# Quantum Dot Modulators

**Brendan Turner**
**Physics, Brigham Young University**

***NNIN REU Site: Nanoscience @ UNM, University of New Mexico***
*NNIN REU Principal Investigator: Diana Huffaker, Electrical and Computer Engineering, University of New Mexico*
*NNIN REU Mentors: Manish Mehta, Electrical and Computer Engr, Ramesh Laghumavarapu, Physics; University of New Mexico*
*Contact: luthe.bwt@gmail.com, huffaker@chtm.unm.edu*

## Abstract:

In this project we perform free-space characterization of stacked InAs quantum dot devices. A crossed polarizer and analyzer combination is used to determine the phase retardation/voltage relation for said materials. We use a span of pump wavelengths to analyze the wavelength dependence on modulation. Further calculations are carried out to determine the theoretical extinction ratio of such devices as part of a mach-zender modulator.

## Introduction:

Mach-zender (MZ) devices are an ideal modulation source for communication networks at 1.3 $\mu$m and 1.55 $\mu$m. Superlinear electro-optic (EO) effects are a desirable feature in MZ modulators since their large second order EO coefficient will theoretically provide complete signal extinction at a small voltage. Quantum dot (QD) devices show promise for such applications in the 1.3 $\mu$m band.

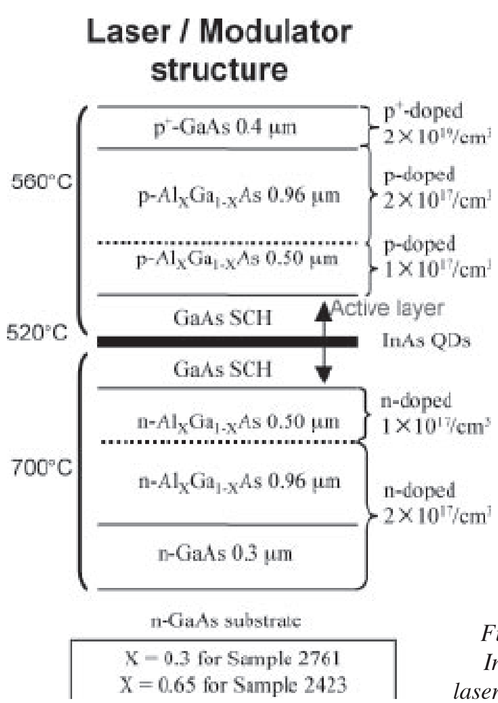


*Figure 1: InAs QD laser structure.*

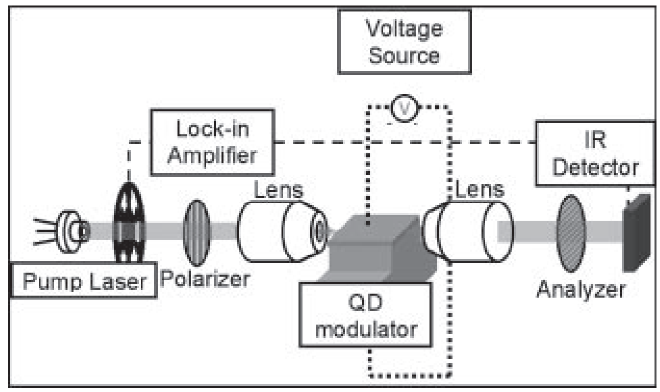


*Figure 2: Setup for measurement of QD modulator.*

## Device Structure, Growth and Fabrication:

Stacked InAs/GaAs QD structures were grown by metalorganic chemical vapor deposition on an n-doped GaAs substrate [1]. Two layers of n-doped $Al_xGa_{1-x}As$ (values of x used were 0.35 and 0.6) were grown at 700ºC followed by a GaAs separate confinement heterostructure (SCH) layer. Six stacks of InAs quantum dots were grown at 520ºC with intermixed GaP strain compensating layers. Another GaAs cladding layer was followed by two p-doped $Al_xGa_{1-x}As$ layers and one layer of p-doped GaAs, all grown at 560ºC.

After growth, the photo-luminescence response was taken to test the active layer. TiPtAu is evaporated to form the top p-contact, followed by a masked mesa etch using $BCl_3$ in an inductive coupled plasma reactive ion etcher. The mesas were etched to 200-300 Å above the SCH layer. Ge/Au/Ni/Au was then evaporated onto the backside of the substrate to form the n-contact and the wafer was cleaved into 2 mm stripes. The sample was then tested to determine its electro-luminescence (EL) response, mounted, and wire-bonded.

## Experimental Setup:

Free space characterization of the InAs QD devices was performed with a probe wavelength of 1350 nm. This wavelength was chosen by red-shifting the peak EL wavelength to reduce absorption in the active layer.

The probe laser was coupled into the active region using a 100X objective lens and the emitted light was gathered and collimated using a 40X objective. The collimated beam was measured using a broad-area IR detector combined with a chopper and lock-in amplifier (see Figure 2). The incoming beam was polarized at a 135° relative to the sample. This angle was chosen so as to give equal vertical and horizontal components of the E-field vector so the modulated light would be linearly polarized. An analyzer was placed after the sample at 45° to eliminate scattered and un-modulated light from reaching the detector.

Initial alignment was done with a HeNe laser aligned to follow the same path as the pump laser. Precise alignment was done using the pump laser and an IR viewing card as well as an IR sensitive CCD camera. The beam was focused on the top edge of the front facet using a beam splitter and the IR viewing card to look at the reflection from the facet. Care was also taken to couple the pump laser into one of the wire-bonded channels. The packaged sample was connected to a power supply and alignment of the second objective was optimized by applying a forward bias to the sample and maximizing the reading of the lock-in amplifier.

Modulation readings were taken by applying a voltage in the reverse bias to the sample using the power supply. Any modulation in the phase of the probe beam registered as an increase in transmission through the crossed polarizer/analyzer pair. Modulation was optimized by applying a reverse bias and adjusting the height of the sample to obtain the maximum amount of light coupled into the quantum dot layer. Various lock-in measurements were taken from 0 to 7 Volts.

## Results and Calculations:

Calculations of the phase retardation were performed by averaging the readings at each voltage and subtracting the background noise. The maximum lock-in reading was assumed to be a 90° phase retardation. All other readings were divided by this value and the square root and arcsine were taken. While previous research has shown a super-linear EO effect for similar InAs QD structures all results were shown to be linear (see Figure 3). This relation was fitted to a linear trendline and this equation was used to calculate the extinction ratio of an ideal MZ modulator employing an InAs QD active layer. First an intensity curve was calculated by adding two sine waves with the phase of one modulated by the phase reduction/voltage relation. This was squared and averaged to determine the voltage for maximum extinction. Also the ratio of full intensity to the intensity of two 180° out of phase was calculated to determine the extinction ratio (see Figure 4). Based on these calculations a theoretical mach-zender modulator could achieve full extinction at approximately 9 V for a 2 mm sample.

Further experiments need to be conducted to determine if the EO linearity is dependent on the probe wavelength and what amount of red-shift will maximize the EO coefficients.


## Acknowledgments:

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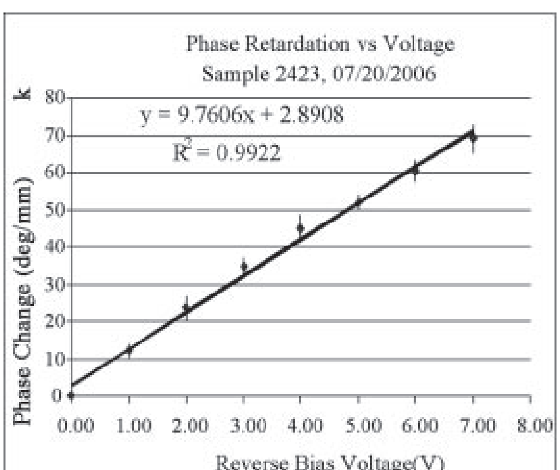
## References:


[1] J. Tatebayashi, N. Nuntawong, Y.C. Xin, P.S. Wong, S. Huang, C.P. Huang, L.F. Lester, D.L. Huffaker, "Low threshold current operation of stacked InAs/GaAs quantum dot lasers with GaP strain-compensation layers," International Conference on Indium Phosphide and Related Materials, 108-111, 2006.

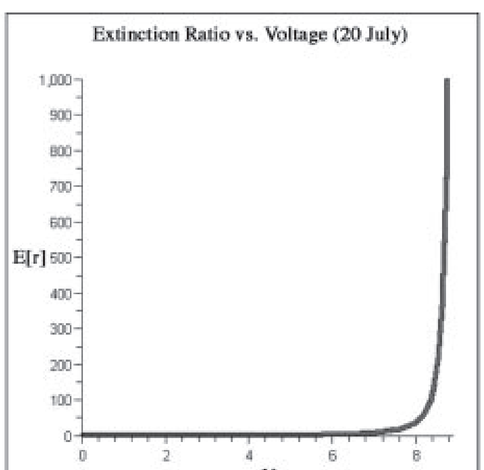




*Figure 3, left: Phase retardation vs. voltage.*

*Figure 4, right: Theoretical extinction ration for InAs QD Mach-Zender modulator.*