be done using electrodes or microwave signals or RF heating. The Plasma properties such as density, current distribution and electromagnetic fields that generate and propagate within the plasma and the geometrical shape of the tube, define modal characteristics. Plasma density can be controlled by electrically varying the input power of ionizing microwave power. This power generates the plasma progressively along the tube so the effective length of a plasma antenna

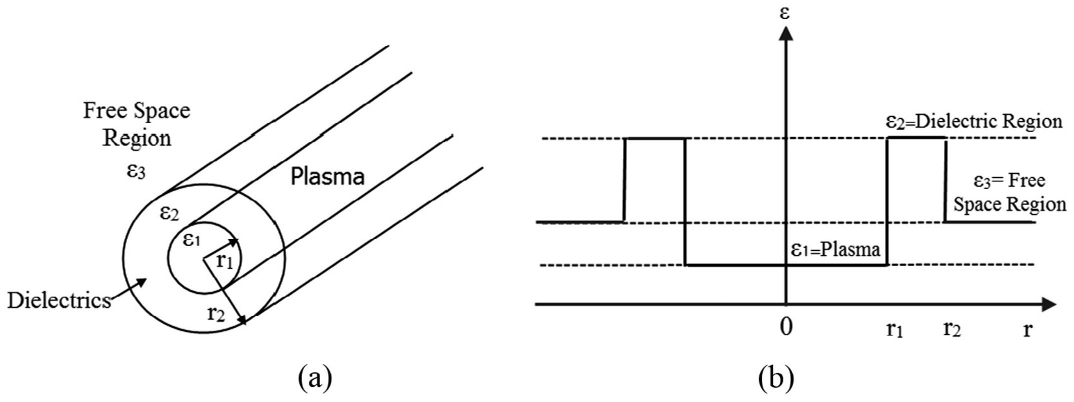

Fig. 1. (a) The geometry of DTWLP structure and (b) refractive index profile.