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Two Models for Electro-Magnetic Wave Amplifier by Utilizing Traveling Electron Beam

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Abstract For the electro-magnetic (EM) wave amplifier, we point out two amplification mechanisms should exist according to the relation between the EM wavelength and the electron size. First model is named as Coherent Electron Wave (CEW) model. Another one is named as Localized Electron (LE) model.

Introduction

The configuration of our proposed amplifier is illustrated in Fig. 1 [1,2], where the emitted electron beam runs along a surface of the waveguide made of high refractive index material. The EM wave propagates through the waveguide with one part penetrating into vacuum area. Then the EM wave can get energy from the electron beam and is amplified. Conditions of the amplification are that the EM wave has to have an electric component in the propagation direction z of the electron beam and that the group velocity v_{el} of the electron coincide with the phase velocity of EM wave v_{em}. Generation and amplification of the optical wave basing on this scheme were experimentally confirmed [3,4]. However, detailed mechanism of the amplification should differ with the relation between the EM wavelength and the electron size. In this paper, we propose two analytical models for the amplification. One is named as Coherent Electron Wave Model (CEW-model) and another is Localized Electron Model (LE-model). Both models are derived biasing on the quantum mechanical point of view, and the two models differences are discussed.

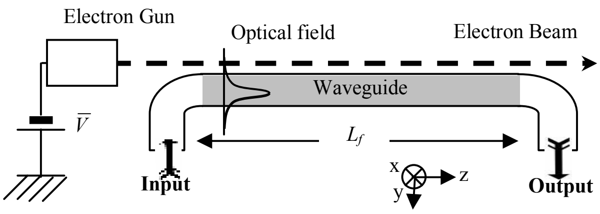

Fig.1 Illustration scheme of EM- wave amplifier.

Coherent Electron Wave Model (CEW-Model)

This model is applicable in the case that the wavelength λ of the EM wave is shorter than the spreading length ℓ of an electron. Dynamics of the electron are formulated with the density matrix equation to examine the quantum statistical behavior of the electrons [1]. The gain coefficient is expressed as

$$g(v_{el}) = \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{e J_o \tau v_{el}}{n_{eff}\, \hbar\omega} \xi D(v_{el}), \ \xi \approx \iint_s | T_z(x,y)|^2 dx\, dy \tag{1}$$

where, n_{eff} is the effective refractive index of waveguide, J_0 is the average electron density, τ is electron relaxation time, $T_z(x,y)$ is the normalized transverse distribution function and ξ is coupling coefficient between the electron beam and the EM wave within cross-section S of the electron beam. $D(v_{el})$ is a dispersion function giving by,

$$D(v_{el}) = \mathbf{Sinc}^2\left[\left\{\frac{\sqrt{2m_o}}{\hbar}(\sqrt{eV_{el}} - \sqrt{eV_{el} - \hbar\omega}) - \frac{n_{eff}\,\omega}{c}\right\}\frac{\ell}{2}\right] - \mathbf{Sinc}^2\left[\left\{\frac{\sqrt{2m_o}}{\hbar}(\sqrt{eV_{el} + \hbar\omega} - \sqrt{eV_{el}}) - \frac{n_{eff}\,\omega}{c}\right\}\frac{\ell}{2}\right] \tag{2}$$

V_{el} is the acceleration voltage corresponding to the electron velocity v_{el}. The gain coefficient $g(v_{el})$ has the peak value at the maximum of $D(v_{el})$. These relations are explained as phase modulation of electron wave by the EM field.

Localized Electron Model (LE-model)

This model is applicable when the electron spreading length ℓ is shorter than the EM wavelength λ. We derived the dynamic equations of electrons from the Schrödinger equation by counting phase distortion of electron wave due to mutual interaction among the electrons, and found that the dynamic equations well correspond to those used in classical manner where the electron is regarded as a point particle. The gain coefficient in the LE-model is formed as

$$g(v_{el}) = \xi \frac{e\mu_o J_o}{m_o \omega} Y(v_{el}),\ Y(v_{el}) = \mathbf{Re}\left\{ \left(j + \frac{1}{\omega\tau} \right) \Big/ \left(\frac{n_{eff}}{c} v_{el} - 1 + \frac{j}{\omega\tau} \right)^2 \right\} \tag{3}$$

where, $Y(v_{el})$ is a dispersing function in the LE-model

Thermal Effects on the Amplification

When we applied voltage $\overline{V}$ to the electron gun, actual electron velocity v_{el} must not be unique and has the thermal distribution around corresponding to the cathode temperature T in the electron gun. Then the gain coefficient $g(\overline{v})$ for the averaged electron velocity $\overline{v}$ should be given as

$$g(\overline{v}) = \int_o^\infty f(v_{el}, \overline{v})\, g(v_{el})\, dv_{el}. \tag{4}$$

Here, $f(v_{el}, \overline{v})$ is the Maxwell-Boltzmann distribution function given as

$$f(v_{el}\overline{v}) = \sqrt{\frac{m_o}{2\pi K_B T}} \exp\left[-\frac{eV_{el}}{K_B T} \left(\frac{\overline{v}}{v_{el}} - 1 \right)^2 \right]. \tag{5}$$

Numerical examples of the gain variation with the EM frequency after taking into account the thermal effect are shown in Fig.4. The gain in the LE-model is much reduced unless $T = 0$. We can expect sufficient gain by the LE-model and the CEW-model in relatively low and high frequency regions, respectively. However, the gain in the THz region is smaller than other frequency regions.

Conclusions

Two models of gain mechanism for the EM wave amplifier by utilizing traveling electron beam are proposed. Classification of these models are basing on relation between the wavelength of the EM wave and the spreading length of the single electron. Boundary of two models is locating in the THz region.

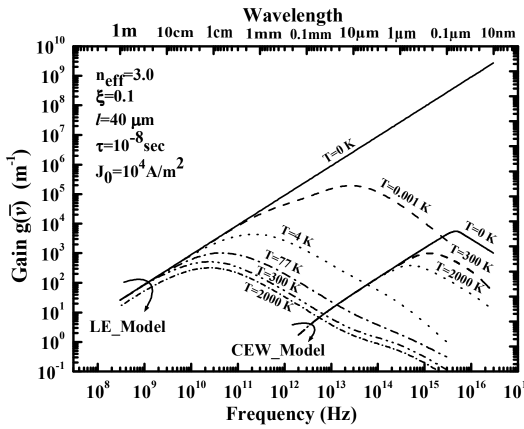

Fig. 4. Gain variation with the EM wave by the CEW-model and LE-model.

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