An Optically Controlled Coplanar Waveguide Phase-Shifter.

P. Cheung, D. P. Neikirk and T. Itoh.

University of Texas at Austin
Department of Electrical and Computer Engineering
Austin, TX 78712.

Abstract

Phase-shift measurements of an optically controlled coplanar waveguide phase shifter are presented. This device is based on the interaction between the guided wave on a coplanar waveguide (CPW) and an optically induced electron-hole plasma in the semiconductor substrate. A prototype device consisting of a CPW on a heterojunction substrate of AlGaAs/GaAs/AlGaAs was fabricated and tested. The measured phase-shift obtained with the total illuminating optical power in the - 20 dBm range was as large as 50° for a 1cm long line at 10 GHz.

Introduction

Studies of coplanar waveguides (CPW) on semiconductor multi-layered substrates have shown, that within that the range of resistivities covered by most semiconductor substrates and the frequency spectrum of interest for microwave and millimeter wave applications, a slow wave (SW) mode of propagation can exist [1]. A typical structure consists of a thin lossless layer immediately below the CPW, followed by a thicker lossy layer and a third lossless layer. The slow wave factor (SWF), which is the ratio of the effective guide wavelength to the free space wavelength, is a measure of the change of the effective refractive index of the substrate. By varying the SWF, the phase constant of the propagating signal is varied, which in turn causes phase shifting action. The magnitude of the SWF is a function of both the resistivity of the buried lossy layer and the thickness of the first layer. Because of the dependence of the SWF on the properties of the underlying substrate, a CPW on a multi-layered substrate can be used as a variable phase-shifter if either the conductivity or layer thicknesses can be actively controlled.

One approach used to vary the thickness of the first layer is to use a Schottky contacted CPW on a doped semiconductor substrate [2]. A reverse D.C. bias is use to vary the depletion layer thickness which forms the first layer. The resultant change in the SWF causes phase-shifter action. In using the Schottky diode approach the semiconductor substrate is often heavily doped. Due to the high doping concentration, the size of the depletion layer thickness is limited by the bulk reverse bias breakdown voltage. Consequently the phase-shift obtained may be limited by the thickness of the depletion layer achievable. Also, in actual practise, Schottky diode approach requires an RF isolation circuit to be included in the design of the phase-shifter.

An alternative approach to obtain phase-shift is by varying the conductivity of a buried lossy layer via optical injection, as proposed in [2]. In this approach, the lossy layer in the substrate is replaced with an optically generated electron-hole plasma layer. The electron-hole plasma is confined within this layer through the use of a heterojunction substrate. The SWF, and hence the phase shift, is then controlled by varying the intensity of the optical excitation. This approach of using optical illumination to obtain phase-shift has also been demonstrated for dielectric waveguide phase-shifters by Lee, et al [3]. The optical illumination approach avoids a number of potential problems associated with the Schottky diode approach.

In this paper we report phase-shift measurements of a prototype device. The results show that substantial phase-shift was achieved for this device at illuminating intensities in the microwatt range. Details of implementation of the optical approach, fabrication and experimental results of the device are presented.

Implementation

To implement the optical approach, a heterojunction consisting of $Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ on a SI GaAs substrate is used. The device is then illuminated with a light source of wavelength below the band gap for the AlGaAs layer but well above that of the GaAs layer. When the substrate is illuminated by this source, the electron-hole pairs are generated only in the GaAs layer. The band gap discontinuity between the AlGaAs/GaAs layer presents a barrier to the diffusion of the electron-hole plasma out of the GaAs layer, thus confining the electron-hole plasma within the GaAs layer. The use of heterojunction layer has the advantage of having a small surface recombination velocity (≈ 400-500 cm/sec compared to 10^6-10^7 cm/sec for an GaAs/air interface) at the junction interface, thus reducing the incident optical power required to achieve a given plasma density.

Fabrication

A cross-section of the device is given in Fig. 1. The heterojunction layers were grown using molecular beam epitaxial techniques on a semi-insulating GaAs substrate with a 1 μm buffer layer. The layers have an unintentional background p-type doping concentration of ≈ 1 x $10^{14}/cm^3$. The coplanar waveguides were fabricated by a lift-off technique using a chlorobenzene soak process. A metal scheme of chrome/gold/silver with a total thickness of ≈ 1 μm was used for the CPW conductors.

Experimental Results

The measurement of the device was done with the HP8510B automatic network analyzer in conjunction with wafer probes made by Design Technique. The illuminating source was a microscope illuminator fitted with a red filter. The measured spectrum of the filtered light showed negligible intensity for wavelengths below 704 nm. Therefore no light is absorbed in the $Al_{0.4}Ga_{0.6}As$ layer (650 nm cutoff) . Measurement was carried out at three illuminating intensities of 2.4 mW/cm^2, 11 mW/cm^2 and 52 mW/cm^2. Since the actual area of the device exposed to the illumination is 1.4 x 10^{-3} cm^2, the optical intensities correspond to the illuminating powers of 3.4 μW, 15 μW and 72 μW. The measured phase-shift as a function of illumination intensity over a frequency range of 0.08 GHz to 18.0 GHz are given in Fig. 2. As seen in Fig.2, phase shift was observed over the full range of frequencies measured. For example, at 5 GHz the device shows a phase-shift of 20° with 2.4mW/cm^2 of illumination in reference to the unilluminated case. The amounts of phase-shift are 30° and 40°, respectively, for 11 ,and 52 mW/cm^2 optical intensity. The largest phase shift was about 50° at 18 GHz for the highest intensity of illumination.

The slow-wave factor SWF (or the effective index of refraction n_{eff}) was calculated from the formula

$$SWF = \frac{\lambda_0}{\lambda_g} = n_{eff} = \frac{\theta c}{2 \pi \ell f}$$

where θ is the measured phase, ℓ is the physical length of the device, c is the speed of light and f is the frequency. A plot of the SWF is given in Fig.3. At low frequencies the SWF increased from 5.0 to 7.2 as the optical intensity was increased. This translates into a change in the effective relative dielectric constant from 25 to 51.8. At the higher frequencies the changes were smaller but still reasonable. For example, at 10 GHz a change of 0.75 in the SWF can still be observed. For comparison purposes the SWF for a CPW on S.I. GaAs was measured and shows an expected value of 2.75 with no change over the measured frequency range and no change for different illuminating intensity. The insertion loss for the device is given in Fig. 4.

Conclusion

Phase-shift measurements of a prototype optically controlled coplanar waveguide phase-shifter for various illuminating intensities have been performed. The results show that the device can produce significant phase-shift even at very low illumination levels. Although the SWF at the higher frequencies is small in comparison to the one at lower frequencies, studies suggests that the SWF at the higher frequencies can be improved by changing the doping concentration of the substrate. The measured results and the advantages of using this approach suggest that optical control is an attractive alternative to the Schottky contacted phase-shifter approach. However, a more detailed study of the loss mechanisms is needed before this device could be used for practical purposes.

References

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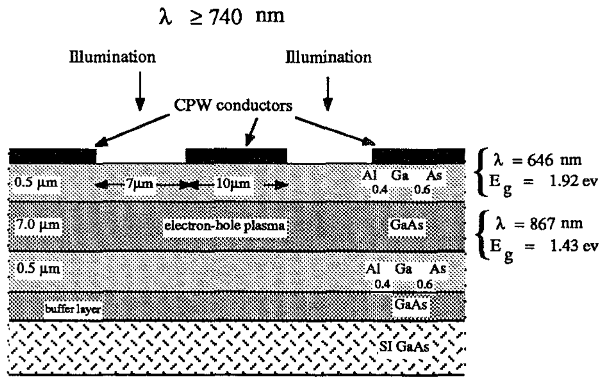

Figure 1: Cross-sectional diagram of a heterojunction substrate and CPW for use as an optically controlled phase shifter. The layers were grown by MBE, with a p-type background doping of about 10^{14} cm^{-3}.

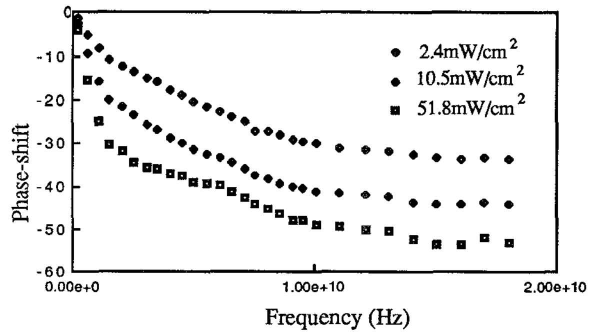

Figure 2: Measured phase shift induced by optical illumination of the CPW shown in Fig. 1. The physical length of the CPW was 1 cm.

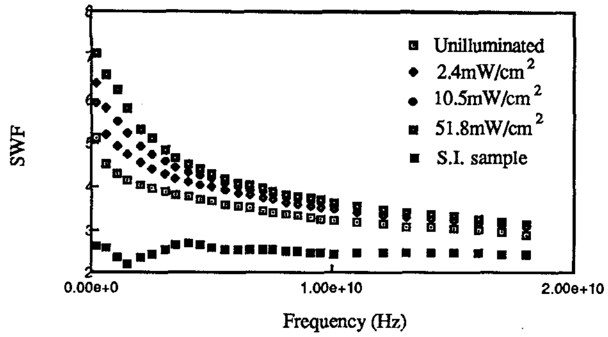

Figure 3: Slow wave factor found from measurements on the structure shown in Fig. 1, as well as on an identical CPW fabricated directly on a SI GaAs wafer.

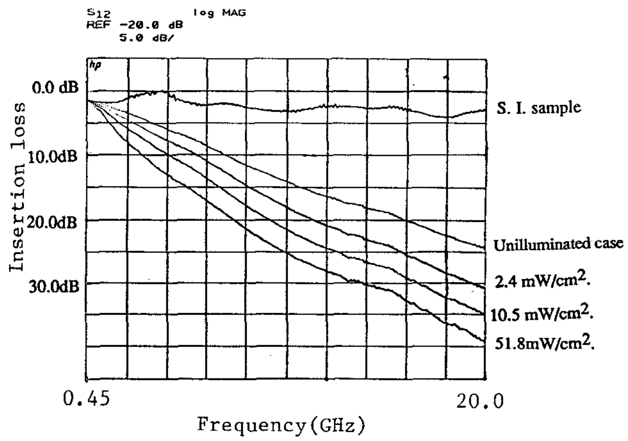

Figure 4: Insertion loss of the optically controlled phase shifter. Since the device was 1 cm long, this plot shows the loss per cm.