

INSTABILITY CHARACTERISTICS OF SOLID-STATE
CARRIER WAVES IN MICROWAVE CIRCUITS

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ABSTRACT - The interaction of solid-state carrier waves with rf circuit waves is analyzed in order to predict the wave instabilities and to investigate the wave characteristics. A general dispersion relation for the coupled waves traveling along a finite semiconductor slab is developed by analyzing the interaction between the carrier waves and the rf waves. The effects of collision, diffusion, insulator thickness, semiconductor thickness and substrate material are included in the analysis. The instability characteristics in solids are obtained by solving the dispersion equation for the system. The results indicate the feasibility of net gain of the microwave signal in several N-type semiconductors. The experimental results are represented to confirm the general feature of the theoretical analysis. The maximum gain of 5.2 db was obtained through the coupled circuit.

Introduction

Several workers (Solymer, Ash, Sumi, and Hines 1966) have investigated the wave amplification due to the coupling between the space charge wave and the rf circuit wave in solid-state materials. In most cases, many important aspects of the analysis such as the boundary condition for wave interaction and the way of finding roots of the dispersion equation were not clearly justified. The reflected waves and surface charge on the semiconductor were usually neglected, in spite of the finite dimension and conductivity of the slab. The approaches were oversimplified and hence the results were either inaccurate or doubtful.

The method of analysis reported thus far has been either an extension of Pierce's approach (Solymer and Ash 1966) or the transverse admittance matching technique (Sumi 1966). Here, a formal way of deriving the dispersion relation is presented. For a nontrivial solution of the fields in the slab, the determinant of the field matrix must vanish, which gives the dispersion relation. The device structure considered is shown in Fig. 1.

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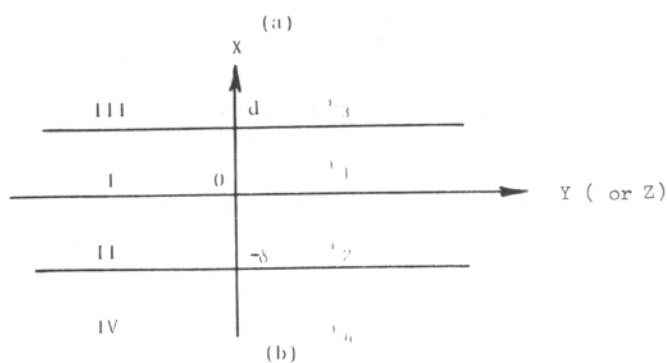
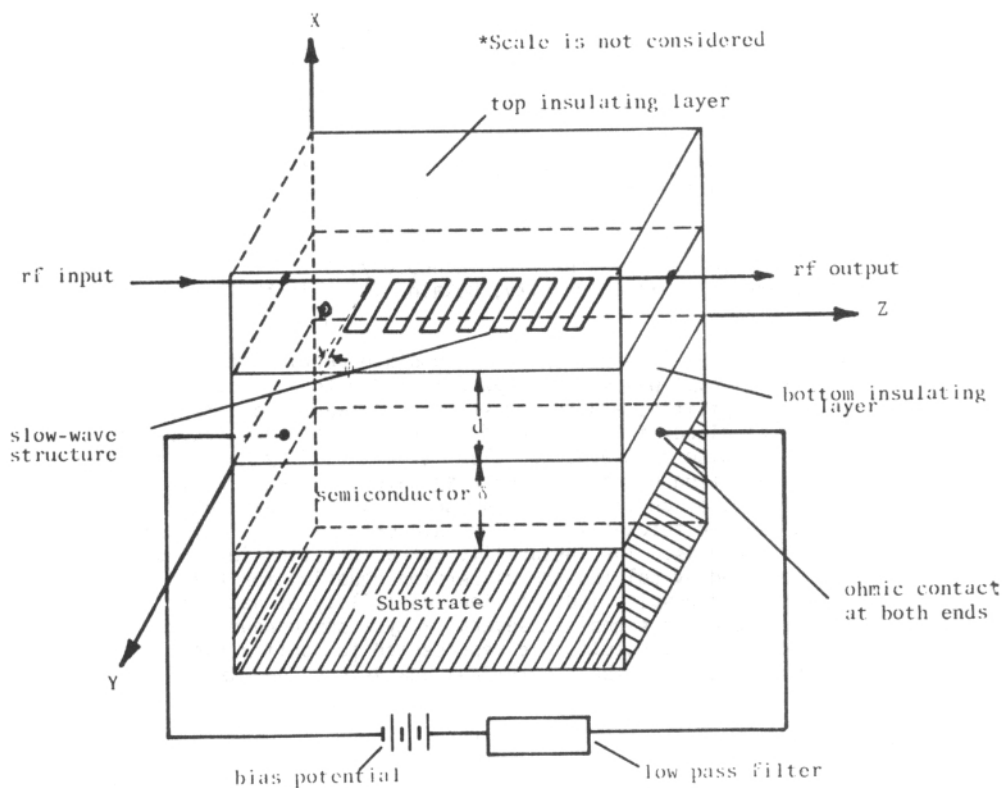


Fig. 1 One possible structure for solid-state traveling-wave amplifier. (a) Sketch showing coupling between space charge waves and external microwave fields (b) Schematic planar layout of (a).

Boundary Conditions

Based on the device configuration presented in Fig. 1, the following boundary conditions are observed: (1) The tangential electric field component is continuous at $x=0$, $x=d$ and $x=-\delta$. (2) The normal rf velocity vanishes at $x=0$ and $x=-\delta$. (3) The tangential magnetic field component is continuous at $x=0$ and $x=-\delta$ since the conductivity of the semiconductor is finite. (4) Along the direction of the tape-line, the tangential electric field at the edge of the tape must vanish since the tape is considered to be a perfect conductor. (5) The component of the magnetic field tangent to the tape-line must be continuous since no current flows perpendicular to the tape. The second boundary condition is well-known in a gaseous plasma. Since the cloud of carriers has the nature of solid-state plasma, the normal rf component of carrier velocity must vanish at the boundaries. The last two conditions for the slow-wave circuit were used by Chu (Chu 1948).

Field Analysis in Solids

In the device operation, a d-c potential is applied across the semiconductor, such that the carrier stream will drift at a velocity of u_0 in the z-direction. One type of charged carrier, namely electrons, will be considered for simplicity and $e^{j(\omega t - kz)}$ is assumed for the wave propagation. The first moment of the Boltzmann equation in Eulerian variables is

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla + \nu\right)\vec{v} = \frac{q}{m^*} (\vec{E} + \vec{v} \times \vec{B}) - \frac{v_t^2}{n} \nabla n$$

where n is carrier density, v_t is thermal velocity, m^* is effective mass of a carrier, and ν is total collision frequency.

Since the gradient of the rf carrier density is $\nabla n_1 = -\frac{e^2}{e} \nabla \nabla \cdot \vec{E}_1$ from

the divergence equation of $\vec{E}$, the rf carrier velocity can be derived from the Boltzmann equation as

$$\vec{v}_1 = \frac{j n^*}{\omega_\nu} \left(\vec{E}_1 - \frac{v_t^2}{\omega_p^2} \nabla \nabla \cdot \vec{E}_1 \right) \quad (1)$$

where $\omega_\nu = \omega - ku_0 - j\nu$, $n^* = |e|/m^*$, $v_t^2 = \gamma kT/m^*$, $\omega_p^2 = n_0 e^2 / \epsilon m^*$

and ν is the collision frequency.

Using Maxwell's curl equations and Equation (1) the wave equation for electric field intensity $\vec{E}$ is

$$\nabla^2 \vec{E}_1 + \omega^2 \mu_0 \epsilon_2 \left(1 - \frac{\omega_p^2}{\omega \omega_\nu} \right) \vec{E}_1 - j \omega \mu_0 \epsilon_2 \vec{u}_0 \cdot \nabla \vec{E} + \left(\frac{\omega \mu_0 \epsilon_2 v_t^2}{\omega_\nu} - 1 \right) \cdot \nabla \nabla \cdot \vec{E}_1 = 0 \quad (2)$$

For two-dimensional analysis, with $\frac{\partial}{\partial y} = 0$, the wave equation can be written in the following form:

$$\begin{bmatrix} \left(\frac{\partial^2}{\partial x^2} + jga^2\right) & 0 & k(g-j) \\ 0 & \left(\frac{\partial^2}{\partial x^2} - a^2\right) & 0 \\ jk\left(\frac{a^2}{k^2} + \frac{b^2}{jg}\right)\frac{\partial}{\partial x} & 0 & \left(\frac{\partial^2}{\partial x^2} - \frac{j b^2}{b}\right) \end{bmatrix} \begin{bmatrix} E_{1x} \\ E_{1y} \\ E_{1z} \end{bmatrix} = 0 \quad (3)$$

where $a^2 = k^2 - \omega^2 \mu_0 \epsilon_2 (1 - \omega_p^2 / \omega \omega_v)$, $b^2 = \omega_v / v_t^2 \cdot [-\omega + k u_0 + \omega_p^2 + k^2 v_t^2] / \omega_v$

and $g = j\omega_v / (\omega \mu_0 \epsilon_0 v_t^2)$.

It can be easily shown that, without the application of the longitudinal d-c magnetic field, the fields can be divided into independent TM and TE waves (Agdur 1958). From the two-dimensional assumption, the only magnetic field for the TM waves is H_{1y} while $H_{1x} = H_{1z} = 0$. By solving Equation (3) and using Maxwell's equations, we obtain the field solutions in the semiconductor region as follows:

TM Waves

$$E_{1z} = A_1 e^{ax} + A_2 e^{-ax} + A_3 e^{bx} + A_4 e^{-bx} \quad (4)$$

$$E_{1x} = \frac{jk}{a} (A_1 e^{ax} - A_2 e^{-ax}) + \frac{jbk (1 - j l/g)}{a^2 - j b^2 / g} (A_3 e^{bx} - A_4 e^{-bx}) \quad (5)$$

$$H_{1y} = \frac{\epsilon_2 c^2}{j \omega} \frac{a^2 - k^2}{a} (A_1 e^{ax} - A_2 e^{-ax}) + \frac{(a^2 - k^2) - j l/g \cdot (b^2 - k^2)}{a^2 - j b^2 / g} b (A_3 e^{bx} - A_4 e^{-bx}) \quad (6)$$

TE Waves

$$E_{1y} = B_1 e^{ax} + B_2 e^{-ax} \quad (7)$$

$$H_{1x} = -\frac{k\epsilon_2 c_2^2}{\omega} (B_1 e^{ax} + B_2 e^{-ax}) \quad (8)$$

$$H_{1z} = j\frac{\epsilon_2 c_2^2 a}{\omega} (B_1 e^{ax} - B_2 e^{-ax}) \quad (9)$$

where $c_i^2 = 1/(\mu_0 \epsilon_i)$ and A_1, A_2, A_3, A_4, B_1 and B_2 are all unknown coefficients to be determined from the boundary conditions. Note that A_2, A_4, B_2 cannot be neglected since the slab thickness is comparable to the skin depth and the reflected waves should be considered.

Electromagnetic Fields in Various Regions

The conduction current in the insulator region is zero, so the wave equation is reduced to the following simple form:

$$\frac{\partial^2 \vec{E}_1}{\partial x^2} - \gamma_1^2 \vec{E}_1 = 0 \quad (10)$$

where $\gamma_i^2 = k^2 - \omega^2/c_i^2$. Since the fields are attenuated in the $\pm x$ -direction as given by the boundary conditions, therefore these fields have solutions of the form $e^{\pm \gamma_i x}$, where $i = 1, 3$, and 4 corresponding to regions I, III and IV respectively. Field solutions in all cases are tabulated in Table 1.

Dispersion Relation

Applying boundary conditions to all field solutions gives a 14×14 field coefficients matrix. A necessary and sufficient condition for a nontrivial solution is that the determinant of the field coefficient matrix shown in Table 2 be zero, which yields the following dispersion relation:

$$\begin{aligned} & \frac{j\omega\epsilon_4}{\gamma_4} \cdot \frac{(h_1+h_2/R) \cosh b\delta + R(h_1+h_2/R)(h_1+h_2/R+1) \sinh b\delta}{-8e^{-a\delta} + (h_1+h_2/R+2) \cosh b\delta + [R+1/R + R(h_1+h_2/R)] \sinh b\delta} \\ &= \frac{j\omega\epsilon_1}{\gamma_1} \cdot \frac{K_3(\Gamma_1 + \tanh \gamma_1 d) - K_4(\Gamma_2 - \tanh \gamma_1 d)}{-K_3(\Gamma_1 + \tanh \gamma_1 d + 1) + K_4(\Gamma_2 \tanh \gamma_1 d - 1)} \end{aligned} \quad (11)$$

$$\text{where: } K_3 = (1 + e^{-2\gamma_1 d}) \left[\frac{\gamma_1 - a}{\gamma_1 + a} - \frac{\gamma_4 - a}{\gamma_4 + a} e^{-2a\delta} \right],$$

TABLE 1

TABLE OF ELECTROMAGNETIC FIELD SOLUTIONS FOR ALL REGIONS

Region	Cases	TM Modes	TE Modes
Solid-state Region	General	$E_{1x} = A(e^{ax} + ne^{bx})e^{j(\omega t - kz)}$ $E_{1y} = \frac{j\omega}{a} \left[ax + \frac{nah(1 - \frac{1}{g})}{a^2 - \frac{b^2}{g}} bx \right] e^{j(\omega t - kz)}$ $H_{1y} = \frac{c_2 c_2^2}{j\omega} A \left[\frac{a^2 - k^2}{a} ax + n \frac{(a^2 - k^2) - \frac{1}{g}(b^2 - k^2)}{a^2 - \frac{b^2}{g}} bx \right] e^{j(\omega t - kz)}$	$E_{1y} = [C_1 a n^{\frac{1}{2}}] e^{j(\omega t - kz)}$ $H_{1x} = \left[-k \frac{c_2^2 c_2^2}{\omega} C_1 a n^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$ $H_{1z} = \left[j \frac{c_2^2 c_2^2}{\omega} C_1 a n^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$
	$ u - ku_0 < v$	$E_{1x} = A_1 \left(e^{a_1 x} + n_1 e^{b_1 x} \right) e^{j(\omega t - kz)}$ $E_{1y} = \frac{j\omega}{a_1} \left[\frac{A_1 n_1 a_1 b_1 (1 - \frac{1}{g})}{a_1^2 - \frac{b_1^2}{g}} b_1 x \right] e^{j(\omega t - kz)}$ $H_{1y} = \frac{j\omega c_2^2}{a_1} \left[\frac{u^2}{(u - \frac{v}{g})} e^{a_1 x} - \frac{jku_0^2}{v(u - ku_0 - \frac{1}{g}C_2^2)} e^{b_1 x} \right] e^{j(\omega t - kz)}$	$E_{1y} = \left[C_1 a_1^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$ $H_{1x} = \left[-k \frac{c_2^2 c_2^2}{\omega} C_1 a_1^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$ $H_{1z} = \left[j \frac{c_2^2 c_2^2}{\omega} C_1 a_1^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$
	Collisionless ($v = u_0$)	$E_{1x} = \left[A_2 e^{a_2 x} \right] e^{j(\omega t - kz)}$ $E_{1y} = \left[\frac{j\omega}{a_2} A_2 e^{a_2 x} \right] e^{j(\omega t - kz)}$ $H_{1y} = \left[\frac{j\omega c_2^2}{a_2} \left(1 - \frac{v_0^2}{u(u - ku_0)} \right) e^{a_2 x} \right] e^{j(\omega t - kz)}$	$E_{1y} = \left[C_2 a_2^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$ $H_{1x} = \left[-k \frac{c_2^2 c_2^2}{\omega} C_2 a_2^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$ $H_{1z} = \left[j \frac{c_2^2 c_2^2}{\omega} C_2 a_2^{\frac{1}{2}} \right] e^{j(\omega t - kz)}$
o/sxd Circuit Region	General	$E_{1x} = \left[F_2 e^{-\gamma_1 x} + F_3 e^{\gamma_1 x} \right] e^{j(\omega t - kz)}$ $E_{1y} = \left[\frac{j\omega}{\gamma_1} (F_2 e^{-\gamma_1 x} - F_3 e^{\gamma_1 x}) \right] e^{j(\omega t - kz)}$ $H_{1y} = \left[-\frac{j\omega}{\gamma_1} (F_2 e^{-\gamma_1 x} - F_3 e^{\gamma_1 x}) \right] e^{j(\omega t - kz)}$	$E_{1y} = \left[G_2 e^{-\gamma_2 x} + G_3 e^{\gamma_2 x} \right] e^{j(\omega t - kz)}$ $H_{1x} = \left[-\frac{j\omega}{\gamma_2} (G_2 e^{-\gamma_2 x} - G_3 e^{\gamma_2 x}) \right] e^{j(\omega t - kz)}$ $H_{1z} = \left[\frac{j\omega}{\gamma_2} (G_2 e^{-\gamma_2 x} - G_3 e^{\gamma_2 x}) \right] e^{j(\omega t - kz)}$
xsd Circuit Region	General	$E_{1x} = \left[F_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$ $E_{1y} = \left[-\frac{j\omega}{\gamma_3} F_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$ $H_{1y} = \left[-\frac{j\omega}{\gamma_3} F_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$	$E_{1y} = \left[G_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$ $H_{1x} = \left[-\frac{j\omega}{\gamma_3} G_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$ $H_{1z} = \left[-\frac{j\omega}{\gamma_3} G_1 e^{-\gamma_3 x} \right] e^{j(\omega t - kz)}$

$$\begin{array}{ccccccccccc} & 1 & -R & R & & & & & & & \\ e^{-a\delta} & -e^{a\delta} & -e^{-b\delta_R} & e^{b\delta_R} & & & & & & & \\ e^{-a\delta} & e^{a\delta} & e^{-b\delta} & e^{b\delta} & & & -e^{-Y_4\delta} & & & & \\ h_1 e^{-a\delta} & h_1 e^{a\delta} & h_2 e^{-b\delta} & h_2 e^{b\delta} & & & -e^{-Y_4\delta} & & & & \\ & & & & e^{-a\delta} & e^{a\delta} & & & & & -e^{-Y_4\delta} \\ & & & & e^{-a\delta} & -e^{a\delta} & & & & & -\frac{\gamma_4}{a} e^{-Y_4\delta} \\ & 1 & 1 & 1 & 1 & & -1 & -1 & & & \\ & & & & 1 & 1 & & & -1 & -1 & \\ \Delta_o h_1 & \Delta_o h_1 & \Delta_o h_2 & \Delta_o h_2 & & & -1 & 1 & & & \\ & & & & 1 & -1 & & & & & \frac{\delta_1}{a} - \frac{\delta_1}{a} \\ & & & & & & -e^{-Y_3 d} & e^{-Y_1 d} & e^{Y_1 d} & & \\ & & & & & & & & & & -e^{-\delta_3 d} e^{-Y_1 d} e^{Y_1 d} \\ & & & & & & \tan \psi & & 1 & & \\ & & & & & & -\Delta_2 e^{(Y-Y_3)d} & 1 & -e^{2Y_1 d} & & -\Delta_3 e^{(Y-Y_3)d} \Delta_1 \Delta_1 e^{2Y_1 d} \\ \text{where } \Delta_o = -\frac{\epsilon_4 Y_1}{\epsilon_1 Y_4}, \Delta_1 = \left(\frac{c_1 Y_1}{\omega}\right)^2 \tan \psi, \Delta_2 = \frac{\epsilon_3 Y_1}{\epsilon_1 Y_3}, \Delta_3 = \left(\frac{c_3}{\omega}\right)^2 \left(\frac{\epsilon_3}{\epsilon_1}\right) Y_1 Y_3 \tan \psi \end{array}$$

TABLE 2

ELECTROMAGNETIC FIELD COEFFICIENT MATRIX

$$K_4 = (1 + e^{2\gamma_1 d}) \left[1 - \frac{(\gamma_4 - a)(\gamma_1 - a)}{(\gamma_4 + a)(\gamma_1 + a)} e^{-2a\delta} \right],$$

$$\Gamma_{\frac{1}{2}} = \gamma_1 \left(\frac{\gamma_1}{\beta_{S_1}^2} \mp \frac{\epsilon_3 \gamma_3}{\beta_{S_3} \epsilon_1} \pm \frac{\epsilon_3}{\epsilon \gamma_3} \right),$$

$$\beta_{S_1} = \frac{\omega}{c_1 \tan \psi}, \quad \beta_{S_3} = \frac{\omega}{c_3 \tan \psi}, \quad h_1 = \left(\frac{\epsilon_2}{\epsilon_4} \right) \left(\frac{\gamma_4}{a} \right) \left(\frac{c_2}{\omega} \right) (k^2 - a^2),$$

$$h_2 = \left(\frac{\epsilon_2}{\epsilon_4} \right) \left(\gamma_4 b \right) \left(\frac{c_2^2}{\omega} \right) \frac{g(k^2 - a^2) + j(b^2 - k^2)}{ga^2 - jb^2}$$

$$R = ab \frac{j - g}{ga^2 - jb^2} - \frac{v_t^2}{\omega_p} \frac{b^2(j - g)}{ga^2 - jb^2} + 1$$

and ψ is the angle between the tape and the y -axis.

As one can see from Equation (11), the equation is too complicated with complex coefficients to obtain the device gain in an explicit analytical form. Hence, numerical analysis has been performed for materials such as N-type Si, Ge, GaAs, and InSb. The results of this calculations are presented in Fig. 2, Fig. 3, and Fig. 4.

Result and Discussion

A formal and straightforward way of obtaining the dispersion relation of a semiconductor slab has been presented. The results are in agreement with the conventional transverse matching technique (Sumi 1966) in general but are more accurate. From the computer solution, InSb is the most promising material, as was predicted by Sumi (Sumi 1966), because InSb possesses the highest drift velocity of most semiconductor materials.

The phase constant of the device is plotted in Fig. 2. Fig. 2 shows that the microwave signal can be amplified only if the phase constant of the coupled system is close to ω/u_0 where ω is operating frequency or $(2\pi f)$ and u_0 is dc carrier velocity. It is interesting to note that the amplification occurs when the phase velocity of the coupled system is synchronous with the carrier drift velocity which is identical to the theory of traveling-wave amplifier tube. In the frequency range of 1-10 GHz, attenuation curves of the $n=10^{14}/\text{cm}^3$ materials are presented in Fig. 3. All material constants for computation are tabulated in Table 3. It should be noted that the device gain

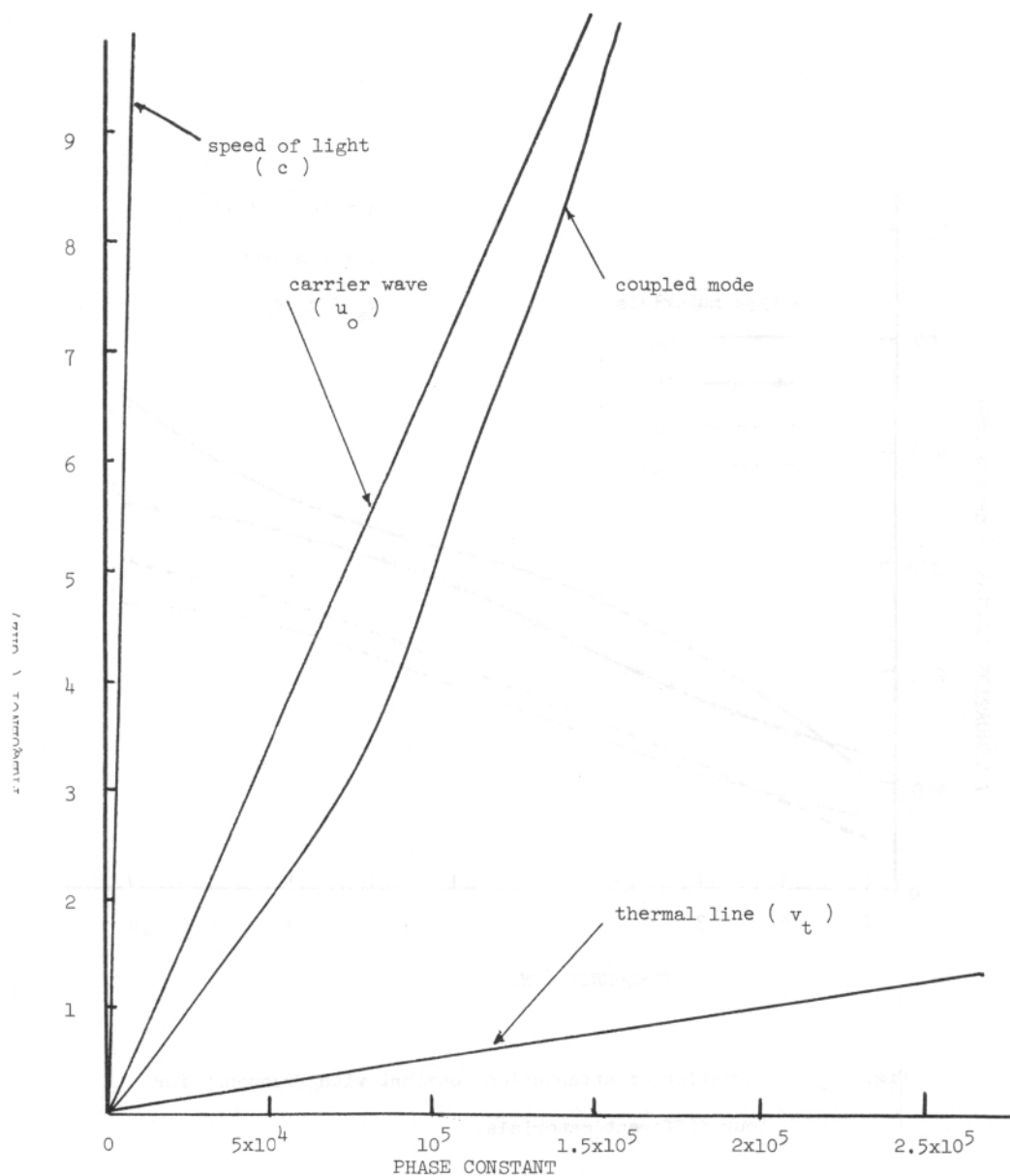


Fig. 2 Frequency vs. phase constant diagram for a $n = 10^{14}$ InSb sample.

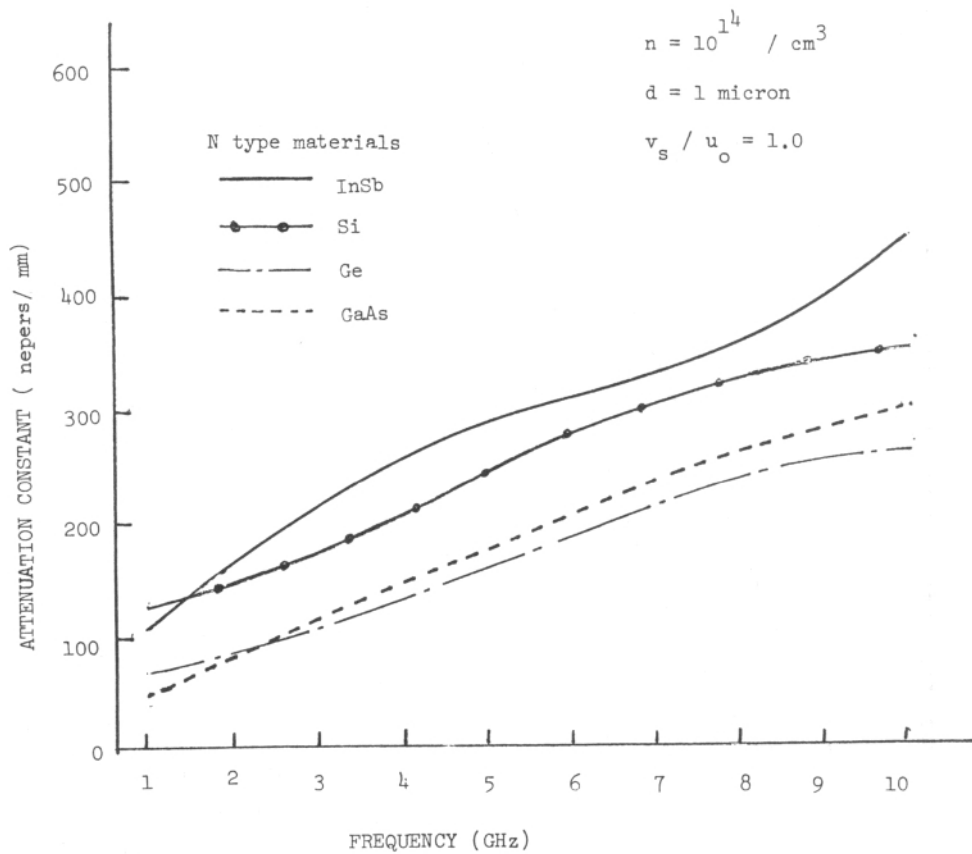


Fig. 3 Variation of attenuation constant with frequency for four different materials.

Material	Energy gap E_g (eV)	Rel. perm. ϵ_r	m^*/m_e	Mobility ($\text{cm}^2/\text{V}\cdot\text{s}$)	Resistivity ($\Omega\text{-cm}$)	Drift velocity u_0 (cm/sec)	Density (g/cm^3)
Si	1.11	11.8	0.33	1.2×10^3	45	$1 \times 10^6 - 2 \times 10^7$	10^{14}
Ge	0.67	16.0	0.04	3.8×10^3	60	$6 \times 10^6 - 1 \times 10^7$	10^{14}
				3.6×10^3	5		10^{15}
GaAs	1.53	12.5	0.072	7.4×10^3	44.2	$6 \times 10^6 - 1 \times 10^7$	10^{13}
				5.8×10^3	9.68		10^{14}
				5.5×10^3	2.50		10^{15}
InSb	0.18	15.7	0.016	3.15×10^5	0.50	$6 \times 10^7 - 9 \times 10^7$	10^{13}
				5.45×10^5	0.031		10^{14}
				4.0×10^5	0.013		10^{15}

TABLE 3

TYPICAL NUMERICAL VALUES FOR SEVERAL SEMICONDUCTOR MATERIALS

increases as the operating frequency increases since in the program the active device length has been assumed to be identical for all frequencies. The actual gain can be easily figured out for an operating frequency, from the figure. Therefore, the actual gain appears decreasing for higher frequencies. However, this device has some merit for the amplification of microwave and millimeter wave signals, compared to most of microwave active device because it has an excellent noise figure and high frequency response, although the electron beam device has no competition for high power operation.

From the dispersion relation, computer solution shows that optimum gain of the device is a strong function of insulating layer thickness, circuit velocity, collision frequency and carrier drift velocity. The insulating layer impairs operation drastically as can be seen in Fig. 4, because electromagnetic field of the tape-line decreases rapidly in the transverse direction. The net gain decreases as the circuit velocity increases, which is expected since the circuit wave and the carrier wave can not be synchronized after then. The result also confirms Vural's suggestion that the collision will only lead to reduction of amplification (Vural and Bloom 1967).

Several experimental devices have been built and tested. One such device is displayed in Fig. 5. The chosen semiconductor for the device is highly doped N-type material as shown in Table 3. To make the capacitively-coupled meander circuit, the dielectric material KMER by Kodak was deposited on the first type of fingers. The thickness of the dielectric layer is a half to one micron while the slab thickness is 3 to 5 microns. One side of circuit pattern is shown in Fig. 5a and the small portion of the complete circuit is taken by the enlargement of a microscope as shown in Fig. 5b. The final test structure is presented in Fig. 5c. Fig. 6 presents relative power level of rf transmitted waves from the device. A maximum power gain for Si-layer, as high as 5.2 db, was observed from Fig. 6. However, the gain variation of the device with frequency is extremely sharp because of large terminal and transmission mismatches.

The device built with the InSb material has not been as successful as predicted from the theoretical analysis, because the etching technique for the InSb has not been well developed yet. The usefulness of this type of device will heavily depend upon proper design and fabrication. If these can be improved by the advanced thin film technology, this device should be most desirable for space communication, considering its weight and low power operation. Further work in fabricating comparatively perfect meander circuit may be developed with electron-beam scanning techniques. This method will reduce the tape size in length and then increase the optimum operating frequencies up to 40 GHz.

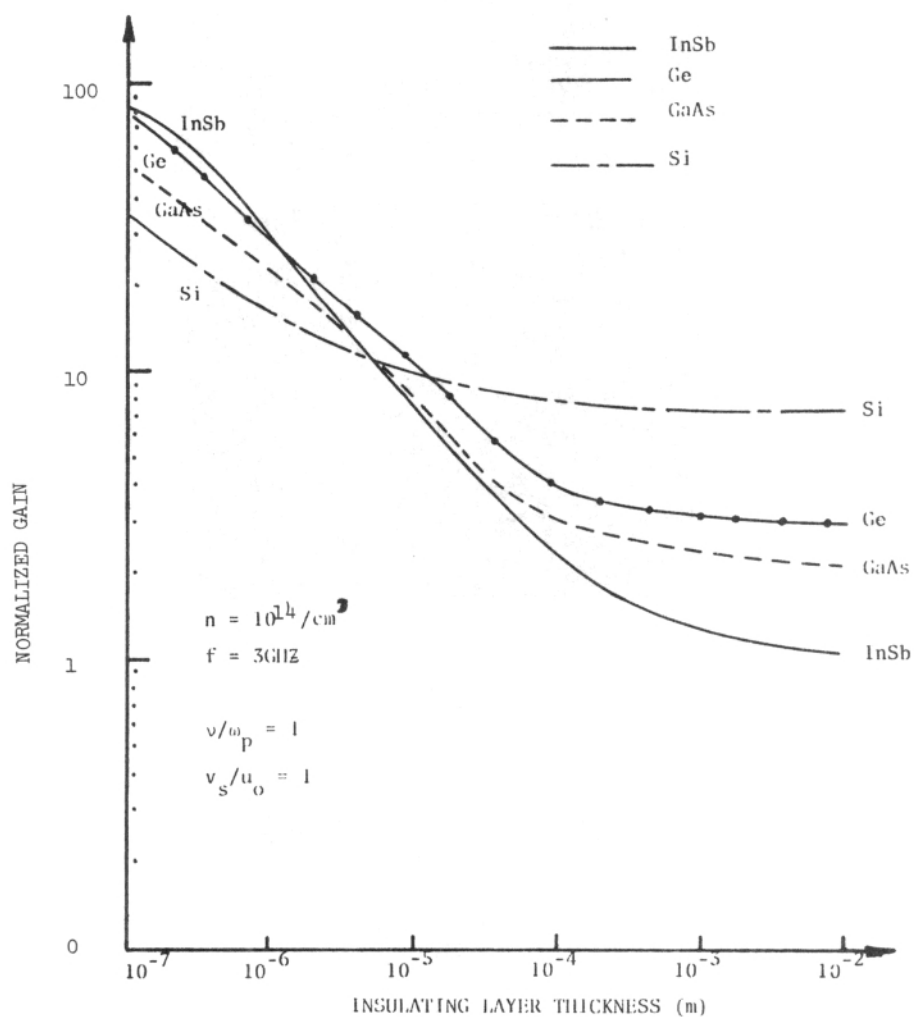


Fig. 4. Gain characteristics for various values of an insulating layer thickness (d)

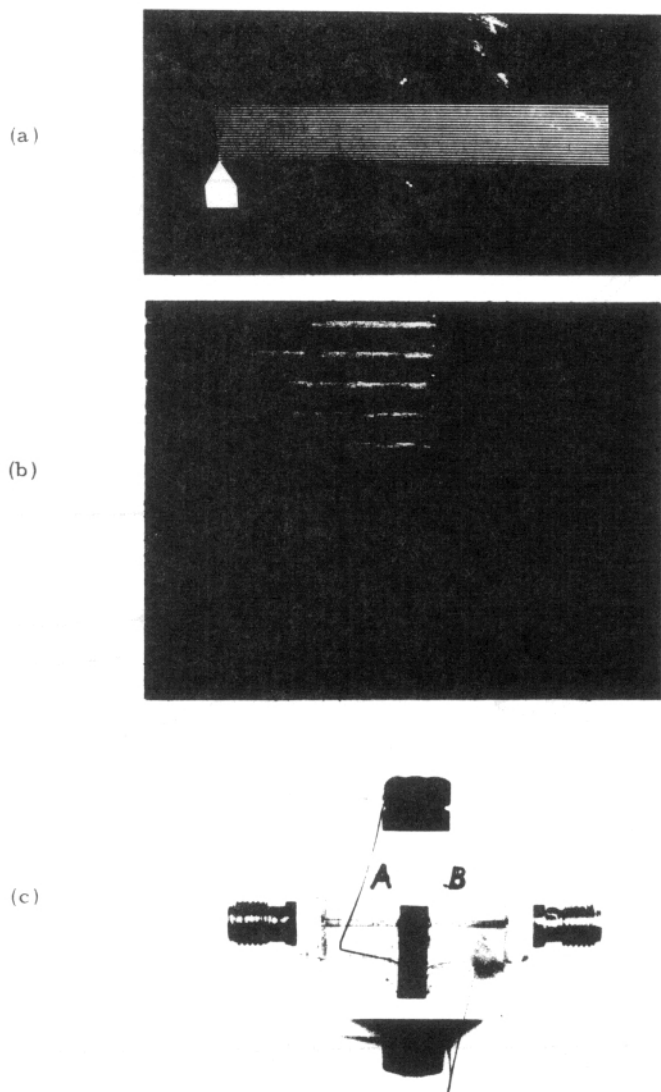
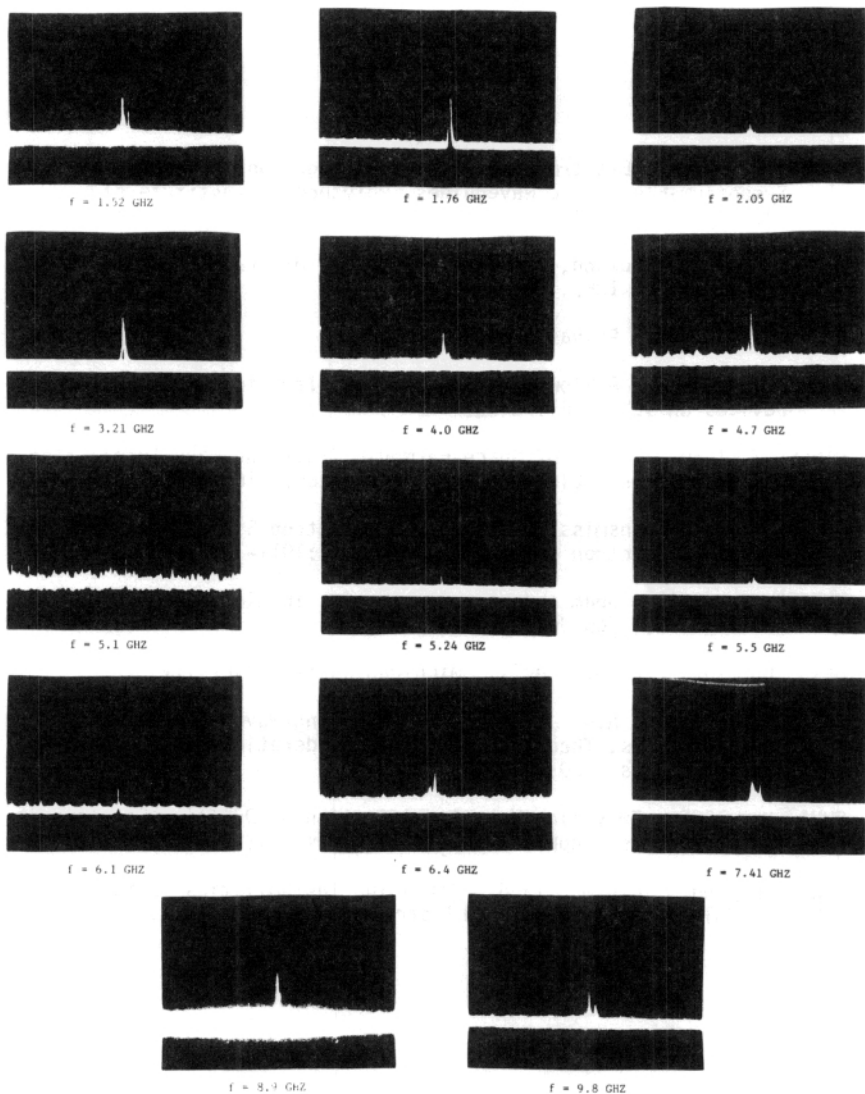


Fig. 5 Slow-wave circuit and test structure of a solid-state traveling-wave amplifier. (a) One side of the meander circuit. (b) A small portion of the complete circuit after fabrication. (c) A final assembly of the test structure.



Relative power level of r.f. transmitted waves for several different frequencies. Increment is taken as power min.

Fig. 6

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