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## HIGH-PERFORMANCE GaAs/AlGaAs OPTICAL PHASE MODULATORS FOR MICROWAVE PHOTONIC INTEGRATED CIRCUITS

Vincent M. Hietala, Stanley H Kravitz, Marcelino G. Armendariz, G. Allen Vawter,  
and Richard F. Carson

Sandia National Laboratories  
Albuquerque, New Mexico 87185-0603

### ABSTRACT

A high-performance high-speed optical phase modulator for photonic integrated circuit (PIC) use is described. Integration of these optical phase modulators into a real system (COMPASS) is also discussed. The optical phase modulators are based on depletion-edge translation and have experimentally provided optical phase shifts in excess of  $60^\circ/\text{V}\cdot\text{mm}$  with approximately  $4 \text{ dB/cm}$  loss while simultaneously demonstrating bandwidths in excess of 10 GHz.

### INTRODUCTION

Optical control of microwave systems offers many merits over traditional electrical methods. The primary advantages are improved electromagnetic compatibility of fibers over metal wires, reduced system weight, and lower distribution loss.[1] Additional system-specific benefits are also commonly seen, such as, simplified signal distribution manifold design, efficient high-speed beam forming, and improved feed line flexibility in phased-array antennas.

This paper briefly describes our efforts at Sandia National Laboratories to develop a PIC technology for the control of microwave signals. Our PIC approach is based entirely on "passive" optical components with optical power provided by an external laser source. Only passive optical phase shifters are required on-chip to provide useful control functions for microwave applications.

Since high-performance optical phase shifters are critical for this technology this paper will primarily address their required performance and our selected approach. A phased-array antenna control system being pursued at Sandia called COMPASS will be discussed to provide modulator performance guidelines.

### COMPASS

COMPASS [2] (Coherent Optical Monolithic Phased-Array Steering System) is an optical concept system which was developed both to address a need for improved phased-array antenna control and to provide a driver for our PIC program. Fig. 1 shows a block diagram of the COMPASS PIC. The PIC is powered by one laser source which is appropriately modulated and split into N-parts and fed through optical fibers to N antenna elements. The light is then detected to provide a phase controlled RF signal at each antenna element. The RF phase control is performed by optical heterodyning. In any heterodyning process (electrical or optical), phase is preserved between the input signals and the resulting tones. This provides a method of directly mapping an optical phase shift into an RF phase shift.[3] This mapping occurs independent of the RF operating frequency. Therefore, the COMPASS system will allow phase control over a large bandwidth, but instantaneous bandwidth will need be restricted to acceptable beam squint performance. For narrow band systems (i.e. radar) this will not be an issue.

Fig. 1a shows the Optical Frequency Translator (OFT) portion of the COMPASS PIC. This circuit generates an optical signal which is frequency translated by the RF operating frequency from the input laser. This signal along with a portion of the input light, provides the signals for the heterodyning process. Generating these two optical signals by such a method provides the benefit of phase noise synchronism. Good spectral purity of the RF signals generated at the antennas will therefore be achieved. For a laser coherence length much longer than the path length difference between the two optical signals from the OFT output to the antenna, laser phase noise will be minimized and good RF spectral purity will result. Since the maximum path length error is expected to be less than  $10 \mu\text{m}$ , a laser with a few cm coherence length should be adequate.

The OFT operates in an analogous manner to a conventional phase-shift-based SSB modulator.[4] The circuit as shown, can be visualized as two Mach-Zehnder modulators which are operated to produce two double-sideband modulated signals with no carrier. Then by combining the appropriately phased outputs of these two modulators, one of the sidebands can be canceled leaving a lone SSB or frequency translated signal. A more detailed discussion of this circuit along with fabrication was given by Izutsu et al.[5]

The second part of the COMPASS PIC is shown in Fig. 1b. This portion of the circuit divides the optical signals into N parts, introduces the optical phase (analog or digital [6]), and provides an interface to N fibers for signal distribution to the N antenna elements. The actual mixing operation occurs in the square-law photodetector at the

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antenna as shown in Fig. 2. The resulting RF signal can then be appropriately signal conditioned and used for the phase-frequency reference for the transmitter or receiver's local oscillator. The two optical signals which produce the RF are sent to the antenna through the same fiber. This reduces fiber length sensitivity to roughly the same requirements as conventional RF waveguide designs. The only phase sensitive paths in the COMPASS system are in the PIC where the two optical channels are routed down different paths. Since these paths are on-chip and by design will be very short and length matched, the system should have excellent temperature stability characteristics for an optical system.

Throughout the COMPASS system optical phase modulators are employed. Phase modulators are the critical component in our PIC technology. These modulators are required to provide high phase-shift-per-unit-length·voltage and low optical loss while simultaneously providing large electrical drive bandwidths. For example, in the COMPASS system the OFT section alone requires in excess of  $480^\circ$  of optical phase shift. Most current optical phase modulator technologies are pushed to provide the meager  $180^\circ$  phase shift required for Mach-Zehnder amplitude modulators in cm size chips. Clearly, such approaches would provide little utility in producing a PIC like COMPASS.

Here, through the use of depletion-edge-translation (DET) optical phase modulators we can achieve phase shifts in excess of  $60^\circ/\text{V-mm}$  at  $1.3 \mu\text{m}$  optical wavelength. With such an approach, assuming 5 V operation is desired, the necessary  $480^\circ$  phase shift can be achieved with simply 1.6 mm of combined phase modulator length. Naturally, additional device length will be required for the passive optical on-chip interconnects (corners, power splitters/combiners,...), but phase modulator length is expected to still dominate overall chip length.

## DEPLETION-EDGE-TRANSLATION MODULATOR

DET optical phase modulators are based on appropriately combining both electro-optic and carrier effects to provide a maximum phase shift.[7] Fig. 3 shows a diagram of a DET modulator. This modulator lends itself well to integration since passive waveguides and phase modulators have the same exact waveguide structure with the only difference being metal contacts placed on top of the modulators. The light is confined closely to the junction's center to provide a maximum overlap between the electric and optical fields. Note the heavy doping levels used provide a high electric field within the junction. Use of these modulators presents several challenges. First, the heavy doping results in a large terminal capacitance which limits device speed. Secondly, the tight vertical confinement of the light causes critical fabrication issues for proper light guiding and large optical losses in fiber butt coupling. A novel design approach addresses the speed issues, whereas fabrication and packaging issues are addressed elsewhere.[8-9]

## DISTRIBUTED ELECTRODE DESIGN

As discussed above, DET optical phase modulators necessarily suffer from a large terminal capacitance. Capacitance cannot be reduced without lowering the high phase shift of the device which would quickly make COMPASS prohibitively large. Therefore, a distributed approach to the modulator's electrode design was developed.

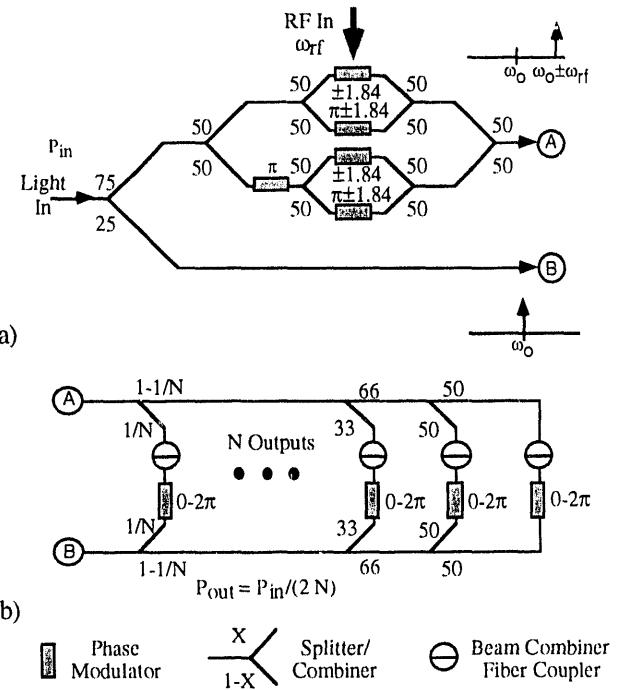


Fig. 1. The COMPASS PIC. a) Optical frequency translator portion. b) Optical power splitters and phase control portion.

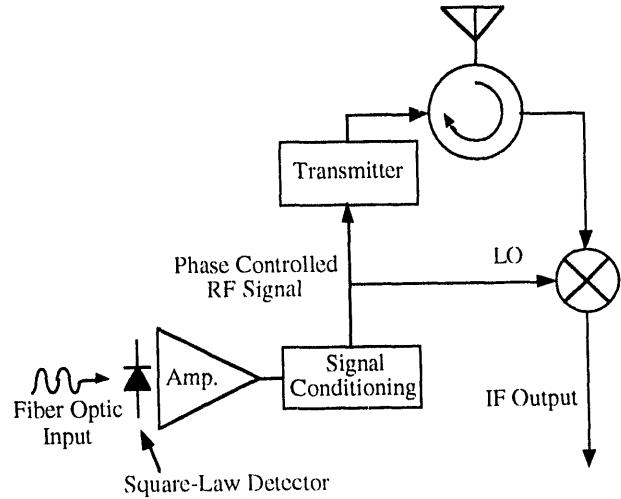


Fig. 2. Transmit/receive module of COMPASS.

Since a DET modulator has heavy doping, propagation along its electrodes is slow-wave.[10] The first DET modulators fabricated in our laboratory, with no regard for distributed effects, had an estimated RF index ( $c/v_p$ ) in excess of 20. Since the optical guides effective index is about 3.5, velocity mismatch was an issue.

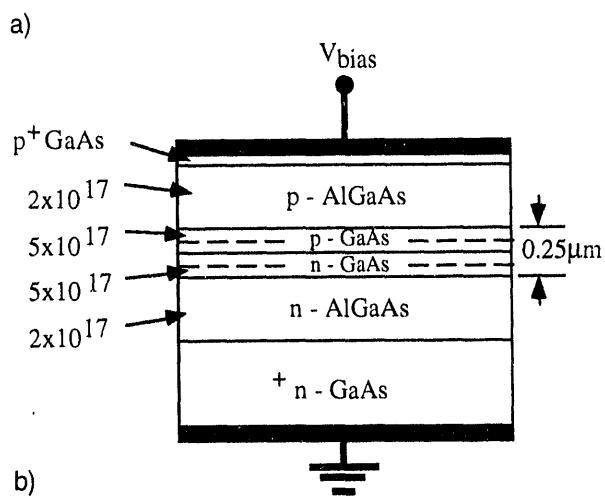
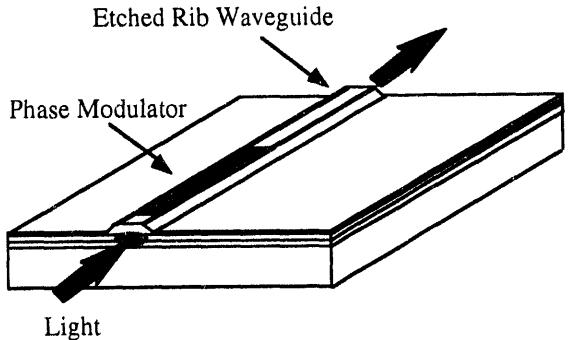


Fig. 3. Depletion-Edge-Translation (DET) optical phase modulator. a) Rib waveguide. b) Modulator cross-section.

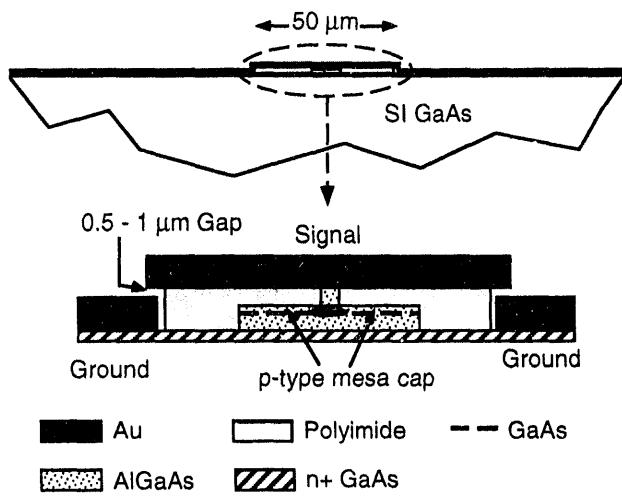


Fig. 4. Cross-section of distributed electrode design of DET modulator.

Since an electrical propagation velocity increase is required and the per unit length capacitance is fixed, the only means left to increase the propagation velocity is to reduce the electrode's inductance per unit length ( $v_p = 1/\sqrt{LC}$ ). This was achieved by changing the device's cross-section to that shown in Fig. 4. The inductance is minimized by reducing the gaps on a slow-wave coplanar waveguide structure[11] to less than 1  $\mu\text{m}$ . This has experimentally been seen to increase the velocity to levels similar to the light's. The only disadvantage to this approach is the resulting decrease in characteristic impedance caused by the reduction of inductance ( $Z_0 \approx \sqrt{L/C}$ ). Line impedances of about  $10\Omega$  result which will require impedance matching for use in  $50\Omega$  systems.

To date, bandwidths of 10 GHz have been demonstrated with devices similar to that shown in Fig. 4. Though the velocity mismatch has been adequately addressed, electrical propagation losses dominate the modulator response. Simulations performed by quasi-TEM analysis based on finite-element solutions[12] have indicated that most power dissipation is in the semiconductor regions. In particular, at least half of the line's loss occurred in the p-type caps on the p-mesa to either side of the rib guide (see Fig. 4). These caps are being ion implanted on current designs to minimize this loss. Theoretical bandwidths are then in excess of 30 GHz while still maintaining approximately  $60^\circ/\text{V}\cdot\text{mm}$  optical phase shift.

## CONCLUSIONS

Optical control of microwave systems is possible provided that an adequate PIC technology can be developed. The critical component of such a technology is the optical phase modulator. Optical phase modulators are required to have large phase shifts per unit length-volt in order to allow for realistic sized PICs. Additionally, they must have sufficient bandwidth to operate at the desired microwave system frequency. A depletion-edge-translation modulator under development at Sandia addresses these needs by providing  $60^\circ/\text{V}\cdot\text{mm}$  optical phase shift with  $<4$  dB/cm optical loss and a 10 GHz bandwidth. Current design considerations predict future bandwidths in excess of 30 GHz.

## ACKNOWLEDGMENTS

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