Two models for electro-magnetic wave amplifier by utilizing traveling electron beam

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

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Abstract An Electro-magnetic (EM) wave amplifier is a device that amplifies the EM wave moving through a planer waveguides by utilizing a traveling electron beam. Two models of amplification mechanisms are proposed basing on relation between the wavelength of EM wave and size of an electron. These models are formed basing on a quantum mechanical point of view; the boundary of these two models is determined in the THz region. The thermal effect of electron velocity broadening is introduced to estimate real amplification gain.

I. INTRODUCTION

Electro-magnetic wave amplifier scheme

The configuration of proposed amplifier is illustrated in Fig. 1; the emitted electron beam runs along a surface of the amplification portion of the waveguide. Then the EM wave can get energy from the electron beam and is amplified. To receive the conditions of amplification; the EM wave has to own an electric component in the propagation direction z of the electron beam. Also, the group velocity v_{el} of the electron is slightly faster than the phase velocity of EM wave v_{em}. This amplifier is covering wide frequency range from the microwave to the X-ray region [1,2].

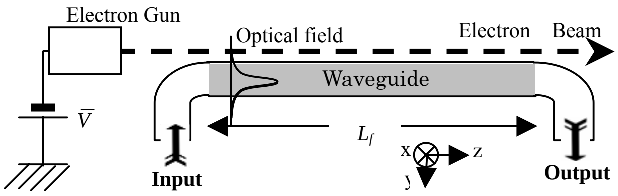

Fig.1 Illustration scheme of EM- wave amplifier.

In this paper, two types of analytical model are proposed, one is named as Coherent Electron Wave Model (CEW-Model) and another model is Localized Electron Model (LE-Model). The experimental data well support these quantum mechanical analyses at least in optical region [3-4].

II. COHERENT ELECTRON WAVE MODEL (CEW-Model)

In this model, we determine the case that electron wave spreads longer than the wavelength λ of the EM wave. The dynamics of the electron are formulated with the density matrix equation to examine the quantum statistical of the electron wave. A gain coefficient form is expressed as

$$g(v_b, v_{em}) = \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{e J_o \tau v_b}{n_{eff} \hbar\omega} \xi D(v_b, v_{em}). \tag{1}$$

where, v_b is the electron velocity at applied voltage V_b, n_{eff} is the effective refractive index of waveguide, J_0 is the average electron density, τ is electron relaxation time and ξ is coupling coefficient between the electron beam and the EM wave within cross-section S of the electron beam

$$\xi \approx \iint_s |T_z(x,y)|^2 dx\, dy. \tag{2}$$

where $T_z(x,y)$ is the normalized transverse distribution function. D is a dispersion function,

$$D(v_b, v_{em}) = Sinc^2\left[\left\{\frac{\sqrt{2m_o}}{\hbar}\left(\sqrt{eV_b} - \sqrt{eV_b - \hbar\omega}\right) - \frac{n_{eff}\,\omega}{c}\right\}\frac{\ell}{2}\right] - Sinc^2\left[\left\{\frac{\sqrt{2m_o}}{\hbar}\left(\sqrt{eV_b + \hbar\omega} - \sqrt{eV_b}\right) - \frac{n_{eff}\,\omega}{c}\right\}\frac{\ell}{2}\right] \tag{3}$$

where l is coherent length of the electron wave. In this model, when both spatial and time variations of the EM wave and mixed electron wave coincide, interaction between the electron and the EM wave is caused.

Numerical Example

In Fig. 2, The gain increases almost linearly with value of $\ell \cdot f$ due to the fact that the value of D/ω is proportional to $\omega \cdot l$ when the peak of D is much smaller than 1. At higher frequency, the gain decrease inversely with f influencing by dominator factor ω in (1) and saturation of D to value 1.

III. LOCALIZED ELECTRON MODEL (LE-Model)

In this model, we discuss the case that the phase of an electron wave is distorted within shorter range than the wavelength λ. Then the electron is regarded as a spatially localized particle. The dynamics of electron flow is described by using Schrödinger equation of total electrons stream wave, the resultant electron dynamics is combatable with the classical analysis describing the electron-EM wave interaction.

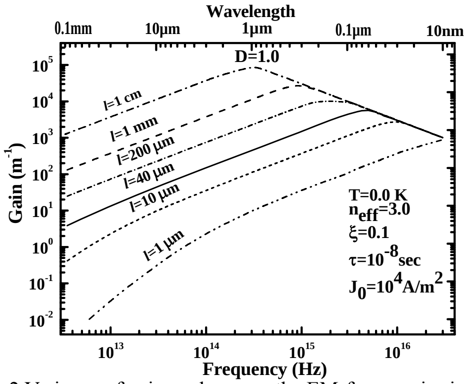

Fig. 2 Variance of gain peak versus the EM-frequencies in CEW-Model.

In the LE-Model, the gain is formed as

$$g(v_b, v_{em}) = \xi \frac{e\mu_o J_o}{m_o \omega} Y(v_b, v_{em}). \tag{3}$$

$Y(v_b, v_{em})$ is a dispersing function

$$Y(v_b, v_{em}) = Re\left\{\left(j + \frac{1}{\omega\tau}\right) \Big/ \left(\frac{n_{eff}}{c} v_b - 1 + \frac{j}{\omega\tau}\right)^2\right\}. \tag{4}$$

In LE-Model, the electron density and velocity will be modulated around its average value. If this average velocity is slightly higher than the EM wave phase velocity, the amplification will be dominated.

Numerical Example

In Fig. 3, since the peak value of the dispersion function proportional to $(\omega\tau)^2$, the gain peak is linearly increasing with the frequency *f*. The thermal effect limits this indefinite increment as will described in next section.

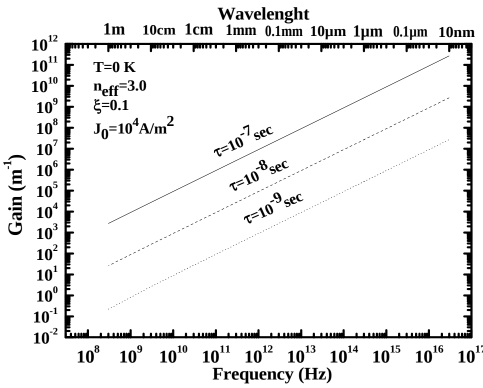

Fig. 3. The gain peak variation with the EM frequency by the LE-Model.

IV. THERMAL EFFECTS ON THE AMPLIFICATION

The velocity of each traveling electron is not identical and should have thermal dispersion. Then the gain coefficient $g(\bar{v})$ for the average electron velocity becomes

$$g(\bar{v}, v_{em}) \approx \int_o^\infty f(v_b, \bar{v})\, g(v_b, v_{em})\, dv_b. \tag{5}$$

where, the average electron velocity is $\bar{v}$ and the real electron velocity is v_b. Both velocities are related by the Maxwell and Boltzmann distribution function as

$$f(v_b, \bar{v}) = \sqrt{\frac{m_o}{2\pi K_B T}}\, exp\left[-\frac{eV_b}{K_B T}\left(\frac{\bar{v}}{v_b} - 1\right)^2\right]. \tag{6}$$

K_B is the Boltzmann constant and *T* is absolute temperature.

Numerical Examples

In both models, when the distribution function is broader than the gain profile in (5), the gain (at *T*=0 K) is suppressed as shown in Fig. 4. The gain becomes larger in lower frequency region if the electron length *l* becomes longer enough as shown in Fig. 5.

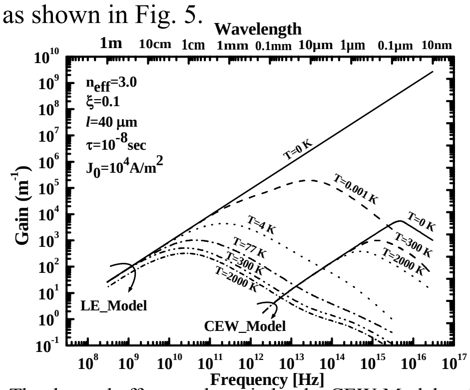

Fig. 4. The thermal effect on the gain by the CEW-Model and LE-Model.

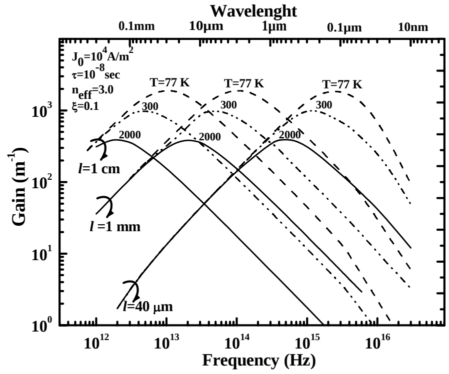

Fig. 5. The gain peak variation with the EM frequency by the CEW-Model.

V. CONCULOSIONS

The frequency dispersion in CEW-Model is between the wavelength of EM wave and the electron coherent length, while that in LE-Model is between the frequency of EM wave and the electron relaxation time. The CEW-Model suffers from the thermal broadening in shorter wavelength range than the visible light, while the (LE-Model) is affected in higher frequency than microwave. THz region is boundary between these models, and the gain in THz region is smaller than that in other region if the coherent length is not long enough.

REFERENCES

[1] M. Yamada, "Theoretical proposal for a unidirectional optical amplifier" IEEE J. of Quantum Electron., vol. **35**, pp. 147-152, 1999.

[2] M. Asada and M. Yamada, "Theoretical analysis of interaction between electron beam and electromagnetic wave for unidirectional optical amplifier" J. Appl. Phys. vol. **95**, pp. 5123-5130, 2004.

[3] Y. Kuwamura, M. Yamada, Y. Ichino, I. Fukamuraand and T. Sekikawa, "Observation of Optical Amplification Excited by Traveling Electron Beam" Jpn. J. Appl. Phys. vol. **43**, pp. 7109-7110, 2004.

[4] Y. Kuwamura, M. Yamada, R. Okamoto, T. Kanai and H. Fares, "Observation of TM guided spontaneous emission in high refractive index optical waveguide excited by the traveling electron beam" Proc. Int CLEO/QELS Conf. (2008).