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LETTER

Efficiency Enhancement in a Cherenkov Laser by a Proper Variation of Dielectric Thickness

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SUMMARY In order to enhance the energy transfer efficiency in a Cherenkov laser, we propose to use a tapered waveguide with a dielectric thickness properly varied stepwise in the longitudinal direction. With the aid of particle simulation, we investigate the nonlinear characteristics of the Cherenkov laser with the tapered waveguide, demonstrating the effectiveness of our proposal for efficiency enhancement.

key words: *Cherenkov laser, dielectric thickness variation, efficiency enhancement, particle simulation*

1. Introduction

The Cherenkov laser is a potential high-power and tunable source of short millimeter or submillimeter waves. In the Cherenkov laser, the kinetic energy of a relativistic electron beam is converted into the electromagnetic (EM) energy through the active coupling between a relativistic electron beam and a slow EM wave propagated along a dielectric-loaded waveguide. Thus the growth of the EM wave in the Cherenkov laser causes the electron beam to lose kinetic energy, leading to the decrease in its average velocity or drift velocity. As a result, the EM wave gradually gets out of synchronism with the electron beam, since the former travels along the latter at a constant velocity. Hence, efficient energy transfer from the electron beam to the EM wave is prevented. Recently, it was reported [1]–[5] that this difficulty can be overcome by gradually increasing the permittivity of the loaded dielectric along the waveguide and thus keeping synchronism between them. However, it seems difficult to fabricate the dielectric waveguide with a permittivity which is gradually varied in the direction of wave propagation. Thus, instead of varying the permittivity of the dielectric, we can equivalently vary the dielectric thickness stepwise in the longitudinal direction, in order to decrease the phase velocity of the EM wave. The purpose of this letter is to demonstrate the effectiveness of this scheme for efficiency enhancement in the energy transfer from the electron beam to the EM wave in the Cherenkov laser, with the aid of particle simulation [3], [5]–[7].

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2. Numerical Results

For the analysis of the problem, we consider a two-dimensional model of the Cherenkov laser composed of a planar relativistic electron beam and a parallel plate waveguide, one plate of which is loaded with a dielectric sheet with relative permittivity ε_r, as shown in Fig. 1. The electron beam is assumed to be ion-neutralized and magnetically confined in the z direction by a sufficiently large magnetostatic field. Various dimensions of the waveguide and the electron beam are given in Fig. 1.

We show in Fig. 2 a proper variation of the dielectric thickness for efficiency enhancement, together with a set of various parameters used for numerical simulation. The dielectric thickness is varied so that the synchronism between the EM wave and the average velocity

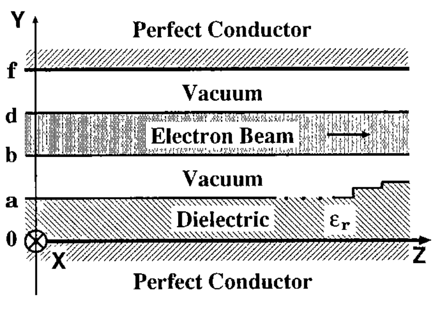

Fig. 1 Geometry of the problem.

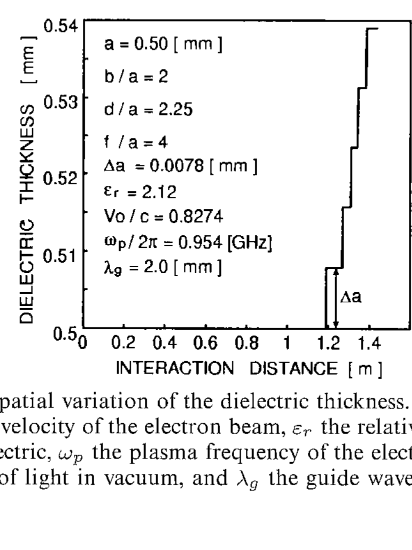

Fig. 2 Spatial variation of the dielectric thickness. V_0 refers to the initial velocity of the electron beam, ε_r the relative permittivity of dielectric, ω_p the plasma frequency of the electron beam, c the speed of light in vacuum, and λ_g the guide wavelength.

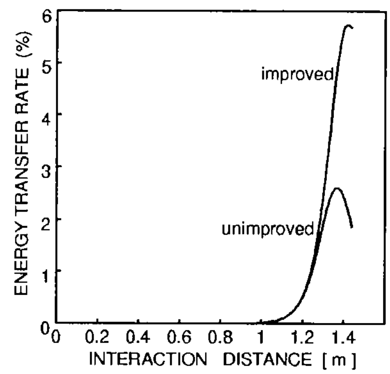

Fig. 3 Spatial variation of the energy transfer rate.

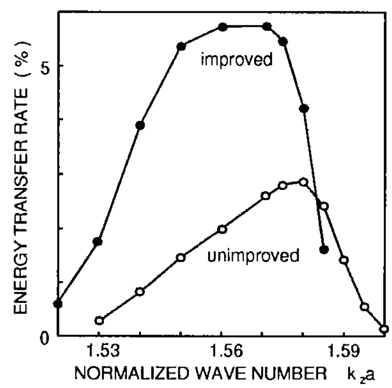

Fig. 4 The dependence of the energy transfer rate on the input wave numbers. All parameters except for λ_g are the same as those in Fig. 2.

of the electron beam is kept. For a detailed procedure of the numerical simulation, refer to Ref. [5], in which the permittivity of the dielectric waveguide is varied instead of the dielectric thickness. Note that the increment of the dielectric thickness Δa must be small enough for the reflection of the EM wave due to the discontinuity of the dielectric thickness to be negligible [4]. As seen from Fig. 2, in order to keep the synchronism between the EM wave and the electron beam, the dielectric thickness should be increased in accordance with the decrease in the average beam velocity in the direction of wave propagation.

Next, we discuss the rate of energy transfer [3], [5] from the electron beam to the EM wave. For the proper variation of the dielectric thickness given in Fig. 2, we illustrate in Fig. 3 the spatial variation of the rate of energy transfer from the electron beam to the EM wave. As is evident from Fig. 3, the proper thickness variation leads to great enhancement in the growth characteristics for the Cherenkov laser. The maximum value of the rate of energy transfer, i.e., the energy transfer efficiency, is found to be 2.6% for a uniform dielectric thickness while it is enhanced to 5.7% for the properly tapered dielectric thickness.

Finally, we show in Fig. 4 how the energy transfer efficiency depends on the input wave numbers (i.e., on the input frequencies) for the tapered dielectric waveguide. Note that the initial drift velocity of the electron beam is chosen so that the growth rate, at the initial state, becomes maximum for the normalized wave number $k_z a = \pi/2\,(\simeq 1.57)$, and the EM energy is extracted at the point where the EM wave reaches saturation for $k_z a = \pi/2$. As seen from Fig. 4, the energy transfer efficiency is greatly enhanced for broader input wave numbers by properly varying the dielectric thickness of the waveguide. This is another remarkable feature of the Cherenkov laser with the tapered waveguide, in addition to efficiency enhancement in energy transfer.

3. Conclusion

With the aid of particle simulation, we discussed the nonlinear characteristics and the efficiency enhancement in a Cherenkov laser with a tapered waveguide, in which the dielectric thickness is properly varied stepwise in the longitudinal direction. Numerical results show that the efficiency of energy transfer from the electron beam to the EM wave is greatly enhanced over broader input wave numbers by properly varying the thickness of the dielectric sheet.

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