

# Monolithic Integration of GaAs/AlGaAs Phase Modulator and Photodetector for RF Photonics

Mona Jarrahi, David A. B. Miller, Thomas H. Lee

SMIRC Lab, Stanford University, Stanford, CA, 94305-4070

Tel: (650) 497-0565, Fax: (650) 735-3383

**Abstract:** We report the design and monolithic fabrication of phase modulator and photodetectors for RF photonics. We demonstrate phase modulation efficiency of  $270^0\text{V}^{-1}\text{mm}^{-1}$ , and a bandwidth of 18GHz. Photodetectors response time is measured to be 8ps.

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OCIS codes: 060.5625

There has been an increasing interest in employing optics to enhance the performance of analog RF integrated circuits. Some of the potential applications of microwave photonics include RF distribution links, antenna remoting, and time delay [1]. The primary advantages of optoelectronics are simplified distribution, low propagation loss, large modulation bandwidths, and large computational parallelism of the optical wave as the information carrier. Optical semiconductor-based phase modulators and photodetectors are key components in the development of such integrated optoelectronics. For a phase modulator, the combination of high modulation efficiency and high modulation bandwidth is essential for RF photonics applications. Additionally, the ability to fabricate high speed photodetectors, capable of operating with high optical powers, on the same substrate with the phase modulator can be very useful.

This work describes the design and monolithic fabrication of high modulation efficiency, high electrical bandwidth phase modulators with high efficiency, high-speed photodetectors on a GaAs substrate. The wavelength dependence of phase sensitivity and intensity modulation are experimentally studied. Application of these integrated devices to analog-to-digital conversion at very high bandwidths [2] has already been demonstrated.

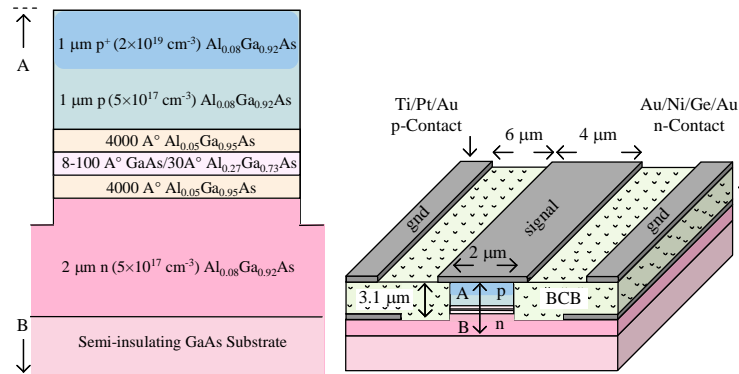


Figure 1. Schematic of traveling wave phase modulator

Phase modulation arises from the quantum-confined Stark effect, in which an applied perpendicular electric field induces a shift in the absorption spectrum, and an accompanying shift in the refractive index of a multiple quantum well (MQW) structure [3]. In this work, MQW layers are integrated with the intrinsic region of a p-i-n diode inside the optical waveguide operating with a single transverse mode at 860 nm or longer (Figure 1). The phase modulating electric signal propagates on a coplanar electrical waveguide (CPW) along the optical waveguide, to provide the electric field across MQW layers in combination with the substrate bias. The traveling wave phase modulating electrical signal, velocity matched with the optical wave, allows a long modulation path while maintaining a small junction area [4]. Therefore, high modulation bandwidth and efficiency are achieved simultaneously.

The introduced phase shift in the optical mode is given by:

$$\Delta\phi = \chi V_m L \frac{1 - e^{-\alpha L}}{\alpha L} e^{-\left(\frac{t}{T_{\text{settling}}}\right)} \quad (1)$$

where  $\chi$  is the phase modulation efficiency (degrees  $V^{-1} mm^{-1}$ ),  $V_m$  is the modulating electric voltage,  $L$  is the length of modulator,  $\alpha$  is the microwave attenuation, and  $T_{settle}$  is given by [5]:

$$T_{settle} = 2.2 \frac{d}{v} + 2\pi \frac{\rho \epsilon}{d} + 2\pi L \frac{V_0 - V_c}{V_0 V_c} \quad (2)$$

where  $d$  is the depletion region depth,  $v$  is the carrier average drift velocity across the depletion region,  $\rho$  is the p-i-n diode contact resistivity, and  $v_o$  and  $v_c$  are the velocities of the optical wave and the microwave, respectively.

The photodetector comprises p-i-n diodes monolithically fabricated along the output waveguides. It consists of an active region terminated in  $50\Omega$  through  $6\mu m$  metal spacing on either side. The generated photocurrent along the active region is a function of the MQW reverse bias as set by the substrate voltage. The simulation results suggest an optical absorption coefficient of  $1.5 mm^{-1}$  along the photodetector under 6 V reverse bias. The combination of the  $0.218 fF/\mu m$  parasitic capacitance along the photodetector and the  $50\Omega$  termination resistance implies a full-width half-maximum (FWHM) output pulse width of 5.5 ps for a  $400\mu m$  photodetector.

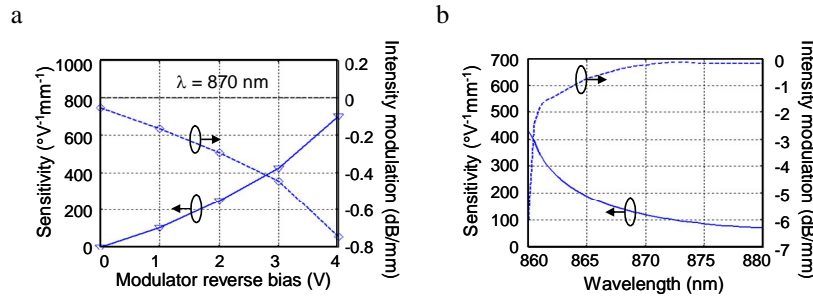


Figure 2. Phase modulation sensitivity and associated intensity modulation as a function of a) substrate bias b) wavelength

The GaAs/AlGaAs p-i-n layers are grown by molecular beam epitaxy on a semi-insulating GaAs substrate using Be and Si as p and n dopants. The semi insulating GaAs substrate has the resistivity and thickness of  $5.7 \times 10^8 \Omega \cdot cm$  and  $250\mu m$ , respectively. The  $2\mu m$ -wide ridge waveguides are defined by Cl reactive ion etching. Au/Ni/Ge/Au n-contact metal region with total thickness of about  $0.5\mu m$  was formed by standard lift-off and then rapid-thermal annealed (RTA) at  $415^\circ C$  for 30s. A benzocyclobutene (BCB) layer was spun on the device and etched back up to the top of the waveguide for planarization of the etched surface such that the microwave coplanar waveguide (CPW) lines can be put on the top. A Ti/Pt/Au evaporation and lift-off step forms the metallization of the CPW and the p-type metal contact. The center stripe and air gap widths of the integrated CPW line were  $4\mu m$  and  $6\mu m$ , respectively, to achieve  $50\Omega$  characteristic impedance.

Phase modulation characteristics are measured by integrating a  $1.5mm$  phase modulator in a Mach-Zehnder interferometer. Figure 2 illustrates the tradeoff between phase modulation sensitivity and the associated intensity modulation, as a function of substrate bias and operation wavelength. Voltage tunable phase modulation efficiencies of  $75$ - $270^\circ V^{-1} mm^{-1}$  at low propagation losses of  $0.02$ - $0.6 dB/mm$  for TE polarization have been observed at the operating wavelengths of  $865$ - $880nm$ .

At  $870 nm$ , the phase-change is relatively linear at  $270^\circ V^{-1} mm^{-1}$  (Fig. 2a), and optical losses vary by less than  $0.28 dBV^{-1} mm^{-1}$  at  $2.1 V$  reverse bias voltage. Using a  $1.5 mm$ -active region phase modulator we measured  $2\pi$  phase shift over a range of  $\pm 450 mV$  input analog signal. By calculating the CPW propagation constant from scattering parameter measurements as a function of frequency an electric field settling time of  $2.1 ps$  is estimated for a  $1.5 mm$  long phase modulator. The expected operating bandwidth of the quantizer with this phase modulator is  $30 GHz$ , where the microwave attenuation of the CPW is the primary bandwidth-limiting mechanism.

Experimental characteristics of the fabricated photodetector are shown in figure 3. The photodetector transient response is measured by a pump-probe electro-optic (EO) sampling technique [6]. The optical excitation pulses were obtained from a mode locked Ti:sapphire laser at  $870nm$  wavelength, giving  $150fs$  pulses. The  $400\mu m$  photodetector offers an impulse response time of  $8ps$  full-width half-maximum (FWHM) under  $6 V$  substrate bias (Fig. 3a). The photodetector quantum efficiency approaches  $10.8\%$  under  $6 V$  substrate bias (Fig. 3b), while maintaining saturation power levels of as high as  $330mW$  required for large dynamic range applications (Fig. 3c).

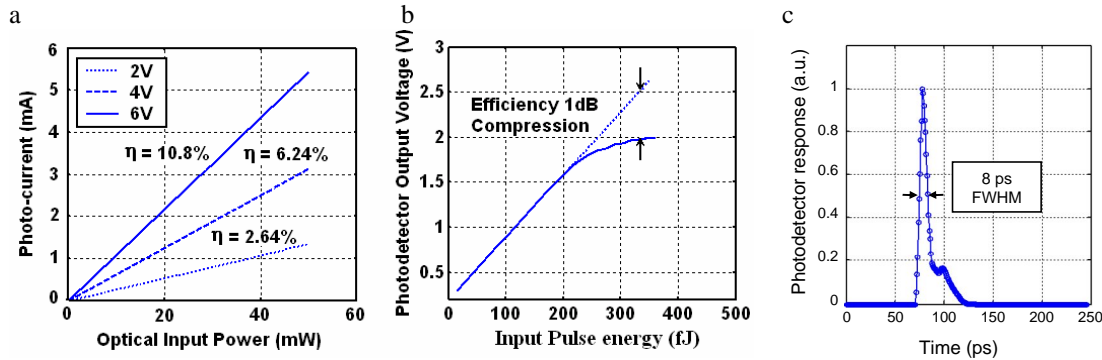


Figure 3. a) The 400  $\mu\text{m}$  photodetector transient and frequency response. b) Photodetector DC quantum efficiency. c) Photodetector AC quantum efficiency

In order to investigate the small signal modulation bandwidth the output of the MZ modulator to a 6dBm sinusoidal input was monitored by a spectrum analyzer. Figure 4 shows the output response at 2.1V reverse-bias voltage. The interferometer output did not drop more than 3dB over 1-18GHz frequency range. Therefore, a measurement instrument-limited small signal bandwidth of more than 18GHz, projected to the estimated bandwidth of 50 GHz, is demonstrated for the phase modulator.

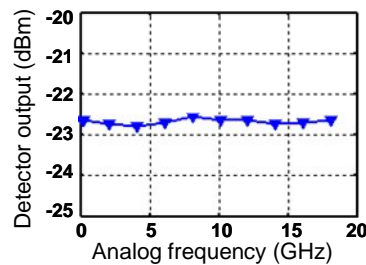


Figure 4. Small signal modulation at 2.1V bias

As a summary, we have designed and fabricated a traveling wave phase modulator and a high-speed photodetector on the same GaAs substrate. We achieve high phase modulation efficiency by utilizing QCSE and high-speed modulation speed by employing a traveling wave phase modulation scheme to relax the efficiency-bandwidth tradeoff. We demonstrated a relatively linear phase shift efficiency of  $270^\circ\text{V}^{-1}\text{mm}^{-1}$ , and optical loss variations of less than  $0.28\text{dBV}^{-1}\text{mm}^{-1}$ , and a measurement instrument limited phase modulation bandwidth of 18GHz at 2.1V bias voltage and 870nm wavelength TE mode. Monolithically integrated photodetectors, show an impulse response time of 8ps full-width at half-maximum (FWHM), and 10.8% quantum efficiency and saturation power levels of as high as 330mW at 6V bias voltage. The results are promising in satisfying the required specification for RF photonics, for future high speed high-bit-rate telecommunications and optical signal processing of high-frequency electromagnetic signals.

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