A Reconfigurable Optoelectronic Interconnect Technology for Multi-Processor Networks

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Abstract - This paper describes a new optical interconnect architecture and the integrated optoelectronic circuit technology for implementing a parallel, reconfigurable, multiprocessor network. The technology consists of monolithic arrays of optoelectronic switches that integrate vertical-cavity surface-emitting lasers with three-terminal heterojunction phototransistors, which effectively combine the functions of an optical transceiver and an optical spatial routing switch. These switches have demonstrated optical switching at 200 Mb/s, and electrical-to-optical data conversion at >500 Mb/s, with a small-signal electrical-to-optical modulation bandwidth of ~4 GHz.

INTRODUCTION

In order to link many electronic processors together to form an interactive network with a parallel processing capability, an interconnect technology is needed to provide real-time, multi-point transfer of a large volume of data between multiple nodes, which will exceed the capability of the traditional single-access data bus. New interconnect paradigms are needed that will allow many processors to communicate simultaneously with each other and with shared resources on separate modules, and with a high-speed switching capability to facilitate the dynamic reconfiguration of the interconnections. This paper describes an OEIC technology and an optical interconnect architecture that provide high-speed, multi-access optoelectronic interconnections between electronic processors, allowing them to communicate through integrated optoelectronic transceivers and compact, monolithic, space-division-multiplexed switches that provide an optical link to other nodes and electrical access to each processor.

THE INTERCONNECT ARCHITECTURE

Figure 1 shows a multi-stage ring network consisting of monolithic optoelectronic switch arrays, which can be programmed to produce optical and electrical outputs with different spatial configurations. Each node is connected to an electronic processor, which can access the network through an optoelectronic interface. The ring geometry enables the end-to-end connection between any two nodes through intermediate hops. A physical connection between nodes is made by selecting a routing path through one or more stages of the switching fabric using simple voltage control. Each node can either *transmit* or *receive* optical data, or to *re-route* it optically to the next stage

Figure 1: A reconfigurable, close-ring, interconnect architecture linking clusters of nodes through parallel optical paths set by optoelectronic switch arrays with electrical input and output ports. Each switch contains a segmented HPT interconnected individually to different VCSELs in the array, and can receive, transmit, or re-route optical signals.

(bypass mode). The received optical data is converted into an electrical signal (E_{out}), which may be *dropped* at that node, or it may be *regenerated* optically and routed to the next stage (P_{out}). The switch may also accept electrical input data (E_{in}) from a local electronic processor and convert it into an optical format (P_{out}) for transmission and routing. The modes of data transfer through the network include point-to-point, multi-point, broadcast, and the optical data transmission can be terminated at any stage by programmable voltage control. Examples of these functions are shown in Figure 1.

In this architecture, each switch node needs to provide an optical source and a photodetector, as well as their drive circuitry and the optical/optoelectronic switching functions that convert digital signal between various combinations of electrical and optical input/output formats. In the following, we will describe an OEIC technology suitable for the implementation of the above design.

THE INTERCONNECT TECHNOLOGY AND OPTOELECTRONIC SWITCH DESIGN

The technology consists of multi-functional optoelectronic switches based on the monolithic integration of GaAlAs/GaAs vertical-cavity surface-emitting lasers (VCSELs)

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with heterojunction phototransistors (HPTs) and heterojunction bipolar transistors (HBTs), some components of which were previously reported in [1, 2]. One motivation for this work is to achieve the functional integration of the photodetector, optical source and drive electronics that enable the processing and routing of data in either an optical or electrical format, thus providing an efficient interface between the optical network and electronic processor. Significant advances have been made in the performance of discrete devices such as VCSELs, HPTs, and HBT integrated circuits in recent years [3-8]. Current state-of-the-art VCSELs grown by MOCVD with compositionally-graded DBR heterointerfaces can operate at a bias voltage under 2-3V and at current levels that are less than 5-10 mA. The VCSEL can also be integrated with HBTs and HPTs, which share the same epitaxial layers and operate at current densities that are

Figure 2: The (a) schematic diagram and (b) device layout of an integrated three-terminal HPT/VCSEL switch.

comparable to those of the VCSEL, in order to achieve both optical and optoelectronic switching, and to provide an integrated electronic driver technology. This OEIC technology provides a high performance OEIC platform with potential applications in optical switching networks and reconfigurable optical interconnects, which was described previously in [9].

An integrated switch with a *minimum* number of elements, which can perform the optoelectronic conversion and optical bypass and switching functions required by the interconnect architecture, is shown schematically in Figure 2a. It consists of a three-terminal heterojunction phototransistor (3T-HPT) and a vertical-cavity surface-emitting laser (VCSEL). The switch can be activated by either an optical signal (P_{in}) from another node or by the electrical input (E_{in}) from a local processor, which produces a switched optical output (P_{out}) from the VCSEL that is transmitted to the next node, as well as a

modulated current output (E_{out}) that is coupled to an electronic processor. The phototransistor base terminal serves as an electrical input port for both data and prebias. With electrical access to the base, the operating characteristics of the switch can be adjusted through a bias voltage. For example, the switch can be prebiased near the lasing threshold of the VCSEL to minimize the optical power needed to effect switching. More importantly, by segmenting the HPT into two contiguous but electrically isolated elements that share a common optical input, and connecting each segment to a different VCSEL output port, reconfigurable spatial routing of the optical data can be achieved by independently controlling the bias voltage of each HPT/VCSEL pair [1].

The crystal growth of the switch epilayers starts with the VCSEL structure on an n-GaAs substrate, which consists of two GaAlAs/GaAs Distributed Bragg Reflectors (DBRs) enclosing a graded-index-separate-confinement-heterostructure (GRINSCH)-multiple-quantum-well (MQW) active layer [10]. Undoped AlAs and GaAs buffer layers are then grown for electrical isolation, followed by the growth of the HPT/HBT epilayers, which have an emitter-up configuration [11]. This structure provides the integrated HPTs and VCSELs with a common n-contact, which is suitable for the emitter-follower circuit configuration that is used in the spatial routing applications. Another potential application of the integrated HBT/VCSEL circuits is for high-speed electrical-to-optical signal conversion, where a common-emitter driver configuration (in which the laser is connected to the collector of the HPT) may be advantageous, since it offers a lower base bias voltage and a lower input impedance. However, this requires a structure that is grown on a semi-insulating or p-type GaAs substrate, or alternatively, an individually optimized hybrid approach is needed.

Figure 2b shows the device layout of an integrated, unsegmented three-terminal HPT/VCSEL switch (one-half of a routing switch). The HPT shown has a $20 \times 20 \mu m^2$ emitter area that is partially covered by a $4 \times 10 \mu m^2$ emitter contact, and a base-collector junction area of $30 \times 40 \mu m^2$. The VCSEL has an active area diameter of $20 \mu m$, which is defined by proton-implantation, and a $16 \mu m$ diameter optical output aperture. The optical input (P_{in}) illuminates an area between the emitter and base contacts which is approximately $30 \times 18 \mu m^2$. The differential current gain of the HPT is $\beta = 25-50$ in the current range that is 1-3 times the threshold current of the VCSEL ($I_{th} = 5.2 mA$). The collector-emitter voltage of the HPT saturates at $\sim 1.6V$ at $I_c = 17 mA$, and since the VCSEL bias voltage is less than $2.8V$ at $I_c = 20 mA$ ($2.1V$ at threshold), the switch can operate with a total bias voltage of $< 4.5V$. The differential slope efficiency η_s of the VCSEL is $\sim 12\%$ at $2I_{th}$, which is lower than its value near I_{th} as a result of multiple transverse modes.

DEVICE CHARACTERISTICS AND EXPERIMENTAL DEMONSTRATION OF THE SWITCHING FUNCTIONS

The optical input to the HPT and the optical output from the VCSEL are both surface-normal. In the experimental setup shown in Figure 3, the optical input is coupled to the HPT through a single-mode fiber. The differential power conversion efficiency $\eta_{HPT} = \Delta I_c / \Delta P_{in}$ ($2.1-3.5 mA/mW$, measured) is also defined by the relation $\eta_{HPT} = (e/h\nu)\eta_c\eta_d\beta$, where η_c ($\sim 30\%$) is the input coupling efficiency, η_d is the external quantum efficiency of the HPT, e is the electron charge, $h\nu$ is the photon energy, and

β is the differential current gain (~ 25). The value of η_d (60–65%) is determined by using a large area photodetector with the same base-collector junction which is fabricated on the same material. The optical output from the VCSEL is collected by a multi-mode fiber with a coupling efficiency of $>85\%$, and is detected by a silicon PIN photodiode and a transimpedance amplifier (bandwidth ~ 1 GHz, transimpedance ~ 2.8 k Ω). The eye-

Figure 3: The experimental setup for optical and optoelectronic switching.

diagrams shown in Figure 4 represent the optical response P_{out} (lower traces) and electrical response E_{out} (upper traces) of the switch to large-signal modulation by pseudorandom optical input data P_{in} (left) and electrical input data E_{in} (right) at 200Mb/s. The 10%-90% rise time of each pulse is 0.8ns.

The switching functions are demonstrated using different combinations of optical and electrical inputs and outputs. The HPT is modulated optically and electrically by two distinct, non-overlapping, 16-bit-long word patterns with a bit rate of 200Mb/s. The electrical input contains a voltage modulation superimposed on a dc bias (~ 3 V) that sets the switch near the lasing threshold of the VCSEL. The same electrical prebias is also applied in the case of an optically modulated input. The first two traces in Figure 5 show the modulated collector current I_c in the presence of *only* the electrical (trace 1) or optical (trace 2) input data, which also demonstrate the electrical-to-electrical and optical-to-electrical conversion of the input data. Traces 3 and 4 show the modulated electrical and optical output (P_{out}) when the optical and electrical data are *both* present, each trace containing replicas of both the optical and electrical inputs, thus showing the

Figure 4: Eye-diagrams showing the optical (lower traces) and electrical (upper traces) response of a single HPT/VCSEL switch to large-signal, pseudorandom modulation by optical (left) and electrical (right) input data at 200Mb/s.

Figure 5: Time traces showing the electrical (trace 3) and optical (trace 4) response of the switch to combined electrical (trace 1) and optical (trace 2) input data.

conversion of P_{in} and E_{in} into both an optical output (P_{out}) and an electrical output (E_{out}). The modulated P_{in} has an amplitude of $\sim 356 \mu\text{W}$, while the corresponding modulated I_c has an amplitude of 1.5mA, giving a signal conversion efficiency of $\eta_{HPT} = 4.3 \text{ mA/mW}$. The corresponding modulated optical output has an amplitude of $\sim 145 \mu\text{W}$. The lack of optical gain for this device is due to the low values of its current gain β and VCSEL slope efficiency η_s , which can be improved to achieve cascaded operation. The HPT design and processing must be optimized to achieve a larger optical gain-bandwidth product, which is necessary for efficient, cascaded optical switching operation.

Figure 6a shows the small-signal electrical-to-optical modulation response of an integrated HBT/VCSEL switch with a reduced emitter size of $10 \times 10 \mu\text{m}^2$. The optical response of the VCSEL to a small-signal modulation of the base voltage has been measured for different values of bias current I_c . The forward transmission coefficient S_{21} shows the typical resonant frequency response of a laser modified by the current transfer characteristic of the emitter-follower circuit, which is proportional to $(1 - S_{11})(1 + \beta)L(f)$, whose terms represent, respectively, the ratio of the transmitted signal to the signal incident to the base (S_{11} is the reflection coefficient), the current gain of the HBT, and the current-to-light modulation response of the VCSEL. As the bias current I_c is increased, the resonant frequency shifts from 1.2 to 4GHz, and the resonance peak is increasingly attenuated. The modulation response saturates at a maximum bandwidth of ~ 4 GHz. Further increasing I_c introduces multiple transverse modes in the VCSEL response, giving rise to an additional resonance which appears at a lower frequency (1–2 GHz). The small-signal base-to-collector current gain (h_{21}) of the integrated HBT/VCSEL switch is shown in Figure 6b, which indicates a unity-gain bandwidth of ~ 500 MHz. Figure 7 shows the eye diagrams of the above switch under 500Mb/s large-signal pseudorandom data modulation (PRBS 2²³-1). The electrical current I_c and the optical output P_{out} are monitored simultaneously. The upper trace represents the modulated light output of the VCSEL, which has an optical power amplitude of 0.35 mW. The bottom trace shows the modulated collector current I_c , with a 6.8mA current modulation superimposed on a 7.2mA dc bias. The modulated electrical pulses have symmetrical rising and falling edges, with a 10%-90% transition

the fall time is limited by the HBT.

SUMMARY AND CONCLUSIONS

In conclusion, we have described a new optical interconnect architecture for multi-processor networks and the design of integrated HPT/VCSEL switches for its implementation. The functional integration of optical source, photodetector and drive circuitry achieved by the monolithic HPT/HBT/VCSEL switch provides a combined optical and optoelectronic switching capability to convert either electrical or optical input data into both optical and electrical outputs. The optical switching functions have been experimentally demonstrated at a data rate of 200Mb/s. An integrated HBT/VCSEL switch has also achieved a small-signal electrical-to-optical modulation bandwidth of 4GHz, and large-signal modulation at 500Mb/s has been demonstrated. Optimizing the HPT/HBT design and processing, especially reduction of the device size, can significantly improve the gain-bandwidth product of the switch, which is important for achieving lossless optical regeneration and optically cascaded switching operation.

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Figure 6: The small-signal modulation response of an HBT/VCSEL switch, showing (a) the forward transmission coefficient S_{21} and the current gain h_{21} , and (b) the electrical-to-optical modulation response at different dc bias currents.

Figure 7: The eye diagram of an HBT/VCSEL switch under 500Mb/s pseudorandom data modulation, showing the modulated optical output of the VCSEL (upper trace) and the modulated collector current (bottom trace).

time ($\sim 2.2\tau$) of 0.6ns. When the switch is pre-biased above the laser threshold, the optical response shows no significant pulse narrowing due to a turn-on delay. The modulated optical output has asymmetrical rise and fall times, with a rise time of 0.6ns and a longer fall time of 0.8ns. The rise time is limited currently by the HBT while the fall time is limited by the VCSEL. When the switch is pre-biased with the VCSEL near or below threshold, a turn-on delay occurs and the rise and fall times of the optical signal are significantly reduced as a result of electrical gain-switching. A fast rise time of less than 100ps is observed, while

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