Velocity-Matched Electrodes for Compound Semiconductor Traveling-Wave Electrooptic Modulators: Experimental Results

Nicolas A. F. Jaeger, Farnoosh Rahmatian, Hiroshi Kato, Robert James, Ezio Berolo, and Zachary K. F. Lee

Abstract— **Coplanar strips, capacitively loaded with fins and pads and capable of achieving the microwave/optical wave velocity-match condition in GaAs- and InP-based electrooptic modulators, are described. Measurements on electrodes, fabricated to have dimensions appropriate for use in conventional, Mach-Zehnder-type modulators in the 5–40 GHz range, show that these electrode structures can be made to obtain the desired match between the microwave effective index and the effective indexes of AlGaAs and InGaAsP optical waveguides, while having loss coefficients ~0.7 Np/cm at 40 GHz.**

I. Introduction

TRAVELING-WAVE (TW), coplanar electrodes can be used in integrated-optic modulators to obtain wider bandwidths than those that can be obtained by using lumped electrodes [1]. They can be used in modulators fabricated in oxygen octahedra ferroelectrics, such as lithium niobate [2]–[5], and in modulators fabricated in compound semiconductors, such as GaAs- and InP-based materials [6]–[9]. In the case of lithium niobate, the effective index of the modulated optical wave, n_{eff}, is typically less than the effective index of the modulating microwave, n_μ, whereas for GaAs- and InP-based materials typically $n_{eff} > n_\mu$. In this letter, the results of measurements on slow-wave (SW) electrodes, designed to match the effective indexes of optical waves and microwaves in AlGaAs/GaAs or InGaAsP/InP, are presented. The dimensions of the electrodes discussed have been chosen to be appropriate for use in conventional, Mach-Zehnder-type modulators.

It is well known [1] that both the phase-velocity mismatch between the optical wave and the microwave and the frequency-dependent attenuation of the microwave along the length of the modulator are limiting factors with regard to the bandwidths that such modulators can attain. Devices having optical 3-dB bandwidths of tens of GHz have been demonstrated [3]–[9]. The results presented here indicate that it should be possible to use the electrode structures discussed in modulators designed for optical 3-dB bandwidths >100 GHz.

For coplanar electrodes the value of n_μ for GaAs is close to that for InP, ~2.6. Also, optical waveguides can be fabricated in both the AlGaAs and InGaAsP systems with n_{eff}'s in the range 3.2–3.3. To demonstrate the principle that the electrode structures are capable of obtaining the velocity-match condition, measurements on only GaAs substrates were performed. For modulators using TW-CPS (traveling-wave coplanar strips) and AlGaAs optical waveguides fabricated on a thick SI-GaAs (semi-insulating gallium arsenide) substrate, the microwave effective index is, as mentioned above, about 2.6 whereas the optical wave effective index is a function of the mole fraction, x, and the free-space wavelength λ_o [10]; when $\lambda_o = 1.3\,\mu$m the refractive index of $Al_xGa_{1-x}As$ varies from 3.4 for $x = 0$–3.2 for $x = 0.4$. Specifically, we have made the effective index for a graded-index $Al_{0.35}Ga_{0.65}As \rightarrow Al_{0.30}Ga_{0.70}As$ optical waveguide, $n_{eff} \approx 3.25$, a target value for n_μ.

II. Slow-Wave Electrodes

The electrodes studied consist of TW-CPS periodically loaded with capacitive elements [11], [12]. These capacitive elements consist of narrow fins and pads arranged between the electrodes (Fig. 1). The effect of these narrow fins and pads is that the ratio of the line capacitance to the line inductance is increased for such a "loaded" electrode as compared to an "un-loaded" electrode having the same CPS (coplanar strips) dimensions. The loading results in a higher effective index for the microwave, i.e., producing SW-CPS (slow-wave coplanar strips), and a lower characteristic impedance for the transmission line. The amount of slowing depends on numerous parameters; nonetheless, it is possible to achieve an n_μ nearly equal to the effective index of the optical mode guided by the AlGaAs waveguide (typically a rib or ridge type waveguide). Since the line impedance, Z_o, is also a function of capacitance, $Z_o \propto 1/\sqrt{C}$, and the loss coefficient, $\alpha(f)$, is a function of the CPS dimensions, various electrodes having different geometries were fabricated and n_μ, Z_o, and α were measured.

The electrodes reported on here were fabricated by lift-off photolithography. They consisted of SW-CPS surface deposited on SI-GaAs substrates. Two types of electrodes

Manuscript received August 1, 1995. This work was supported by the Advanced Systems Institute of British Columbia and the Natural Sciences and Engineering Research Council of Canada.

N. A. F. Jaeger, F. Rahmatian, and H. Kato are with the Department of Electrical Engineering, University of British Columbia, Vancouver, BC V6T 1Z4 Canada.

R. James and E. Berolo are with the Communication Research Center, Ottawa, ON, K2H 8S2 Canada.

Z. K. F. Lee is with the Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

Publisher Item Identifier S 1051-8207(96)00916-6.

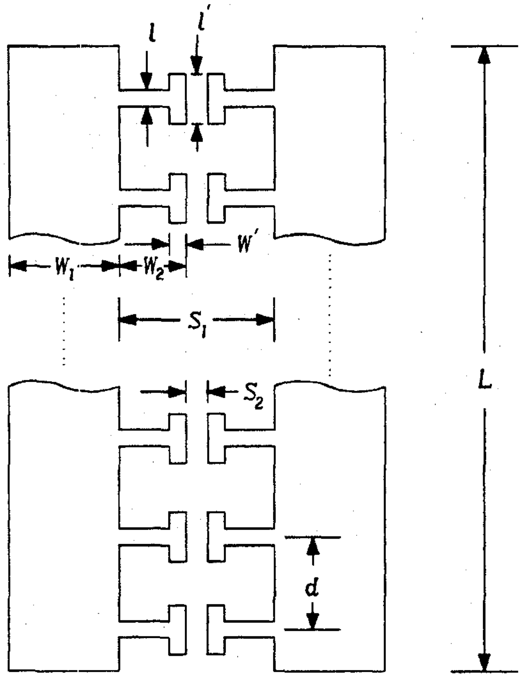

Fig. 1. Plan view of slow-wave coplanar strip electrodes.

were made: one set consisted of aluminum electrodes laid down directly on the surface of the substrate (Sample 1), and the other had a 0.4 μm SiO_2, sputter-deposited, buffer layer between the aluminum electrodes and the substrate (Sample 2). The electrodes were 1 μm thick; the other dimensions varied from electrode to electrode.

III. Experimental Results and Discussion

The scattering parameters, s_{11}, s_{21}, s_{12}, and s_{22}, were measured from 100 MHz–40 GHz in 100-MHz steps. The electrodes were terminated with a 50-Ω load. The values of Z_o, α, and n_μ were calculated from the scattering parameters (see [13] and [14]).

The electrodes on Sample 1 were designed to have a characteristic impedance of 50 Ω and microwave effective indexes between 3.0 and 3.4. The design was done using conventional mathematical models [11], [15] that, either implicitly or explicitly, assumed that the electrodes would be half-buried in the SI-GaAs substrate. One effect of this is that since the electrodes fabricated were surface deposited and t, the electrode thickness, was on the order of S_2, the gap between the pads (see Fig. 1), the capacitive effects of the fins and the pads were lower than the calculated values. Since $Z_o \propto 1/\sqrt{C}$ and $n_\mu \propto \sqrt{C}$, the measured Z_o was expected to be somewhat larger than 50 Ω and the measured n_μ was expected to be lower than the effective index for a corresponding half-buried SW-CPS, $n_{\mu\text{-}hb}$ (also see [15]). For this reason, and to allow for fabrication tolerances, devices were designed for $n_{\mu\text{-}hb} =$ 3.0–3.4, covering the range around 3.25. The electrodes on Sample 2 had the same dimensions as the ones on Sample 1, with the difference being the inclusion of the SiO_2 layer. Since the dielectric constant of SiO_2 is less than that of GaAs, the electrodes on Sample 2 were expected to have higher Z_o's and lower n_μ's than those of the corresponding electrodes on Sample 1.

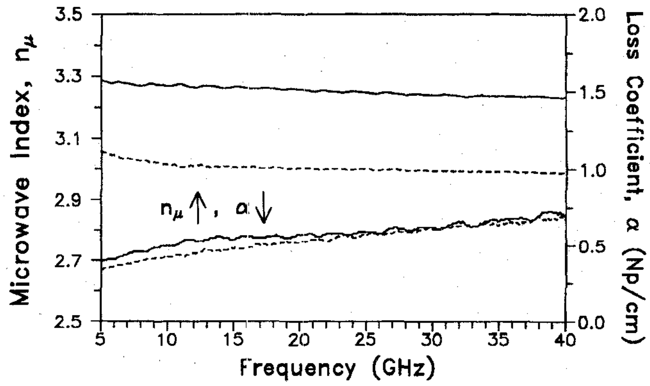

Fig. 2. Microwave effective indexes (top two lines) and loss coefficients (bottom two lines) as functions of frequency for two electrodes of identical dimensions on Sample 1 (solid lines, no SiO_2) and Sample 2 (dashed-lines, with SiO_2). The design value $n_{\mu\text{-}hb} = 3.4$ for the electrode on Sample 1. Electrode dimensions are: $L = 22$ mm, $W_1 = 29.5\,\mu\text{m}, W_2 = 7.5\,\mu\text{m}, W' = 3.5\,\mu\text{m}, l = 1.5\,\mu\text{m}, l' = 6\,\mu\text{m}, d = 12.5\,\mu\text{m}, S_2 = 2\,\mu\text{m}$, and $t = 1\,\mu\text{m}$.

Fig. 2 shows n_μ and α for two identical electrodes on Samples 1 and 2. Since we are mostly interested in the higher frequency responses of the electrodes, the plots are done for the 5–40 GHz range. At frequencies lower than 5 GHz, the velocity-mismatch being discussed here is not an issue.

There were five pairs of electrodes, i.e., five electrodes from Sample 1 and the corresponding ones from Sample 2, on these samples for which the measurements were compared. To show the spread of these parameters, the standard deviations for the reported parameters are given in parentheses. On average, the change in the microwave effective index, $\Delta n_\mu \equiv n_\mu - 2.6$, was 81% ($\sigma_n = 4.7\%$) of the original design value, $\Delta n_{\mu-hb} \equiv n_{\mu-hb} - 2.6$, for the electrodes on Sample 1. Also, Δn_μ for an electrode fabricated on Sample 2 was about half (41–52%) of that of the corresponding electrode on Sample 1. Z_o was, on average, about 61 Ω ($\sigma_Z = 2.8\,\Omega$) for electrodes on Sample 1 and 65 Ω ($\sigma_Z = 5\,\Omega$) for electrodes on Sample 2. In general, the closer the measured Δn_μ was to the design value, the closer Z_o was to 50 Ω, and, as expected, all measured values of Δn_μ were less than their corresponding design values and all values of Z_o were greater than 50 Ω.

In order to lower the characteristic impedance of CPS the electrodes should be widened, i.e., W_1 should be increased. Widening the electrodes should have the additional effect of reducing the electrode losses [16].

For the structures reported on here, the measured electrode losses were small: the median α for the electrodes on Sample 1 was 0.69 Np/cm (the minimum value was 0.47 Np/cm) at 40 GHz, and the median α for the electrodes on Sample 2 was also 0.69 Np/cm (the minimum value being 0.45 Np/cm). In the range of 5–40 GHz, where the electrode thickness, t, is between one and three times the skin depth, δ, for aluminum (see for example [16]), we used the expression $\alpha(f) = \alpha_o\sqrt{f} + K_o$ to model our electrode loss as a function of frequency, f, where α_o and K_o are determined by fitting to the measured data. At frequencies higher than 40 GHz, where $t \gtrsim 3\delta$, the loss is modeled by the expression $\alpha(f) = a_o\sqrt{f} + b_o f$, where the average value of the loss at about 40 GHz is used to find a_o, using $b_o = 4.6 \times 10^{-4}$ Np/cm/GHz ($b_o f$ accounts for the dielectric loss of GaAs, see for example [16]). Here, for clarity, we define the optical 3-dB bandwidth of a TW electrooptic modulator as $\Delta f \equiv f_1 - f_o$, where f_1 is the frequency at which the electrooptically induced phase change for a particular mode at the modulator's output is reduced to half of that induced at f_o, a lower frequency (here $f_o = 5$ GHz), for the same magnitude of input voltage applied to the electrodes at both f_o and f_1. The magnitude of the voltage on the electrode will be a function of the distance x along the electrode, $V(x) = V_i e^{-\alpha x}$, where V_i is the magnitude of the voltage at the input of the electrode, and α is the loss (in Np/unit length). Using the above models, an α_o of 0.07 Np/cm/$\sqrt{\text{GHz}}$, a $K_o = 0.19$ Np/cm, and an $a_o = 0.11$ Np/cm/$\sqrt{\text{GHz}}$ (all being median values for our GaAs measurements) would allow for a Δf of ~120 GHz for a 2-cm-long electrode if the velocity-match condition is achieved.

IV. Summary

Slow-wave coplanar electrodes, consisting of CPS periodically loaded with capacitive fins and pads, were fabricated and tested. Characteristic impedances of the electrodes are larger than 50 Ω; nevertheless, they can be easily adjusted in future work by choosing CPS with larger strip widths. We obtained electrodes in which the microwave/optical wave velocity-matched condition is well met for frequencies up to 40 GHz. Also, the electrodes fabricated were low-loss. Such electrodes should be suitable for use in very high speed (~100 GHz) electrooptic modulators.

References

[1] T. Tamir, Ed., *Guided-Wave Optoelectronics*. Berlın Heidelberg: Springer-Verlag, 1988, pp. 159–162.
[2] H. Chung, W. S. C. Chang, and E. L. Adler, "Modeling and optimization of traveling-wave $LiNbO_3$ interferometric modulators," *IEEE J. Quantum Electron.*, vol. 27, no. 3, pp. 608–617, 1991.
[3] M. Rangaraj, T. Hosoi, and M. Kondo, "A wide-band Ti : $LiNbO_3$ optical modulator with conventional coplanar waveguide type electrode," *IEEE Photon. Technol. Lett.*, vol. 4, no. 9, pp. 1020–1022, 1992.
[4] D. W. Dolfi, M. Nazarathy, and R. L. Jungerman, "40 GHz electro-optic modulator with 7.5 V drive voltage," *Electron. Lett.*, vol. 24, no. 9, pp. 528–529, Apr. 1988.
[5] K. Noguchi, O. Mitomi, K. Kawano, and M. Yanajibashi, "Highly efficient 40 GHz bandwidth Ti:LiNbO3 optical modulator employing ridge structure," *IEEE Photon. Technol. Lett.*, vol. 5, no. 1, pp. 52–54, 1993.
[6] R. G. Walker, "High-speed III-V semiconductor intensity modulators," *IEEE J. Quantum Electron.*, vol. 27, no. 3, pp. 654–667, 1991.
[7] J. Nees, S. Williamson, and G. Mourou, "100 GHz traveling-wave electro-optic phase modulator," *Appl. Phys. Lett.*, vol. 54, pp. 1962–1964, 1989.
[8] S. Y. Wang and S. H. Lin, "High-speed III-V electrooptic waveguide modulators at $\lambda = 1.3\,\mu\text{m}$," *J. Lightwave Technol.*, vol. 6, no. 6, pp. 758–771, 1988.
[9] M. N. Khan, A. Gopinath, J. P. G. Bristow, and J. P. Donnelly, "Technique for velocity-matched traveling-wave electrooptic modulator in AlGaAs/GaAs" *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 2, pp. 244–249, 1993.
[10] T. Tamir, Ed., *Guided-Wave Optoelectronics*. Berlin, Heidelberg: Springer-Verlag, 1988, pp. 320–322.
[11] N. A. F. Jaeger and Z. K. F. Lee, "Slow-wave electrode for use in compound semiconductor electrooptic modulators," *IEEE J. Quantum Electron.*, vol. 28, no. 8, pp. 1778–1784, 1992.
[12] Z. K. F. Lee and N. A. F. Jaeger, "Electrode structures for microwave to optical wave velocity-match in III-V semiconductor electro-optic modulators," in *CLEO 92*, Anaheim, CA, May 1992, paper CThS5, pp. 554–555.
[13] R. Spickermann and N. Dagli, "Experimental analysis of millimeter wave coplanar waveguide slow wave structures on GaAs," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 10, pp. 1918–1924, 1994.
[14] R. E. Collin, *Foundation for Microwave Engineering*, 2nd ed. New York: McGraw-Hill, 1992, pp. 551–557.
[15] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*. Norwood, MA: Artech House, 1979, pp. 260–280.
[16] R. K. Hoffman. *Handbook of Microwave Integrated Circuits*. Norwood, MA: Artech House, 1987.