Technique for Velocity-Matched Traveling-Wave Electrooptic Modulator in AlGaAs/GaAs

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***Abstract*— A new design for a velocity-matched traveling-wave directional-coupler intensity modulator in AlGaAs/GaAs is proposed. The proposed structure ultilizes a thin coating of Ta_2O_5 (which has a high dielectric constant at microwave frequencies and a low refractive index at optical frequencies) on the top of the modulator/electrode structure in order to achieve velocity matching between the optical wave and microwave signal. The addition of the Ta_2O_5 film does not significantly affect the optical properties or voltage requirements of the modulator since the coating is thin (≈ 1000Å) and the refractive index at optical frequencies is low compared to that of AlGaAs/GaAs. The optical and RF characteristics of the proposed modulator are analyzed using the effective index and the finite difference methods. The optical bandwidth is calculated numerically taking into account both the anticipated velocity mismatches due to fabrication tolerances and the calculated frequency-depenent microwave losses. The predicted small-signal bandwidth, primarily limited by microwave losses, of a 3-mm-long direction coupler biased at a null point is greater than 45 GHz, and exceeds 100 GHz (~ 50 GHz electrical bandwidth) when biased in the linear region. This device is designed to operate at 830 nm with a maximum modulation voltage (full on/off modulation at low frequencies) of 5 V. The figure of merit of the proposed device is therefore at least 10 GHz/V when the electrical bandwidth of 50 GHz is used.**

I. Introduction

LARGE-BANDWIDTH optical-intensity modulators that can be driven with low RF input power are needed for many optical signal processing, communication, and computer technology applications. Conceptually, traveling-wave structures should provide extremely large bandwidths and have low power requirements. The bandwidth of most traveling-wave electrooptic modulators, however, is generally limited by a combination of the velocity mismatch between the RF modulating signal and the optical wave, microwave dispersion, and a frequency-dependent microwave loss due to the skin effect. In most III-V and $LiNbO_3$ modulators, it is predominatly the velocity mismatch that limits the 3 dB bandwidth to 20 GHz and less [1], [2].

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Recently, several designs for broadband electrooptic $LiNbO_3$ and III-V modulators have been reported. Most of these modulator designs involve velocity matching techniques for bandwidth enhancement. In $LiNbO_3$, the RF index is normally larger than the optical index, and therefore RF index is decreased by reducing capacitance or inductance to match the two velocities. The popular velocity matching techniques in this material are to use a dielectric layer between the electrode and substrate, and to increase the electrode thickness. Several groups have studied and demonstrated velocity matching using such techniques in $LiNbO_3$. Korotky used a quantitative technique to optimize several parameters of a traveling-wave Ti:$LiNbO_3$ Mach–Zehnder modulator including the SiO_2 buffer layer thickness for velocity matching [3]. Chung *et al.* also described a modeling procedure that optimizes the drive power requirement for a given bandwidth taking into account the velocity mismatch, electrode length, and microwave attenuation for a number of electrooptic $LiNbO_3$ channel waveguide modulators [4]. Parsons *et al.* [5], Wey *et al.* [6], and Seino *et al.* [7] experimentally demonstrated the improvement in bandwidth using similar velocity matching techniques in $LiNbO_3$ modulators. In contrast to the broadband traveling-wave $LiNbO_3$ modulators, an artificial velocity matching technique over limited bandpass has been widely used in $LiNbO_3$ modulators for ultrahigh-frequency applications that incorporates electrodes with phase-reversal [8]–[10].

In the III-V semiconductor materials, the RF index is smaller than the optical index, and therefore velocity is matched by slowing the RF wave. A number of groups have demonstrated bandwidths beyond 20 GHz in velocity-matched devices in semiconductors. In the literature, several definitions of bandwidth are used by different authors, which makes bandwidth and hence figure of merit comparisons rather inconsistent. In our calculations, we shall use the definition for the optical bandwidth based on a 3 dB reduction in intensity (-6 electrical dB). Walker *et al.* achieved a very high electrical bandwidth greater than 27 GHz using a traveling-wave GaAs Mach–Zehnder interferometer where capacitive loading was used in the slow-wave structure [11]. Wang *et al.* demonstrated an optical bandwidth greater than 20 GHz using a traveling-wave GaAs/AlGaAs polarization modulator [12]. An optical bandwidth of 44 GHz was predicted by Kim *et al.* [13] for a GaAs n^--i-n phase modulator in which an n^+ epitaxial layer is used for velocity matching. An actual version of this structure had a measured bandwidth of 26.5 GHz and a required modulation voltage of 35 V [14]. Nees *et al.* [15] experimentally achieved a 3-dB electrical bandwidth of 110 GHz in a GaAs phase modulator, using a thick GaAs superstrate which reduced the velocity mismatch and electrical dispersion in the device. This device had an extremely high modulation voltage of 288 V which limits its use in practical systems. For integrated amplitude/intensity modulation and switching, the traveling-wave phase-modulator structures must be incorporated in an interferometer or directional coupler. While III-V semiconductor devices offer better velocity matching compared to $LiNbO_3$ devices, due to the smaller difference between the optical and microwave index, polymer devices are naturally velocity matched and have been shown to yield bandwidth in excess of 40 GHz by Teng *et al.* [16].

In this paper, a velocity-matched low-optical-loss directional-coupler modulator (DCM) operating at 830 nm that provides a very high modulation bandwidth and requires a low drive voltage is proposed. In the proposed modulator, velocity matching is achieved by covering the modulator and its electrode structure with a thin coating of Ta_2O_5. The dielectric coating on the modulator increases the capacitance of the structure and thereby reduces the microwave phase velocity to match the optical wave velocity. Since the microwave dielectric constant is very high for Ta_2O_5 ($\epsilon_r \approx 27$), only a very thin coating is required for velocity matching. Furthermore, the optical refractive index of Ta_2O_5 (approximately 2.03 around 800 nm [17]) is small compared to those of the AlGaAs/GaAs layers used in the modulator. The Ta_2O_5 coating is therefore expected to have a negligible effect on the optical properties or required drive voltage of the coupler.

The optical and microwave characteristics of the proposed DCM modulator are analyzed using the effective index method (EIM) and the finite difference method (FDM). The optical characteristics and drive voltage requirements of the two-guide directional coupler is discussed in the next section. In Section III, the quasi-static microwave analysis used to calculate the RF phase velocity and RF loss is described. Velocity mismatches for the modulator are calculated for different coating thicknesses, and the required coating thickness for velocity matching is extracted from this calculation. The small signal 3 dB optical bandwidth of the modulator is also calculated in this section using a numerical technique which takes frequency-dependent microwave loss and velocity mismatch into account.

II. Optical Analysis of Directional Coupler Modulator

The proposed DCM is shown in Fig. 1. The two-guide directional coupler was designed using the effective index and finite difference methods to propagate only the lowest order even and odd TE optical modes of the structure. The coupler is differentially etched, as shown in Fig. 1, so that the etch depth in the gap region is smaller than that in the outside regions. The differentially etched coupler structure offers several advantages. Coupling is increased because of the increased evanescent fields in the gap, while the optical field is sharply reduced in the outer regions because of the larger etch depth. The reduction of field in the outside regions reduces the scattering loss because of sidewall roughness and minimizes the effects of the ground electrodes on the optical field. The ability to adjust the differential etch depth also permits more flexibility in choosing guide widths and coupling lengths while allowing propagation of only the lowest order modes. The coupler is designed to be symmetric about the vertical direction so that high modulation efficiency can be achieved [18].

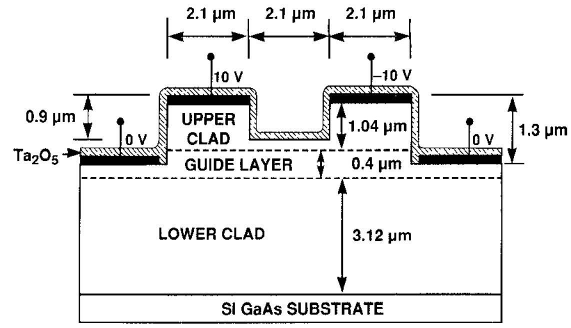

Fig. 1. The two-guided differentially etched directional-coupler modulator (DCM) structure used in the optical and microwave analyses.

For low-loss operation at 830 nm, the Al mole fractions of the guiding and the cladding layers were chosen to be 0.20 and 0.40, respectively. All of the layers are assumed to be undoped. The resultant large refractive index difference between the guiding and cladding layers, ≈ 0.12, gives strong mode confinement in the vertical direction. For convenience, the lateral and vertical dimensions of the coupler were chosen to be integer multiples of the x and y grid units used in the finite-difference RF calculations. The final dimensions chosen for the coupler are indicated in Fig. 1: rib width = 2.1 μm, gap = 2.1 μm, etch depth (gap region) = 0.91 μm, etch depth (outer region) = 1.3 μm, upper clad thickness = 1.04 μm, and the guide layer thickness = 0.39 μm. The propagation constants of the even and odd optical modes of this structure were calculated using the effective index method to determine the coupling length. Effects of the dielectric coating were included in the calculation. While the effective index method gives the modal propagation constants within very good accuracy when compared to those obtained from the full-vectorial finite element method, sufficiently accurate field distributions are difficult to obtain using the effective index method. Therefore, the semivectorial finite difference method is used to obtain the two-dimensional optical field distributions of the even and odd modes to calculate the overlap between the optical and microwave fields needed to determine the required modulation voltage. The even and odd field distributions are shown in Fig. 2(a) and (b). Because of the large optical confinement in the vertical direction, the substrate and electrodes on top of the ribs have a negligible effect on the optical modes. The ground electrodes also have little effect since the optical field is greatly reduced in the outer regions as discussed previously. Since the dielectric coatings considered have low refractive indices at optical frequencies, substantial changes in the coating thickness effect the effective indices of the optical modes only in the fifth decimal place. The coupling length L_c for this device is

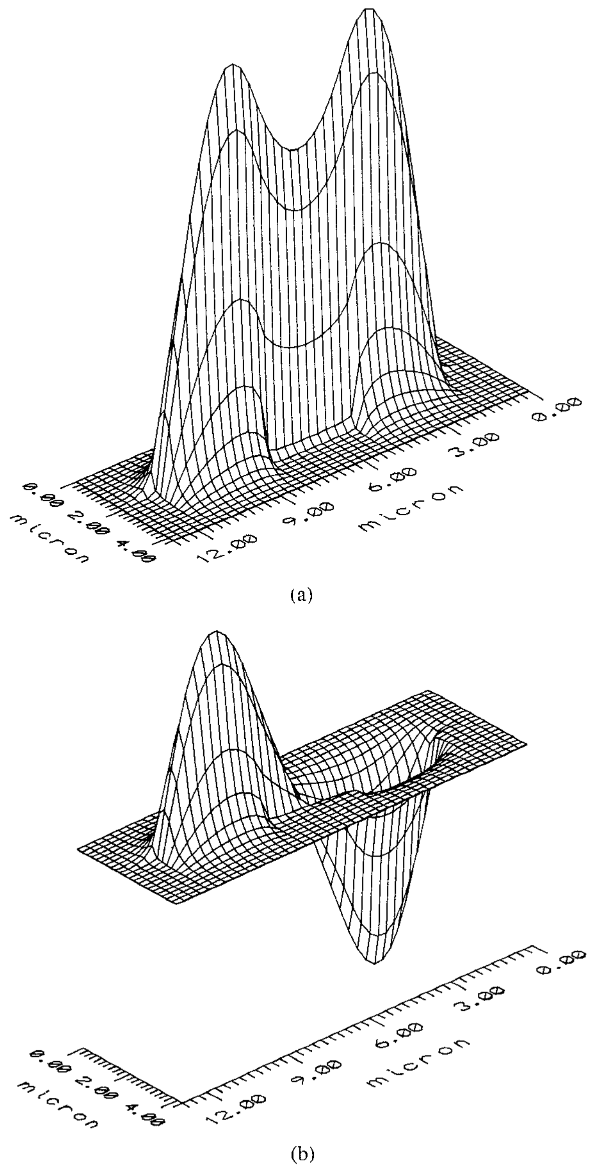

Fig. 2 Optical field distributions for the DCM structure shown in Fig. 1 calculated using the semivectorial finite difference method: (a) fundamental even TE mode, and (b) fundamental odd TE mode profiles.

approximately 1 mm and is relatively independent of the dielectric coating and electrode structure. For the traveling-wave DCM, the device length l is chosen to be 3 mm $(3L_c)$ to reduce drive voltage while maintaining high modulation efficiency [19].

When voltages are applied on the top electrodes as indicated in Fig. 1, the optical modes are perturbed because of an increase in effective index in one rib and a decrease in the other, and the difference in phase velocity between them increases. The changes in effective index with applied voltage were calculated by the usual perturbation technique [20] using the optical and electric field distributions and an r_{41} electrooptic coefficient of 1.5×10^{-10} cm/V. From these calculations, the maximum modulation voltage, i.e., the voltage required to switch the output of the coupler from the coupled guide to the input guide, is calculated to be about 5 V.

For velocity matching, the lightwave velocity is taken as the average velocity of the even and odd optical modes (which differ by less than 0.1%) and is assumed to be independent of dielectric coating thickness.

III. Microwave Analysis of Directional Coupler Modulator

The microwave propagation characteristics for the structure shown in Fig. 1 are calculated using a quasi-static finite difference technique. Since the separation between the ground electrodes is much smaller than the wavelength of the RF modulating signal (about three orders of magnitude smaller at 20 GHz), the quasi-static analysis is justified. In the absence of a dielectric coating, the RF phase velocity is faster than the lightwave velocity by approximately 28%. This large mismatch in the velocities is significantly reduced using the proposed dielectric-loading velocity-matching technique. Two dielectric materials—Al_2O_3 (alumina) and Ta_2O_5—were investigated for the velocity-matching analysis. The values of the microwave dielectric constants of Al_2O_3 and Ta_2O_5 used are 10 and 27, respectively. These dielectric films may be deposited on GaAs substrates by RF triode sputtering to obtain reasonable stoichiometry and thickness precision [21].

A 60×60 array with a rectangular grid size of $0.19\,\mu\text{m} \times 0.13\,\mu\text{m}$ is used in the FDM microwave analysis. The dielectric constant array $\varepsilon_r(x, y)$ is set up using a value of 13 for both the AlGaAs layers and the GaAs substrate. The thickness of the electrodes is taken to be one y-grid unit (0.13 μm), and their conductivity is taken to be that of gold. The electrodes on top of the coupler are assumed to be the same width of the ribs, while the ground electrodes are assumed to be 3.04 μm wide (extending to the boundary of the mesh) and located 0.57 μm from the edge of the rib.

The electrodes on top of the coupler are two coupled transmission lines that run along the entire length of the device. The two ground electrodes, placed on either side of the coupler, also run along the device length. The high-frequency modulating signal is applied on one end of each transmission line, and the other end is terminated in its characteristic impedance. The electric potentials on the electrodes are specified as shown in Fig. 1 to excite the odd microwave mode. Exciting the odd mode allows the coupler to operate in a push–pull mode which reduces the modulation voltage by a factor of two. For the quasi-static finite difference analysis, the potentials on the two top electrodes were kept constant at +10 and -10 V. Since all the AlGaAs layers are assumed to be undoped and hence fully depleted, the structure will have negligible fixed charge. Therefore, neglecting charge in the semiconductor layers, Laplace's equation is solved using the relaxation technique to obtain the odd mode potential distribution which satisfies the appropriate air, metal, and dielectric boundary conditions. The odd mode electric potential distribution of the DCM obtained from the solution of Laplace's equation is shown in Fig. 3.

The electric field $\boldsymbol{E}$ and the displacement vector, $\boldsymbol{D} = \varepsilon \boldsymbol{E}$, are then calculated from the odd mode potential distribution. The total charge Q on each electrode is calculated by integrating the normal component of $\boldsymbol{D}$ over the electrode

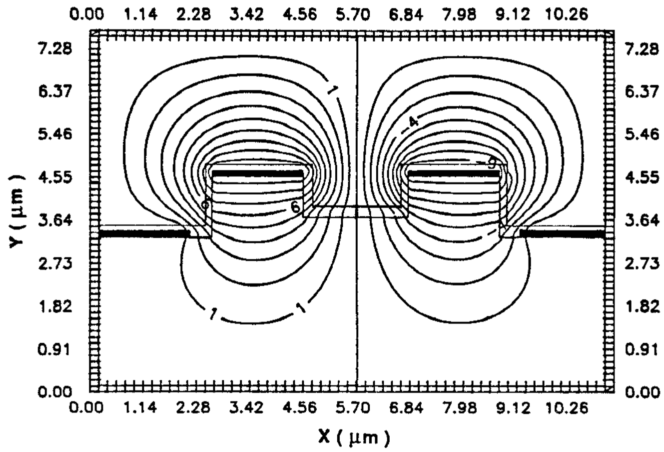

Fig. 3. The odd mode electric potential distribution for the DCM structure shown in Fig. 1.

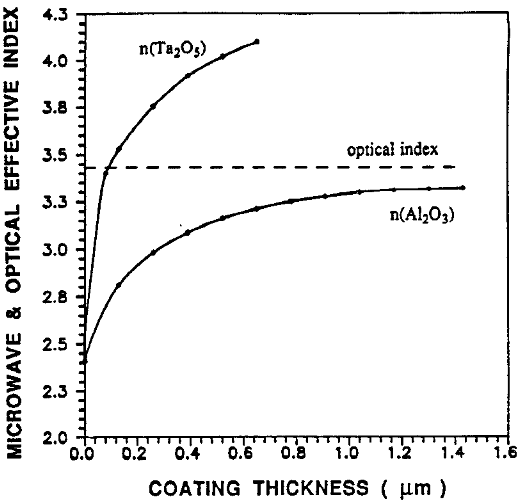

Fig. 4. Microwave and optical effective indices of the directional coupler device as a function of Al_2O_3 and Ta_2O_5 coating thicknesses.

surface

$$\int (\boldsymbol{D} \cdot \boldsymbol{n}) \cdot \boldsymbol{dS} = Q. \tag{1}$$

The capacitance for the odd mode is then calculated from the charges and voltages on the electrodes.

The microwave odd mode velocity is determined from the odd mode capacitance C of the modulator structure, and the odd mode capacitance C_o of the identically biased electrode structure in the absence of all dielectrics. The RF phase velocity for the odd mode is given by

$$v_{\text{RF}} = c_o \sqrt{\frac{C_o}{C}} \tag{2}$$

where c_o is the speed of light in vacuum. The effective microwave index is then given by

$$n_\mu = \sqrt{\frac{C}{C_o}}. \tag{3}$$

The microwave effective indices for the DCM structure are calculated for different coating thicknesses of Al_2O_3 and Ta_2O_5. Results of these calculations are plotted versus coating thickness in Fig. 4. The effective optical index is also plotted on this figure. As indicated, perfect velocity matching between the RF wave and the lightwave can be achieved with a Ta_2O_5 coating of about 1000 Å. However, it may be difficult to reduce the velocity mismatch below 7%, even with a thick Al_2O_3 coating.

The microwave loss is also calculated for the DCM structure using the quasi-static Green's function approach [22]. The conductor and dielectric losses for the metal electrodes are calculated to determine the total RF loss. For each electrode, the conductor loss α_c is evaluated using the equation

$$\alpha_c = \frac{R_s}{2Z_o I^2} \int_o^w J^2 \, dl, \tag{4}$$

where J is the strip longitudinal current density, Z_o is the characteristic impedance of the DCM, I is the total strip current, R_s is the electrode sheet resistivity in $\Omega/\square$, and w is the width of each electrode. The characteristic impedence Z_o of the proposed modulator is approximately 120 Ω, which is calculated from the capacitances C and C_o. It is possible to design a velocity-matched structure with a characteristic impedence of 50 Ω by appropriately designing the coupled transmission lines and the ground planes to yield the proper combination of C and C_o. At frequencies at which the skin depth is smaller than the electrode thickness, R_s and therefore α_c are proportional to the square root of frequency. At lower frequencies, the sheet resistance and α_c are essentially independent of frequency. In order to keep drive power requirements reasonable, the thickness of the electrodes should be at least twice the skin depth at the maximum frequency of interest. For a desired bandwidth of 40 GHz and gold electrodes, the electrodes should be at least 0.8 μm thick. This thickness is substantially greater than that used in above finite-difference calculation. Calculations using thicker electrodes (up to 1 μm) showed that most parameters, including Ta_2O_5 thickness required for velocity matching, are not significantly affected by the thickness of the electrodes.

The dielectric loss α_d is evaluated from

$$\alpha_d = \frac{q\varepsilon_r \tan\delta}{\sqrt{\varepsilon_{\text{eff}}}\lambda_o}, \tag{5}$$

where ε_r is the substrate dielectric constant ($\varepsilon_r = 13.0$), $\varepsilon_{r\text{eff}}$ is the effective microwave dielectric constant of the DCM, λ_o is the RF free space wavelength, $\tan\delta$ is loss tangent approximated by $\sigma/\omega\varepsilon_r\varepsilon_o$, and q is the coupler filling factor given by $(\varepsilon_{r\text{eff}} - 1)/(\varepsilon_r - 1)$. Equation (5) is a plane wave approximation which is valid at microwave frequencies. In the high-frequency regime, the total RF loss increases as the square root of the frequency. The total high-frequency microwave loss calculated for the proposed DCM with a 1000 Å of Ta_2O_5 coating is approximately 3.20 dB/(cm $\sqrt{\text{GHz}}$). This frequency-dependent microwave loss may be an overestimation of the loss in an actual device since the widths of the ground electrodes considered in the analysis are fairly small.

The small-signal 3 dB bandwidth of the proposed DCM is calculated taking velocity mismatch and frequency-dependent microwave loss into account. The response of a directional coupler to an electrical signal depends on the detail of the phase mismatch $\Delta\beta$ between the two guides at each point along the device length, rather than the integrated value of $\Delta\beta$ over the entire length of the coupler [23]. Therefore, it is difficult to obtain an analytic expression for the frequency response of a directional coupler in the presence of frequency-dependent microwave loss. The frequency response of the coupler is therefore determined numerically by dividing the coupler into small sections and determining the voltage that affects the light in each section for each discrete frequency and loss. The transfer matrix element of each section is the calculated, and the overall transfer function is obtained by matrix multiplication [24].

The small-signal frequency response of the DCM is determined for two different dc electrical bias conditions. The first case is for the device biased at a null point, i.e., where the optical power out is a maximum or a minimum. This voltage is either zero, where all the power at the output is in the coupled guide, or V_m, the voltage at which all the power at the output is in the input guide. In this paper, V_m is also referred to as the maximum modulation voltage. The second case is for the device biased in a region where the optical output intensity is a linear function of the applied voltage. The 3 dB bandwidth for the second bias condition is considerably larger than that of the first and is more relevant to small-signal amplitude modulation of the optical intensity. It is also the bandwidth that should be used when making comparisons to the other optical bandwidths for modulator devices in the literature.

When the thickness of the Ta_2O_5 coating is controlled to within 300 Å, the velocity mismatch falls in the range of $\pm 2\%$. Using a 2% velocity mismatch for our coupler, the small-signal frequency response is calculated for the two bias conditions. The small-signal relative responses for the DCM biased at a null point and in the linear region of the transfer function for different values of frequency-dependent microwave loss are plotted versus frequency in Fig. 5(a) and (b), respectively. The small-signal 3-dB optical bandwidth for a frequency-dependent microwave loss of 3.20 dB/(cm $\sqrt{\text{GHz}}$) exceeds 45 GHz when the DCM is biased at the null point, and 100 GHz when it is biased in the linear region. For velocity mismatch less than or equal to 4%, the bandwidth is determined almost entirely by the microwave loss. Microwave loss of less than 1 dB/(cm $\sqrt{\text{GHz}}$) would be required before a velocity mismatch lower than 4% affects the bandwidth. As discussed above, these bandwidth calculations assume thick electrodes. For thin electrodes, i.e., those thinner than twice the skin depth at the cutoff frequency, the bandwidth of the device will actually be greater, but at the expense of increased drive power requirements and a deterioration in on/off switching performance.

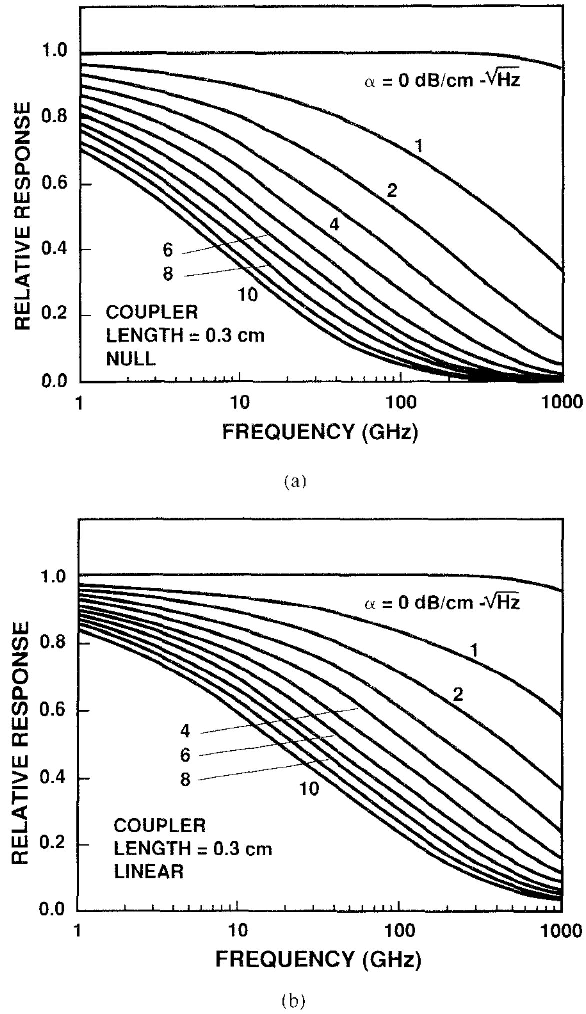

Fig. 5. The small-signal relative response of the DCM for different microwave losses in dB/(cm $\sqrt{\text{GHz}}$) using 2% velocity mismatch: (a) dc biased at a null point, and (b) dc biased in the linear region.

IV. Summary

A new velocity-matched traveling-wave directional-coupler intensity modulator in AlGaAs/GaAs has been proposed. The velocity-matching technique proposed employs dielectric loading of the microwave transmission line by means of a thin coating of Ta_2O_5. Tantalum pentaoxide is ideally suited for this purpose since it has a very high microwave dielectric constant which enables it to match the optical and microwave effective indices with only a thin coating. Furthermore, the optical index of $Ta_2O_5 (n \approx 2.03)$ is small compared to the refractive index of AlGaAs ($n \approx 3.43$) at 830-nm wavelength, and therefore the coating has only a negligible effect on the optical properties of the coupler. The directional-coupler modulator structure has been modeled using the effective index and finite difference methods. Microwave loss and velocity mismatch have been calculated using the quasi-static approximation. The small-signal 3 dB bandwidths for two electrical bias conditions have been calculated numerically taking frequency-dependent microwave loss and velocity mismatch into account. The calculated bandwidth of the coupler exceeds 45 GHz when biased at a null point and 100 GHz when biased in the linear region. The electrical bandwidth exceeds 50 GHz when biased in the linear region, which gives a figure of merit of 10 GHz/V using the calculated modulation voltage of 5 V for the 3-mm-long device. This figure of merit for the proposed DCM is greater than the figures of merit predicted for other III-V modulators.

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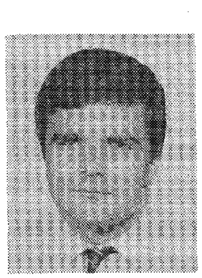

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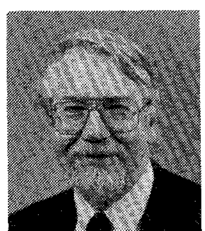

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