TERAHERTZ CHERENKOV FREE-ELECTRON LASER*

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Abstract

In the development of compact terahertz radiation source, a table-top Cherenkov free-electron laser is proposed. The simplified model is a double-slap device, including a rectangular wave guide partially filled with two lined parallel dielectric slabs, driven by a 50 kev electron beam. The dispersion relation of such a model is investigated theoretically and the dispersion equation is solved numerically. With the help of a particle-in-cell simulation code, the mechanism of beam-wave interaction is carefully studied.

INTRODUCTION

The interest on the terahertz radiation source keeps growing in recent years since this frequency provides widely applications in medical, industrial and material science [1-4]. The popular way to generate terahertz radiation is to use the femtosecond solid-sate lasers to drive crystal, due to its small size in comparison with other approaches. But, the average power is small in such a way, limited around 10 μ W. The electron beam based systems have advantage in average power, like usual free-electron laser and gyrotron, and they can provide tens of watt output. However, the free-electron laser facility usually requires an accelerator and a big size wiggler, and the terahertz gyrotron requires superconductor magnet system, and therefore, they can not be handy.

The Cherenkov free-electron laser can generate terahertz radiation with low energy electron beam, and a compact device can be realized since the wiggler is not necessary. According to this goal, we are developing a compact electron beam source [5]. In this paper, we aimed at analyzing the high frequency structure to be adopted.

BASIC THEOREY

A double slab with conductor pad structure is as shown in Fig. 1. It is like a waveguide partially loaded with dielectric medium. Those two dielectric mediums can be same or different. We will analyze the dispersion relation of such a structure at the condition of without electron beam.

Field Expression

Region 1 is vacuum area, and components of field here can be written as

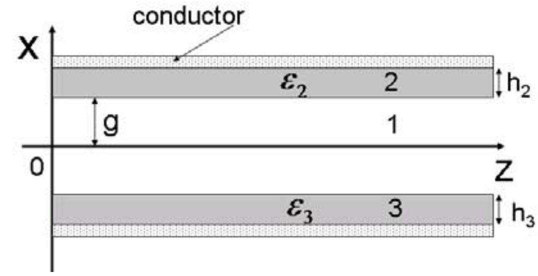

Figure 1: A double slap structure for Cherenkov free-electron laser

$$H_{y1} = A\exp(jk_1x) + B\exp(-jk_1x) \quad (1)$$

for the magnetic component, and

$$E_{z1} = -\frac{k_1}{\omega\varepsilon_0}(A\exp(jk_1x) - B\exp(-jk_1x)) \quad (2)$$

for the electric component.

Here, ω is the angle frequency, ε_0 the vacuum permittivity, $k_1 = \sqrt{\omega^2/c^2 - k^2}$, c is the light velocity and k the wave number in vacuum.

Region 2 and region 3 are dielectric medium areas, and we have the following expressions.

$$H_{y2} = C\exp(jk_2x) + D\exp(-jk_2x) \quad (3)$$

$$E_{z2} = -\frac{k_2}{\omega\varepsilon_0\varepsilon_2}(C\exp(jk_2x) - D\exp(-jk_2x)) \quad (4)$$

$$H_{y3} = E\exp(jk_3x) + F\exp(-jk_3x) \quad (5)$$

$$E_{z3} = -\frac{k_3}{\omega\varepsilon_0\varepsilon_3}(C\exp(jk_3x) - D\exp(-jk_3x)) \quad (6)$$

$$k_2 = \sqrt{\varepsilon_2\omega^2/c^2 - k^2} \qquad k_3 = \sqrt{\varepsilon_3\omega^2/c^2 - k^2}$$

Where, ε_2 and ε_3 stand for relative permittivity of media 2 and 3, respectively.

Dispersion Equation

The longitudinal electric field disappears at the boundary of conductor pad. Based on this fact we get the boundary conductions as

$E_{z2} = 0 \qquad (x = g + h_2)$

$E_{z3} = 0 \qquad (x = -(g + h_1))$.

And we also have $H_{y1} = H_{y2}$, $E_{z1} = E_{z2}$ at $x = g$; $H_{y1} = H_{y3}$, $E_{z1} = E_{z3}$ at $x = -g$.

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With the help of above conditions, the dispersion equation can be derived as

$$\exp(j4k_1 g) = \frac{(1+M)(1-N)}{(1+N)(1-M)} \qquad (7)$$

where

$$M = \frac{jk_1\varepsilon_2}{k_2}\cot(k_2 h_2)\ ,\quad N = \frac{jk_1\varepsilon_3}{k_3}\cot(-k_3 h_1)\ .$$

Numerical Calculation

The dispersion equation can be solved numerically, so that we can study the dispersion characteristics of the mentioned structure. At first, we make the same medium and focus on the influence from the asymmetrical thickness of the dielectric medium. The gap g is chosen 500 μ m , relative permittivity $\varepsilon_2 = \varepsilon_3 = 21.96$, and h_2 is fixed as 100 μ m. Calculations are carried out for a series thickness h_1, and the results are as shown in Fig. 2. The top line indicates the case of $h_1 = 100$ μ m, meaning that a higher frequency radiation can be achieved at the same electron beam energy, in comparison with the other cases. With the increase of thickness h_1, the dispersion lines become lower.

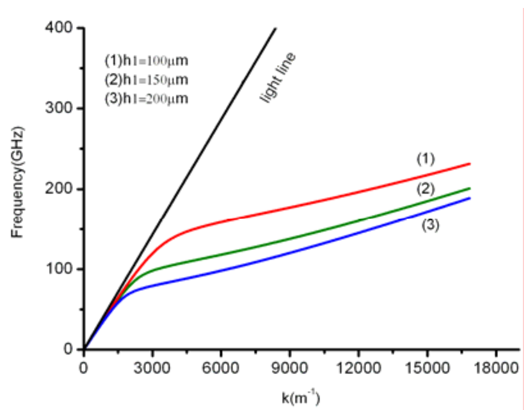

Figure 2: Dispersion curves for different slab thickness .

Next, let us make the media thickness be the same, i.e., $h_1 = h_2 = 100$ μ m, and see the effect of different permittivity. Under the condition of fixed $\varepsilon_2 = 21.96$, the dispersion equation is solved and the results are as shown in Fig. 3. Obviously, with the increase of ε_3 the dispersion line becomes lower.

SIMULATION

A preliminary experiment is planed based on the developing electron beam source. With the help of MAGIC code, we carried out a two dimensional simulation to investigate the beam-wave interaction in the high frequency structure. MAGIC is a commercial

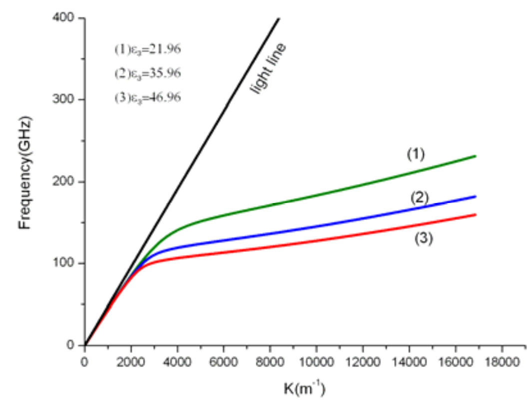

Figure 3: Dispersion curves for different relative permittivity.

particle-in-cell code for simulating processes involving interactions between space charge and electromagnetic fields [6].

Simulation Model

The simulation model involving a double-dielectric-medium structure and a sheet electron beam with limit thickness is shown in Fig.4. It is an oscillator structure with mirrors at the upstream and downstream ends. L stands for the length of the dielectric medium, d the

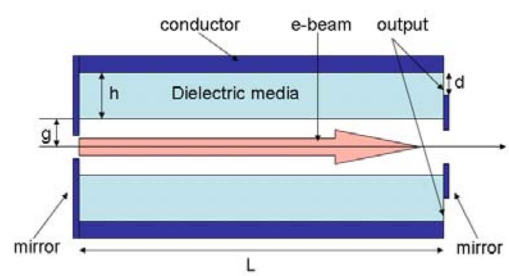

Figure 4: Simulation model of Cherenkov FEL.

outlet to output the radiation, h the medium thickness and g the half gap for transporting the electron beam. We use a sheet electron beam with the thickness of 100 μ m. It is produced by the MAGIC algorithm and is generated from a cathode located at the left boundary of the simulation box. The initial distribution of electrons is uniform in the longitudinal and transverse direction. The electron-wave interaction occurs in the vacuum area of the gap, and the radiation propagates in the vacuum and the dielectric medium regions. The electron beam can be absorbed at the downstream end, which is a special region (called free space in MAGIC). The external magnetic field is used to ensure stable beam propagation. The main parameters are given in Table 1. The whole simulation area is divided into a mesh with small rectangular cells in the region of beam propagation and dielectric media area.

Table 1: Main Parameters for Simulation

Dielectric medium length	L=11 cm
Dielectric medium thickness	h=0.65 mm
Outlet for output	d=0.22 mm
Half gap	g=0.5 mm
Electron energy	E=50 KeV
Current intensity	J=1E7 A/m^2
External magnetic field	B=2 T
Relative permittity of media	ebs=11.6

As for the diagnostics, the MAGIC algorithm allows us to determine a variety of physical quantities such as electromagnetic fields as functions of time and space, power outflow, and electron phase-space trajectories. We can set the relevant detectors anywhere in the simulation area.

Simulation Results

The beam-wave interaction modulates the electron beam along the interaction region and this can be seen

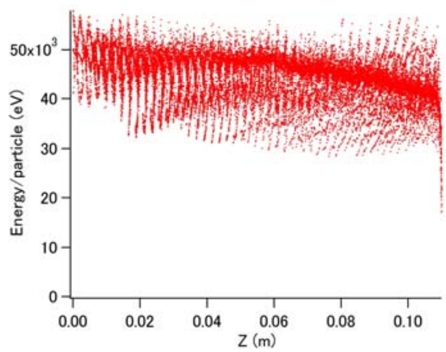

Figure 5: Energy modulation of electron beam.

from the phase space as shown in Fig. 5. The energy modulation brings magnification of the radiation and the wave continually increases between the mirrors to realize oscillation. The frequency spectrum comes from the FFT of the temporal signal as shown in Fig. 6. Obviously, it

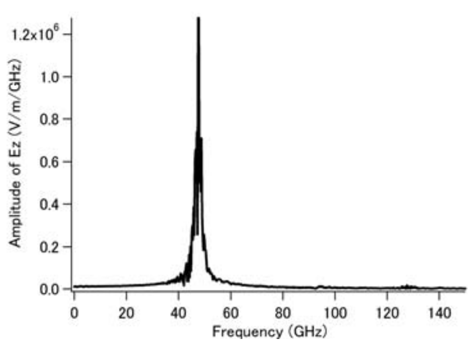

Figure 6: Spectrum of radiation frequency.

radiates at 47 GHz. The radiation energy can be seen from the loss of the electron energy, which is shown in Fig. 7. It is the average energy loss of the electrons, and the loss energy turns into the radiation energy, since any kind of loss in the media and the conductor surface are not considered in the simulation.

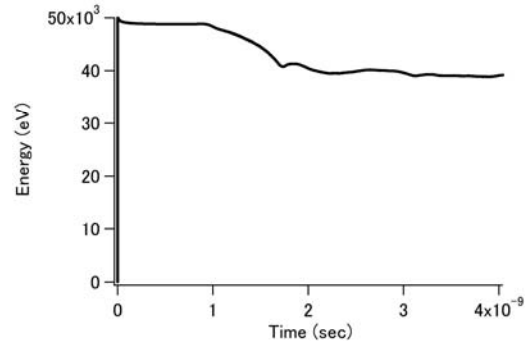

Figure 7: Average energy loss of the electron beam.

CONCLUSION

A double slab structure for the compact Cherenkov free-electron laser is analyzed theoretically. Trough the numerical method we solved the dispersion equation and illustrate its dispersion characteristic. Based on this structure, we simulate an oscillator model for a planed experiment. The frequency spectrum is achieved and the radiation energy is estimated.

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