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on

**INTEGRATED PHOTONIC SWITCHES AND LOGIC GATE ARRAYS FOR
PARALLEL OPTICAL SWITCHING AND COMPUTER ARCHITECTURES**

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**TWO-DIMENSIONAL OPTICAL SWITCHING AND LOGIC ARRAYS FOR
COMMUNICATION AND COMPUTING SYSTEMS**

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The goal of this AASERT research program is to develop novel optoelectronic switches based on vertical-cavity surface-emitting lasers (VCSELs), by developing an in-depth understanding of the material properties and device physics, leading to new switch designs with improved performance and greater functionality. Three of my graduate research students - **Christopher Hains, Drew Alduino, and Gerry Ortiz** (all U. S. citizens) - were the primary recipients of the AASERT support. Their progress will be summarized below.

Hains has been pursuing his doctoral research full-time since completing his coursework requirements (with a 3.6/4.0 GPA) and passing his Ph.D. qualifying exams in 1993. He has been actively engaged in research on the design, modeling and fabrication of coherent and incoherent VCSEL arrays, and has been studying the impact of device design on their modal properties. He has successfully fabricated coherent VCSEL arrays.

Drew Alduino joined my group in 1993 after completing his Master's degree, passed his Ph.D. qualifying examinations in Feb., 1994, and has been pursuing his doctoral research full-time on the design, fabrication, and modeling of monolithic arrays of high performance optoelectronic switches based on the integration of VCSELs and photodetectors with HBTs. His Ph.D. research is on the design and characterization of multi-functional smart pixel arrays that can perform optical switching and routing, and their integration with HBT electronic technology. He has become thoroughly trained in the design and fabrication of VCSELs, as well as their integration with HBT technology, and has successfully fabricated monolithic arrays of HBT/VCSEL switches. Drew has also become an expert in analytical techniques such as atomic force microscopy and electron microscopy.

Geraldo Ortiz is a minority graduate student who began his doctoral research program in Spring 1994, after having done research in my group on the high speed modulation characteristics of VCSELs, and completing his master degree at the end of 1993. He has completed all course required for his Ph.D. degree, with an outstanding GPA of 3.82/4.0. Jerry joined us from the Jet Propulsion Laboratory in the Fall of 1991, and is working towards his Ph.D. degree under my supervision. He passed his Ph.D. qualifying examinations in February 1995. Jerry has done excellent research on the modeling and experimental studies of the high speed performance of VCSELs and heterojunction bipolar transistors (HBTs), culminating in several published papers and conference presentations based on his research, including an invited talk. He is currently evaluating the performance of monolithic optoelectronic switches based on the integration of HPTs, HBTs, and VCSELs, and has demonstrated modulation speed in excess of 1Gb/s.

Ortiz and Alduino are collaborating on a subsystem experiment to experimentally demonstrate the performance of cascaded arrays of monolithic optoelectronic switches

comprising of VCSELs and heterojunction phototransistors (HPTs), which will be reported below.

SUMMARY OF PROGRESS:

1. A Monolithic Optoelectronic Switching System - Component Design, Fabrications, and Experimental System Demonstration:

In the course of this program, the AASERT students designed and fabricated the necessary components for a 4x4 optical switch, which included monolithic arrays of high performance optoelectronic transceivers and routing switches based on vertical-cavity surface-emitting lasers (VCSELs), PIN photodiodes, and heterojunction bipolar transistors (HBTs). This project began three years ago at the individual component level, and culminated at the end in a multi-stage system demonstration of the cascaded optical routing of parallel optical data channels.

The students first designed the physical layout of the heterojunction bipolar transistors and the PIN photodetectors. Different types of photodetectors were compared, including PIN photodiodes in different contact configurations, and MSM (metal-semiconductor-metal) photodetectors with different ratios of linewidth to spacing. It was determined that PIN detectors offer a much higher coupling efficiency and are thus preferable for the monolithic integration with VCSELs. After several iterations, they have optimized the detector area and shape to balance the competing requirements of high coupling efficiency and small capacitance. The original binary optical switch design contains a two-segment photodetector whose optical apertures formed a single optical input window, but due to both a relatively large separation between the detectors and their square shape, the coupling efficiency was relatively poor and the optical loss was high. By redesigning the detectors so that they better match the shape of the fiber coupling the light into the detectors, and also by altering the processing to allow much closer separation between the detector pairs, the coupling efficiency has been substantially increased (from <20% to >50%).

Several different HBT epitaxial structures were designed by the students in order to determine the optimal trade-off between high gain and high speed. It was determined that transistors with a current gain of at least 50 are needed, and therefore HBT structures with a very

thin or heavily-doped base layer were eliminated due to their inherently lower gain. Using the epitaxial structures that were designed, integrated HBT/PIN devices have been processed, and have shown modulation speeds in excess of 700 MHz and a current gain β in excess of 300. A self-aligned technology was designed to reduce the size of the transistors drastically, and should result in a significant improvement in speed to the order of ~ 10 GHz.

During the final months of this program, these students began a complete system demonstration using arrays of the HBT/PIN/VCSEL switches that they have designed and fabricated. The full functionality of the basic switching fabric has been demonstrated, including the conversion of either an electrical or optical input into both electrical and optical outputs, as well as the reconfigurable routing of optical input data to different optical output ports. Although the system still needs to be optimized, both in terms of packaging and the routing/control signals, to date they have already demonstrated the switching functions at a data rate of >500 Mb/s. This represents an impressive improvement over previous demonstrations based upon HPT/VCSEL switches. The most pressing concern for the system experiments was the packaging, both electrical and optical, and a great deal of time and effort were devoted to several iterations of the package design in order to realize high frequency modulation and to minimize the parasitic coupling between neighboring devices. Other areas that need to be investigated further include different designs in which the VCSEL is placed at a different part of the circuit. By improvements in packaging and the use of a self-aligned HBT technology, the operation of a PIN/HBT/VCSEL switch at a data rate of > 1 Gb/s is possible.

2. Monolithic Coherent VCSEL Arrays:

In the course of this program, the AASERT student (C. Hains) also designed and fabricated coherently-coupled high power VCSEL arrays, and measured their electrical and optical characteristics.

A photolithographic mask incorporating a variety of different types of arrays was designed, along with single devices and transmission lines for diagnostic purposes. The arrays consisted of individual VCSELs arranged in a square or hexagonal format, the former laid out in 4x4, 6x6, 8x8, 10x10, and 12x12 configurations. For each arrangement three different size

apertures were used (with 6, 8 and 10 μm active area diameters), with varying separation between apertures (1 and 2 μm). The arrays were fabricated using a GaAs/AlGaAs VCSEL epilayer structure, using standard VCSEL-processing methods that employed a proton implant for current confinement and a deep wet chemical etch for isolation between arrays.

Optical and electrical characterization of the single test devices as well as the arrays were then undertaken. The electrical and optical characteristics of the single VCSEL were comparable to those of lasers previously fabricated with this material. Single VCSELs with 10 μm and 6 μm apertures exhibited a peak cw power of 6 mW and 2 mW, respectively, and their slope efficiencies were $\sim 34\%$. The arrays tested in this series contained VCSELs with 6 μm and 8 μm apertures, and are spaced 1 μm apart, where the close spacing is expected to produce a stronger coherent coupling between neighboring lasers. The arrays were tested in a pulsed mode using 60 ns pulses and a 0.1% duty cycle in order to eliminate the self-heating effects. In the cw mode of operation, the smallest arrays (4x4, 6 micron diameter) achieved a peak optical output power of 90 mW at a drive current of 450 mA (limited by the pulse driver circuit). The highest output power was demonstrated by an 8x8 array of VCSELs with an 8 μm aperture, which produced a peak power of 800 mW at a 2.0 A drive current (again pulser-limited), with a slope efficiency of 40% in the linear region of its lasing characteristic. The optical turn-on of the arrays became increasingly 'soft' as the array size is increased. This was probably due to non-uniform current injection caused by insufficient current spreading in the upper layers of the VCSEL material, which prevented all elements of the array from turning on in unison, as was observed in a near-field image of the array. The far-field pattern, which contains a four-lobed distribution, showed that the elements within an array were lasing coherently, with each element lasing out-of-phase (by π) with its nearest neighbors.

In conclusion, the AASERT student has demonstrated the fabrication and operation of high power, coherent VCSEL arrays, producing an optical output power in the hundreds of milliwatts regime. In the future the epitaxial structure and array design can be modified to produce a pulsed lasing output in excess of 1 W peak power, with in-phase coupling between neighboring lasing elements in order to produce a single-lobe optical far-field pattern.

PUBLICATIONS:

- [1] G. G. Ortiz, Julian Cheng, "High-speed Modulation and Small-signal Circuit Modeling of Deeply-Implanted VCSELs with a GRINSCH Active Layer and Graded Heterointerfaces", SPIE Vol. 2147, Vertical Cavity Surface Emitting Laser Arrays, pp. 28-39, 1994.
- [2] G. G. Ortiz, (Invited) "The High-speed Modulation Response and Circuit Modeling of VCSELs", Engineering Foundation Workshop on High-Speed Interconnects, San Luis Obispo, CA; July, 1994.
- [3] (Invited) Julian Cheng, Y.-C. Lu, B. Lu, D. Alduino, G. Ortiz, C. Hains, J. C. Zolper, J. Klem, K. L. Lear, "The Monolithic Integration of Vertical-Cavity Surface-Emitting Lasers with Optical and Electronic Devices for High Speed Optical Interconnects", Proc. of 1995 SPIE Conference on Optical Interconnects III.
- [4] D. Alduino, G. Ortiz, C. Hains, J. Cheng, J. A. Klem, J. C. Zolper: "400 Mb/s Operation of an Optically Cascaded Routing Switch Integrating Surface-emitting Lasers with PIN diodes and Heterojunction Bipolar Transistors", LEOS Annual Meeting, Nov. 1995.
- [5] D. Alduino, G. Ortiz, C. Hains, J. Cheng: "Optically-Cascaded, High-Speed Operation of a Reconfigurable Array of VCSEL-Based Optical Routing Switches with High Optical Gain", submitted to Electronics Letters, 1995.

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