Characteristics of Metallic Waveguides Inhomogeneously Filled with Dielectric Materials with Surface Plasma Layers

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Abstract **—The propagation of millimeter waves in metallic waveguides inhomogeneously filled with dielectric materials having surface plasma layers is characterized. The modal phase shift and attenuation of a 94-GHz wave are computed for a 10-μm plasma layer thickness as a function of carrier density. In the unexcited state, 90 percent of the millimeter-wave power is confined to the interior air region of the guide, while the remaining 10 percent propagates in the semiconductor insert. In the excited state at high injection levels, over 99 percent of the wave power propagates in the air region. Consequently, in this state, the waveguide will have a very low loss. A resonant cavity using the waveguide configuration is shown to have a wide tuning range and high cavity Q.**

I. Introduction

FREE-CARRIER EFFECTS in semiconductors have been used to create millimeter-wave devices such as phase shifters and switches. The devices are dynamically controlled by injecting free carriers into the semiconductor via contacts [1], [2] or by optical injection [3], [4]. Optical injection shows lower losses in the phase shifter application if the carriers are confined to a thin layer near the surface of the semiconductor. If diffusion into the bulk of the semiconductor is allowed, losses can remain significant even at high plasma densities [5]. The desire to prevent carrier diffusion makes a semiconductor such as GaAs appear attractive for these applications. An appropriate heterojunction might be constructed to confine the carriers near the surface.

The optically controlled phase shifter studied previously uses an open-waveguide configuration. This is preferred in some applications, for example, where integration of the phase shifter with other elements of a radar front end may be desirable.

In this paper, we analyze a structure that employs a closed metallic waveguide that is partially filled with a bulk semiconductor material. The phase shift is induced by the creation of a plasma region on the semiconductor surface. A similar analysis for a closed-waveguide configuration has been presented [2], [6], [7] for use as a p-i-n diode phase shifter. We show the phase shift and attenuation characteristics using the thinner plasma regions more characteristic of optically controlled phase shifters. Clearly, injection of light or carriers into the closed waveguide requires the existence of suitable apertures in the waveguide wall. The effects of these apertures are not addressed in this paper since they have been adequately treated in textbooks.

One advantage of the closed-waveguide configuration is that most of the electromagnetic wave energy is confined to the air region, especially when high plasma densities are achieved on the surface of the semiconductor slab. This limits the attenuation of the mode caused by the interaction of the wave with the diffused carriers in the semiconductor slab, and allows attenuation to be reduced to very low values for the high plasma densities. Because the fields are mostly excluded from the semiconductor at high plasma densities, we will use the uniform plasma layer approximation in this paper rather than the more complicated approach of [5], which uses a nonuniform plasma density.

We extend the analysis of the waveguide configuration to assess the performance of the device when used in a closed cavity for frequency modulation. We plot the tuning range which can be obtained and the variation in cavity quality factor with plasma density. These results predict that, at suitable plasma densities ($\approx 10^{17}$ cm^{-3}), large tuning ranges can be obtained (≈ 5 percent) while losses due to the injected plasma are low. The cavity Q considering only losses due to the injected plasma is high enough that the total Q could be dominated by other losses, such as those due to walls or apertures, in a practical situation.

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II. Waveguide Modes of the Inhomogeneously Filled Metallic Guide

The basic modes of propagation for slab-loaded rectangular guides may be derived from magnetic and electric types of Hertzian potential functions having single compo-

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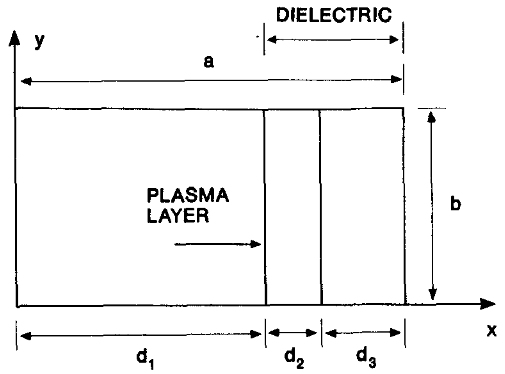

Fig. 1. Metallic millimeter waveguide with a semiconductor slab inserted on the guide wall. The surface plasma layer is formed from photon flux irradiated from the opposite side.

nents directed normal to the air–dielectric interface. The resultant fields may be classified as E or H modes with respect to the interface normal [8], [9]. From the magnetic Hertzian potential, we obtain the solution for a mode which has no component of electric field normal to the interface plane. The mode is referred to as a longitudinal-section electric (LSE) mode.

Fig. 1 shows the basic geometry of the metallic guide structure. We assume the plasma is of uniform density and is confined to region 2. This assumption should lead to reasonable results for this configuration for reasons discussed earlier. Propagation in the z direction is assumed with dependence $\exp(j\omega t - \gamma z)$. There are many types of modes that can propagate in this structure; however, we limit our discussion to the dominant LSE mode.

For a magnetic-type Hertzian potential $\overline{\Pi}_m = \hat{x}\psi_m(x, y)e^{-\gamma z}$, the electric and magnetic fields are given by

$$\overline{E} = -j\omega\mu_0 \nabla \times \overline{\Pi}_m \tag{1}$$

$$\overline{H} = \nabla \times \nabla \times \overline{\Pi}_m \tag{2}$$

and the wave function ψ_m satisfies the wave equation

$$\frac{d^2\psi_m}{dx^2} + \frac{d^2\psi_m}{dy^2} + \left[\gamma^2 + k_0^2\kappa_i\right]\psi_m = 0 \tag{3}$$

where k_0 is the free-space wavenumber and κ_i is the relative dielectric constant of the region i. We may solve for the fields in each region and match the tangential components at interfaces to obtain the solution valid for all x. Appropriate solutions for ψ_m in each region, such that the tangential electric field will vanish on the guide boundary, are

$$\psi_m = \begin{cases} A_1 \sin px \cos(m\pi y/b) & 0 \leqslant x \leqslant d_1 \\ A_2 \sin(qx - \phi)\cos(m\pi y/b) & d_1 \leqslant x \leqslant d_1 + d_2 \\ A_3 \sin r(a - x)\cos(m\pi y/b) & d_1 + d_2 \leqslant x \leqslant a \end{cases} \tag{4}$$

where

$$p = \left[\gamma^2 + k_0^2\kappa_1 - \left(\frac{m\pi}{b}\right)^2\right]^{1/2} \tag{5}$$

$$q = \left[\gamma^2 + k_0^2\kappa_2 - \left(\frac{m\pi}{b}\right)^2\right]^{1/2} \tag{6}$$

$$r = \left[\gamma^2 + k_0^2\kappa_3 - \left(\frac{m\pi}{b}\right)^2\right]^{1/2}. \tag{7}$$

The requirement of continuity of ψ_m and its derivatives at $x = d_1$ and $x = d_1 + d_2$ yields the eigenvalue equation

$$-\tan qd_2 = \frac{\frac{q}{p}\tan pd_1 + \frac{q}{r}\tan rd_3}{1 - \frac{q^2}{pr}\tan pd_1 \tan rd_3} \tag{8}$$

determining the allowed values of the propagation constant γ.

The constants A_1, A_2, and A_3 of the field expressions can be determined from the appropriate boundary condition equations. The amplitude constants are written in terms of the amplitude constant A_2, which is easily found from a normalization condition:

$$A_1 = A_2 \frac{\sin(qd_1 - \phi)}{\sin pd_1} \tag{9}$$

$$A_3 = A_2 \frac{\sin\left[q(d_1 + d_2) + \phi\right]}{\sin rd_3}. \tag{10}$$

III. Phase Shift and Attenuation

The propagation velocity of a waveguide with a plasma layer will differ from its velocity in the unexcited guide. The difference between the propagation constants of the excited guide β_a and the unexcited guide β_p is a measure of the phase shift at output (along 1 cm length). This phase shift can be expressed as

$$\delta\phi = 2\pi(\beta_a - \beta_p). \tag{11}$$

The attenuation difference is simply the attenuation of the excited structure since we assume the unexcited structure is lossless. Therefore

$$\delta\alpha = \alpha_a. \tag{12}$$

The plasma region width d_2 is assumed to have a uniform density of free carriers that are injected in this region by photo excitation. The existence of the free carriers, or plasma, changes the dielectric constant of the semiconductor according to the Drude–Lorentz formula [10]:

$$\kappa(\omega) = \kappa_\infty\left(1 - \sum_i \frac{\omega_i^2}{\omega^2 + \gamma_i^2} - \frac{j}{\omega}\sum_i \frac{\omega_i^2\gamma_i}{\omega^2 + \gamma_i^2}\right) \tag{13}$$

where the subscript i denotes the different kinds of carriers

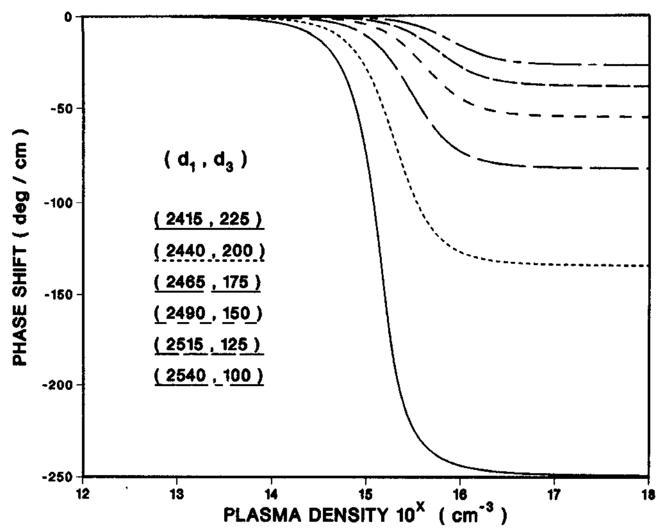

Fig. 2. Phase shift versus plasma density for the cross sections are $a = 2.65$ mm and $b = 1.27$ mm.

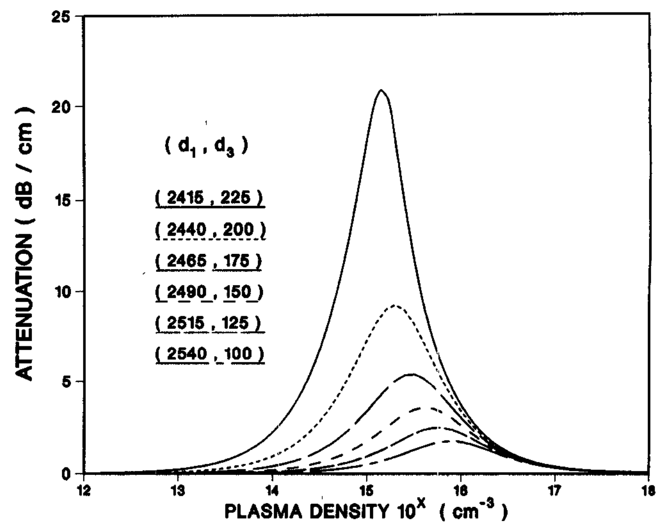

Fig. 3. Attenuation characteristics of the waveguide.

and

κ_∞ dielectric constant in the absence of free carriers,
τ_i relaxation time of carrier i,
γ_i collision frequency $(1/\tau_i)$,
ω_i plasma frequency $(N_i q^2/m_i \epsilon_0 \kappa_\infty)^{1/2}$
q electronic charge,
ϵ_0 permittivity of free space,
m_i effective mass of carrier i,
N_i number density of charge carrier i.

The material parameters for GaAs required in (13) can be obtained from the literature. The dielectric constant of these materials has recently been measured with high accuracy [11]. The properties of GaAs required in the Drude–Lorentz equations are summarized in [3].

Plots of the phase shift and attenuation for the LSE mode as a function of plasma density are given in Figs. 2 and 3 for GaAs. We assumed waveguide dimensions of 2.65×1.27 mm^2 for these calculations. We held the plasma layer thickness d_2 constant at 10 μm. Fig. 2 indicates that very marked values of phase shift per unit length can be obtained when the plasma density is sufficiently high. The different curves in Fig. 2 correspond to different thicknesses of the semiconductor slab. As the thickness of the slab is increased, the air gap is decreased by the same amount, and the plasma layer moves closer to the center of the waveguide. Fig. 2 illustrates that high phase shifts are obtained when the semiconductor slab fills about 10 percent of the total waveguide thickness. Fig. 3 also indicates that the attenuation can be reduced by sufficiently increasing the plasma density. The general shapes of these curves are the same as those obtained from open-waveguide configurations [3], [5]. High attenuation occurs in the region where the plasma is sufficiently dense to attenuate the field but not yet dense enough to exclude it. As plasma density increases further, the fields are "pushed out" of the plasma region and attenuation is reduced substantially.

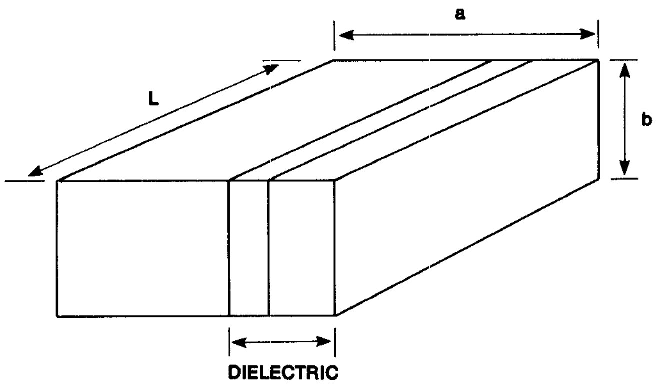

Fig. 4. Resonant cavity design for metallic waveguide.

Attenuation also increases as the plasma layer is moved toward the center of the waveguide.

IV. Resonant Cavity Configuration

In this section, we discuss the use of the partially filled metallic waveguide in a resonant cavity configuration. The cavity is formed from the waveguide geometry shown in Fig. 1 and has a length L, as shown in Fig. 4. The boundary at $z = L$ is assumed to be totally reflecting. At the input boundary, located at $z = 0$, external power is supplied in an amount that offsets internal losses in the plasma layer. Although the backward-traveling wave at the input plane will have a diminished amplitude relative to the forward wave, due to propagation losses, it is replenished by the input field. These assumptions lead to a steady-state condition in the cavity. The power absorption in the cavity is easily computed by integrating the z component of the Poynting vector over the waveguide cross section at $z = 0$. The cavity resonates in the unexcited state at 94 GHz. We address the performance of the cavity by calculations of (1) the cavity Q and (2) the ratio $\delta f/f_0$, where f_0 $(=94$ GHz) is the passive resonant frequency and δf is the change in the resonant frequency from f_0. The particular mode studied for the rectangular box is one of an infinite number of possible modes. If we adopt the point of view that a resonant mode is the standing wave pattern for incident and reflected waveguide modes, any one of the infinite number of possible waveguide waves might be used, with any integer number of half waves between shorting ends. However, we restrict our attention to the dominant LSE_{101} mode.

The resonant Q in the cavity is

$$Q = \omega W / P_L \tag{14}$$

where

- ω resonant frequency,
- W total stored energy in cavity,
- P_L average power loss.

The total power loss in the cavity will be composed of losses due to the induced plasma, the waveguide walls, and coupling apertures for both the millimeter waves and the injected optical signal. The net cavity Q can be obtained by separately computing the Q due to each loss mechanism and then combining the separate values as

$$1/Q = \sum_i 1/Q_i. \tag{15}$$

In this formula, each Q_i is computed by considering only its type of loss. In this paper, we compute only the Q_i due to the injected plasma layer in the semiconductor insert. We consider three different regions: region 1 is air, region 2 is plasma excited in GaAs, and region 3 is unexcited GaAs. The power P_L is the integral of the Poynting vector at the $z = 0$ plane. This integral is composed of three parts, separately evaluated over the three surfaces associated with the three regions; we designate them as P_1, P_2, and P_3. The total energy stored in the cavity also can be similarly calculated from three separate volumes, designated as W_1, W_2, and W_3.

The standing wave field pattern in the cavity will be obtained by superposing oppositely directed traveling waves. The electric and magnetic fields in region 1 are

$$\begin{aligned}\bar{E}_1 &= \hat{y}(E_{y1^+} + E_{y1^-}) \\ &= \hat{y}\left[j\omega\mu_0\gamma A_1 \sin px \left(e^{-\gamma z} - e^{-2\gamma L} e^{\gamma z}\right)\right] \end{aligned}\tag{16}$$

$$\begin{aligned}\bar{H}_1 &= \hat{x}\left[-\gamma^2 A_1 \sin px \left(e^{-\gamma z} + e^{-2\gamma L} e^{\gamma z}\right)\right] \\ &\quad + \hat{z}\left[-\gamma A_1 p \cos px \left(e^{-\gamma z} - e^{-2\gamma L} e^{\gamma z}\right)\right]. \end{aligned}\tag{17}$$

We have written the fields so that the forward-traveling wave has an amplitude determined by A_1 at the position $z = 0$. As the wave traverses the cavity, it loses energy due to absorption in the plasma. This energy loss is exhibited by the exponential attenuation of the mode. We have assumed a perfect reflector at $z = L$, but power absorbed in the cavity is replenished at $z = 0$. In an actual device, a suitable coupling aperture would be required at $z = 0$ to allow power to be coupled into the cavity. At resonant condition, $\beta L = n\pi$, where $n = 1, 2, 3, \cdots$. For the dominant mode, put $n = 1$, so that

$$e^{-2\gamma L} = e^{-2(\alpha + j\beta)L} = e^{-2\alpha L}. \tag{18}$$

The integral of the Poynting vector over the region 1 input surface is

$$P_1 = \frac{b\omega\mu_0\beta(\alpha^2+\beta^2)|A_1|^2}{4} \cdot \left[\frac{\sinh 2p_i d_1}{2p_i} - \frac{\sin 2p_r d_1}{2p_r}\right]\left(1 - e^{-4\alpha L}\right) \tag{19}$$

where the subscripts r and i designate, respectively, the real and imaginary parts of the variable.

The total energy stored, computed from that stored in the electric and magnetic fields, is

$$\begin{aligned}W_1 &= \frac{\mu_0 b(\alpha^2+\beta^2)|A_1|^2}{8}\left(\frac{1-e^{-4\alpha L}}{2\alpha}\right) \\ &\cdot \left[\left(\frac{\sinh 2p_i d_1}{2p_i}\right)\left(p_r^2 + p_i^2 + \alpha^2 + \beta^2 + \omega^2\mu_0\kappa_1\epsilon_0\right)\right. \\ &\left. + \left(\frac{\sin 2p_r d_1}{2p_r}\right)\left(p_r^2 + p_i^2 - \alpha^2 - \beta^2 - \omega^2\mu_0\kappa_1\epsilon_0\right)\right]. \end{aligned}\tag{20}$$

The calculations for regions 2 and 3 are similar to those for region 1. The Q is calculated by first summing the power loss and stored energy for the three regions and then substituting into (14). After considerable algebraic manipulation, the Q can be expressed as

$$Q = \frac{C + (\alpha^2+\beta^2)D}{4\alpha\beta D} \tag{21}$$

where

$$D = I_1 + I_2 + I_3 \tag{22}$$

$$\begin{aligned}C &= \left(k_0^2\kappa_{1r} + p_r^2 - p_i^2\right)I_1 \\ &\quad + \left(k_0^2\kappa_{2r} + q_r^2 - q_i^2\right)I_2 \\ &\quad + \left(k_0^2\kappa_{3r} + r_r^2 - r_i^2\right)I_3 \end{aligned}\tag{23}$$

and

$$I_1 = \frac{1}{p_i p_r} Q_1 \tag{24}$$

$$I_2 = -\frac{1}{q_i q_r}(Q_1 + Q_3) \tag{25}$$

$$I_3 = \frac{1}{r_i r_r} Q_3 \tag{26}$$

$$Q_1 = \frac{|q|^2 \operatorname{Im}(p^* \sin pd_1 \cos^* pd_1)}{|q^2 \sin^2 pd_1 + p^2 \cos^2 pd_1|} \tag{27a}$$

$$Q_3 = \frac{|q|^2 \operatorname{Im}(r^* \sin rd_3 \cos^* rd_3)}{|q^2 \sin^2 rd_3 + r^2 \cos^2 rd_3|} \tag{27b}$$

where Im implies the imaginary part of the term in parentheses, and $*$ denotes the complex conjugate.

Plots of the cavity Q for different thicknesses of the semiconductor slab insert are given in Fig. 5. The Q is very high at the low plasma densities where there is little loss. As plasma density increases, the Q decreases until the

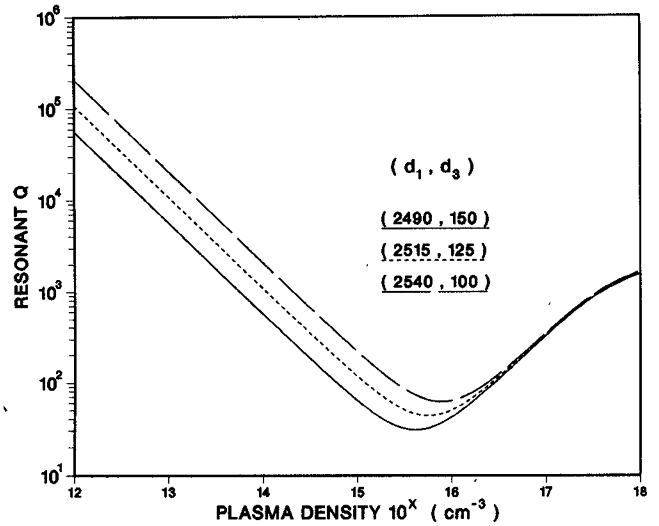

Fig. 5. Cavity Q for the waveguide structure of the guide dimensions support only the fundamental LSE mode.

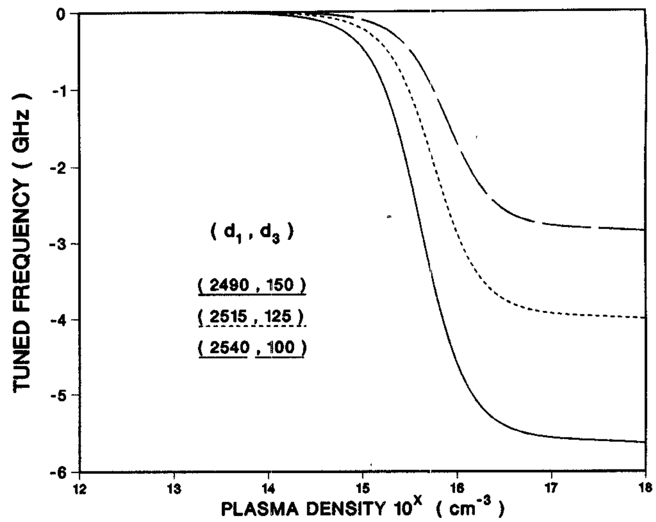

Fig. 6. Tuning characteristic of the millimeter-wave oscillator for resonant cavity design.

plasma is dense enough to push the fields out of the semiconductor and into the air region. The Q then begins to increase.

An approximate formula suitable for estimating Q can be obtained by realizing that most of the energy is confined to the air region. We can then approximate

$$D \cong I_1$$
$$C \cong \left(k_0^2\kappa_1 + p_r^2 - p_i^2\right) I_1$$
$$Q \cong \frac{k_0^2\kappa_1 + p_r^2 - p_i^2 + \alpha^2 + \beta^2}{4\alpha\beta}.$$

The Q is then inversly proportional to α as long as α is small.

A given cavity should have many possible modes, and for each mode the resonant frequency is determined by the mode, the cavity dimensions, and the constants of the dielectric filling the cavity. In order to get the tuned frequency, we obtain from the resonant condition

$$\lambda_0 = 2BL \tag{28}$$

where $B = \beta/k_0$ is the normalized propagation constant.

When the resonant frequency is shifted by a small amount δf, then the relation between wavelength and frequency changes is

$$\delta\lambda/\lambda_0 = -\delta f/f_0. \tag{29}$$

Combining (28) and (29), we can get

$$\delta f/f_0 = -\delta B/B_0 \tag{30}$$

where δB is the change in the normalized propagation constant; it is dependent upon the carrier density of the plasma layer. Consequently, we can control the resonant frequency by controlling the plasma density of region 2 of the dielectric slab. In Fig. 6, we show the results for the frequency shift δf for a GaAs dielectric insert with a plasma surface layer. Note that a plasma density of 10^{17} cm^{-3} produces a substantial frequency shift with high cavity Q. The shapes of the tuning curves are similar to the shapes of the phase shift curves because both phase and frequency shifts are due to a change in the phase velocity of the wave as the plasma density varies. It is possible that the cavity Q in an actual device would be determined by losses in the conducting walls or in the apertures and would be lower than the Q due to the injected plasma. If this is the case, then the cavity Q would not change appreciably as a function of plasma density.

V. Conclusions

In this work we have developed the theory of the "closed" millimeter waveguide configuration. The metallic waveguide configuration has been used for a discussion of the performance of a millimeter-wave phase shifter and a millimeter-wave resonator. The main features of this new structure are: (1) the system is closed, (2) millimeter-wave losses are relatively small, and (3) the structure can be used as a resonant cavity configuration with a wide tuning range and high cavity Q.

The main reason for low-loss propagation in the present configuration is that a majority of the millimeter wave field propagates in the air region of the guide at high plasma densities. With high plasma levels, the effective guide width is determined by the air-gap width because the fields are forced from the plasma region.

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