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OPTICALLY CONTROLLED MILLIMETER WAVE PHASE SHIFTER IN A METALLIC WAVEGUIDE

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Abstract

Analytical and experimental results of an optically controlled millimeter wave phase shifter enclosed in a metallic waveguide are presented. The analysis predicts that large phase shifts and low attenuation can be achieved with this configuration. An experimental study of the feasibility of inducing phase shift in a 94 GHz signal propagating in a metallic waveguide inhomogeneously filled with a silicon slab, is reported.

Introduction

The amplitude or phase of millimeter waves can be altered by passing the electromagnetic wave through a semiconductor medium whose properties (complex dielectric constant) can be dynamically controlled. Free carrier injection into the semiconductor via contacts [1][2], or optical injection [3][4], have been used for efficiently designing millimeter-wave switches and phase shifters. The shortcomings of contact injection (slow response, high losses per degree of phase shift) have been minimized by using optical injection. Photocarriers (electron-hole pairs) are created in a semiconductor material by above-the-band-gap laser radiation. The plasma region thus created, produces refractive index changes and perturbs the propagating mode by altering its wave velocity with respect to the unperturbed waveguide, resulting in a phase shift at the end of the device.

The electron-hole pair density distribution is governed by recombination and ambipolar diffusion in the semiconductor. Experimental work has been performed on silicon semiconductor material, however the short lifetime of the carriers in Cr-doped GaAs (~ 100 ps) and the desire to prevent carrier diffusion , makes semi-insulating GaAs an attractive choice for the semiconductor. In addition, an appropriate heterojunction can also be used to confine the free carriers near the surface.

Waveguide Configuration

Configurations studied in the past have been mainly open dielectric waveguides which exhibit low losses and are suitable for integrated structures [3]. Presently we are exploring an alternate structure, using a W-band metallic waveguide inhomogeneously filled with a semiconductor slab, as shown in figure 1.

Free carriers are created in the slab by optical injection through a small aperture in the wall of the metal waveguide. This structure is of interest because for certain dielectric insert thickness, when the plasma region is created, the millimeter wave is pushed into the air filled region of the metal guide. In the air region the fields do not encounter the exponential tail of free carriers extending into the bulk of the semiconductor. These carriers have been shown to contribute losses in the open waveguide configuration, if the carriers are not confined near the surface by a more complicated device structure [5].

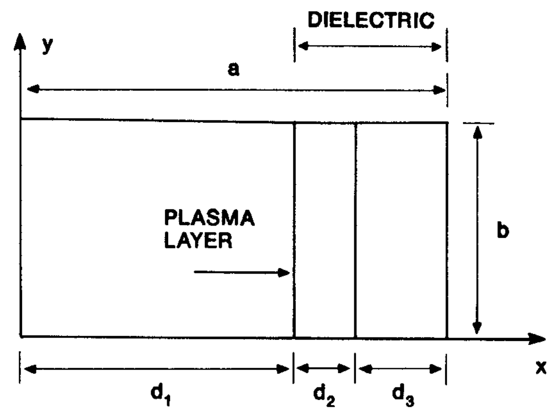

Fig. 1 : Device configuration

Analytical Predictions

Performance predictions for this structure are based on an efficient algorithm for finding the complex propagation constant in dielectric structures with arbitrary complex refractive index profiles [6]. The software developed can be used for studying characteristics of dielectric waveguides formed with binary, ternary and quaternary semiconductor compounds.

Recent analytical results show that our present structure (d_1=1555μm, d_2+d_3=985μm) can support

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more than one propagation mode. Each of these modes will have different phase shift and attenuation characteristics as the density of the injected plasma is varied.

Figure 2. shows that in order to obtain single mode propagation, the thickness of the Si insert has to be less than approximately 250 μm. For thicker dielectric slabs, two or even three modes can propagate.

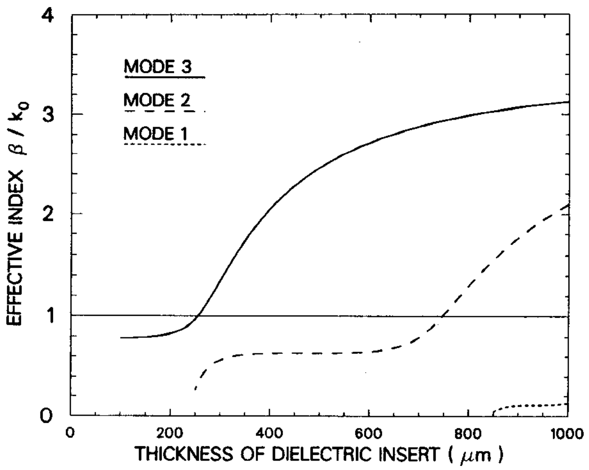

Fig. 2 : Effective index vs dielectric insert thickness for the three propagating modes.

The normalized wavefunction profile for each mode propagating in a 985 μm Si insert structure, is shown in Fig. 3 :

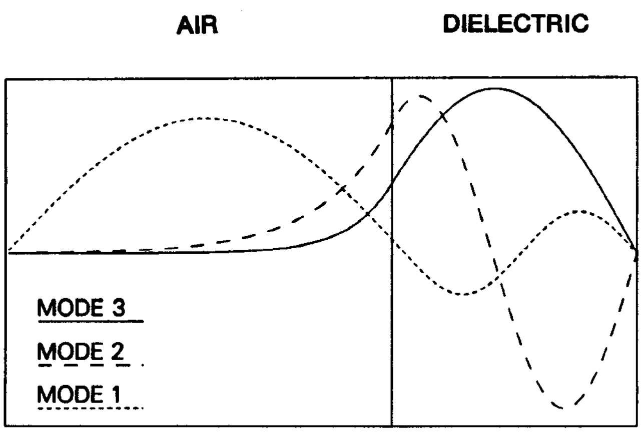

Fig. 3 : Normalized field amplitude profiles for the three propagating modes in our experimental structure.

Figure 4. shows the phase shift and attenuation characteristics for the three modes propagating in the structure of Fig. 1 with d_1=1555μm, d_2=20μm, and d_3=965μm. For mode 1 the attenuation curve saturates even though the propagating field is pushed into the air region. At high plasma densities, modes 2 and 3 propagate entirely in the dielectric. The attenuation for these modes is shown to drop to almost zero, because the analysis uses a uniform plasma layer, which acts as a metallic wall at high densities. This would not have been true if a non uniform plasma layer were used[5]. For a multimode operating device, the effective phase and attenuation characteristics come from a weighted sum over all the participating mode characteristics. The weighting factors can be estimated by evaluating the complex overlap integrals of the incident mode (TE_{01}) and each one of the allowed propagation modes.

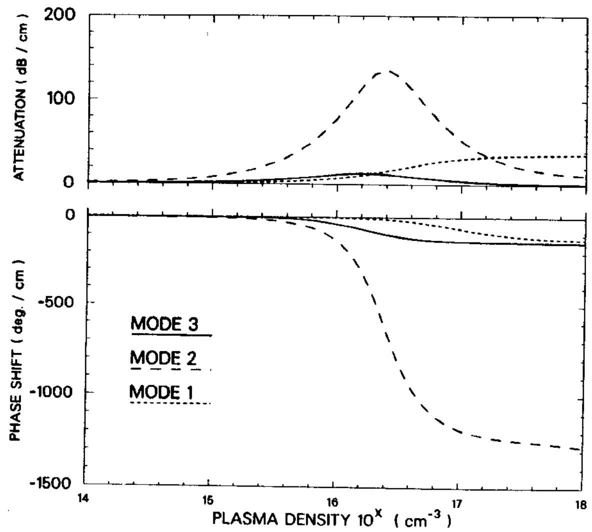

Fig. 4 : Phase and attenuation profiles vs plasma density for the propagating modes of our experimental configuration.

Experiment

The experimental setup is shown in Fig. 5. The optical source is a pulsed GaAs laser with approximately 100 nsec pulse duration. The detector outputs are sampled by a gated integrator/boxcar averager with a sampling gate width of 10 nsec. The SNR can be increased by averaging over many repetitive samples.

The phase shift induced by the laser pulse is measured by first mixing the phase shifted signal with a reference signal at D3. Detector D2 monitors the magnitude of the signal through the phase shifted arm of the bridge. By opening SW2 the portion of the phase-shifted signal that reaches D3 is measured. By balancing initially the bridge for zero output, information about the reference arm signal can be deduced as well. With the magnitude of the interfering signals known, the phase shift and attenuation can be calculated from the measured output of detectors D2 and D3. The micropo-

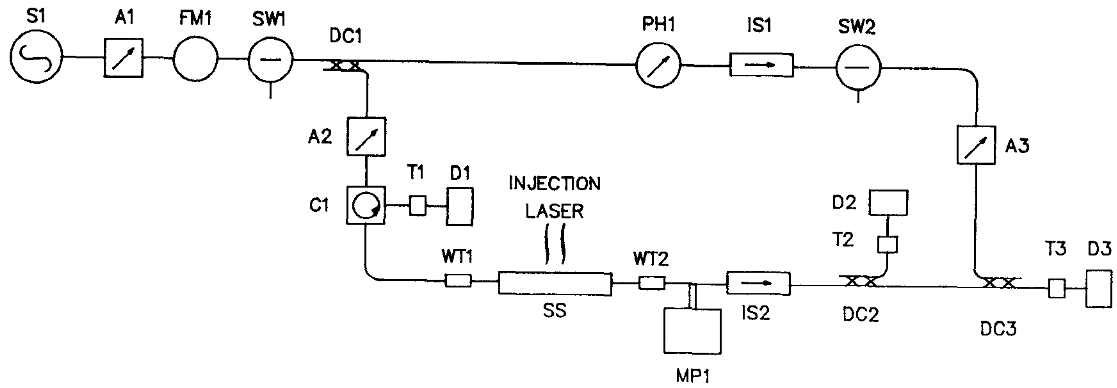

Fig. 5 : Balanced bridge measurement scheme : A attenuators, FM frequency meter, SW switches, DC directional couplers, PH mechanical phase shifter, IS isolators, C circulator, T matching hybrid tuners, D detectors, WT twists, MP micropositioner.

sitioner is used for fine adjustment and positioning of the sample holding guide. The reflected signal as measured by D3 can thus be minimized to almost zero reflection.

Figure 6 shows typical experimental results of attenuation and phase shift, for three different photocarrier injection levels. The maximum of the phase shift always occurs immediately after the excitation. Its slow decay reflects the carrier transport dynamics (diffusion and recombination) which results in a decrease in carrier density. If the initial injection is high enough, the decreasing plasma density sweeps through a peak in the attenuation curve.

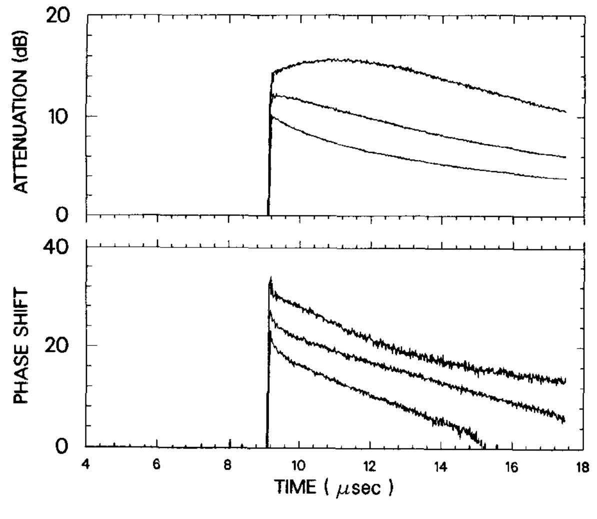

Fig. 6 : Experimental results for the attenuation and phase shift, calculated for 3 different semiconductor laser currents.

With our present multimode configuration, it is difficult to match experimental results with theoretical predictions. Experimentally, we obtained 35° of phase shift with 14 dB of attenuation at relatively low injection levels, just after the laser excitation. For higher injections, as the plasma density decreases by carrier recombination, the attenuation goes through a maximum of approximately 30 dB, shutting off almost completely the phase shifted arm of the bridge. We estimated that for no plasma present, the incident TE_{01} millimeter energy is divided as follows : 33.6% in mode 3, 14.5% in mode 2, and 51.9% in mode 1. However, with a plasma region present, the above percentages will be sensitive to the plasma density. Nevertheless, the peak in the attenuation curve can be associated with the fact that modes 2 and 3 experience a similar peak as a function of plasma density.

Conclusion

We have demonstrated an optically controlled millimeter-wave phase shifter using a semiconductor insert in metallic waveguides. Proper match of the theory and experiments have been hindered because of the multimode operation. Single mode operation can be accomplished by using a silicon insert of a thickness less than 200 μm. The analysis predicts that for a 150 μm thickness Si, the attenuation goes through a maximum of 4 dB/cm, dropping down to zero at high plasma densities as the propagating field is being pushed entirely into the air region of the metallic waveguide. The phase shift saturates at a value of more than 50 °/cm.

References

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