2

SAND93-1590 C
64-940142-1

**High-performance GaAs/AlGaAs optical phase modulators
for microwave/photonic integrated circuits**

V. M. Hietala, S. H. Kravitz, M. G. Armendariz, G. A. Vawter, and R. F. Carson

Sandia National Laboratories, Albuquerque, NM 87185-0603

R. E. Leibenguth

AT&T Bell Laboratories, Breinigsville, PA 18031

ABSTRACT

High-speed high-performance optical phase modulators are being developed for use in a coherent Photonic Integrated Circuit (PIC) technology. These phase modulators are the critical component of a PIC program at Sandia National Laboratories targeted for microwave/millimeter-wave signal processing and control including phased-array antenna control. The primary design goals for these modulators are amenability for integration into PICs, high "figure of merit" (FOM -- phase shift per unit length-voltage), and large bandwidths allowing for operation at millimeter wave frequencies. Depletion-edge-translation optical phase modulators (GaAs/AlGaAs based) have been selected as the device technology of choice due to their high FOM ($>60^\circ/\text{V}\cdot\text{mm}$ @ $1.3\ \mu\text{m}$). These modulators unfortunately suffer from a large terminal capacitance which greatly limits speed. To overcome this problem, a distributed electrode design based on the use of slow-wave coplanar strips has been developed. Device design and measurements are presented in this paper.

2. MOTIVATION

High performance optical phase modulators for photonic integrated circuit (PIC) applications must not only be high-speed but also physically small. This can be appreciated by inspecting the symbolic layout of COMPASS shown in Figure 1. COMPASS (Coherent Optical Monolithic Phased Array Steering System) is an internal program at Sandia which drives many of our PIC efforts. This proposed system, which has been discussed in detail elsewhere,¹ is an ideal example of the type of complexity anticipated in PIC's based entirely on optical phase shifters.² COMPASS has several optical phase modulators in every signal path from input to output. Specifically, in the optical frequency translator portion of the circuit alone, the total peak phase shift required is 8.4 radians or approximately 480° of phase shift. Assuming a reasonable bias level of 5 V, circuit size can easily become prohibitively large. If a given phase modulator had a meager FOM of $4.5^\circ/\text{V}\cdot\text{mm}$ (as with some high-speed optical phase modulators³), the optical frequency translator alone would need be 2.1 cm in length -- a length not realistic for a semiconductor circuit. Using instead a modulator with a FOM of $60^\circ/\text{V}\cdot\text{mm}$ as typical of the modulators discussed here, the total length would be only 0.16 cm. In practice significant additional lengths might be required for the necessary power splitters and combiners for the circuit, but total circuit length will still be dominated by phase shifter length.

This example shows that a high FOM phase modulator is essential for producing complex PICs. Certainly, a high FOM will have a very significant impact on device yield. To obtain this necessary high

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

878

Fig. 1. Symbolic layout of COMPASS. a). Optical frequency translator. b). Output power dividers and phase control.

FOM, depletion-edge-translation optical phase modulators (GaAs/AlGaAs) have been selected as the device technology of choice for our PIC effort.

3. DEPLETION-EDGE-TRANSLATION PHASE MODULATOR

Figure 2 shows details of the depletion-edge-translation phase modulator. This and similar designs have been discussed in detail in the literature.⁴ Based on the basic design outlined in Fig. 2, we have observed phase shifts as large as $64^\circ/\text{V}\cdot\text{mm}$ at $1.3\mu\text{m}$ with optical losses around 4 dB/cm. Fabrication details of this structure can be found in a separate paper.⁵ Unfortunately, these depletion-edge-translation optical phase modulators suffer from large device capacitance which greatly limits device speed if conventional lumped designs are used. This large capacitance occurs due to the heavy doping required to produce large electric fields within the modulator for high FOM operation. Lumped depletion-edge-translation modulators in our laboratory have exhibited experimental bandwidths of only about 1 GHz -- a speed inadequate for all but the slowest of microwave applications. To obtain high-speed operation, a distributed electrode design based on the use of slow-wave coplanar transmission lines has been developed.

Fig. 2. Reverse-biased depletion-edge-translation optical phase modulator. a) Rib waveguide design. b) Cross section of modulator region. Dashed lines represent depletion layer edges. Center GaAs layers provide index change for light guiding.

4. ELECTRODE DESIGN

In order to produce a high-speed depletion-edge-translation optical phase modulator it is necessary to provide impedance control and a velocity match to the degree sufficient to avoid "phase cancellation" along the device's length. Impedance control is necessary to provide an optical power match from the drive electronics to the modulator. As a minimum, it is desirable for the modulator to have a frequency-independent real load impedance. This is generally not difficult, if the characteristic impedance of the device is known, and a resistive termination is used.

Avoiding "phase cancellation" is a more complex problem. In general, optical phase modulators are large, due to the weak interaction between light and the modulating media. Due to this extended length of interaction with the light, velocity synchronism of the light to the electrical drive signal along the length of the modulator becomes important. In the worst case, the electrical drive signal can become exactly 180° out of phase with the modulated light along the device length. This will occur periodically with frequency with the lowest frequency (f_{rf}) at :

$$f_{rf} = \frac{c}{2L|\Delta n|} \quad (1)$$

in which L is the length of the device, c is the speed of light, and Δn is the difference between the optical index n_o and the rf index n_{rf} . This equation sets an absolute maximum frequency limit on the allowed velocity mismatch in a distributed phase modulator. Naturally, the -3 dB point will be at a somewhat lower frequency, but Eq. 1 is still a good goal for design. Here, the rib guide structure discussed earlier has an optical index of approximately 3.3 with a FOM of approximately 60°/V·mm. Assuming a device length of 1.0 mm (300° for 5 V bias) and operation to 30 GHz, Δn must be less than 5.0. This is equivalent to n_{rf} being between 1.0 to 8.3. This large range of acceptable rf index is a result of the short length of the device

Fig. 3. Cross section of the slow-wave coplanar-strip electrode design.

due to the device's high FOM. In spite of this large index range, it is still difficult to design an appropriate modulator electrode structure.

It has long been known that planar transmission lines fabricated over doped semiconductors result in slow wave propagation.⁶ Depletion-edge-translation optical phase modulators are based on high doping levels which results in very slow electrical propagation along the device's length. Some of our first lumped modulator designs had propagation velocities of less than 1/20 the speed of light. ($n_{rf} \approx 20$) -- a speed not useful in spite of the minimal velocity-match requirements developed above. Fortunately, it is not too difficult to increase the velocity propagation to acceptable levels.

Propagation along slow-wave transmission lines of the type relevant here can be described to first order by quasi-TEM analysis.⁷ That is, the propagation can be adequately described by the unit length impedance Z and admittance Y of the transmission line. Once knowing Z and Y , the transmission lines characteristic impedance Z_0 and propagation constant γ can be found from:

$$Z_0 = \sqrt{\frac{Z}{Y}} \quad \text{and} \quad \gamma = \sqrt{ZY} \quad (2)$$

The real part of γ gives the propagation loss along the electrode and the imaginary part gives the velocity along the electrode. The rf index ($n_{rf} = c/v_g$) is related to the imaginary part of γ by $n_{rf} = c/\omega \text{Im}(\gamma)$ in which c is the speed of light, and ω is the angular rf frequency. Z and Y can be estimated analytically for simple structures or calculated numerically for more complex structures. We have selected a quasi-static finite element package from Ansoft⁸ to determine the admittance and impedance per unit length of our devices.

Analysis of various possible electrode structures indicated that it is very difficult to obtain a perfect velocity match between the light and electrical drive signal due to the necessary large device capacitance per unit length. This is particularly true if a characteristic impedance close to 50 Ω is desired. As a first attempt, the coplanar strip-like structure shown in Fig. 3 was selected. One of the interesting features of

this electrode structure is the small gap selected between the ground and signal electrodes. This requirement for a small gap may be counter-intuitive, as it increases the capacitance of the device which would be expected to further slow propagation. Though capacitance is increased, decreasing this gap also reduces the inductance per unit length so that the net effect is to increase the velocity of propagation along the line. Being able to separately adjust a transmission line's inductance and capacitance per unit length is a feature of slow-wave transmission lines. In conventional linear transmission lines the inductance and capacitance per unit length are coupled by the propagation velocity ($v_g = 1/\sqrt{LC}$) which is determined by the dielectric in the transmission line.

5. EXPERIMENTAL

Devices were fabricated and tested both electrically for transmission line properties and optically for phase modulator performance. Fig. 4 shows measured and simulated results for the electrical transmission line properties of the modulator. These measurements were made with on-wafer microwave probes. The measured S-parameters were directly converted to the transmission line parameters shown in Fig. 4. The rf index is seen to still be too large (>7); the characteristic impedance is rather low; and losses are somewhat excessive.

The propagation velocity along the device can be increased by minimizing device capacitance and inductance per unit length. Capacitance can be minimized by reducing stray capacitances and junction area (implantation). Capacitance can also be reduced by increasing junction width with some sacrifice of FOM. The inductance can be reduced by further minimizing the gap between the electrodes. The low characteristic impedance is unfortunately a requirement for a fast transmission line with large capacitance per unit length ($Z_0 \approx 1/(C \cdot v_g)$).

Propagation losses are the primary factor limiting device speed. They can be reduced somewhat by increasing metal thickness, but a more important factor is to minimize the doped materials where the electric field is large within the structure. This was a rather surprising result discovered during simulation. The small (sub micron thickness) moderately doped p-type mesa cap to either side of the waveguide rib as shown in Fig. 3, constitute most of the propagation loss at microwave frequencies. The elimination of this cap is expected to at least halve the rf loss along the electrodes. An electrical isolation implant is being used to effectively remove this cap in future device designs.

To perform high-speed testing, the modulators were packaged with optical connections made by butt-coupling to single-mode fibers. Electrical connections were made by ribbon bonding from microstrip lines. Fig. 5 shows the measured response from 0.045-20 GHz, using an HP 8510C network analyzer. The modulator was driven optically with a 1.3 μm Nd:YAG laser. Electrical drive was directly applied from one port of the network analyzer and a 35 GHz bandwidth photodetector was used at the other port to detect the modulated light. Normalization of the response occurred during network analyzer calibration. No correction for detector response or other system losses was performed which makes the normalization in Fig. 5 arbitrary. Signal strength is seen to be somewhat low in Fig. 5. The measured noise floor, however, was in excess of 100 dB so the measurements should be valid. Several factors contribute to the low signal strength. The most significant signal loss was due to the large optical loss resulting from the fiber butt-coupling. Additionally, the phase modulator's facets were anti-reflection coated prior to packaging which eliminates all Fabry-Perot modes in the modulator. This means, true phase-modulation was used which is inefficient when detected by a photodetector. Finally, the measurement was performed with no impedance matching of the rf source (50Ω) to the device ($\approx 9\Omega$).

Fig. 4. Transmission line properties of modulator. Lines are measured. Symbols are theory.

Several interesting features are present in the measured response. First, a large initial roll-off is evident at low frequencies. This is due to the bias network used in the experiment. The device was packaged with a 10Ω resistive termination which required a blocking capacitor in series for DC bias. This results in a theoretical 16 dB response roll off at low frequencies-- similar to that measured. Secondly, device response

Fig. 5. Measured response of a packaged 1 mm length optical phase modulator. The solid line is co-propagating operation and the dashed line is counter-propagating. The notches in both responses at approximately 11 GHz are believed to be due to a package resonance.

is limited to an approximate usable bandwidth of 10 GHz. This bandwidth limitation is due to device loss rather than velocity mismatch. This can be seen by observing the "counter-propagating" response which is also shown as a dotted line in Fig. 5. The counter-propagating response is seen to have a notch at 13 GHz. Applying Eq. 1 and assuming the light propagates with $n_o = -3.3$ (opposite the electrical drive signal), the rf index must be $n_{rf} = 8.2$. This rf index is in reasonable agreement with the measured n_{rf} in Fig. 4. Again applying Eq. 1, the bandwidth for co-propagating operation should be 30 GHz. This frequency is much higher than the present device bandwidth; so therefore, device speed is not presently limited by velocity mismatch. These calculations indicated that the bandwidth is limited by excessive electrical propagation loss along the device. This is particularly evident in light of the measured electrical loss in Fig. 4.

This present modulator design suffers from several disadvantages, with the most significant problem being electrical propagation loss. A new modulator design employing the changes outlined here is currently in process. The new design uses a slow-wave coplanar transmission line design for the electrodes. This will allow for a faster electrical propagation, which will virtually eliminate the velocity matching issue except for operation in excess to 100 GHz. Additionally, great care is being taken to eliminate all excess electrical losses in the device. The theoretical bandwidth of this new device is 30 GHz with useful operation extending well within the mm-wave band. Fabrication details of this new device can be found elsewhere.⁵

6. CONCLUSIONS

The design and test of a high-speed large-FOM optical phase modulator was presented. The current design has obtained usable operation to 10 GHz while maintaining high FOM. Calculations indicate and measurements confirm that a velocity match in depletion-edge-translation optical phase modulators is difficult, making true traveling-wave operation unlikely. Nevertheless, the technique presented here offers the reduction of velocity mismatch and provides for a controlled drive impedance. It should be possible to produce depletion-edge-translation optical phase modulators for PIC use which can operate at millimeter-wave speeds (> 30 GHz) while simultaneously maintaining very high FOMs ($> 600/V \cdot \text{mm}$) for small circuit size.

7. ACKNOWLEDGMENTS

This work was performed at Sandia National Laboratories supported by the U. S. Department of Energy under contract #DE-AC04-94AL85000.

8. REFERENCES

- ¹ V. M. Hietala, G. A. Vawter, W. J. Meyer, and S. H. Kravitz, "Phased-array antenna control by a monolithic photonic integrated circuit", Proceeding of the SPIE, Vol. 1476, Optical Technology for Microwave Applications V, pp. 170-175, April 3-5, Orlando, FL, 1991.
- ² G. A. Vawter, "Processing Issues and Technologies for Optoelectronic Integrated Circuits and Devices (Invited)", Proceeding of the SPIE, Vol. 1582, Integrated Optoelectronics for Communication and Processing, pp. 178-184, Sept. 3-4, Boston, MA, 1991.
- ³ R. G. Walker, "High-Speed III-V Semiconductor Intensity Modulators", IEEE J. of Quantum Electronics, Vol. 27, No. 3, pp. 654-667, March 1991.
- ⁴ J. G. Meddoza-Alvarez, L. A. Coldren, A. Alping, R. H. Yan, T. Hausken, K. Lee, and K. Pedrotti "Analysis of Depletion Edge Translation Lightwave Modulators", IEEE J. Lightwave Tech. Vol. 6, No. 6, pp. 793-808, June 1988.
- ⁵ S. H. Kravitz, G. A. Vawter, V. M. Hietala, M. B. M. Snipes, Jr., M. G. Armendariz, R. F. Carson, B. E. Hammons, and R. E. Leibenguith, "Fabrication of high-performance GaAs/AlGaAs optical phase modulators for microwave/photonic integrated circuits", to be published in Proceeding of the SPIE, Vol. 2155-s15, January 26-27, 1994.
- ⁶ H. Guckel, P. A. Brennan, and I. Palocz, "A Parallel-Plate Waveguide Approach to Microminiaturized, Planar, Transmission Lines for Integrated Circuits", IEEE Trans. Microwave Theory and Techniques, Vol. MTT-15, no. 8, pp. 468-476, August 1967.
- ⁷ Y. R. Kwon, V. M. Hietala, and K. S. Champlin, "Quasi-TEM Analysis of "Slow-Wave" Mode Propagation on Coplanar Microstructure MIS Transmission Lines", IEEE Trans. Microwave Tech., MTT-35, June 1987.
- ⁸ Maxwell 2-D, Ansoft Corporation, Pittsburgh, PA 15219.

END

DATE

FILMED

3/15/94