PHASE COMPENSATION IN AN OPTICALLY CONTROLLED MICROWAVE ATTENUATOR

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ABSTRACT

A microwave attenuator has been developed whose attenuation can be controlled by illuminating the silicon substrate. The phase shift which appeared together with the attenuation can be compensated by a ferrite phase shifter under dc magnetic field to the line. The attenuation characteristics without phase shift are shown by experiments in X band and confirmed theoretically by the spectral domain approach.

INTRODUCTION

The interaction between optical waves and microwaves has been paid much attention these days. Electron-hole plasma which is induced in a semiconductor by above band-gap radiation is able to be applied to optical control of microwave devices [1]. Recently, an optically controlled microwave attenuator of a coplanar guide was proposed, whose maximum attenuation reached more than 30dB by a laser diode illumination [2][3]. This operation, however, also yielded the phase shift of the wave, which degraded the performance as an attenuator.

In the attenuator proposed here, the attenuation can be controlled by the intensity of the illuminating light and the phase shift which simultaneously appears is compensated by a ferrite phase shifter. So the disadvantage of the undesired phase change in the conventional optically-controlled attenuators has been overcome. It is also useful for a signal control in which the amplitude and the phase are independently variable.

The fabricated waveguide is a microstrip line with a slot on the lower ground plane [4], and a ferrite slab is loaded on the line. We have experimentally demonstrated that the change in the phase caused by the illumination to the silicon substrate is balanced against a dc magnetic field imposed to the ferrite slab [5]. This paper describes the theoretical confirmation together with the experimental results for the feasibility of the phase compensation.

EXPERIMENTAL RESULTS

The top view and cross section of the prototype attenuator are shown in Fig.1. It is a microstrip line whose substrate consists of silicon and ferrite slabs. The ferrite slab is overlaid on the microstrip. There is a slot on the ground plane under the strip.

The thicknesses of the silicon and the ferrite are 0.21, 1.0mm, and the widths of the strip and the slot are 1.0, 3.0mm, respectively. The waveguide length is 49mm, within which the ground plane conductor is slotted for 43mm. A white light from a xenon arc lump with a parabolic mirror is focused by a lens to the silicon surface through the slot. The intensity of the light is not uniform along the slot direction. By the illumination, electron-hole pairs are induced and the permittivity and conductivity of the silicon are changed, which vary the phase and the amplitude of the microwave. A dc magnetic field is imposed to the ferrite perpendicular to the wave propagation and parallel to the slab surface. Then since the permeability of the ferrite changes [6], the change in the phase constant of the propagating wave can make up for the phase shift by the illumination.

When illuminating by the optical power of 240mW, the attenuation of 17-26dB was obtained in the frequency range from 8 to 12GHz. The phase, however, changes about 60 degrees as shown in Fig.2. The phase shift means the change in the phase angle compared with that in the original state where neither illumination nor Hdc field is given. The dotted line is the case under illumination and with no Hdc field. In keeping the illumination on, when a magnetic field is applied, the characteristics change to the solid line in the figure. The phase shift decreases because of the change in the permeability of the ferrite. This means that the phase has been equalized to the original dark state.

Figure 3 shows the attenuation characteristics for the optical powers of 70mW, 240mW,

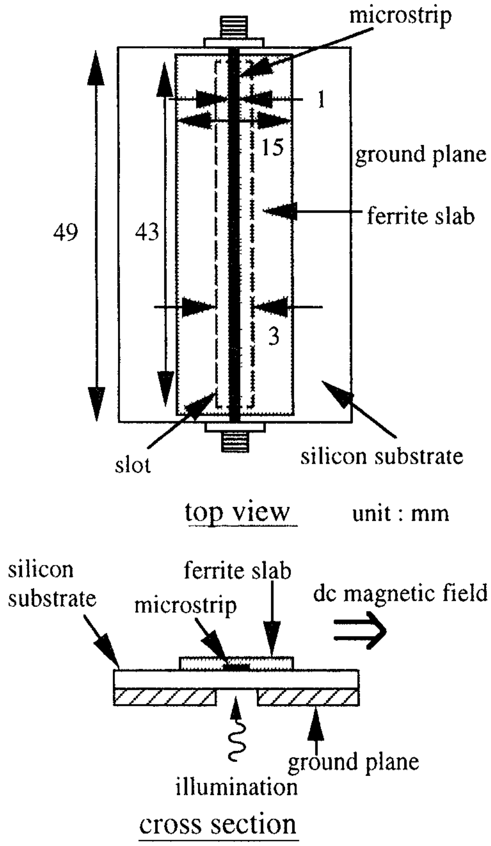

Fig.1 Microstrip-slot line attenuator on a silicon substrate with an overlaid ferrite slab.

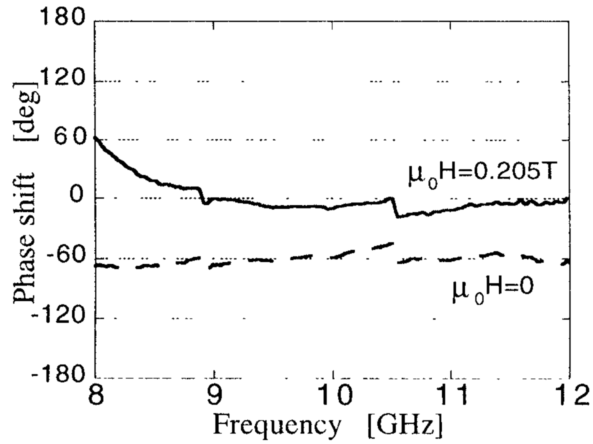

Fig.2 Effect of the dc magnetic field on the phase shift from the dark state.

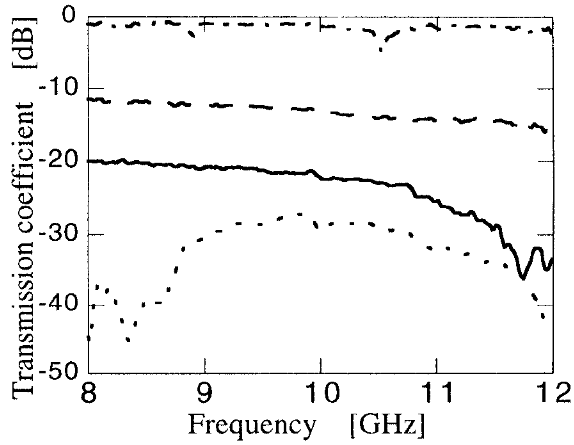

Fig.3 Attenuation characteristics.

- - - - - Po = 0 , $\mu_0 H$= 0
— — - 70mW , 0.140T
——— 240mW , 0.205T
· · · · · 2.2W, 0.246T

and 2.2W with compensating dc magnetic flux densities of 0.140, 0.205, 0.246 tesla, respectively. Though the flatness of the attenuation over this frequency range is broken, the amount of the attenuation at 10GHz can be continuously varied to 13.4, 22.1, 29.6dB. But the phase compensation is not strictly completed to zero degree, and the maximum error is about 20 degrees at that frequency. The insertion loss (in the dark state) is 1.4dB. The maximum return loss is 15dB at 10GHz.

Though a xenon arc lump is employed as an optical source in this experiment, a semiconductor laser diode or an infrared LED is alternatively available for the plasma injection[4][7].

In the prototype attenuator, the length of the ferrite slab is 6mm shorter than the whole line length, so there are comparably large discontinuities of the line near the input/output ports. They are considered to affect the spurious reflection and the spectral flatness of the attenuation, which should be improved.

Moreover the structural parameters such as the widths of the strip and the slot, the thicknesses of the silicon and the ferrite are needed to be optimized.

THEORETICAL RESULTS

The transmission characteristics are analyzed using the spectral domain method. As the first order model we treat the structure without a slot on the ground plane. The plasma region is not only under the strip but spreading in the whole layer on the ground conductor, and its thickness is 0.02~0.12mm out of the silicon layer of 0.21mm. The permeability of the ferrite is represented in a tensor form, so the usual immittance approach could not be utilized to this guide.

The density of the induced carrier is considered to be proportional to the intensity of the illumination. So we will take the carrier density n_p instead of the light power as a parameter of the optical control in the theoretical treatments.

First the dependency of the transmission characteristics on the carrier density is calculated. Figure 4 shows the attenuation and phase shift per unit length as a function of the density for four values of the plasma layer thickness t_p and the frequency of 10GHz. For t_p=0.1mm, the density of $n_p=2\times10^{20}/m^3$ causes the attenuation of about 8dB, while the phase angle has decreased by 30 degrees.

The phase shift by applying a dc magnetic field under the dark state is shown in Fig.5. It linearly increases with the magnetic flux density up to 0.2tesla, over which the linearity is broken. Therefore in order to obtain a large phase shift, the intensity of the dc magnetic field had better not be strong, and it is necessary to use a longer ferrite slab instead.

The shift by the illumination is lagging while the shift by the ferrite phase shifter is leading. These facts mean that the phase can be balanced. It is also seen that this line has non-reciprocity so the wave propagating to the reverse direction has a larger phase shift.

The next calculation is for the line length corresponding to the fabricated device. Figure 6 shows the phase shift. The carrier density is chosen for $n_p=1.2\times10^{20}/m^3$ so that the calculated phase shift correspond with the measured one. When the magnetic flux density is applied by μ_0H=0.195tesla, the phase shift can return to the dark state, which agree with the measured data shown in Fig.2. The attenuation was 20-25dB in the range above 9GHz, but there was a dis-

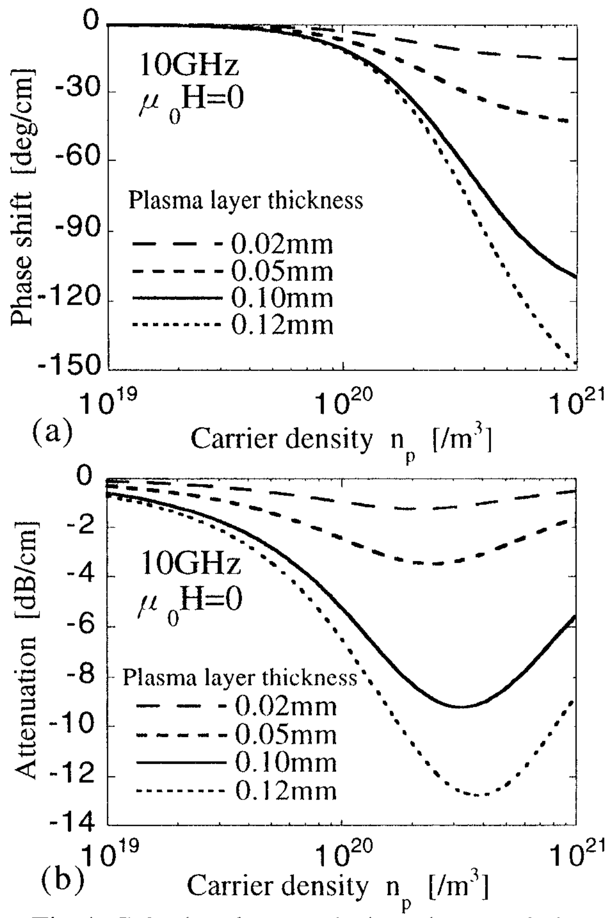

Fig.4 Calculated transmission characteristics as a function of carrier density, (a) phase shift, (b) attenuation.

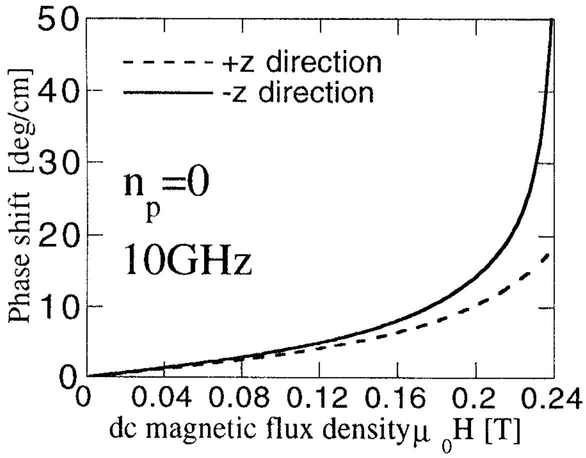

Fig.5 Dependency of the phase shift on the applied dc magnetic field.

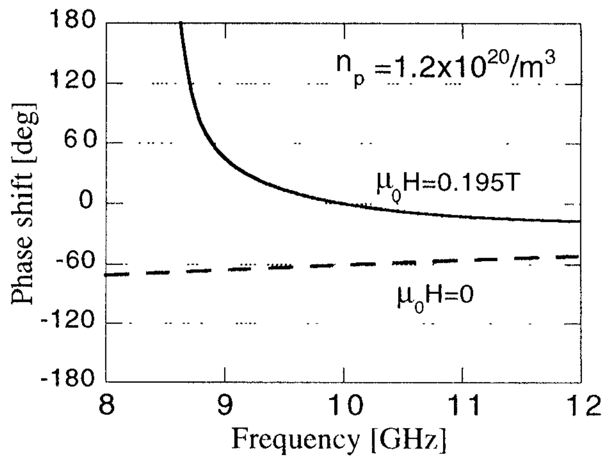

Fig.6 Theoretical phase shift compensated by applying dc magnetic field.

crepancy below 9GHz in which the attenuation was less than 20dB. This discrepancy would be reduced by analyzing a model with a slot and by considering the inhomogeneous distribution of the induced carrier.

CONCLUSION

A microstrip line attenuator was fabricated on a silicon substrate with an overlaid ferrite slab. The attenuation of microwaves was continuously variable by an illumination to the substrate, and the phase shift which appeared simultaneously with the attenuation could be compensated by an application of a dc magnetic field. The experiment was carried out in the X band using a xenon arc lamp as an optical source. The transmission characteristics have been analyzed by the spectral domain method and compared with the experiment.

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