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BULK SEMICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES FOR ADVANCED MILLIMETER WAVE DEVICES

Metro M. Chrepta Harold Jacobs

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Metro M. Chrepta Harold Jacobs

Semiconductor & Frequency Control Devices Technical Area Electronics Technology and Devices Laboratory

September 1971

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ABSTRACT

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Recent suggestions have been made for the design of bulk semiconductor millimeter wave devices, and in particular, a new type of phase shifter. In order for these designs to perform in a satisfactory manner it was found necessary to demonstrate that electromagnetic propagation would occur largely in the interior of a semiconductor dielectric waveguide with relatively low loss. In this report an analysis is made of electromagnetic waves guided in an infinite slab of material with the properties of high resistivity silicon. Calculations and preliminary experiments are demonstrated at frequencies near 16.0 GHz. It is concluded that propagation in the semiconductor medium offers the possibility of low loss circuitry and satisfies the requisites for device design.

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i.



BULK SENICONDUCTOR QUASI-OPTICAL CONCEPT FOR GUIDED WAVES FOR ADVANCED MILLIMETER WAVE DEVICES

INTRODUCTION

In a recent proposal¹ we have suggested the design of bulk semiconductor devices and the use of semiconductor waveguides to replace more conventional stripline and metal waveguides for the millimeter wave regions of the spectrum.

It is well known that metallic waveguides become lossy at shorter wavelengths (1 dB per foot at 3.2 mm or 1.5 dB per foot at 2.15 mm). The use of dielectric guides offers a promise of lower losses as the wavelengths approach the optical regions. With the advent of recently obtainable high resistivity silicon, low loss semiconductors offer an attractive potential as a guide material. The additional factor here is that components and devices could conceivably be "built in" the semiconductor line so that in effect one would have an optical line with active elements incorporated. The first considerations involved in evaluating such a concept is the direct test of a single straight section of semiconductor dielectric guide to determine the losses which might result. A factor in this line of thought is that if the energy flow is almost entirely within the waveguide, it would be relatively easy to control by electrical means. If the energy flow is along the direction of the guide but contained in the air space surrounding the semiconductor guide it would be relatively difficult to control. See Figure 1.

The first consideration is to estimate the chances of power flow within the guide material, where it can be modulated, amplified, detected, etc., by devices constructed and located within the semiconductor structure. In what follows we shall describe first some analytical considerations of the semiconductor system relying on the wave guided in a dielectric slab. This will then be followed by some initial experiments designed to prove that almost all of the energy is contained in the semiconductor.

DIELECTRIC SLAB WAVEGUIDE

We consider a dielectric slab oriented in the indicated position in Figure 2. Here we assume an infinite dielectric slab with no variations of field in the x direction.

The general form of Maxwell's Equations are²:

$$\frac{\partial Hz}{\partial y} = \frac{\partial Hy}{\partial z} = j \omega \epsilon E_{x}$$

$$\frac{\partial Hx}{\partial z} = \frac{\partial Hz}{\partial x} = j \omega \epsilon E_{y}$$

$$\frac{\partial Hy}{\partial x} = \frac{\partial Hx}{\partial y} = j \omega \epsilon E_{z}$$

$$\frac{\partial E_{z}}{\partial y} - \frac{\partial E_{y}}{\partial z} = -j\omega_{x}H_{x}$$

$$\frac{\partial E_{x}}{\partial z} - \frac{\partial E_{z}}{\partial x} = -j\omega_{x}H_{y}$$

$$\frac{\partial E_{y}}{\partial x} - \frac{\partial E_{x}}{\partial y} = -j\omega_{x}H_{z}$$
(1)

$$\frac{\partial^{2} \overline{E}}{\partial x^{2}} + \frac{\partial^{2} \overline{E}}{\partial y^{2}} + \frac{\partial^{2} \overline{E}}{\partial z^{2}} = -\omega^{2} \omega \epsilon \overline{E}$$

$$\frac{\partial^{2} \overline{H}}{\partial x^{2}} + \frac{\partial^{2} \overline{H}}{\partial y^{2}} + \frac{\partial^{2} \overline{H}}{\partial \overline{z}^{2}} = -\omega^{2} \omega \epsilon \overline{H}$$

$$(2)$$

Propagation is in the z direction so that we use the form

$$e^{-\overline{8}z}$$
, $\overline{8}=\overline{x}+\overline{4}\overline{B}$.

Furthermore \overline{E} and \overline{H} can be a function of y but cannot be a function of x, bu assumption. This means that all terms with $\frac{1}{\sqrt{x}} = 0$, and $\frac{1}{\sqrt{2}}$ is replaced by $-\frac{1}{\sqrt{2}}$.

We next take this into account in (1).

$$\frac{\partial H_{z}}{\partial y} = J^{w \in E_{x}} \qquad \frac{\partial E_{z}}{\partial y} = J^{w \cup H_{x}} \qquad \frac{\partial$$

These equations can now lead us into the calculations of either TM or TE modes. We choose the former to illustrate physical principles.

The TM mode:

$$H_x = H_x^0 e^{-\tilde{s}z}, \quad H_y = H_y^0 e^{-\tilde{s}z}, \quad H_z = 0$$

$$E_x = E_x^0 e^{-\tilde{s}z}, \quad E_y = E_y^0 e^{-\tilde{s}z}, \quad E_z = E_z^0 e^{-\tilde{s}z}$$
(3B)

We also require

$$\nabla^{2}E_{x}^{\circ} = -\omega_{x}^{2}t E_{x}^{\circ}$$

$$\frac{\partial^{2}E_{x}}{\partial \gamma^{2}} + \delta^{2}E_{x}^{\circ} = -\omega_{x}^{2}eE_{x}^{\circ}$$

$$\frac{\partial^{2}E_{x}}{\partial \gamma^{2}} = E_{x}^{\circ}(-\delta - \omega_{x}^{2}e)$$

$$\frac{\partial^{2}E_{x}}{\partial \gamma^{2}} = E_{x}^{\circ}(-\delta - \omega_{x}^{2}e)$$

$$(3C)$$

Next we consider the fields outside the dielectric slab, $y > \frac{9}{2}$ and inside the dielectric slab $y < \frac{4}{2}$.

First consider the fields outside the slab, $y > \frac{q}{2}$

$$H_{X} = H_{X}^{\circ} e^{-\chi_{c}^{2}}, \qquad (4)$$

$$b_{Y} \nabla^{2} H_{X} = -\omega^{2} \nu e H_{X}$$

$$\frac{\partial^{2} H_{X}}{\partial y^{2}} + \chi_{0}^{2} H_{X} = -\omega^{2} \nu e H_{X} \qquad (5)$$

 $\frac{\partial^2 H_x}{\partial y^2} = -(\delta_0^2 + \omega_{\mathcal{U}}^2 \epsilon) H_x - h_e^2 H_y$ where ho = - to - where.

(6)

(9)

(10)

- It = Ce hoy Next, . (7) Yo Hx = - Jwe Ey by (3A) $E_{y} = \frac{1}{\omega} E_{y} H_{y},$ (8)
- $b_{Y}(3B) \quad E_{Z} = \underbrace{z}_{w \in v} \frac{\partial H_{x}^{c}}{\partial y}, \quad b_{v} t \quad \underbrace{\partial H_{x}^{c}}_{\partial y} = -h_{o} H_{x}^{o}$ $E_{2}^{\circ} = -f_{W}^{\circ} e_{V} H_{X}^{\circ}$

 $E_{z}^{\circ} = -\frac{f_{b}}{\omega \epsilon_{w}} C e^{-h_{oy}}$

Note we have the following terms as a function of H_X^{O}

H." - Ce-hey Ey = J to Hx $E_{z}^{\circ} = -\frac{1}{4} \frac{h}{k_{x}} H_{x}^{\circ}$

 $h_0^2 = -\frac{y_0^2}{10} + \frac{y_0^2}{10} + \frac{y_0^2}{1$

This is related to rectangular guide as in Figure 4.

Inside the slab; $\mathcal{N}_{j} \in \mathcal{N}_{j}$, $\mathcal{N}_{j} \neq \mathcal{N}_{j}$ In the z direction of propagation

$$H_x = H_x^{\circ} e^{-\chi_z^2} \qquad (11)$$

Note: $J_1 = J_0$ in order for fields to match across the surface. Also by

$$\frac{\partial^2 H_x}{\partial y^2} + \delta_i^2 H_x = -\omega^2 \nu \epsilon H_x \qquad (12)$$

$$\frac{\partial^2 H_x}{\partial y^2} = -k_i^2 H_x^0 \qquad k_i^2 = \delta_i^2 + \omega^2 \nu \epsilon, \qquad (13)$$

$$H_x^c = \sin k_i \gamma \quad \text{or} \quad H_x^c = \cos k_i \gamma. \qquad (14)$$

These two cases are indicated as in Figure 5.

The surface impedance is

Outside the Slab

$$\overline{Z}_{5} = -\frac{\overline{E}_{2}}{H_{\chi}} = \frac{1}{\omega \epsilon_{\nu}}.$$
 (15)

Inside the Slab

-

Since h_0 is real, \geq_5 is inductive reactive. In summary we have the equations shown in Table I.

Table I: Equations for the TM Mode

Hx = Hx e - Kz	$H_x = H_x^{\circ} e^{-\lambda_z^{2}}$
$\frac{\partial^2 H_x^o}{\partial y^2} = h_o^2 H_x^o$	$\frac{\partial^2 H_x^{\circ}}{\partial x^2} = -k_1^2 H_x^{\circ}$
$h_0^2 = -Y_0^2 - \omega_{\mathcal{L}}^2 \epsilon_{\mathcal{L}}$	$k_{i}^{2} = k_{0}^{2} + \omega^{2} \omega \epsilon_{i}$.
Hx = Ce-hoy	Hx = sink, y did Cosk, j
$E_{y}^{\circ} = \frac{1}{4} \frac{\chi_{0}}{\omega_{E_{0}}} H_{x}^{\circ}$	$E_{\gamma} = \frac{1}{2} E_{\gamma} H_{\chi}^{\circ}$
$E_{z}^{\circ} = \frac{1}{\omega \epsilon_{v}} \frac{1}{\delta \gamma} \frac{H_{x}}{\delta \gamma}$	$E_{Z} = \frac{\partial}{\partial c_{i}} \frac{\partial}{\partial y} \frac{\partial H_{x}}{\partial y}$
,	$E_{z} = \frac{1}{2} \frac{\partial}{\partial y} \sin k, y = \frac{1}{2} \frac{h}{\omega \epsilon_{i}} \cos h, y$
о <i>ү</i>	$E_{z} = \frac{1}{4} \frac{\partial (usk, y)}{\partial (x, y)} = -\frac{1}{4} \frac{h}{uc} sink, y$
δ,	- 00

Consider two possible modes of propagation.

Case I For
$$-a/2\langle y \langle a/2, assuming H_x^0 = \sin k_1 y$$

 $/f_x = Be^{-\delta e_3} \sin k_1 y$

$$H_{x} = A e^{-h_{0}y} \quad y > \frac{y}{2} \quad (17)$$

(16)

At the boundary, y = a/2

$$Ae^{-h_0 \frac{g}{2}} = B\sin(h_0 \frac{g}{2}). \qquad (18)$$

Also at the boundary

-

$$E_{z_i} = E_{z_i} \quad b_{Y}(3A).$$

In general,

$$E_{z} = -\frac{1}{J^{w} \epsilon_{i}} \frac{\partial H_{x}}{\partial y} \qquad H_{x} = Be^{-kz} \sin k_{i}y \qquad (19)$$

$$E_{z_{i}} = -\frac{k_{i}}{J^{w} \epsilon_{i}} Be^{kz} \cos k_{i}y \qquad , \qquad -\frac{\alpha_{i}}{2} \langle \gamma \langle \gamma_{2} \rangle \qquad (20)$$

for
$$y > a/2$$

 $E_{z_v} = -\frac{1}{\int u \in v} \frac{\partial H_x}{\partial y}, \quad H_x = A e^{-h_0 y}$ (21)
 $E_{z_v} = \frac{h_v}{\int u \in v} A e^{-h_0 y}.$ (22)

Hence at y = a/2, $\frac{h_0}{J} A e^{-h_0 \frac{y}{2}} = -\frac{k_1}{J^{w_c}} B \cos k_1 \frac{y}{2}.$ (2.3)

$$By(18) and(23), \qquad \frac{h_0}{\epsilon_v} A \in \frac{-h_0 \frac{4}{4}}{\epsilon_v} = \frac{h_c}{\epsilon_v} B_{va}(k, \frac{4}{4}), \\ \frac{h_u}{\epsilon_v} A \in \frac{-h_0 \frac{4}{4}}{\epsilon_v} = -\frac{h_c}{\epsilon_v} B_{va}(k, \frac{4}{4}), \\ \frac{h_a}{\epsilon_v} \sin(k, \frac{4}{4}) = -\frac{h_c}{\epsilon_v} \cos(k, \frac{4}{4}), \\ \frac{\epsilon_v}{\epsilon_v} h_i = -\cos(k, \frac{4}{4}), \\ \frac{\epsilon_v}{\epsilon_v} h_i = -\cos(k, \frac{4}{4}), \\ -\frac{\epsilon_v h_i}{\epsilon_v} \cot(k, \frac{4}{4}) = h_0. \qquad (24)$$

In addition:

$$h_0^2 = -y_c^2 - u_{i}^2 \epsilon_{i}$$

$$k_i^2 = y_i^2 + u_{i}^2 \epsilon_{i}$$
 by definition,

adding

$$h_0^2 + k_1^2 = \omega^2 \omega(\epsilon_1 - \epsilon_2).$$
 (26)

(25)

Multiplying (24) by a/2, and (26) by $\binom{a}{2}^{2}$

$$-\frac{\epsilon_{\mu}h_{\mu}}{\epsilon_{\mu}}\frac{a}{2}\cot\left(\frac{h_{\mu}e}{2}\right) = h_{0}\frac{a}{2}$$
(27)

$$\frac{h_{a}^{2}a^{2}}{2^{2}} + \frac{k_{i}^{2}a^{2}}{2^{2}} = \omega'(\ell_{i} - \ell_{u})a^{2} \qquad (28)$$

 $let q = h_{0} \frac{\alpha}{2}, \quad p = k_{1} \frac{\alpha}{2} \qquad (29)$

$$-\frac{\epsilon_{r}}{\epsilon_{i}}p^{cot}p = g \qquad (30)$$

$$g^{2} + p^{2} = \omega^{2} \omega (\epsilon_{7} - \epsilon_{r}) \frac{a^{2}}{4} = R^{2}.$$
 (31)

For Ku Band,

$$a = .311' \times 2.54 = 7.9 \times 10^{-1} cm = 7.9 \times 10^{-3} m$$

$$\omega' = 2\pi f = 2\pi r \times 15 \times 10^{9} = 94 \times 10^{9} = 9.4 \times 10^{10}$$

$$\ell_{1} = 12 \times 8.854 \times 10^{-12} = 106 \times 10^{-12} = 1.06 \times 10^{-10}$$

$$\ell_{2} = 1 \times 8.854 \times 10^{-12} = 8.854 \times 10^{-12}$$

$$\iota = 1.257 \times 10^{-6}$$

$$(\ell_{1} - \ell_{2}) = 11 \times 8.854 \times 10^{-12} = 97 \times 10^{-12} = 9.7 \times 10^{-11}$$

$$R^{2} = (9.4)^{2} \times 10^{20} \times 1.257 \times 10^{-6} \times 9.7 \times 10^{-11} \times \frac{(7.9)^{2} \times 10^{-6}}{4}$$

$$R = 9.4 \times 10^{10} \times (1.257 \times 10^{-3} \times 197 \times 10^{-6} \times \frac{7.9 \times 10^{-3}}{2} \qquad (3.2)$$

$$= 9.4 \times 1.12 \times 9.9 \times 3.95 \times 10^{-2}$$

$$R = 4.4$$

$$R = 4.4$$
 (33)
 $R^2 = 19.3$. (34)

A complete plot of 30 and 31 was run solving for p and q. The results are indicated in Figure 6.

From this

$$g = \frac{h_{0}g}{2} = 3.16$$
(35)
$$h_{0} = \frac{3.16 \times 2}{a} = \frac{6.32}{7.9 \times 10^{-3}} = 0.80 \times 10^{3}$$
(36)
$$e^{-h_{0}y} = e^{-1}$$

$$h_{0}y = 1$$

$$Y = \frac{1}{0.8 \times 10^{-3}} = 1.25 \times 10^{-3} \text{ m}.$$
(37)

$$P = k_1 \frac{a}{2} \qquad k_1 = \frac{3c}{c} = \frac{3c6x2}{c} = .78 \times 10^3 \quad (38)$$

sin $\left(\frac{k_1 a}{2}\right) = 3in 3c6$

3.14 - 3.06 = .08 below TT or above π_1 , Sin(k, q) = sin .08 = .0199.

Case II

$$H_{x} = \cosh k_{i} y \qquad (3.9)$$

$$h_{0}^{2} + k_{i}^{2} = \omega^{2}(\epsilon_{i} - \epsilon_{v}) \qquad g = h_{0} \frac{\omega}{2}$$

$$\frac{h_{0}^{2} a^{2}}{2^{2}} + \frac{h_{i}^{2} a^{2}}{2^{2}} = \omega^{2}(\epsilon_{i} - \epsilon_{v}) \frac{a^{2}}{2^{2}} \qquad f = k_{i} \frac{a}{2}$$

$$g^{2} + f^{2} = R^{2} = (4.4)^{2} \qquad (4c)$$

$$\frac{\epsilon_{v}}{\epsilon_{i}} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} = h_{0} \qquad (41)$$

$$\frac{\epsilon_{v}}{\epsilon_{i}} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} = h_{0} \qquad (41)$$

$$\frac{\epsilon_{v}}{\epsilon_{i}} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} = h_{0} \qquad (42)$$

$$\frac{\epsilon_{v}}{\epsilon_{i}} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} = h_{0} \qquad (42)$$

$$\frac{\epsilon_{v}}{\epsilon_{i}} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} + \frac{\epsilon_{v}}{2} = h_{0} \qquad (42)$$

ມ

$$\left(\frac{1}{12}\right)^2 p^2 \tan^2 p^2 = 8^2$$

$$\frac{1}{144} p^2 \tan^2 p^2 \exp^2 \left(\frac{1}{144}\right)^2$$

The roots for equations (40) and (43) are shown in Figure 8. Case II a.

$$p = 1.5396$$

$$g = 4.122$$
(44)

$$C = e^{h_{0} \frac{q_{2}}{2}} \cos\left(\frac{k_{1} \frac{a}{2}}{2}\right) \qquad (4s)$$

$$k_{1} \frac{a}{2} = p \qquad h_{0} \frac{a}{2} = g.$$

Solve for

$$h_{0} = g \frac{2}{a} = \frac{4.122 \times 2}{7.9 \times 10^{-3}} = 1.04 \times 10^{3} \text{ m}^{-1} (46)$$

$$h_{0}y = 1, \quad y \equiv 10^{-3}$$

$$k_{1} = f \frac{2}{a} = \frac{1.54 \times 2}{7.5 \times 10^{-3}} = .263 \times 10^{3}$$

$$\cos(h_{1}a) = \cos f = \cos 1.5386 = .0308$$

$$k_{1}e_{1}hear = 5ee(-ig.(9))$$

Case II b.

$$p = 4.315, \quad g = .058$$

$$h_{0} = \frac{24}{44} = \frac{1.7}{7.9} \times 10^{3} = 2.15^{5} \times 10^{2}$$

$$h_{0}y = 1, \quad y = \frac{1}{2.15} \times 10^{-2} = .465^{5} \times 10^{-2}. \quad (47)$$

$$k_{1} = \frac{24}{44} = \frac{8.63}{7.9} \times 10^{3} = 1.09 \times 10^{3}. \quad (48)$$

$$\cos(k_{1}q_{1}) = \cos p = \cos 4.315 = -.605^{-1}$$

This tells us that in this mode, more of the field is external to the dielectric and hence there is a greater chance for loss.

EXPERIMENTAL DATA

A laboratory bench was set up with the components arranged as indicated in Figure 12. This is essentially a bridge arrangement with a klystron source capable of supplying Ku-band radiation, a bridge with an attenuator and phase shifter in one arm and sections of waveguide which can be removed in the other arm. A standard diode detector was used, the output of which was fed into an oscilloscope. The tuner is also indicated in the figure. The section of guide labelled "A" could be removed and four post conditions were studied as indicated in Figure 13. In Case A, the empty waveguide is filled with silicon 4-7/32" long with cross sectional area of .311 x 622", i.e., fitted into the inner dimensions of a Ku-band waveguide.

The following procedures were used particularly in the cases of Conditions B and C.

1. The attenuator was set at maximum, i.e., greater than 50 dB so that all of the power would flow through the arm containing the semiconductor.

2. The klystron frequency was changed slightly, at the same time adjusting the tuner on the detector for maximum power transfer. Usually three or four peaks were found which were indications that at these particular frequencies the semidonductor block was acting as a 1/2 wavelength transformer. It was found that these peaks were approximately .78 GHz apert. The data obtained is shown in Table II indicating the RF frequency at test, attenuation, and changes in attenuation over the control. From this table, it can be seen that the silicon filled waveguide gave an added attenuation of 4 dB, while the silicon waveguide with no cover gave an added attenuation of 5 dB. We conclude from this that one additional dB of attenuation was found by completely removing the metal cover from the silicon.

TABLE II

TRANSMISSION DATA

Condition	Frequency	Attenuation	Attenuation
	GH _z	₫B	^A Control - ^A Test dB
Air filled		9.7	
(A) waveguide	16.50	9.0 9.5	C
(control)		9.35 Average	
Silicon filled	15.40	13.0	
(B) waveguide	15.46	13.0	<u>1</u> 4
	16. 1 8	1 3.5	
Silicon waveguide	15.54	14.1	
$2\frac{1}{2}$ " exposed	16.40	13.9 14.7	5
(C) to air	1 7.1 6	14.5	
Silicon removed $2\frac{1}{2}$ " air space (D)	17.04	26.5	17

We should like to discuss the interpretation of the data in Table II.

1. The control test showed no resonance points under Condition A. There was no sign of 1/2 wavelength transformer action as might be expected.

2. Under Condition B, 1/2 wavelength transformer action was observed. The peaks in transmission are assumed to eliminate surface reflections and the 4 dB attentuation which was noted can be attributed entirely to the losses due to conductivity in the silicon.

3. Under Condition C, measurements were made at peak transmission values for the same reason the attenuation was found to be 5 dB indicating additional 1 dB loss. The exposed silicon was probed with metal structures such as a screwdriver or metal plate. Little or no effect on transmission was found by placing flat plates on the top of the silicon guide or on the sides of the silicon guide near its conter of exposure. However, when placing a round metal rod approximately 1/8" diameter near the corner of the exit of the waveguide flange and the silicon on the upper flat piece, a slight change in balance was noted of approximately 0.2 to 0.3 dB. Changes from this preliminary probing appear to show that there may be some indication of power loss due to a poor fit between the silicon and the wavguide wall. This must be further examined and if so, there are still two approaches to overcome this problem. First a horn can be used to launch the wave. Second, antireflection coatings or grooves can be cut into the silicon section to obtain better matching from metal waveguide to silicon. In any case, we have demonstrated experimentally that there is very little, if any, electronic radiation emanating from the walls of the exposed silicon guide. This is a verification of the calculations which indicate only a very small frection of power is located cutside the semiconductor guide walls, and that indeed most of the power is being transmitted inside the semiconductor.

CONCLUSIONS

An analysis was made of waves in a dielectric slab. In considering this structure, it was expected that some insight would be obtained relating to the fraction of power propagating inside a dielectric waveguide.

The properties of the slab were chosen to match possible experiments with high resistivity silicon at frequencies associated with Ku band. That is, in the calculations chosen it was assumed that silicon has a dielectric constant of 12 and can be obtained losaless ($\mathbf{U} = 0$). The height of the dielectric slab was taken at the same dimensions as the inner height of metallic waveguide for Ku band (Figure 3 and 4), and a TM mode was calculated.

For the TM mode in the dielectric slab with materials and dimensions given it is seen that three possible modes can be maintained.

Mode 1,	$H_{X}^{D} = \cos k_{1} y$,	$k_1 = .263 \times 10^{3}$
Mode 2,	$H_{x}^{o} = \sin k_{1} y$,	$k_{1} = .78 \times 10^{3}$
Mode 3,	$H_x^o = \cos k_1 y \text{ or }$	$k_1 = 1.09 \times 10^3$

If we address ourselves to the question as to where most of the energy is located, we find that in all three cases, most of the power flows in the dielectric. This is a significant point, since if we want to construct active devices in the semiconductor dielectric, it is necessary for these devices to be in a location where they can interact with the energy being propagated.

In addition, we find that for the lower modes, the energy tends to be confined more tightly into the dielectric. This tendency appears as indicated in the following figures. (Figure 11).

The situation now appears hopeful for guiding the electromagnetic wave proregetion in the cemiconductor.

In the next phase of work we must analyze the mode characteristics for a rectangular waveguide³. We shall need this information in order to know best how to launch this wave from metal waveguide to semiconductor dielectric and vice verse with a minimum of losses or reflections. In addition, the coupling from the semiconductor guide to the devices will be of prime concern,

ACKNOWLEDGEMENT

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GLOSSARY

$$f = \text{frequency} = 15.4 \text{ GHz}$$

$$\lambda_{oir} = \text{vavelength in free space} = 1.94 \text{ cm}$$

$$\lambda_{5i} = \text{vavelength in silicon} = .55 \text{ cm}$$

$$\lambda_{0} = 2a = \text{cutoff wavelength} = 3.16 \text{ cm}$$

$$\eta = \text{free space impedance} = 376 \text{ ohms}$$

$$\eta_{5i} = \text{impedance in silicon} = 107 \text{ ohms}$$

$$T = \text{conductivity} = 5.4 \times 10^{-2} \text{ (R m)}^{-1}$$

$$d_{02} = \text{attenuation of silicon in guide} = 2.89 \text{ neper/m}$$

$$Z_{c1} = Z_{o3} = \text{impedance in air filled waveguide} =$$

$$\frac{376}{\sqrt{1-(\frac{\Lambda_{si}}{\Lambda_{o}})^{2}}} = 476 \text{ ohm}$$

$$Z_{02} = \text{impedance in silicon filled guide}$$

$$= \frac{\Lambda}{\sqrt{1-(\frac{\Lambda_{si}}{\Lambda_{o}})^{2}}} = 107 \text{ ohms}$$

$$\int_{0A} = \text{ propagation constant in silicon filled guide}$$

$$= \Delta_{02} + f \beta_{0A}$$

$$\lambda_{ig} = \text{ wavelength in silicon in guide}$$

Block length = $\frac{10 \text{ cm}}{.558} \approx 18 \text{ wavelengths}$







POWER FLOW INTERNAL TO AND EXTERNAL TO DIELECTRIC



FIG. 2 DIELECTRIC SLAB WAVEGUIDE



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FIG. 5 POSSIBLE DISTRIBUTION OF FIELD IN DIELECTRIC



FIG. 6 GRAPHICAL METHODS OF SOLUTIONS









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GRAPHICAL SOLUTIONS



FIG.9 COSINE MODE



FIG. 10 SECOND COSINE MODE

















FIG. 14

MODEL FOR ANALYSIS OF MULTIPLE REFLECTIONS IN SILICON

APPENDIX A

Calculation of Attenuation Due to Silicon Block in the Experiment

The attenuation due to the conductivity and the multiple reflections within the sewiconductor slab used in these experiments can be calculated from the ratio of the transmitted electric field to the incident electric field. This ratio is given by

$$\frac{E_0}{E_{in}} = Y_t \left(c c_{3h} \int_{o_2} l - \frac{Z_{o_2}}{Z_{a,b}} s inh \int_{o_2} l \right), \quad (1)$$

where the transmission coefficient,

$$f = \frac{2 Z_{ab}}{Z_{ab} + Z_{ol}}$$
(2)

and Z_{o1} , the impedance of waveguide in air is

$$Z_{o1} = \frac{376}{\sqrt{1 - \left(\frac{\lambda_{cir}}{\lambda_{o}}\right)^{2}}}$$

 $Z_{a,b}$ the impedance at the first interface of the dielectrics is

$$\overline{Z}_{ab} = \overline{Z}_{o2} \left(\frac{\overline{z}_{o3} + \overline{Z}_{o2} \tan h \int_{o2} f}{\overline{z}_{o2} + \overline{z}_{o3} \tan h \int_{o2} f} \right), \quad (3)$$

as in Figure (14A) where $Z_{03}\int_{03} = Z_{01}\int_{01}^{1}$ and $\int_{02} = \propto_{02} + \frac{1}{f}\int_{02}^{1}$. The impedance in the semiconductor is approximately

$$Z_{02} = \frac{376}{VE}$$
, $E = 12$

Substituting into (3),

Appendix A (Cont)

and the identities,

$$\tanh (x + y) = \frac{t_{onhx} + t_{onhy}}{1 + t_{onhx} t_{anhy}}$$
$$\tanh f_{oy}^{2} = f_{onh}^{2} f_{oy}^{2}$$

equation (3) becomes

$$\overline{Z}_{ob} = \overline{Z}_{og} \left(\frac{\overline{Z}_{og} + \overline{Z}_{o2} + \overline{z}_{og} + \overline$$

when $\beta_{02} l = hTT$.

Substituting into (1) $\int_{\partial 2} = \alpha_{\partial 2} + \beta_{\partial 3} l$ and the identities,

$$cosh(x+y) = cosh x cosh y + sinh x sinh y$$

$$sinh(x+y) = sinh x cosh y + cosh x sinh y$$

$$sinh f B_{0y} l = f sin B_{0y} l$$

equation (1) becomes

$$\frac{E_{o}}{E_{in}} = Y_{t} \begin{pmatrix} \cosh \sigma_{vol} - \frac{Z_{o2}}{Z_{ob}} \sinh \sigma_{vol} P \\ \frac{Z_{ob}}{Z_{ob}} \end{pmatrix}.$$

At 15.40 GHz ($\lambda \operatorname{air} = 1.94 \operatorname{cm}$) the 10 cm long silicon slab is a half wave transformer making $\beta_{o2} \mathcal{A} = h \pi$. The λ_0 cutoff wavelength for the metal guide is 3.16 cm, therefore

$$\overline{Z}_{05} = \overline{Z}_{01} = \frac{376}{\sqrt{1 - \left(\frac{\lambda_{01r}}{\lambda_{0}}\right)^{2}}} = 476 \text{ ohms}$$

$$\overline{Z}_{02} = \frac{376}{\sqrt{\epsilon_{s1}}} = 107 \text{ ohms}$$

$$\Delta_{02} \hat{I} = \frac{Z_{02} \sigma_{s2}}{2} = 0.289 \text{ hepers for } 10 \text{ cm / ength}$$

$$\overline{\sigma}_{s2} = 5.4 \times 10^{-2} \text{ ohm motor}$$

Appendix A (Cont)

 $\frac{2(223)}{223+476} = 0.64$

Inserting these values into equations (3) and (2) yields

$$Z_{ab} = 107 \left(\frac{1176 + 107 \tan 229}{107 + 476 \tanh 289} \right) = 223 \text{ ohms}$$

and

Equation (1) then becomes,

$$\frac{E_0}{E_{in}} = .64 \left(\frac{\cos h, 289}{23} - \frac{107}{233} \sin h, 289 \right) = 0.576$$

and the ratio of power transmitted is

 $r_t =$

$$\left|\frac{E_{o}}{E_{in}}\right|^{2} = \left|\frac{.576}{....}\right|^{2} = .331 \text{ or } 4.8 \text{ dB}.$$

The measured value of attenuation in silicon filled waveguide was approximately 4 dB. Considering the range of resistivities measured over the 10 cm long silicon slab, (1050 - 3300 chm-cm) the average value used, (1830 chm-cm) could be in error by approximately 20%. An agreement of calculated vs measured attenuation in this case is considered valid. APPHNDIX B

and the for sector of Haustions 30 and 31

FILE: CJELUA -34/21/71 4:02 PM. 123 BEGIN 1987 (SA START) 386 "Henry" 400 ISA START2 500 3 CARD 600 BEA COT 700 \$ CARD 800 ISA FINDALLROOTS 940 5 CARD 1000 REAL PROCEDURE FCT(X); REAL X; FCT:=X*2\(1+COT(X)*2/144)-19.36; 1100 1200 REAL ARRAY P, Q, CK[0:20]: 1300 INTEGER K; 1403 FORMAT FMI1(X4, "P", X8, "Q", X8, "CK"); 1500 FINDALLRODIS(FCT, -4.4, 4.4, 100, 9, P); 1500 FOR K:=1 STEP 1 UNTIL P(0)+.1 DO Q[K]:=-P[K]\COT(P[K])/12; 1780 1300 CK[K]:=P[K]\P[K]+Q[K]\Q[K]-19.36; 1900 WRITE (TYPE, FMTI); 2000 FOR K:=1 STEP I UNTIL P(0)+.1 DO 2100 WRITE (TYPER, PIK), QIK), CK(K)): 2200 \$\$A FINI 2300 END.

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Appendix B (Cont)

FILE:CSEQUA -04/22/71 10:35 AM. 100 BEGIN 200 \$\$A STARTI 300 HENRY 400 \$\$A START2 500 \$ CARD 600 \$\$A TAN 700 \$ CARD 800 \$\$A FINDALLROOTS 900 \$ CARD 1000 REAL PROCEDURE FCT(X); REAL X; 1100 FCT: = X*2\(1+TAN(X)*2/144)-19.36; 1200 REAL ARRAY P, G, CK[0:20]; 1300 REAL PI, GI; 1400 INTEGER K; 1500 FORMAT FMT1(X4, "P", X8, "0", X8, "CK"); 1600 FINDALLROOTS(FCT, -4.4, 4.4, 100, 9, P); 1700 FOR K:=1 STEP 1 UNTIL P(0)+.1 DO Q[K]:=P[K]\TAN(P[K])/12; 1800 1900 CK[K]:=P[K]\P[K]+Q[K]\Q[K]-19.36; 2000 WRITE(TYPE, FMT1); 2100 FOR K:=1 STEP 1 UNTIL PI01+.1 DO WRITE(TYPER, PIK), GIK), CKIK)); 2200 2300 WRITE(TYPER); 2400 FOR PI: =-4.4 STEP .I UNTIL 4.41 DO 2500 BEGIN 2600 Q1:=P1\TAN(P1)/12; 2700 WRITE(TYPER, PI, QI); 2800 END: 2900 \$\$A FINI 3000 END. END QUIKLST 1.3 SEC. COMPILING. END COMPILE 9.7 SEC. RUNNING TIME ON 1036

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Appendix B (Cont)

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РС	СК	
· 4.315520+00 8.	580760-01	a aaaaaa+aa
-1.60339@+00-A.	00745@+00	0.000000+00
-1.539689+00 4.	121820+00	0.000000+00
1.53%6×@+00 4.	121820+00	N. NNNNN@+NN
1.60339@+00-4	007250-00	0.0000000000
A 31552@+00 8	580760-01	0 000000000000
41019926-00 81	200/04 01	0.0000000000
-4.400000+00 1.	135320+00	
-A.30000@+00 8.	190950-01	
-A.20000@+00 6.	22223@+01	
-A.100000+00 A.	863720-01	
-4.000000+00 3.	859400-01	
-3.900000+00 3.	07913@-01	
-3.800000+00 2.	449590-01	
-3.700000+00 1.	926260-01	
-3.600000+00 1.	480400-01	
-3.500000+00 1.	092540-01	
-3.400000+00 7.	128980-02	
-3 300000-00 A	303010-02	
-3 200000-00 1	550300-02	
	075100-02	
-3 000000+00-1.	563660-02	
-2 9000000+00-5	054800-02	
-2 900000+00-0.	295700-02	
-2 700000+00-0.	255700-02 063610-01	
-2,100000-00-1.	20246-01	
-2 5000000-00-1	555300-01	
	930030-01	
-2 100000-00-10	145160-01	
-2.2000000+00-2.	519690-01	
-2 100000+00-2.	000030-01	
-2 000000+00-2.	532239-D1	
-1.900000+00-A	634570-01	
-1.800000+00-6.	429390-01	
-1.700000+00-1.	a9a35@+aa	
-1.600000+00-4	56434@+00	
-1-500000+00 1	762680+00	
-1.400000+00 6.	764200-01	
-1.300000+00 3.	902280-01	
-1.200200+00 2~	572150-01	
-1.10000@+00 1.	801030-01	
-1.000000+00 1.	29784@-01	
-9.000000-01 9.	451190-02	
-8.000000-01 6.	864260-02	
-7.0000000-01 4.	91335@-02	
-6.00000@-01 3.	42068@-02	
-5.000000-01 2.3	276260-02	
-4.000000-01 1.	40931@-02	
-3.000000-01 7.	73341@-03	
-2.000000-01 3.	378500-03	
-1 000000-01 8	361220-04	

Appendix B (Cont)

2.009988-10 3.366698-21
1.000000-01 8.361220-04
2.000000-01 3.378500-03
3.000000-01 7.733410-03
4.000000-01 1.409310-02
5.000000-01 2.276260-02
6.000000-01 3.420680-02
7.000000-01 4.913350-02
8.000000-01 6.864260-02
9.000000-01 9.451190-02
1.000000+00 1.297840-01
1.10000@+00 1.80103@-01
1.200000+00 2.572150-01
1.300000+00 3.902280-01
1.400000+00 6.764200-01
1.500000+00 1.762680+00
1.60000@+00-4.56434@+00
1.700000+00-1.090350+00
1.800000+00-6.429390-91
1.900000+00-4.634570-01
2.000000+00-3.641730-01
2.100000+00-2.992230-01
2.200000+00-2.518680-01
2.300000+00-2.145160-01
2.400000+00-1.832030-01
2.500000+00-1.556300-01
2.000000+00-1.303460-01
2.100000+00-1.063640-01
2.800000+00-8.295700-02
2.900000+00-5.954800-02
3.300000+00 1.333300-02
3 AGGGGGLGG 7 AGGGGG GO
3.5000000000000000000000000000000000000
3.6000000-00 1.092.740-01
3.700000+00 1.925250-01
3-800000+00 2-00500-01
3.900000+00 3.079130-01
4.000000+00 3.859400-01
4.100000+00 4.863720-01
4.200000+00 6.222230-01
4.300000+00 8.190950-01
4.400000+00 1.135320+00

TIME OFF 1037

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END CSEQUA 3.7 SEC.