Microwave Modulation of Optical Signal by Electro-Optic Effect in GaAs Microstrips

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ABSTRACT:

The microwave modulation of the interference generated by light beams reflected from the top and bottom surfaces of GaAs substrate and adjacent to a microstrip line has been used to directly measure the electro-optic (E-O) effect. This sampling technique of the time-domain waveform of a microwave signal based on the harmonic mixing mechanism results in a highly sensitive method for determining the E-O effect in the substrate.

Introduction

Optical techniques for broadband signal generation and detection have been reported to characterize GaAs devices and monolithic microwave integrated circuits (MMICs) [1-3]. Electro-optic (E-O) sampling of microwave signals, in particular, in GaAs circuits has been demonstrated. However, recent measurements using E-O sampling [2,3] have revealed that some details of the sampling scheme have yet to be studied.

In the previously reported electro-optic sampling techniques, which depend only on the detection of signal from the backside reflection, the interference between the multiple beam reflections from top (front) and bottom (back) surface of the GaAs substrate had not been accounted for. Since the index of refraction of GaAs is about 3.5, a substantial amount of light is reflected at the top surface (30.8 percent of the energy for normal incidence), as well as at the bottom surface. Therefore, when the laser pulse duration is longer than the optical round-trip time in the GaAs substrate, the interference effect can not be neglected.

In this paper, the interference effect on the conventional electro-optic sampling technique, which requires the use of an analyzing polarizer, has been studied. It was observed that the interference effect is significant provided that the optical pulse duration used for electro-optic sampling is longer than or comparable to the optical round-trip transit-time through the substrate. Furthermore, the magnitude of the sampling signal depends critically on the local substrate thickness, causing problem in calibrating the electro-optic sampling of signal amplitude in microwave circuit measurement.

In addition, a new approach to detect the electro-optic effect in GaAs microstrip circuits without using an analyzing polarizer is presented. The scheme utilizes the modulation of the interference pattern generated by the multiple beams reflected from the top and bottom surfaces of the GaAs substrate. The microwave signal modulates the effective optical thickness of the GaAs substrate via electro-optic effect. This in turn gives rise to the modulation of the intensity of reflected optical probing beam.

The summary of theoretical analysis is given in the next section. In the experimental section, the E-O sampling/ harmonic mixing technique, with which we have achieved very high sampling sensitivity, will be discussed.

Analysis of interference effect on $E-O$ sampling

Fig.1 shows the dimensions of the microstrip structure and the coordinates used in the following analysis and experiment. The resultant field caused by the multiple reflections from the top and bottom of a GaAs substrate with incident fields, $E_{y'in}$ and $E_{z'in}$, can be expressed as:

$$E_{y'} = E_{y'in}A(\phi + \Delta\phi)e^{i\Phi(\phi+\Delta\phi)} \qquad (1)$$

$$E_{z'} = E_{z'in}A(\phi - \Delta\phi)e^{i\Phi(\phi-\Delta\phi)} \qquad (2)$$

Where $A(\phi)$ and $\Phi(\phi)$ are the amplitude and phase of the reflection coefficient, $\phi = 2hn_o(2\pi/\lambda)$ is the round-trip phase delay in GaAs, $\Delta\phi = 2\pi n_o^3 r_{41} 2V/\lambda = 2\pi V/V_\pi$ is the phase modulation produced by the applied microwave voltage V, and, h and n_o are the thickness and index of refraction of the substrate, respectively. V_π is the half-wave voltage, for GaAs, and equals to 10kV at a wavelength of $1.06\mu m$. r_{41} is the electro-optic coefficient for GaAs. y' and z' refer to the $[01\bar{1}]$ and $[011]$ axes of GaAs crystal, respectively.

(A) To illustrate how the E-O effect can be detected without a polarizer, let us input a linearly polarized light beam ($E_{y'in} = E_o cos\theta$, $E_{z'in} = E_o sin\theta$) to the GaAs

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sample. The incident polarization angle, θ, can be varied by a half-wave plate.

The reflected light intensity, I, is given by $I = E^*E = E^*_{y'}E_{y'} + E^*_{z'}E_{z'}$.

The reflected light intensity is modulated, and the change of intensity, ΔI, is given by

$$\Delta I = 2E_o^2 A(\phi)\frac{dA(\phi)}{d\phi}\Delta\phi cos2\theta \qquad (3)$$

This modulation can be detected directly by a photodiode without the use of a polarizer.

(B) To show the effect of the interference on the conventional electro-optic sampling detection scheme, let us input a circularly polarized light beam ($E_{y'in} = E_o cos45^o$, $E_{z'in} = E_o sin45^o e^{i\frac{\pi}{2}}$)to the GaAs sample, and vary the analyzing polarizer orientation θ' in front the detector.

Before entering the analyzing polarizer, the reflected light intensity is constant. After passing through the analyzing polarizer, the field ($E = E_{y'}cos\theta' + E_{z'}sin\theta'$) is modulated.

Using a mathematical manipulation similar to case (A), the modulation of the output light intensity is given by:

$$\Delta I = E_o^2\Delta\phi A(\phi)(\frac{dA(\phi)}{d\phi}cos2\theta' + A(\phi)\frac{d\Phi(\phi)}{d\phi}sin2\theta') \quad (4)$$

Next, we assume that the reflections from both surfaces have the same amplitude. This assumption is reasonable, if we consider some optic losses inside the GaAs and at the bottom surface. In this case, equation (3) can be simplified to

$$\Delta I = 2E_o^2\Delta\phi sin\phi cos2\theta \qquad (5)$$

and equation (4) becomes

$$\Delta I = 2E_o^2\Delta\phi cos(\phi/2)sin(2\theta' - \phi/2) \qquad (6)$$

It can be noted that equations (5) and (6) are both a function of ϕ. Thus, the sensitivity of detected signal is related to the local thickness of the substrate, since ϕ depends on h. For optimum thicknesses, equations (5) and (6) show that the same maximum change of intensity, and thus the same sensitivities can be achieved in both cases.

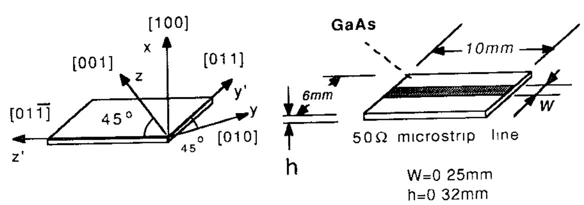

Fig.1 GaAs microstrip line

(C) If the laser pulse duration is shorter than the time for light to travel round-trip in the substrate, there is no interference. In the case of the conventional electro-optic sampling using polarizer, $A(\phi \pm \Delta\phi) = \sqrt{2}$, $\Phi(\phi \pm \Delta\phi) = \phi \pm \Delta\phi$. Therefore,

$$\Delta I = 2E_o^2\Delta\phi sin2\theta' \qquad (7)$$

When the analyzing polarizer is oriented at 45^o from y' or z' axis, the output without interference reaches its maximum. If the interference is included, eq.(6) shows that this angle is shifted by an amount depending on the substrate thickness ($\phi/4$).

Experiment

To verify the above predictions, the experimental setup as shown in Fig. 2(a) and 2(b) were established. In Fig. 2(a), the quarter wave plate converts the linearly polarized laser beam into a circularly polarized beam. The analyzing polarizer, P, can be rotated to measure the change in amplitude of the output signal as function of θ'. In Fig. 2(b), the half-wave plate is used to rotate the linearly polarized input optical beam. An Argon pumped Neodymium glass laser with wavelength of $1.054\mu m$, pulse duration of 15 ps and repetition rate of 100 MHz was used.

The orientation and dimensions of the GaAs microstrip sample have been shown in Fig. 1. The time for light to travel round-trip within this GaAs substrate is 7 ps, which is shorter than the laser pulse duration, therefore, interference between top and bottom surfaces can occur.

The setup for signal generation and detection is shown in Fig. 3. The laser intensity noise bandwidth is less than 5 MHz. At frequencies above 5 MHz, the laser intensity noise is 50 dB below the noise at frequencies below 1 kHz. To avoid measurements within the laser noise band, a harmonic mixing technique, with the frequency scheme given in equation (8), was used. The frequency of the microwave signal, f_m, applied to the sample is set according to the following expression:

$$f_m = N\ 100MHz\ \pm\ f_{IF} \qquad (8)$$

where N is any integer, f_{IF} is an intermediate frequency. In the present case, f_{IF} was 10 MHz. Therefore, the GaAs sampler/detector behaves as a harmonic mixer, which produces a signal at f_{IF} proportional to the E-O effect output. This permits signal detection with very high sensitivity. This kind of harmonic mixer can also be used as a broadband phase comparator which may be used to synchronize a microwave source to laser pulses.[4]

The results obtained without using an analyzing polarizer demonstrated that the E-O sampled signal was caused by the optical interference. Fig. 4(a) shows the experimental and theoretical output dependence on the input light polarization angle θ. Both amplitudes have been normalized, and excellent agreement has been obtained. Fig. 4(b) shows the measured and predicted results from

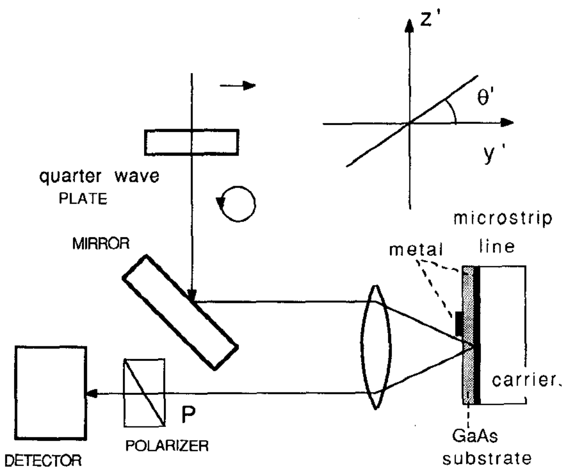

Fig.2(a) Detection of electro-optic effect with polarizer

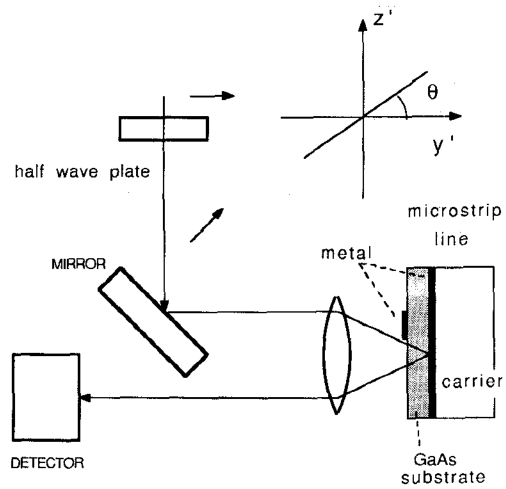

Fig.2(b) Detection of electro-optic effect without polarizer

the conventional electro-optic sampling scheme but with interference effect. These results are significantly different from those theoretical shown in Fig. 4(c) for same scheme without the interference effect. The interference not only causes the signal pattern in Fig. 4(c) to rotate by an angle, but also affects the sensitivity of sampling. These effects were observed when attempts to measure the field distribution across the microstrip line were made. Theoretically, the electric field strength should be monotonically decaying with the distance away from the edge of the microstrip line. However, according to equation(5) and equation(6), the measured results are actually the field distribution modulated by $sin(\phi)$ or $cos(\phi/2)sin(2\theta' - \phi/2)$, respectively. These two terms depend strongly on the substrate thickness. Fig. 5 shows the measurement of the field distribution across the microstrip line at a particular location. Additional sharp drops in electric field intensity due to the variation of substrate thickness were observed. Therefore, to achieve an accurate measurement of the electric field distribution along the microstrip line, one will have to use laser pulses of duration shorter than the time for light to travel round-trip in the GaAs substrate.

Conclusion

A new experimental scheme for the detection of the electro-optic effect in GaAs microstrip line has been demonstrated. This scheme does not require the use an analyzing polarizer but utilizes the modulation of the interference pattern generated by the multiple beams reflected from the top and bottom surfaces of the GaAs substrate.

We show that even if one uses an analyzing polarizer in the conventional E-O sampling techniques, the interference effect has to be taken into account in order to explain the observed E-O signal.

For both detection schemes, it was demonstrated experimentally and theoretically that the amplitude of the E-O signal varies very rapidly with the GaAs thickness. The absolute calibration in the electro-optic sampling technique for device or MMIC characterization is thus very difficult. In order to avoid the interference effect, one has to use laser pulses with a duration shorter than the round-trip time for the optical beam to travel through in the substrate.

Acknowledgement

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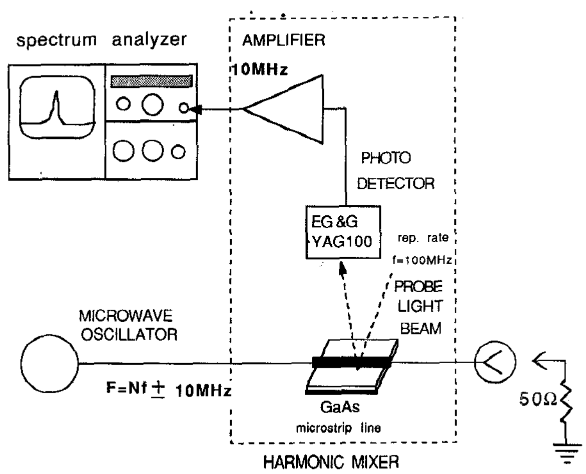
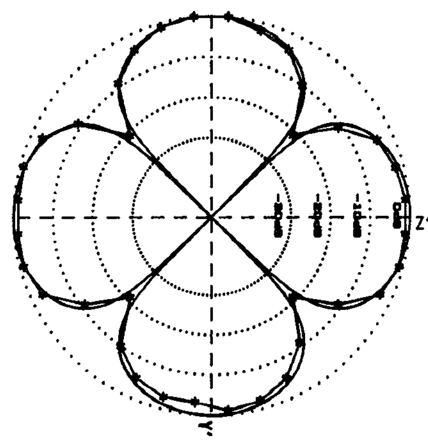


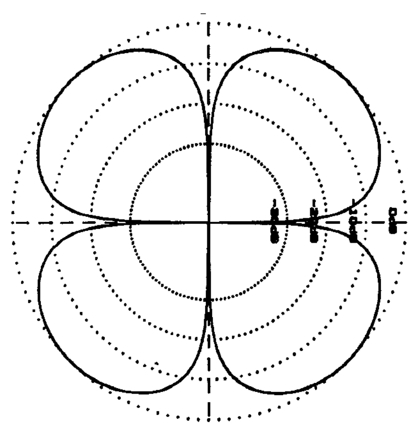
Fig.3 Electro-optic sampling using the harmonic mixing scheme.



theory — $\Delta I \propto 2\Delta\phi \sin(\phi)\cos(2\theta)$

experiment — (ϕ is an adjustable parameter)

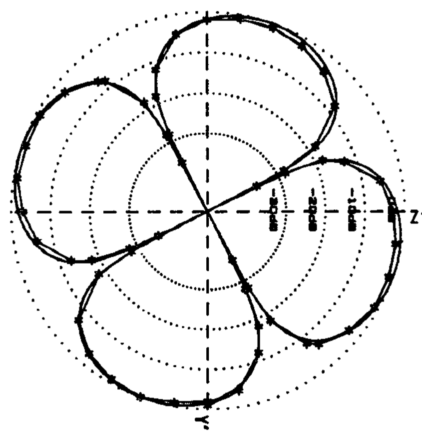
Fig.4(a) E-O signal versus polarization angle of incident light (detection without polarizer)



theory without taking reflection from front surface of microstrip into account $I \propto 1 + 2\Delta\phi \sin(2\theta')$

experiment

Fig.4(c) E-O signal versus polarizer orientation. (detection with a polarizer)



theory taking reflection from front surface of microstrip into account. $\Delta I \propto 2\Delta\phi \cos(\frac{\phi}{2})\sin(2\theta' - \frac{\phi}{2})$

(ϕ is an adjustable parameter)

experiment

Fig.4(b) E-O signal versus polarizer orientation. (detection with a polarizer)

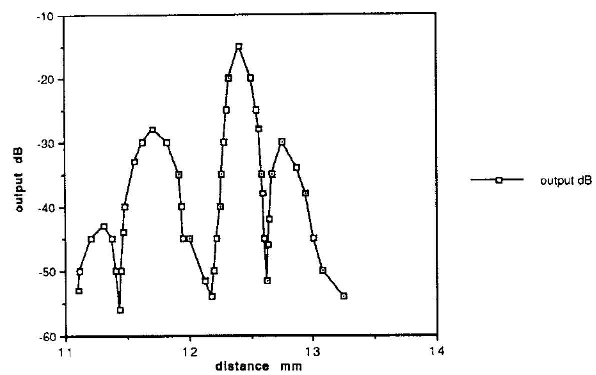


Fig.5 Measured electric field distribution across a microstrip line with inteference effect. The edges of the strip are located at 11.95 mm and 12.2 mm respectively.

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