High Power Microwave Generation using Dielectric Cherenkov Maser with Dielectric Rod and Plasma Column

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Abstract—**The linear theory of electromagnetic radiation from dielectric loaded Cherenkov generator with plasma column in a slow-wave waveguide driven by an intense relativistic electron beam has been studied and analyzed numerically. Various beam plasma waveguide models have been proposed and studied analytically within aim to give a guideline to achieve an optimally designed powerful Cherenkov generator. *The Cherenkov radiation in the plasma-filled coaxial* cylindrical dielectric slow-wave structure is examined by use of self-consistent linear field theory in this paper. The dispersion equation and synchronous condition has been discused. Injection of the backward plasma into the slow-wave structure can enhance the output frequency and the beam-wave interaction enables the high-power microwave source that utilizes this kind of slow-wave structure to gain more output power of the microwave with higher output frequency.**

Keywords— Cherenkov generator; Plasma column; Intense relativistic electron beam; Dispersion equation; Synchronous condition;

I. INTRODUCTION

In recent years, a dramatic resurgence in research activities on the generation of high power microwave and millimeter wave radiation has been taking place all over the world. The rapid growth of this research area has resulted, in part, from the potential application of the microwave sources in a variety of fields, which include: electron cyclotron resonance heating of fusion plasmas, advanced particle accelerator system, plasma and solid state diagnostics, material science, high power space based radar systems, electronic warfare, and etc [1].

The advances in the areas such as magnetic and superconducting structures the development of high quality intense relativistic electron beam accelerator have completely improved the microwave source performances. In addition to improve the overall performance of the conventional microwave sources, researchers have been working to develop a new class of microwave devices to meet the requirements of present and future applications. Gyrotrons and free electron lasers have made it possible to produce short wave length radiation at the modest power levels [2]. The recent development of the multiwave Cherenkov generator (MWCG) and the relativistic diffraction generator (RDG) has led to an exciting increase in the microwave radiation output. The power levels available from these sources are almost an order of magnitude greater than that previously obtained in any device, reaching 3.5 GW at a wavelength of 6.5mm and 15 GW at 3cm.Whatever the microwave source, the ratio of the peak power to square of the wavelength, now a days, has exceeded 1 GW /cm^2, where the sources are driven by the intense relativistic electron beams [3].

The microwave sources can be classified into three major groups:

A. Fast Wave Devices- including FELs and electron cyclotron masers, such as gyrotrons, peniotrons, and CARMs.

B. Slow Wave Devices- including magnetrons, klystrons, Cherenkov masers, BWOs, MWCGs, and TWT s.

C. Plasma Devices- including VIRCATORs and reditron oscillators.

Fundamentally there is no difference in the basic ideas related to the generation of microwave radiation from the devices. Their main purpose is to convert the kinetic energy of the electron beam to the electromagnetic energy [4]. In general, all of these devices have two primary components in common:-

A device for providing an intense relativistic electron beam.

A device for converting beam particle kinetic energy to electromagnetic radiation.

The microwave radiation results from the interaction of the beam space charge wave either with the travelling wave (in the case of fast and slow wave devices) or with the electromagnetic field in a gap (in the case of plasma devices) [5]. The kinetic energy lost by the beam during the interaction with the RF field appears as the electromagnetic radiation. Dielectric Cherenkov maser, travelling wave tube (TWT), and backward -wave oscillator (BWO) usually includes an intense electron beam as its active gain medium. These studies show that the presence of plasma in the dielectric Cherenkov maser liberalizes the growth rate and increases the electromagnetic wave energy. It has experimentally shown that injection of background plasma to the dielectric rod increased efficiency to nearly 40 percent [6].Following this experiment, theoretical studies on plasma filled dielectric Cherenkov maser and BWO have made progress and it can be safely concluded that the variation of plasma density affects the interaction between the wave and electron beam. It is beyond the scope of this paper to give an accurate and useful picture of microwave generation mechanisms in detail for all the devices presented above. Furthermore, the main objective of this paper is to study the dielectric Cherenkov maser theoretically.

II. Basic Theory Of Microwave Generation From Dielectric Cherenkov Maser

The basic mechanism of generating microwave from the slow wave microwave devices, which include Cherenkov maser, is to match the waveguide structure wave velocity with the electron beam velocity. Such a condition means that the phase velocity of the structure wave must be lower than the light velocity, c [7].However, the ordinary waveguides, for example, the smooth-walled empty cylindrical waveguides yield a wave with a phase velocity higher than c, so that it is impossible to have a radiation output when an electron beam with a velocity less than c is passed through the waveguide. At microwave frequencies, the synchronism between the wave field and the beam, however, is maintained in a variety of waves:

The dielectric loading of the waveguides alters the dispersion characteristics of the waveguides, providing electromagnetic waves having phase velocities less than c. An alternative scheme is to replace the dielectric with dense plasma either completely or partially filling the waveguide.

Disk (iris) loading of the ordinary waveguide is one of the most widely used methods for slowing a waveguide field. It has application in linear accelerators, high power TWTs and BWOs [8].

The electromagnetic fields in slow wave structures with periodic boundaries must be distributed in accordance with the Floquet's theorem. The theorem states that for a given mode of propagation at a given frequency, the wave functions at two positions in the structure separated by one period will differ in value only by a complex constant [9]. Assuming a phase factor exp [-i(ωt-kz)] for time and spatial variation of the RF fields, the wave function in the periodic structure can be expressed in the form

$$E(r, z, t)=f(r, z) \exp[-i (\omega t-kz)] \quad (1)$$

Where f(r, z) is spatially periodic in the axial length of periodicity in corrugation for a corrugated wall waveguide (or in the axial length of separation between two adjacent irises for an iris loaded waveguide),z_0.

Now, since it is convenient to construct physically a periodic slow wave structure that produce a pure sine wave field distribution in the z direction, f(r,z) is to expanded into Fourier series of space harmonics, i.e

$$f(r,z)=\sum_{n=-\propto}^{n=\propto} f_n(r)\exp[i(\frac{2\pi nz}{z_0})] \quad (2)$$

Where f_n's are the coefficients of expansion. Substituting Equation (2) in Equation (1),one obtains

$$f(r,z,t)=\sum_{n=-\propto}^{n=\propto} f_n(r) \exp [-i (\omega t- k_n z)] \quad (3)$$

$$k_n=k+nk_0. \quad (4)$$

Here k_n is the propagation constant for the nth space Harmonics,$k_0=2\pi/z_0$. And n is the integer. Equation (4) shows that if once the angular frequency ω as a function of propagation k_n for the zeroth space harmonic (n=0) over the range $-\frac{k0}{2}\leq k_n \leq \frac{k0}{2}$ is known. The ω versus k_n characteristics of zeroth order space harmonic electromagnetic wave for- $\frac{k0}{2} \leq k_n \leq \frac{k0}{2}$ is schematically shown in Fig.1,The straight line represent the corresponding light lines as obtained from $\omega=k_n c$.

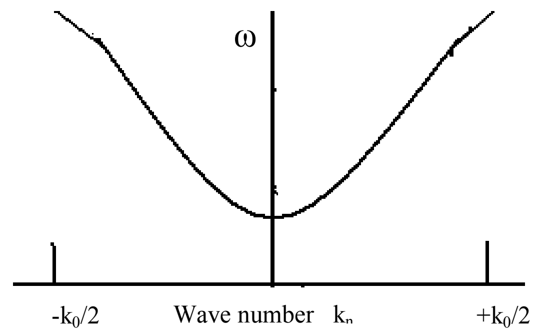


Figure 1.(a)

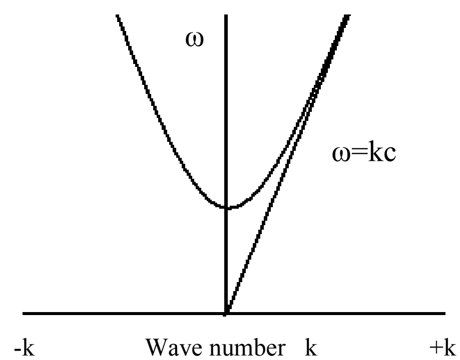


Figure 1.(b)

Figure 1: Schematic TM_{01} mode dispersion relation of (a) Cherenkov maser structure in the ω-k_n plane.(b) a smooth-walled cylindrical waveguide.

When an electron beam is injected into the slow wave structure, we can have coupling between a slow space charge wave of the electron beam, a negative energy wave, and the slow wave structure mode with the positive energy. The interaction between the negative and positive energy waves may lead to instability of the system. It bears mentioning that there are many microwave devices whose operation depends on this type of interaction[10].

III. Dielectric loaded Cherenkov maser and plasma column in a slow-wave waveguide

As the operating frequency is increased, both the inductance and capacitance of the resonance circuit must be decreased in order to maintain the resonance at the operating frequency. Because the gain bandwidth product is limited by the resonance circuit, the ordinary resonator can not generate a large output [11].

Slow-wave devices are special circuits that are used in microwave tubes to reduce the wave velocity in a certain direction so that the electron beam and signal wave can interact. The phase velocity of a wave in ordinary waveguide is greater than the velocity of light in a vacuum [12]. Since the electron beam can be accelerated only to velocities that are about a fraction of velocities of light, a slow-wave device must be incorporated in the microwave devices so that the phase velocity of the microwave signal can keep pace with that of the electron beam for effective interactions. Dielectric Cherenkov maser with a dielectric rod is such slow-wave device, which is used to reduce the velocity of wave in the waveguide [13].

The plasma density in the slow wave structure varies with time, first increasing to a maximum value and then decreasing. Variation of the time interval allowed a measure of control over the plasma density inside the waveguide. The peak power for the fundamental TM mode at nearly 8.4GHz is found to reach a maximum value twice on the plasma pulse time scale, once during density rise and then again during density decay. The experimental results show that the output radiation of the TM01 mode increases with the increase in plasma density [14]. Further increase in the plasma density is found to quench the fundamental TM_{01} mode oscillation; a strong emission at the 12~ 18 GHz level was observed. This high frequency radiation was reported to occur due to mode switching from TM01 to TM_{02} when the Cherenkov maser is overdriven with plasma. The main results of the plasma filled dielectric Cherenkov maser experiment are summarized in the following:

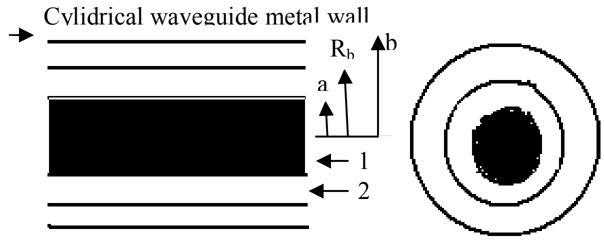
Even for the same beam condition, microwave output rises to a peak of about 600MW, corresponding to an efficiency of about 40%, compared with about 5% for the vacuum Cherenkov maser[15].

Currents as high as 75% of the vacuum limit were successfully propagated in the presence of a background plasma. The oscillation frequency is only slightly shifted (1~5%) in the presence of plasma.

IV. EQUILIBRIUM MODEL

The equilibrium model which we employ is shown in Fig. 2.The plasma column with outer radius R_p and inner radius a, and electron beam are around of a dielectric rod with a relative permittivity ε_r and with radius a, enclosed by a loss-free conducting wall with radius b.For purpose of analytic simplification, it is assumed that the plasma column has a sharp-boundary. The thin annular relativistic electron beam (TAREB) with radius R_b propagates uniformly along the symmetrical axis.(i.e., z) of the dielectric rod. For analytical simplification it is assumed that the TAREB does not diverge.

The derivation of the dispersion relation in this section is based



1=Dielectric rod; 2=plasma column

Figure 2. Dielectric slow-wave system with a plasma column.

on the waveguide in Fig.1. For convenience sake, this particular waveguide model is shown again here in Fig. 2. The slow wave structure consists of an infinitely long axially symmetric cylindrical waveguide with perfectly conducting metal wall. The radius of the waveguide cross section b.

The waveguide cross section of this particular mode shown in Figure 2, can be divided into three different relative dielectric tensor. The first region is dielectric rod, in the range $0 \le r \le a$, the plasma column is the second region in the range $a \le r \le R_p$ .The beam particle while the third region in the range $R_p \le r \le R_b$ Since, Maxwell equations describing the electromagnetic fields in the plasma must contain induced charged and currents. So the modified Maxwell's equations are

$$\nabla \times H = \epsilon_0 \frac{\partial}{\partial t} E + \mathbf{J} \quad (5)$$

$$\nabla \times E = -\frac{\partial}{\partial t} B \quad (6)$$

$$\nabla . B = 0 \quad (7)$$

$$\nabla . E = \frac{\rho}{\varepsilon_0} \quad (8)$$

By solving these Maxwell equations, for electric field we get the electric field at the boundary,

$$E_{z4} = F\, J_0(x_3 b) + G N_0(x_3 b) = 0 \quad (9)$$

Let, F=Dr+Es (10)

Where

$$r = \frac{J_0(x_3R_b)N_1(x_3R_b) - J_1(x_3R_b)N_0(x_3R_b) + \frac{Bf}{x_3}J_0(x_3R_b)N_0(x_3R_b)}{J_0(x_3R_b)N_1(x_3R_b) - J_1(x_3R_b)N_0(x_3R_b)} \quad (11)$$

And,
$$s = \frac{\frac{Bf}{x_3}\{N_0(x_3R_b)\}^2}{J_0(x_3R_b)N_1(x_3R_b) - J_1(x_3R_b)N_0(x_3R_b)} \quad (12)$$

Also Let,G=Dr1 +Es1 (13)

Where,
$$r1 = \frac{\frac{Bf}{x_3}\{J_0(x_3R_b)\}^2}{J_0(x_3R_b)N_1(x_3R_b) - J_1(x_3R_b)N_0(x_3R_b)} \quad (14)$$

and
$$s1 = \frac{N_1(x_3R_b)J_0(x_3R_b) - \frac{Bf}{x_3}N_0(x_3R_b)J_0(x_3R_b) - N_0(x_3R_b)J_1(x_3R_b)}{J_0(x_3R_b)N_1(x_3R_b) - J_1(x_3R_b)N_0(x_3R_b)} \quad (15)$$

V. SIMULATION RESULTS

Equation (9) shows the equation of electric field at the boundary surface, We observed that this equation is a function of radiation frequency ω, and propagation constant k. From the boundary condition at the boundary surface, the tangential electric field must be zero.

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So we get ω-k diagram i.e dispersion relation diagram.
Then we observed the effect of plasma frequency on the dispersion relation diagram.

- Let plasma frequency ω_p = 2π*4 GHz

Then the dispersion relation diagram will be as in Fig. 3.
Dispersion curve will be flatten due to increae in plasma frequency and wave number. At the fixed ω_p, dispersion curve will be flatten due to wave number. So at the starting (wave number 0-2), it is nt flatten.
As we know, since the wave number, k is inversely proportional to wavelength. So the angular frequency is inversely proportional to wavelength, and hence directly proportional to wave number. As a result dispersion curve (ω-k diagram) is sharply changes.

Now if we increase the plasma frequency then we observed that, The dispersion curves of the structure waves as well as vacuum case are shown in Fig. 3.The waveguide parameters used in this case same as described above. It is clear from the Fig.3 that the more the presence of plasma in the waveguide shifts the dispersion curves up in frequency. Figure 3 also shows that the increase in the plasma density i.e. plasma frequency tends to flatten the dispersion curves.

Consider a=1 cm, b=2 cm, ε_r =2.1

The beam space charge curve corresponding to v_b=0.9c is shown by the straight line in the same figure. The interaction of this straight line with the electromagnetic structure wave are the expected oscillation frequency of the plasma loaded dielectric Cherenkov maser interaction at least for infinitesimal electron beam densities. This oscillation frequency for the three different plasma frequency is plotted as a function of plasma density i.e plasma frequency in Fig. 4.

The oscillation frequencies increase almost linearly with the plasma frequency. Now we observed the dispersion relation diagram by changing the relative permittivity of dielectric rod region. In Figure 5, shows the effect of relative permittivity of the dielectric rod region.
In Figure 7, the oscillation frequency as a function of relative permittivity is shown.

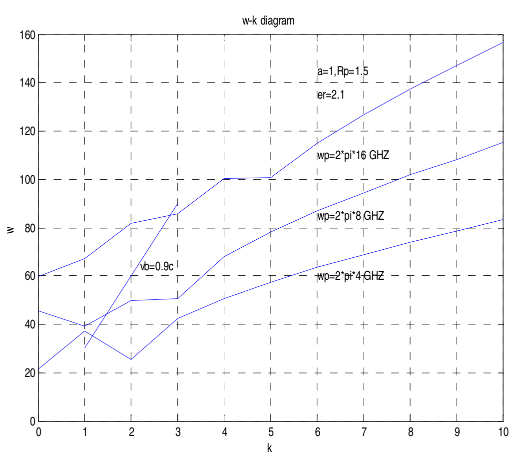

Figure 3. The effect of plasma frequency on the oscillation frequency.

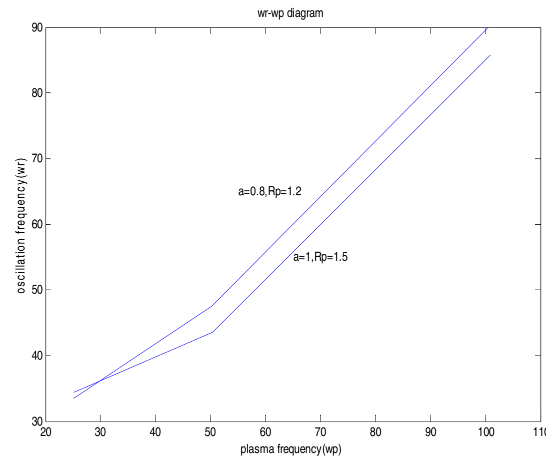

Figure 4. Effect of dielectric rod radius and plasma column radius on the oscillation frequency as a function of plasma frequency.

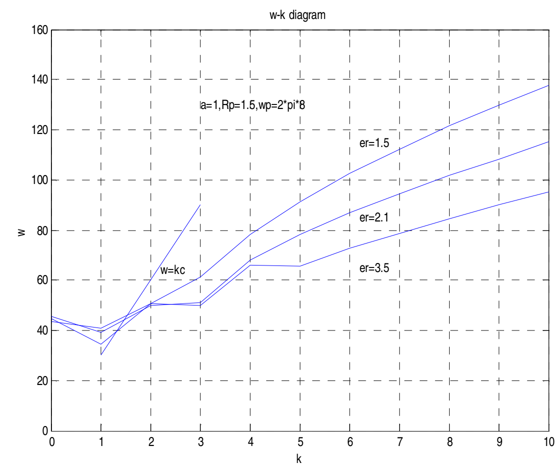

Figure 5. Effect of relative permittivity of the dielectric rod on the dispersion curve for a=1, Rp=1.5.

Now we consider the system, letting the dielectric rod radius a=0.8 cm and plasma column radius R_p is 1.2 In this case also, the more the presence of plasma in the waveguide shifts the dispersion curves up in frequency, and oscillation frequency as a function of plasma frequency shown in Figure 4.
Fig. 4 also shows that the comparison between two systems both of which indicate the expected oscillation frequency as a function of plasma frequency.We observed that the oscillation frequency is higher if the radius of the dielectric rod is less. Now we observed the dispersion relation diagram by changing the relative permittivity of dielectric rod region. In Figure 6, shows the the effect of relative permittivity of the dielectric rod region.The waveguide parameters such as dielectric rod radius a,Plasma column radius R_P , the electron beam radius R_b ,and the waveguide boundary radius of b , are the same as explained above. i.e a=0.8 and R_p=1.2 cm.And all other waveguide

parameters are same in all the case. It is clear from the Figure 10, that the more the value of relative permittivity ϵ_r of the dielectric rod it shifts the dispersion curves down in frequency. The beam space charge curve corresponding to v_b=0.9c is shown by the straight line in the same figure.The interaction of this straight line with the electromagnetic structure wave are the expected oscillation frequency of the dielectric loaded cherenkov generator iteraction at least for infinitesimal electron beam densities. The figure also shows that one may expect a high frequency oscillation from plasma loaded slow-wave waveguide with dielectric cherenkov maser with small value of relative permittivity of the dielectric rod.
The oscillation frequency as estimated from the intersection of the beam space charge wave with the structure wave found to increase with the decrease in relative permittivity ε_r .
This is also shown in Figure 7. In Figure 7, the oscillation frequency as a function of relative permittivity is shown. Fig. 7 also shows the comparison between two systems both of which indicate the expected oscillation frequency as a function of relative permittivity.

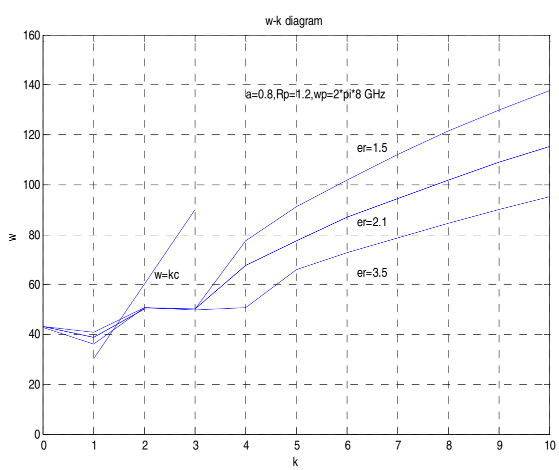

Figure 6. Effect of relative permittivity of the dielectric rod on the dispersion curve for a=0.8, R_p=1.2

We see that,the expected frequency is more when we use dielectric rod radius a=0.8 and Rp=1.2 as compared to the oscillation frequency obtained by using dielectric rod radius a=1 and Rp=1.5, for the same value of plasma frequency. The comparism between this two curves is shown in Figure 7.We observed that the oscilation frequency is higher if the the radius of the dielectric rod is less**.**

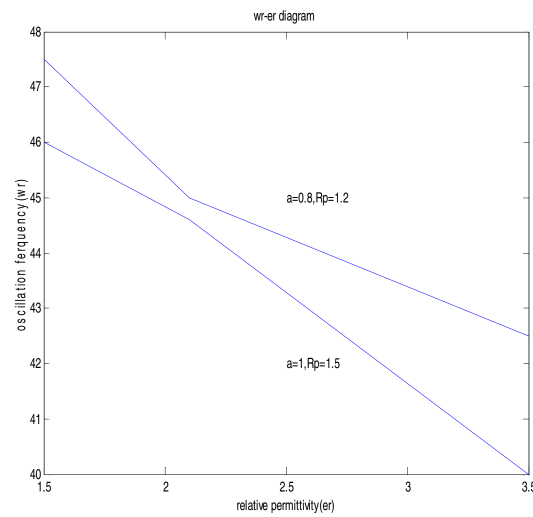

Figure 7: Effect of 'a' and R_p on the oscillation frequency as a function of relative permittivity.

VI. CONCLUSION

The linear dispersion relation of the slow-wave waveguide with dielectric loaded Cherenkov generator driven by an intense relativistic electron beam has been analysed. Dispersion relation of various plasma frequency, proposed by author has been studied and analysed to conceive the optically designed dielectric loaded Cherenkov generator .For dielectric loaded Cherenkov generator with plasma, we have a dispersion relation in which the plasma term ω_p is included in the arguments of Bessel functions.

In this paper we consider the interaction of electromagnetic wave with TAREB and plasma in the absence of external magnetic field inside the dielectric rod Cherenkov maser slow-wave waveguide. This medium includes a dielectric rod with a plasma column and a TAREB. The effect of background plasma density on the oscillation frequency of the wave are numerically calculated and discussed. Comparing the oscillation frequency of the wave for two different radii of dielectric rod and plasma column, it can be concluded the latter is greater than former. So we can conclude that, by placing dielectric rod in the centre of waveguide, the oscillation frequency of the wave, hence the growth rate of the wave increases.

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