Analysis of a Buried Layer Millimeter-Wave Phase Shifter

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Abstract **—The results of an analysis of an optically controlled millimeter-wave phase shifter are presented. The phase shift is obtained when electron–hole pairs are created in a thin region in the interior of a semiconductor waveguide. The device exhibits maximum phase shifts for the transverse electric mode. This behavior is different from phase shifters using surface excitation, which give maximum phase shifts for the transverse magnetic mode. The new configuration gives higher phase shifts per decibel attenuation than devices employing surface excitation.**

I. Introduction

Millimeter-wave phase shifters controlled by optical injection into a semiconductor crystal have been the subject of recent research [1]–[3]. In these devices, light incident on the semiconductor is absorbed in a narrow region near the surface, creating a thin layer of free carriers. A millimeter-wave signal propagating in the waveguide will alter its phase velocity when the plasma layer is created, resulting in a phase shift at the end of the guide.

Optimum phase shifts are obtained with this configuration when the propagating mode is transverse magnetic (TM). However, the TM mode transverse field distribution becomes strongly asymmetric when the plasma region is created [3]. The TE mode remains more symmetric as the plasma is created, but produces less phase shift. The more symmetric field distribution may be desirable if the mode must make a transition to another waveguide or free space.

An alternative waveguide configuration employs a thin plasma region created in the middle of the waveguide. This will be called a buried layer configuration. The geometry is depicted in Fig. 1. The plasma region can still be created by optical injection in GaAs by, for example, making region 2 out of GaAs and region 1 out of $Al_xGa_{1-x}As$ with a heavy aluminum concentration x. An $Al_yGa_{1-y}As$ laser with a lighter aluminum concentration, $y < x$, can then be used to inject light through region 1 into region 2. Region 1 can be made transparent because its band gap will be increased by the heavy aluminum according to the relation [4]

$$E_g = 1.424 + 1.266x + 0.266x^2.$$

The cutoff wavelength of region 1 is decreased, so the region is transparent to the wavelength of the $Al_yGa_{1-y}As$ laser.

The buried layer configuration exhibits behavior different from that of the "surface plasma" waveguide. The largest phase shifts are now associated with the TE mode. Peak phase shifts occur when the plasma region is near the center of the waveguide. The fields are still distorted by the presence of the plasma, but now retain their symmetry when the layer is centered in the waveguide.

II. Results

The phase shift in degrees per centimeter length of waveguide is shown in Fig. 2 for the buried layer structure. The width of the plasma region was taken to be 10 μm and the total width of the waveguide, 0.1 cm. The dielectric constants of regions 1, 2, and 3 were assumed to be initially equal at the guide frequency of 94 GHz. The dielectric constant of region 2 changes with the injection of the optical pulse. Equations for the computation of the dielectric constant are given in [1].

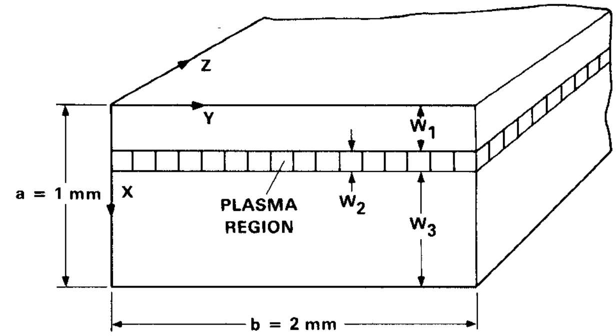

Fig. 1. Geometry of buried layer millimeter-wave phase shifter. The plasma region thickness, W_2, is taken to be 10 μm for the results presented here.

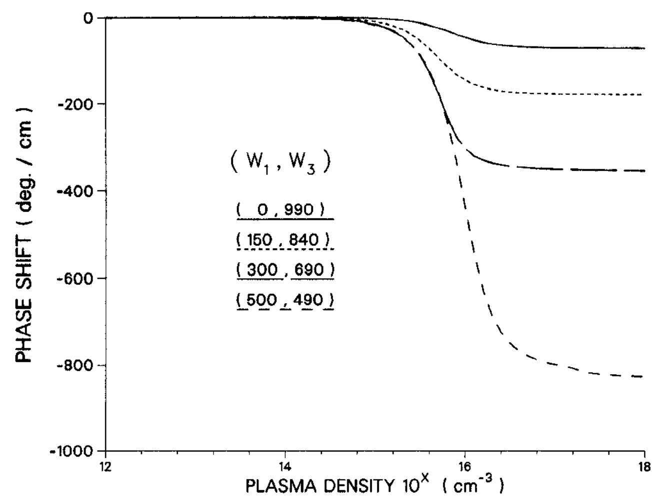

Fig. 2. Phase shift per unit length versus plasma density for 94-GHz TE mode operation. Different curves are for different locations of the plasma region within the waveguide.

Fig. 2 illustrates that very high phase shifts can be obtained at plasma densities on the order of 10^{16} cm^{-3}. Phase shift values begin to saturate at 10^{17} cm^{-3}. The curves indicate that the highest phase shift is obtained when the layer is in the middle of the waveguide.

In Fig. 3 we have plotted power attenuation versus plasma density. (References [1]–[3] show plots of wave attenuation, which is a factor of two lower.) These curves indicate that plasma densities as high as 10^{17} cm^{-3} are desirable in order to decrease attenuation. Note that the buried layer structure consists of a heterojunction between AlGaAs and GaAs, leading to carrier confinement within the buried layer. The structure should more nearly approach the uniform layer model used here than a bulk semiconductor with a surface plasma, where carrier diffusion can prevent losses from decreasing at high carrier densities [3].

A useful figure of merit for the phase shifter is the phase shift per unit attenuation in degrees/dB, which is plotted in Fig. 4. These curves indicate that several hundred degrees/dB can be obtained at plasma densities of 10^{17} cm^{-3} or more. They also show that the exact position of the layer in the waveguide is not

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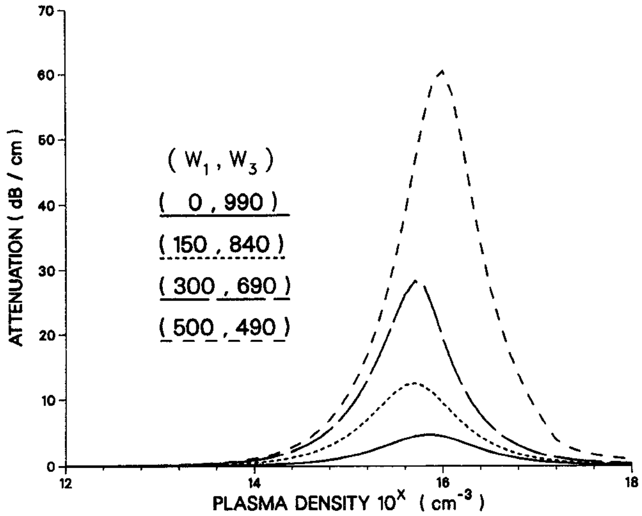

Fig. 3. Attenuation per unit length versus plasma density for 94-GHz TE mode operation. Different curves are for different locations of the plasma region within the waveguide.

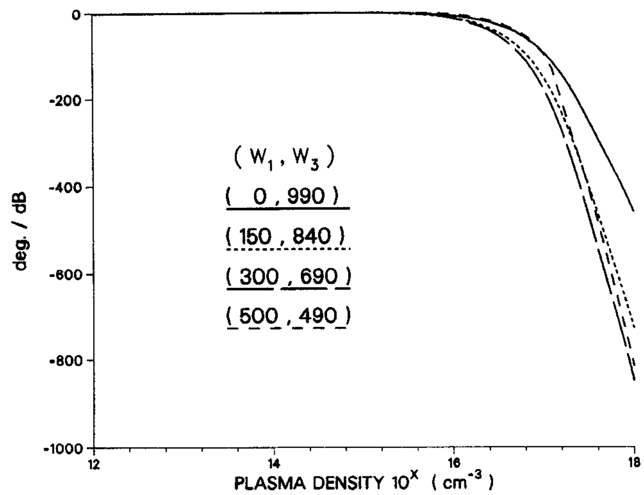

Fig. 4. Phase shift per decibel attenuation versus plasma density for the buried layer structure assuming 94-GHz TE mode operation.

critical to obtaining good performance. Positioning tolerances are quite reasonable.

To compare the buried layer device to a surface plasma device, we have plotted the same figure of merit for the surface plasma device in Fig. 5. The surface plasma layer is assumed to be a

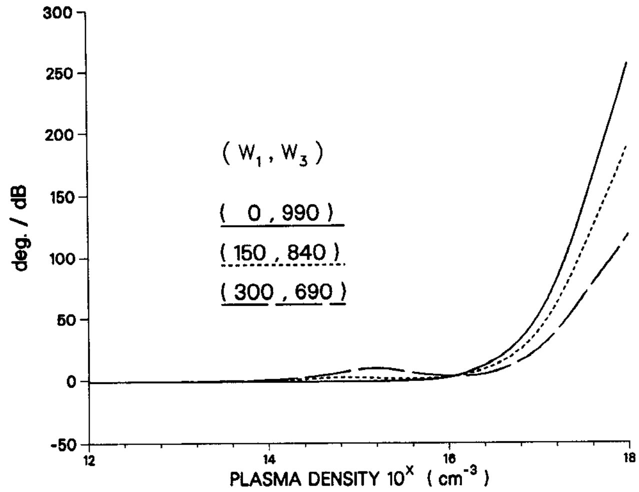

Fig. 5. Phase shift per decibel attenuation versus plasma density for the surface-layer structure assuming 94-GHz TM mode operation.

uniform layer and the propagating mode is the TM mode. The degrees/dB obtained with this device are lower than the buried layer structure for corresponding plasma densities.

Another parameter which may be of interest for some applications is the efficiency. If a carrier concentration of $n = 10^{17}\ \mathrm{cm}^{-3}$ is required, the energy per unit volume of plasma required is about 0.05 $\mathrm{J/cm}^3$ for a GaAs laser. The lifetime of carriers in GaAs at $n = 10^{17}\ \mathrm{cm}^{-3}$ is about $T = 10^{-7}$ s [4]. If the phase shift must be maintained for times greater than this value, the required power is $5 \times 10^5\ \mathrm{W/cm}^3$. If we assume a plasma thickness of 10 μm, a width of 0.1 cm, and a phase shift (from Fig. 2) of 800°/cm, we compute an efficiency of 16°/W. Of course, if the phase shifter is operated in a pulsed mode, the required energy, given earlier, is the more appropriate parameter.

References

[1] C. H. Lee, P. S. Mak, and A. P. DeFonzo, "Optical control of millimeter wave propagation in dielectric waveguides," *IEEE J. Quantum Electron.*, vol. QE-16, pp. 277–288, Mar. 1980.

[2] A. M. Vaucher, C. D. Striffler, and C H. Lee, "Theory of optically controlled millimeter-wave phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 209–216, Feb. 1983.

[3] J. K. Butler, T. F. Wu, and M. W. Scott, "Nonuniform layer model of a millimeter-wave phase shifter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 147–155, Jan 1986.

[4] H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LEDs*. New York: Academic Press, 1977.