High-Speed Directional Coupler Modulator with Velocity-Matched Electrode Structure

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ABSTRACT

The 3dB bandwidth of 17GHz has obtained for the directional coupler modulator with capacitive-loaded electrode structure, and is in good agreement with the 20GHz predicted result. We believe that this is the highest bandwidth obtained in the directional coupler modulators.

INTRODUCTION

The ultimate limit of the bandwidth for traveling-wave electrooptic modulators in GaAs is the difference in phase velocity of the optical and electrical signals. This phase velocity mismatch causes the optical phase front, which is slower in semiconductor structures, to walk-off from the electrical phase front. In most techniques one designs a structure to modify the effective propagation velocity of either the optical or, more typically, the electrical signal to equalize the optical index, n_{op}, and the microwave index, n_{rf}. Such velocity-matching techniques allow one to increase the bandwidth for a given length device. In this paper, we present a velocity-matching technique by using the capacitively loaded electrode in the directional coupler modulator, which provides a reduction of microwave phase velocity, and experimentally evaluate the slow-wave characteristics of the electrode structure. The optical modulators were fabricated for several configurations, and the measured results of high speed response are given.

THEORY

An electrode structure for the directional coupler modulator based on the capacitive-loaded design was designed, as shown in Figure 1, where the RF signal line and ground plane are placed on either side of optical waveguides, and connected to the electrodes on top of the ridges through 50 μm wide air-bridges. The impedance matching and tapers are designed using the constant impedance in coplanar waveguide. As the RF signal is applied to one end of the electrode, it travels through the side electrode which has the capacitance C_d, and because it is connected to the electrode on top of the ridge, additional lump capacitance C_d' will be added to the structure, as shown in Figures 2a and 2b. Thus, the effective microwave index, $\sqrt{\varepsilon_{reff}}$, for the capacitive-coupled electrode becomes

$$n_{rf} = \sqrt{\frac{C_d + C_d'}{C_0}} \tag{1}$$

and the microwave phase velocity is

$$v_{rf} = \frac{c_0}{n_{rf}} \tag{2}$$

where c_0 is the velocity of light in vacuum. We may show this electrode structure as a matched RF transmission line, shunted by parallel capacitances. This additional lumped capacitance added to the line results in an artificial transmission line, with a cutoff frequency, and thus a reduction of the rf bandwidth. Three different optical modulators using capacitive-loaded electrode with one coupling length 2500 μm were designed based on different values of S and W for the gap G=2 μm. Their effective microwave index and impedance are calculated and summarized in Table 1.

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The calculated RF effective indices in Table 1 suggest that the slow-wave effect may be enhanced by moving the RF signal line close to the ridge, and using large width of RF signal line. With the capacitve-loaded design, we can improve the velocity match by 40%, however, with a further reduction of the cutoff of the RF bandwidth. We have simulated the small-signal relative response [1,2] of the first case in Table 1, W= 6 μm and S= 20 μm, biased in the linear region of the transfer function for several different frequency-dependent losses, and is shown in Figure 3. The results predict that for the transmission line loss less than 2 dB/cm, half power bandwidth is about 23 GHz, and for 4 dB/cm, the 3 dB bandwidth is about 20 GHz.

Figure 4a shows the insertion loss of one of the capacitive-loaded electrode structure, which has 2500 μm long coupled guides, with conductor's thickness of 1 μm for the range of 45 MHz and 26.5 GHz. Note that the S_{12} response is less than 2dB insertion loss, and its 3dB bandwidth is approximately at 14.5 GHz. The impedance varies between 45Ω and 55Ω of up to 12 GHz, and at 10 GHz we have an exact match at 50Ω. Figure 5 shows the measured phase response of the electrode for W= 6μm, 10μm, and 20 μm compared with the referenced phase response of a uniform line which has effective index $n_{rf}= \sqrt{(\varepsilon_r+1)/2}$, where ε_r= 13 for GaAs. The referenced phase is determined by multiplying the RF propagation constant with the line length which is approximately 3600 μm, including 2500 μm interaction length and the input and output sections. It can be seen that the rate of change in phase with repect to frequency is higher for the capacitively loaded structures. As we calculate the RF phase velocity slowing factor, we consider only the section where the electrical signal interacts with the optical wave, which is 2500 μm long. Therefore, the electrical length of input and output sections should be subtracted from the measured phase delay. As an example, for the case of W=20μm, the measured phase delay is 195° at 15.27 GHz, and the subtracted result is 142°, whereas the phase delay is 121° for 2500 μm length reference line. Since the ratio of phase velocity is inversely proportional to the ratio of phase response, the velocity reduction is therefore found to be 0.85 and the effective index is then $\sqrt{7}/0.85$= 3.11. This proves that a slow-wave effect occurs in this capacitive-loaded electrode design. The measured bandwidth of the modulator with 2500 μm interation length for electrode widths W= 20 μm by extrapolation, shown in Figure 6, was obtained to be approximately 17 GHz, which is the highest bandwidth obtained in directional coupler modulators.

REFERENCES

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2. S. K. Koroky and R. C. Alferness, "Time and frequency-domain response of directional-coupler traveling-wave optical modulators," *J. Lightwave Technol.*, Vol. 1, pp. 244-251, 1983.

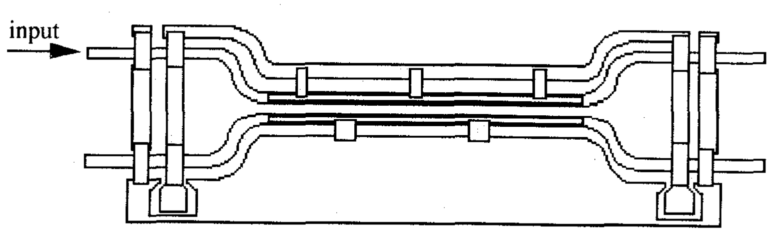

Figure 1 The optical modulator design with capacitive-loaded electrode structure

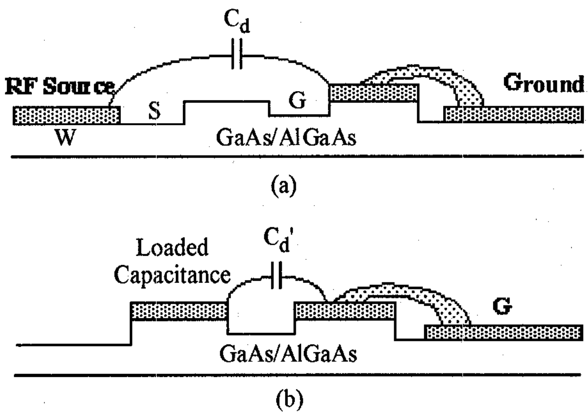

Figure 2 Cross section of capactive-loading electrode, (a) capacitance of signal electrode, (b) loading capacitance resulting from ridge electrodes.

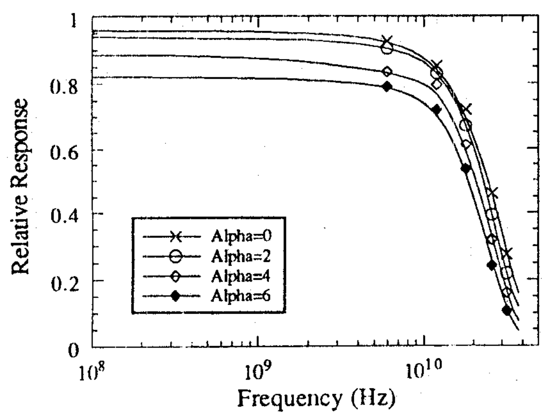

Figure 3 Small-signal relative response for several loss factors biased in the linear region of the transfer function for a modulator with 2500 μm coupling length and W= 6 μm and S= 20 μm.

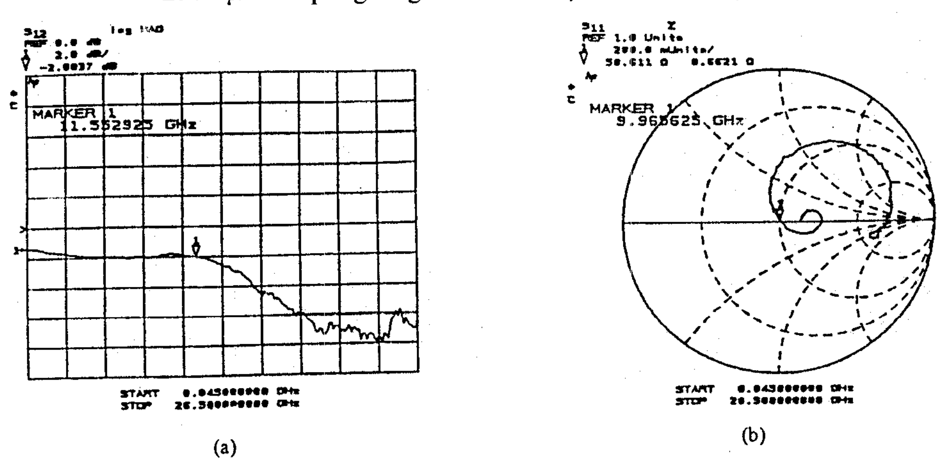

Figure 4 Typical RF response for capacitive-loading electrode with (a) less than 2dB insertion loss, and (b) impedance varied between 45½ and 55½ up to 11.5 GHz.

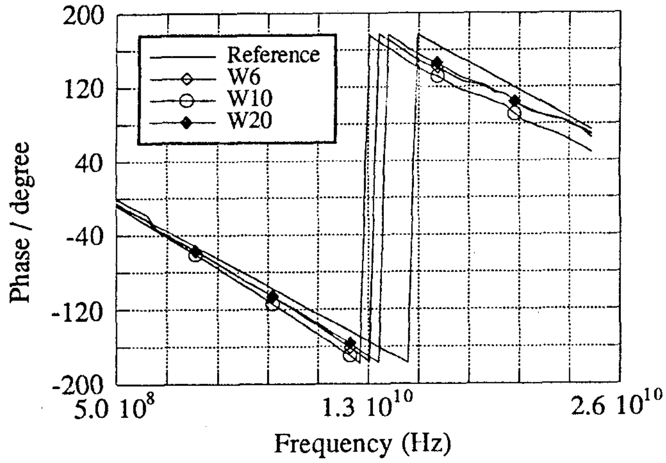

Figure 5 Measured phase response of capacitively loaded electrodes with W= 6μm, 10μm, and 20μm compared with the phase response of a uniform line.

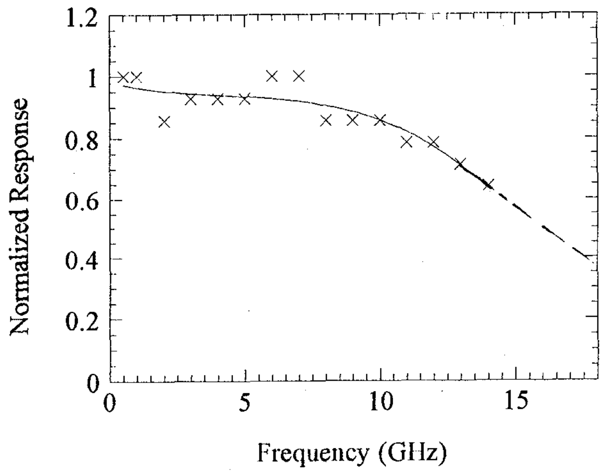

Figure 6 High speed response of capacitively loaded modulator with S=20 μm and W= 20 μm at 14 dBm RF power.

		C_0 (pF/m)	C_d (pF/m)	C_d' (pF/m)	N_{rf}	Z_0 (Ω)
W= 6 μm	S= 20 μm	30.7	123.6	110.5	2.76	39.3
	S= 10 μm	31.2	157.7	110.5	2.93	36.4
W=20 μm	S= 20 μm	35.8	164.2	110.5	2.77	33.6

Table 1 Calculated RF index and impedance for the optical modulators using capacitive-loading electrode structure