Traveling wave Amplification due to the Carrier wave Interaction in Solids

論 文
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Abstract

A coupled-mode approach is used to analyze the interaction of the carrier wave in solid-state materials with the external slow electromagnetic wave. A general condition for an active coupling is derived. Gain characteristics is also examined as a function of operating frequency and thermal-to-drift velocity variations.

1. Introduction

Solid state traveling-wave amplifier (STWA) has been studied by many research workers recently (1), (5), (7), (8). Its most attractive feature is the extremely high gain, and broad frequency band characteristics, which make it a potential active device in microwave integrated circuit systems. There are some practical difficulties such as the device heating problem and the saturation of carrier drift velocity. However, with the rapid advance in solid state technology, it is feasible that STWA might be able to operate at higher power and higher frequencies. The methods of analysis were either using an extended classical Pierce's approach (2). or matching the wave admittance at the slow wave and semiconductor boundary (3). Both approaches are rather lengthy, but the results are inaccurate or doubtful.

In most cases, some of the important aspects such as coupling scheme, energy exchange between the circuit and carrier wave, and the way of finding dispersion relation were not clearly revealed. In this paper, the coupled mode approach is presented, which appears to be simpler and clearer in describing the various possible interactions.

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2. Theoretical Analysis

Consider a single type of charged carrier in solids drifting a tightly coupled electromagnetic slow wave circuit. The equivalent transmission line equation for the collisionless longitudinal carrier wave is given by Ho and Fanson, and Kang (4), (7), (9).

$$\left(\frac{\partial}{\partial z}+j\beta_1\right)V=-Z_sJ \tag{1}$$

$$\left(\frac{\partial}{\partial z}+j\beta_1\right)J=-Y_{sh}V \tag{2}$$

where $V=V_1+V_t$ is the total kinetic potential, $V_1=-\frac{u_0 v}{\eta}$ is the kinetic potential due to longitudinal modulation, $V_t=-\frac{\rho}{\rho_0}\frac{v_t^2}{\eta}$ is the kinetic potential due to thermal diffusion, and

$$\beta_1=\frac{\beta_e}{1-a^2}\quad \beta_e=\frac{\omega}{u_0}\quad \beta_p=\frac{\omega_p}{u_0}\quad a=\frac{v_t}{u_0}$$

$$Z_s=\text{series impedance}=j\frac{\beta_e X^2}{(1-a^2)\,\epsilon\omega_p\beta_p}$$

$$Y_{sh}=\text{shunt admittance}=j\frac{\beta_e\epsilon\omega_p\beta_p}{(1-a^2)}$$

$$X=\left[a^2+\frac{\omega_p^2}{\omega^2}(1-a^2)\right]^{\frac{1}{2}}$$

The characteristic impedance of the equivalent line is

$$Z_0=\sqrt{\frac{Z_s}{Y_{sh}}}=\frac{u_0X}{\epsilon\omega_p^2} \tag{3}$$

The normal modes of the fast and slow carrier waves are defined as (5).

$$a_1^{\pm}=\frac{1}{\sqrt{8Z_0}}(V\mp Z_0J) \qquad (4)$$

The upper and lower signs are for the fast and slow carrier waves repectively.

For a lossless slow wave circuit, the transmission line equation is

$$\frac{\partial V_2}{\partial z}=-ZJ_2 \qquad (5)$$

$$\frac{\partial J_2}{\partial z}=-YV_2 \qquad (6)$$

where Z and Y are the series impedance and shunt admittance of the circuit respectively. The normal modes are [6].

$$a^{2\pm}=\frac{1}{\sqrt{8Z_c}}(V_2\pm Z_cJ_2) \qquad (7)$$

Upper sign is for the forward circuit wave, Z_c is the circuit characteristic impedance. When the circuit and the carrier stream are closely coupled, the couple-mode equations are

For carrier wave

$$\left(\frac{\partial}{\partial z}+j\beta_1\right)V=-Z_sJ+\frac{\partial V_2}{\partial z} \qquad (8)$$

$$\left(\frac{\partial}{\partial z}+j\beta_1\right)J=-Y_{sh}V \qquad (9)$$

For slow wave circuit

$$\frac{\partial V_2}{\partial z}=-ZJ_2 \qquad (10)$$

$$\frac{\partial J_2}{\partial z}=-YV_2-\frac{\partial J}{\partial z} \qquad (11)$$

In terms of normal modes, the above equations become

$$\left(\frac{\partial}{\partial z}+j\beta_1-\frac{Z_s}{Z_0}\right)a_1^++\left(\frac{\partial}{\partial z}+j\beta_1+\frac{Z_s}{Z_0}\right)a_1^-$$
$$=\sqrt{\frac{Z_s}{Z_0}}\ \frac{\partial}{\partial z}(a_2^++a_2^-) \qquad (12)$$

$$\left(\frac{\partial}{\partial z}+j\beta_1+Y_{sh}Z_0)\right)a_1^--\left(\frac{\partial}{\partial z}+j\beta_1-Y_{sh}Z_0\right)$$
$$a_1^+=0 \qquad (13)$$

$$\left(\frac{\partial}{\partial z}+j\beta\right)a_2^++\left(\frac{\partial}{\partial z}-j\beta\right)a_2^-=0 \qquad (14)$$

$$\left(\frac{\partial}{\partial z}+j\beta\right)a_2^+-\left(\frac{\partial}{\partial z}-j\beta\right)a_2^-$$
$$=-\sqrt{\frac{Z_c}{Z_0}}\ \frac{\partial}{\partial z}(a_1^--a_1^+) \qquad (15)$$

For traveling-wave amplification the forward circuit wave a_2^+ is strongly coupled to the slow carrier wave a_1^-. The coupled-mode equation are then reduced to

$$\frac{\partial a_1^-}{\partial z}=-jC_{11}a_1^-+C_{12}a_2^+ \qquad (16)$$

$$\frac{\partial a_2^+}{\partial z}=-jC_{22}a_2^++C_{21}a_1^- \qquad (17)$$

where

$$C_{11}=\beta_1+\frac{Z_c}{jZ_0} \qquad C_{12}=-j\sqrt{\frac{Z_c}{4Z_0}}\beta_1$$

$$C_{22}=\beta=\sqrt{ZY} \qquad C_{21}=j\sqrt{\frac{Z_c}{4Z_0}}\beta_1$$

The transfer factor, which is defined as the fraction of the total power transfer between modes (6), is found to be

$$Fa_1-a_2^+=\left[1-\left(\beta-\beta_1+j\frac{Z_s}{Z_0}\right)^2\frac{(1-a^2)^2u_0x}{\beta_e^2Z_c\epsilon\omega_p^2}\right]^{-1} \qquad (18)$$

Chose coupling occurs when two modes are synchronized, that is

$$\beta=\beta_1-j\frac{Z_s}{Z_0}=\beta_e\frac{(1+X)}{(1-a^2)} \qquad (19)$$

Assuming the coupled modes have the form $e^{\Gamma z}$, the propagation factor Γ is found from Eqs. (16) and (17) to be

$$\Gamma=-j^{\frac{1}{2}}\left\{\beta+\frac{\beta_e}{1-a^2}\left[1+\sqrt{a^2+\frac{\omega_p^2}{\omega^2}(1-a^2)}\right]\right\}$$
$$\pm\left\{\frac{\beta_e^2Z_c\epsilon\omega_p^2}{4u_0X(1-a^2)}-\frac{1}{4}\left[\beta-\frac{\beta_e}{(1-a^2)}\right.\right.$$
$$\left.\left.\left(1+\sqrt{a^2+\frac{\omega_p^2}{\omega^2}(1-a^2)}\right)\right]\right\}^{\frac{1}{2}} \qquad (20)$$

The positive real part of Γ gives growing wave. Maximum gain occurs at the synchronized given by Eq. (19). The maximum gain per wavelength is

$$G_m=\left[\frac{Z_c\epsilon\omega_p^2}{4(1-a^2)u_0\sqrt{a^2+\frac{\omega_p^2}{\omega^2}(1-a^2)}}\right]^{\frac{1}{3}} \qquad (21)$$

3. Discussions

Computer plots of gain per wavelength as a function of thermal to carrier drift velocity and operating frequency are shown in Figs. 1 and 2 respectively. It is noted from Fig. 1 that the device gain increases indefinely as the carrier drift velocity by the bias potential approaches the thermal velocity. This, however, will not occur in this interaction since the slow carrier wave will slow down tremendously as $u_0\rightarrow v_t$ and eventually propagates backward as $u_0<v_t$ [5].

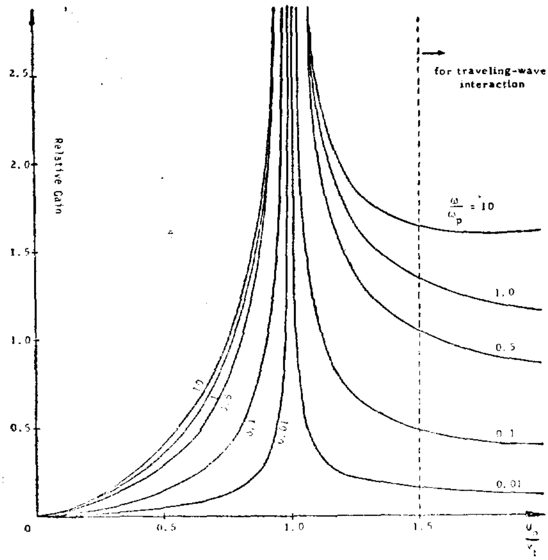

Fig. 1. Relative gain as a function of drift-to-thermal velocity ratio.
$\frac{\omega}{\omega p}$ as parameter.

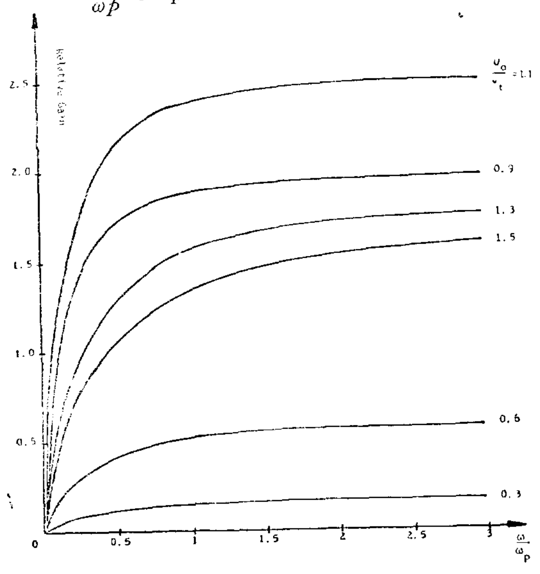

Fig. 2. Relative gain as a function of operation frequency.

In order to maintain synchronism between the waves of the carrier and a practical slow wave circuit the u_0-to-v_t ratio should have a value about 1.5 or greater as indicated in the figure. Figure 2 shows the interaction itself is almost independent of operating frequency for $\omega > \omega_p$.

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