REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank)*

2. REPORT DATE
01/18/00

3. REPORT TYPE AND DATES COVERED
FINAL: 01 OCTOBER 96 through 30 SEPTEMBER 99

4. TITLE AND SUBTITLE
Novel WDM Device and System Research For Ultra High Capacity Optical Interconnects

5. FUNDING NUMBERS
FDN00014-96-1-1267
96PR07977-00

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10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Massively parallel interconnection planes can provide an extremely high bandwidth 2-D switching system. By adding wavelength selectivity into the interconnect system, we can significantly increase both the interconnect capacity as well as the dynamically reconfigurable functionality. This program includes a cohesive and comprehensive multi-disciplinary effort at both device and system levels, with novel devices and new systems using these devices. We achieved device-to-systems technology transfer and systems-to-device technology feedback between the two labs. Successful collaborations among students from the two PI's groups were accomplished resulting in many joint publications and patents.

The major accomplishments for devices include demonstrations of a tunable VCSEL and tunable detector with the widest continuous tuning range; and demonstration of multi-wavelength VCSEL array and detectors for WDM optical interconnects applications. Detailed characterizations have been performed on packaged devices. Mathematical modeling on tuning-dependent device performance and fabrication/design tolerance was also performed.

The accomplishments for systems include demonstration of a multiple-plane WDM interconnection and a highly connected and robust ShuffleNet network using a WDM multiple-plane optical interconnection and analysis of its physical limitations concerning: power budget and speed, and the use of integrated electronics for reducing power requirements.

14. SUBJECT TERMS
VCSEL, vertical cavity surface emitting lasers, semiconductor diode lasers, optical communications, wavelength division multiplexing, optical interconnects

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-102

ULTRA PHOTONICS II PROGRAM
ONR CONTRACT NUMBER N00014-96-1-1267

NOVEL WDM DEVICE AND SYSTEM RESEARCH FOR ULTRA HIGH CAPACITY OPTICAL INTERCONNECTS

DURATION: 10/1/96 TO 9/30/99

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1 OVERVIEW

Massively parallel interconnection planes can provide an extremely high bandwidth 2-D switching system. By adding wavelength selectivity into the interconnect system, we can significantly increase both the interconnect capacity as well as the dynamically reconfigurable functionality. Wavelength selectivity will allow for any given plane to communicate simultaneously and reconfigurably with many other 2-D planes, thereby considerably increasing the overall interconnect capacity. Furthermore, functionality can be dramatically enhanced in this 2-D configuration by implementing parallel control signals, novel switch configurations (i.e., ShuffleNet), and bi-directional transmission. This will allow the data to remain in optical form for considerably more of the data path, thereby reducing any optoelectronic speed bottleneck. Additionally, scalable growth is enabled as pixel densities and the number of wavelength channels increase. Finally, the multiple-spatial-path and low-delay nature of our WDM interconnection significantly decreases message delay and contention probabilities, as well as provide broadcasting capability

This program includes a cohesive and comprehensive multi-disciplinary effort at both device and system levels, with novel devices and new systems using these devices. The major accomplishments for devices include demonstrations of a tunable VCSEL and tunable detector with the widest continuous tuning range; and demonstration of multi-wavelength VCSEL array and detectors for WDM optical interconnects applications. Detailed characterizations have been performed on packaged devices. Mathematical modeling on tuning-dependent device performance and fabrication/design tolerance was also performed.

The accomplishments for systems include demonstration of a multiple-plane WDM interconnection and a highly connected and robust ShuffleNet network using a WDM multiple-plane optical interconnection and analysis of its physical limitations concerning: power budget and speed, and the use of integrated electronics for reducing power requirements.

With this program's support, we strengthened our multi-disciplinary interactions to allow for a quantum leap in ultra-high-capacity wavelength-selective multiple-plane interconnects. We achieved device-to-systems technology transfer and systems-to-device technology feedback between the two labs. Successful collaborations among students from the two PI's groups were accomplished resulting in many joint publications and patents. The goal of our technology transfer has been to provide a design for the manufacture an ultra-high-density WDM-based multi-chip interconnect module. This was largely accomplished.

The creation of our novel devices will open the door to the development of novel systems with significantly improved functionality, performance and capacity. The evolution of Terabit per second systems will rely heavily of the exploitation of such devices. As the number of 1 Gb/s channels grows from the 10s to the 100s to the 1000s in dense interconnections, the demonstration of Tb/s systems will be realized. The novel systems we built will capitalize on the massively parallel and wavelength-selective nature of our interconnections.

2 MAJOR ACCOMPLISHMENTS

2.1 TUNABLE VCSEL

We demonstrated a tunable VCSEL with the widest tuning range of 32 nm, the widest continuous tuning for all diode lasers reported to-date, to the best of our knowledge. Excellent laser characteristics were attained with 0.5-1.5 mA threshold current and ~1 mW output power under room temperature CW operation throughout the entire tuning range. This tunable laser uses a single electrode and less than 1 microWatts to tune and has a tuning speed of ~3 microseconds. The process is wafer-scale and naturally yields 2D array.

The performance of tunable VCSELs as a function of temperature and wavelength has been characterized in details. The temperature-dependent wavelength shift for the tunable VCSEL is 25% less than that of a typical DFB laser, making it highly desirable for WDM applications.

2.2 MULTI-WAVELENGTH VCSEL ARRAYS AND CHANNEL-DROPPING DETECTORS

We fabricated, tested, and packaged pixel array of multi-wavelength detector arrays for system demonstration. Wafer-scale fabrication of MW detector array was demonstrated using novel periodically patterned substrate in MBE (molecular beam epitaxy growth). These devices have been crucial for the implementation of very high capacity plane-to-plane WDM interconnects.

We fabricated, tested, and packaged pixel array of multi-wavelength VCSEL arrays for system demonstration. The electrical interconnects problem was solved by introducing a novel oxidation isolation process, which lead to uniform and very high yield VCSEL array.

We fabricated, characterized and packaged novel channel-dropping detectors for WDM interconnects. This detector increases signal to noise ratio by 10 fold comparing to a regular quantum well detector. Three detector planes were packaged, with three selection wavelengths, were delivered to USC for system implementations

2.3 WDM SYSTEMS

We constructed and characterized an experimental interconnection using VCSEL and detector arrays. The system consists of: (i) the transmitting and detecting planes contain integrated device arrays, (ii) 3 WDM pixels are available on each plane, and (iii) a multiple quantum well (MQW) with an integrated distributed Bragg reflectors (DBR) mirror is used at the middle detector plane to enhance wavelength selectivity. This experiment demonstrated the reconfigurable and simultaneous WDM interconnections between planes at 155 Mbit/s. The transmitting plane incorporated 3 transmitting pixels each identically containing a 3-wavelength VCSEL array, and detector planes used MQW detectors in which the middle detector plane is the novel channel-dropping detector, which includes an integrated DBR mirror with the MQW structure. This detector provided superior wavelength selectivity and lower crosstalk by selectively detecting only the desired wavelength as well as simultaneously: (i) blocking the shorter wavelength signals from being either detected at a given plane or transmitted to any successive planes, and (ii) transmitting the longer wavelength signals.

Multiple-wavelength technologies can be used to efficiently connect many users by employing the optical Multihop Shuffle Network architecture. This architecture allows each network node to use only a few available wavelengths while still enabling that each node connect to many nodes through multiple "hopping" (i.e., detection and retransmission). We have demonstrated a 2-stage Multihop Shuffle Network using a 2-D multiple-plane WDM optical interconnection. The data-relay hopping was realized by using four 2-D WDM optical interconnection planes with integrated multiple-wavelength WDM VCSEL arrays and wavelength-selective detector arrays. Two-hop interconnections of the Shuffle Network were performed at 622 Mbps. Note that our data rate was 4 times greater than in previous WDM interconnections. The multihop data relaying is performed by using two interconnection modules, in which each module represents one stage (i.e., hop) in the network. By combining the 2-D WDM interconnection and the Shuffle Network, we provided efficient and high-capacity switching.

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	W. Yuen, PhD 1999
	Giorgio Giaretta, PhD 1997
	Yongan Wu, PhD 1997
	Dan Francis, Postdoc, 1998
	J. Yoo, PhD 1999
	J.E. Leight, PhD 1997

4 PUBLICATIONS, CONFERENCE TALKS AND PATENTS

- 34 journal publications and conference presentations
- 12 invited talks
- 1 patent application

4.1 REPRESENTED PUBLICATIONS

1) C.J. Chang-Hasnain, "Advances of VCSELs", published by the Optical Society of America, Trends in Optics and Photonics Series, 1997.
2) M.Y. Li, W. Yuen, G.S. Li, and C.J. Chang-Hasnain, "Top-Emitting Micromechanical VCSEL with a 31.6 nm Tuning Range", Photonics Technology Letters, 10, 1, pp. 18-20, Jan. 1998.
3) M. S. Wu, G. S. Li, W. Yuen and C. J. Chang-Hasnain, " Widely Tunable 1.5μm micromechanical optical filter using AlOx/AlGaAs DBR", Electronics Letters, vol. 33, no. 20, pp. 1702-3, September, 1997.
4) G. S. Li, W. Yuen and C. J. Chang-Hasnain, "A Wide and Continuously Tunable Detector with Uniform Characteristics Over Tuning Range," Electronics Letters, 33, 13, 1122-4, June 1997.
5) E.C. Vail, G. S. Li, W. P. Yuen, C. J. Chang-Hasnain, "High Performance And Novel Effects of Micromechanical Tunable Vertical Cavity Lasers", to appear in IEEE Journal of Selected Topics in Quantum Electronics on Semiconductor Lasers, 3, 2, pp 691-697, April 1997.
6) W.Yuen, G.S.Li, and C.J. Chang-Hasnain, "Multiple-wavelength vertical-cavity surface-emitting laser arrays," IEEE Journal of Selected Topics in Quantum Electronics on Semiconductor Lasers, 3, 2, pp 422-428, April 1997.
7) J.J. Yoo, J.E. Leight, C. Kim, G. Giaretta, W. Yuen, A.E. Willner, and C.J. Chang-Hasnain, “Experimental Demonstration of a Multihop Shuffle Network Using WDM Multiple-Plane Optical Interconnections with VCSEL and MQW/DBR Detector Arrays,” IEEE Photonics Technology Letters, vol. 10, pp. 1507-1509, 1998.
8) J. Yoo, J.E. Leight, G. Giaretta, W. Yuen, A.E. Willner, and C.J. Chang-Hasnain, “Experimental Demonstration of a 4-Plane 2-D Multiple-Wavelength Optical Interconnection Using Integrated VCSEL Arrays and MQW/DBR Detectors,” IEEE Photonics Technology Letters, vol. 9, pp. 1646-1648, 1997.
9) J.E. Leight, J. Yoo, and A.E. Willner, “System Design and Performance of Reconfigurable and Simultaneous 2-D Multiple-Plane WDM Optical Interconnects,” IEEE Electronics Letters, vol. 33, pp. 613-614, 1997.

10) J.E. Leight, S. Homan, A.E. Willner, G. Giaretta, M.Y. Li, and C.J. Chang-Hasnain, "Experimental Demonstration of a Reconfigurable and Simultaneous Wavelength-Division-Multiplexed Multiple-Plane Optical Interconnections," IEEE Photonics Technology Letters, vol. 8, pp. 302-304, 1996.

4.2 PATENT APPLICATIONS

1. Wupen Yuen and C. Chang-Hasnain, "Reproducible Multiple-Wavelength Vertical-Cavity Surface-Emitting Laser Arrays Using A Novel In-Situ Monitored Thermal Redesoption Method", US patent application filed May 13, 1998.

FINAL REPORT

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NOVEL WDM DEVICE AND SYSTEM RESEARCH FOR ULTRA HIGH CAPACITY OPTICAL INTERCONNECTS

DURATION: 10/1/96 TO 9/30/99

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TABLE OF CONTENTS

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3 DEVICE RESULTS

Semiconductor diode lasers with precise wavelengths are critical for optical communications. This is clearly exhibited by the explosive growth of DFB laser market for dense wavelength division multiplexed (DWDM) applications. A wavelength-tunable laser and multi-wavelength laser array are expected to further enhance the capacity and reconfigurability of DWDM systems and, thereby, enable a large set of advance applications.

VCSEL is uniquely well suited for making wavelength tunable or multi-wavelength devices. The VCSEL has an ultrashort cavity length – more than two orders of magnitude shorter than an EEL – and thus typically has only one Fabry-Perot (FP) mode (within the laser gain bandwidth), which determines the lasing wavelength. Thus, by varying the cavity length slightly, the lasing wavelength can be varied accordingly. This presents an excellent and unique opportunity for engineering multi-wavelength laser arrays and wavelength-tunable lasers. Multi-wavelength laser array can be attained by implementing thickness variation in some of the layers in the vertical cavity, whereas continuous tuning can be achieved by directly tuning the Fabry-Perot modes. Both are simple and elegant solutions for communication applications.

A VCSEL array with 140 uniformly spaced distinct wavelengths was first demonstrated in 1990,[1] which marked the beginning of wavelength-engineering of VCSELs and VCSELs for WDM system applications.[2] A multi-wavelength VCSEL array can be grown by simply tailoring the thickness of some of the layers in the VCSEL cavity (Fig. 1). A variety of techniques have been reported to fabricate monolithic multi-wavelength arrays. The most effective method is to introduce a few layers with spatially graded thickness into the VCSEL cavity. The spatial gradient can be created during the growth on a prepatterned substrate, using pattern-induced effects. By adding an *in situ* optical monitor, these pattern-induced growth effects can be precisely monitored to yield repeatable wavelengths in VCSEL arrays (Fig. 2). [3] Such arrays are promising transmitters for low-cost WDM systems. In this program, we achieved a record high wavelength span with excellent device performance.

Wavelength-tunable VCSELs were first made using well-known effects such as the carrier plasma and thermal effects. However, it was clear that no effect can vary wavelength as effectively and over as large a range as the physical change of the cavity length itself.[4, 5] One solution of this problem is to create a structure where the VCSEL top mirror may be translated via a micromechanical structure. Figure 3 shows a micromechanical tunable VCSEL, with its entire mechanical structure made of GaAs/AlGaAs epitaxial material with very high-thickness precision. An air–gap was made in the VCSEL cavity by selective removal of some of the epitaxy (GaAs) material. Thus, most of the VCSEL's top DBR is suspended above the rest of the heterostructure and is supported by a cantilever. A voltage is applied to the two contacts surrounding the air-gap, which makes the cantilever move up and down to vary the gap size, and thus, the VCSEL cavity length is varied, altering the Fabry-Perot wavelength. A third contact is used to inject current into the active region beneath the air-gap.

The VCSEL tuning range is limited by the smaller of the two: (1) the FP wavelength difference resulted from the maximum deflection, and (2) the free spectra range (FSR) of the cavity, which is now much less due to the longer effective cavity length. Since the maximum deflection is typically 1/3 of the default airgap size, for the same default airgap size, the farther the airgap is from the center the cavity, the less the FP wavelength difference can be obtained. To maximize the tuning range, the airgap size should thus be increased. This, however, leads to a longer cavity, which leads to a smaller FSR and thus clamps the tuning range. As the two factors operate in opposite directions, an optimum can be obtained. A very wide, nearly continuous tuning range of 32 nm (13 TH_Z) was achieved for this structure, shown in Fig. 4. This VCSEL also exhibits excellent and uniform light-current characteristics over the entire tuning range, as seen in Fig. 5.

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1. C.J. Chang-Hasnain *et al.,* "Multiple wavelength tunable surface emitting laser arrays," IEEE J. Quantum Electron. **27** (6), 1368-1376 (1991).
2. M.W. Maeda *et al.,* "Multi-gigabit/ s operation of 16-wavelengthvertical cavity surface emitting laser array," IEEE Photonics Technology Lett. **3** (10), 863-865 (1991).
3. W. Yuen *et al.,* "Multiple-wavelength vertical-cavity surface-emitting laser arrays," IEEE Journal of Selected Topics in Quantum Electronics on Semiconductor Lasers **3** (2), 422-428 (1997).
4. E. C. Vail et al. "High performance micromechanical tunable vertical cavity surface emitting lasers," Electron. Lett., vol. 32, no. 20, p. 1888-1889, 1996.
5. M.Y. Li *et al.,* "Top-emitting micromechanical VCSEL with 31.6-nm tuning range," IEEE Photonics Technology Lett. **10** (1), 18-20 (1998).

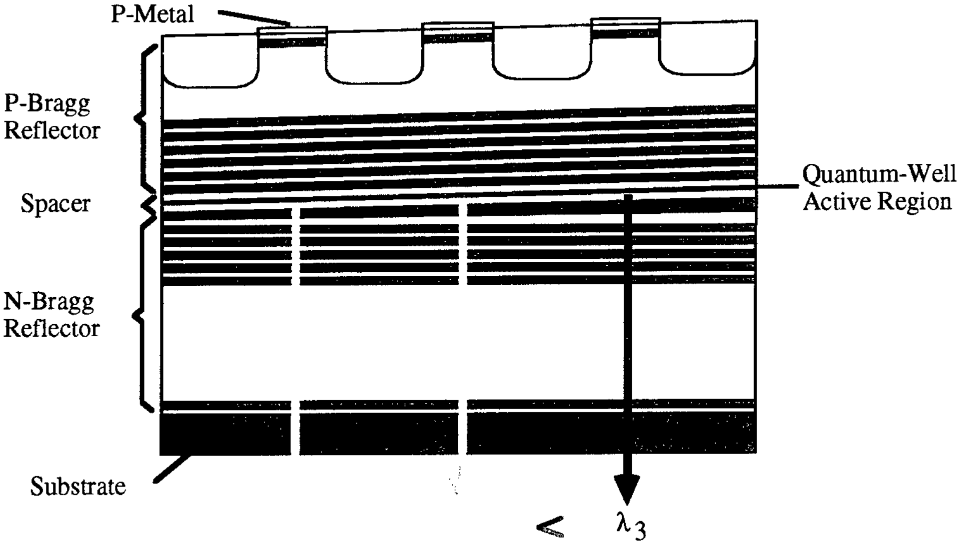


Figure 1 Schematic of the multi-wavelength VCSEL Array

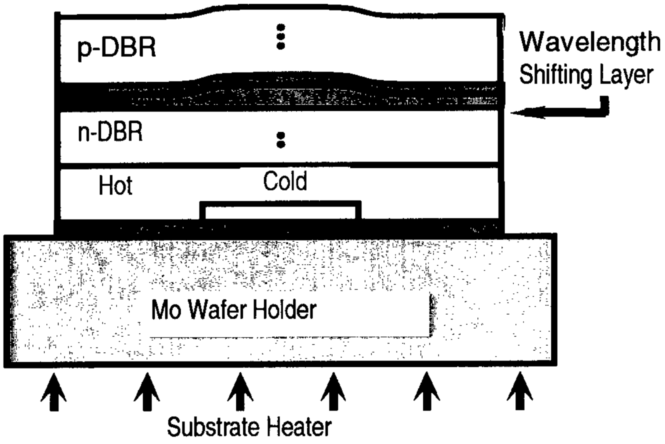


Figure 2 Schematic of the patterned substrate growth method for multi-wavelength VCSEL Array

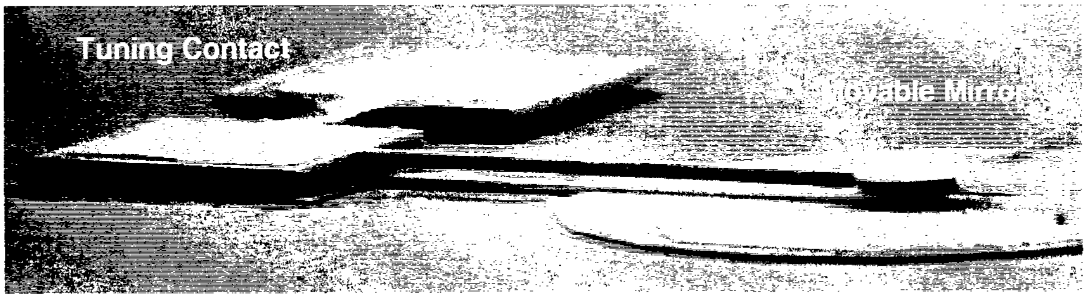


Figure 3 Scanning electron micrograph of a typical top-emitting tunable VCSEL. The cantilever is 100um long.

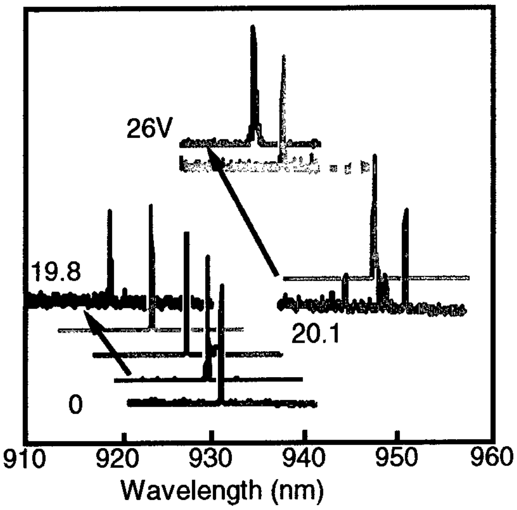


Figure 4 Tuning spectrum of a typical tunable VCSEL with 32 nm tuning range.

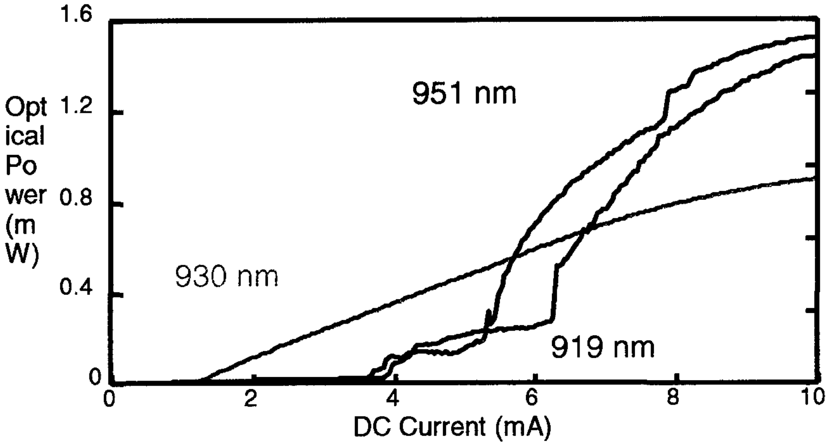


Fig. 5 Optical power vs. drive current characteristics. The laser emits ~1 mW over the tuning range.

4 SYSTEMS EXPERIMENTS

4.1 SHUFFLE NETWORK:

Figure 1 shows our 2-stage multihop shuffle network with 3-wavelength paths using the 2-D WDM multiple-plane optical interconnection. At the transmitting plane, each pixel containing a 3-wavelength VCSEL array is assigned a node number. At each detecting plane, an entire column of detector pixels represents a node number. The 4-plane WDM optical interconnection from the first-stage to the second-stage nodes provides a unidirectional interconnection module from the nodes of the transmitting plane to those of the detecting planes (upper part of Fig. 1). Another 4-plane WDM unidirectional interconnection module connects nodes from the shuffle network's second stage back to the first stage, thereby providing the reverse-direction interconnection (lower part of Fig. 1). We have created a fully connected multihop network by providing a data regeneration circuit for each node for the 2-stage shuffle network structure in which data relay can occur by rapid detection and retransmission.

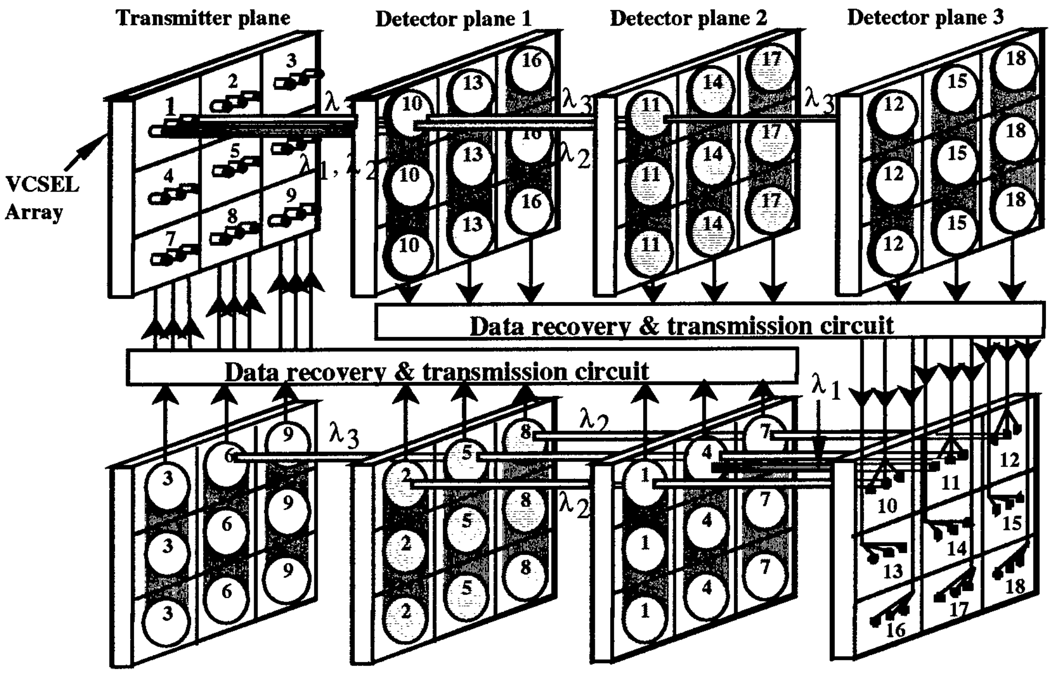


Figure 1. The 2-stage Shuffle Network structure using a 4-plane 2-D WDM optical interconnection

Figure 2 shows the responsivity of the detectors at each detecting plane and the spectra of the lasers from a transmitting pixel. The wavelength selectivity of the MQW detectors was attained by varying the composition of the quantum wells. In general, there is crosstalk from shorter wavelength signals at a given plane due to the residual optical power that is not fully absorbed at the previous planes. Furthermore, there is also longer wavelength signal crosstalk due to the partial detection of longer wavelength signals at the edge of the responsivity curve cutoff. To further enhance the wavelength selectivity and reduce crosstalk, a distributed Bragg reflector (DBR) was incorporated in the second detecting plane. This detector has a peak response near the desired wavelength λ_2 (939 nm) for Plane 2 and also has a very low response at both the shorter (λ_1, 930 nm) and longer (λ_3, 950 nm) undesired wavelengths. This uniquely shaped spectral response is a result of a novel design using the highly wavelength-dependent penetration depth of a distributed Bragg reflector (DBR) and by placing the MQW at the resonant positions of the desired wavelength. The standing wave peak resonant condition corresponds to λ_2, while the standing wave null anti-resonant condition matches λ_1 and λ_3. This allows Plane 2 to recover λ_2 signal even though the shorter (λ_1) and longer wavelengths (λ_3) are still present. Furthermore, λ_1 and λ_2 signals are attenuated by the DBR mirror after Plane 2 while λ_3 is allowed to pass. This ensures that unnecessary interference from shorter wavelength signals is practically blocked for all subsequent detecting planes, while the longer wavelength signal is transmitted for detection at subsequent planes. The third MQW detector plane then detects the remaining light, that being mostly λ_3.

The experimental results of the 2-stage shuffle network are shown in Figs. 3 (a) and 3 (b). For the 2-stage shuffle network demonstration, the data is regenerated after the first connection and retransmitted through the second connection. The bit-error-rate (BER) curves from the two-hop-relay connections are shown in Fig. 3 (a) at 155 Mbps for a 3-wavelength fanout, and in Fig. 3 (b) at 622 Mbps for a 2-wavelength fanout; note that single-hop connection measurements are shown for comparison. At 622 Mbps, only 2-wavelength fanout is shown due to the performance degradation of detecting plane 3 at the bit rate. For interconnections at 155 Mbps, Fig. 3 (a) shows the results for the reconfigurable cases, which do not include any crosstalk from other wavelengths. For the 622 Mbps cases, both reconfigurable and simultaneous interconnections are shown (Fig. 3 (b)). For the simultaneous interconnection, there is another signal wavelength operating within the same pixel, thereby causing crosstalk. For all cases, each two-hop-relay connection has a power penalty of 2-5 dB as compared to the single-hop connection. Comparing Figs. 3 (a) and 3 (b), the connections at 622 Mbps compared to 155 Mbps require an increase in power (3-6 dB) due to the limited bandwidth of the packaged devices.

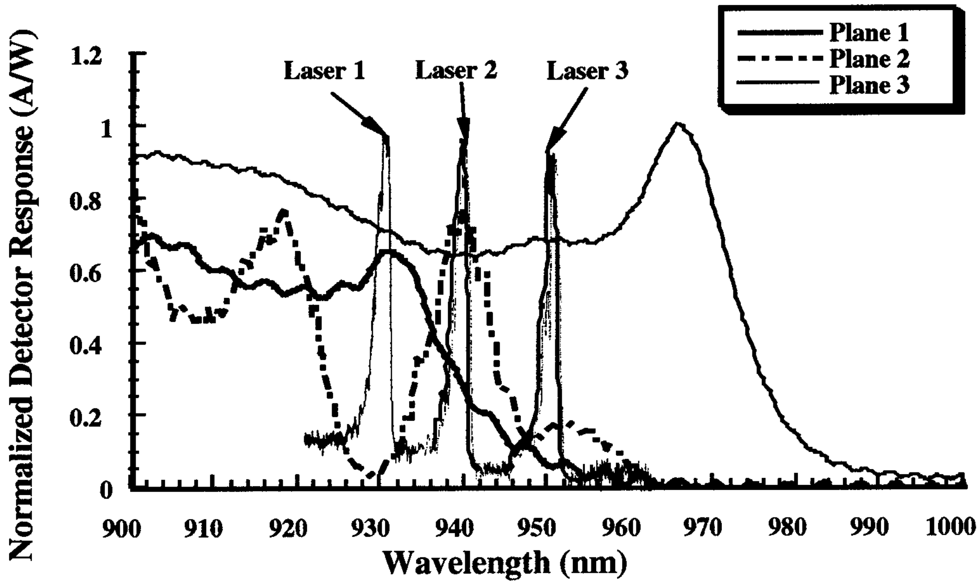


Figure 2. Responsivities of detecting planes and laser signal power spectra of the transmitting plane.

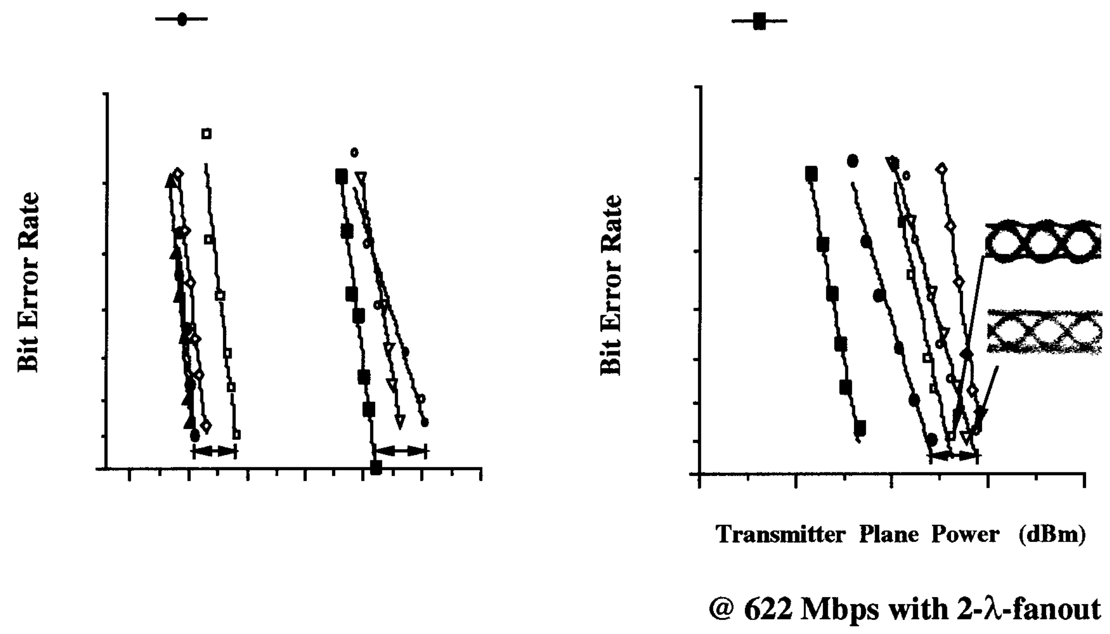
4.2 BI-DIRECTIONAL ROW-COLUMN MULTIHOP INTERCONNECTION

The amount of hardware needed to produce a shuffle network is 2 uni-directional multiple-plane buses. We explored the possibility of using a single bus that can function in a bi-directional mode, thereby saving nearly half of the required hardware. In this scenario, the planes have both transmitters and receivers on the same planes.

We experimented with 2x2 VCSEL/MSM detector chips to demonstrate the bi-directionality of the multihop optical interconnection. For the multihop interconnection structure, the row-column structure is the experimental model. Fig. 4 shows the basic concept of row-column 2-D optical interconnection. As the data is transmitted to the nodes on the next plane, it is retransmitted to the following planes as necessary (multihop). The row-column structure provides full connections between adjacent planes due to the N-dimensional fanout.

First, we investigated the effect of electrical interference from other devices on the same plane due to bi-directionality. Since the VCSEL and MSM detectors are on the same plane, the performance of the MSM detector is affected by neighboring VCSELs operating at the same time. We established an optical link between one VCSEL on another plane and one MSM detector and then turned on other VCSEL's on the same plane one by one to investigate what effect it has on the established optical link. Fig. 5 shows the result with BER curves and eye diagrams. Since the electrical current driving each VCSEL is bigger than the electrical current drawn from the detector, it has a significant effect on the eye diagram. Furthermore, the BER curves required about 2-5 dB more optical power to achieve the same performance compared to the case where there is no interference from neighboring VCSEL's.

Figure 6 shows the result of multihop optical interconnections with interference from other pixels. One-hop and two-hop interconnection with different types of interference are demonstrated. As shown, the interferences have some effect on the requirement of optical power needed to establish the optical link.



(a) (b)

Figure 3. (a) BER vs. optical power at the transmitter plane for the two-hop-relay at 155 Mbps. (b) BER vs. optical power at the transmitting plane for the two-hop-relay with at 622 Mbps.

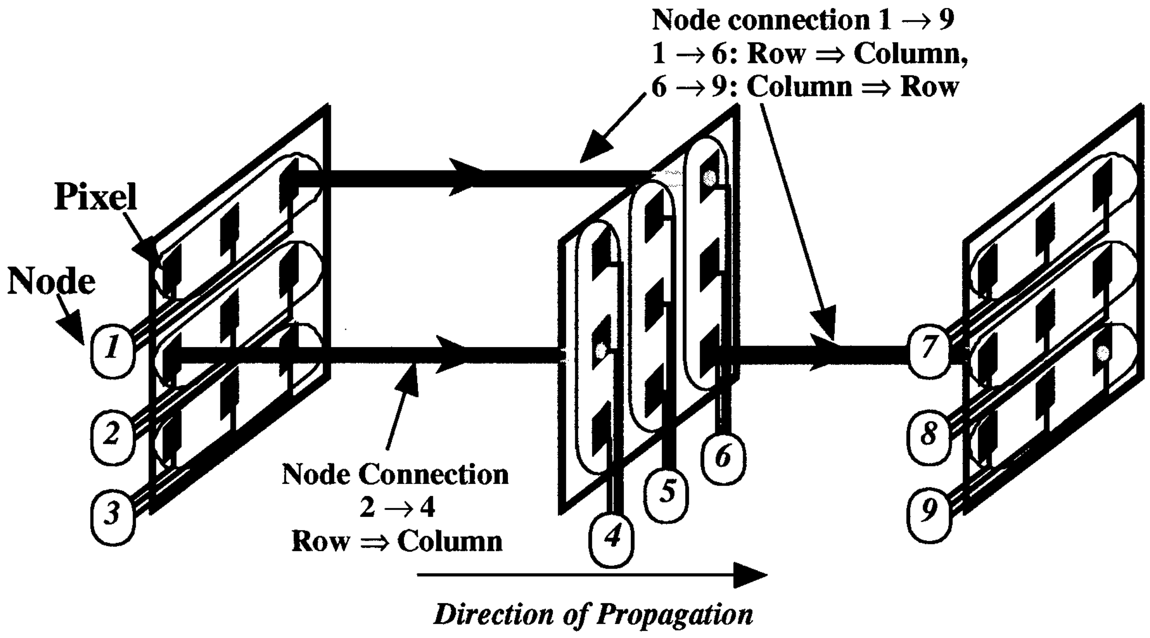


Figure 4. Row-column 2-D optical interconnection structure.

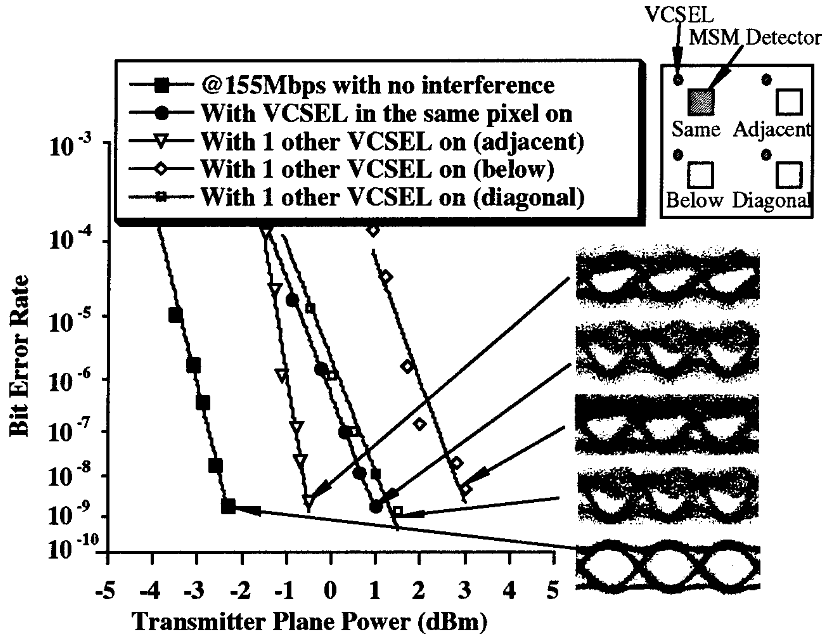


Figure 5. Electrical interference from neighboring VCSEL's on the same plane

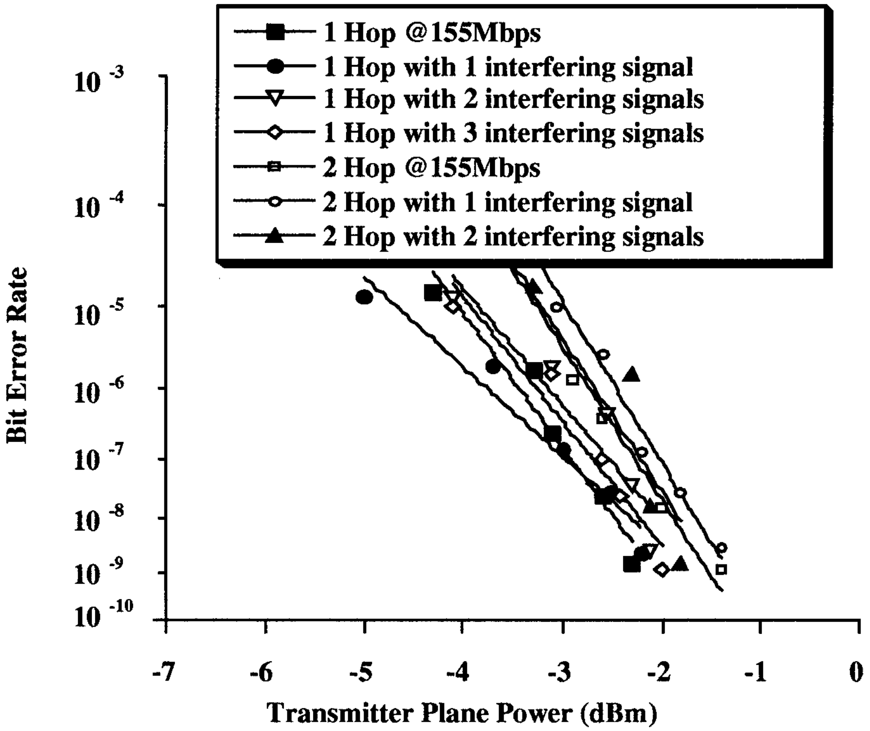


Figure 6. Multihop experiment with various interferences from other pixels.

5 IMPACT ON EDUCATION

The on-going research efforts in Chang-Hasnain group include novel high-performance and low-cost optoelectronic devices and their applications in new optical systems. The novel devices include multi-wavelength laser arrays, wavelength tunable lasers, widely tunable polarization-insensitive filters, and tunable detectors. Her group's activities spans from material growth, device design, fabrication, characterization, to some initial device packaging and fiber coupling.

The research program provided our students the opportunity to develop expertise in the crucial multi-disciplinary areas of optical system, device design and intelligent epitaxy.

The close collaboration with Prof. Willner's group and other system experts allowed device designers to be well informed of systems requirements and material realizability, system engineers to be trained to understand device/material issues, and in general, provide a broader technical training for PhD students.

Another major function for this program was to train undergraduates as well as Masters and Ph.D. students. The devices and research facility have been useful for in class demonstration and teaching of both undergraduate and graduate classes.

Prof. Willner's Optical Communications Laboratory has a satellite teaching facility for students to take basic optical communications measurements. With the support of this program, the students extended their learning, and experimental skills to take 10 Gbit/s measurements, quite impressive for any student to learn and quite important as a skill in their employment search.

6 STUDENTS AND VISITORS

Former students:
M. Y. Li, PhD 1999
G. S. Li, PhD 1999
W. Yuen, PhD 1999
Giorgio Giaretta, PhD 1997
Yongan Wu, PhD 1997
Dan Francis, Postdoc, 1998
Hao-Lin Chen, Visiting Scholar 1998

Current Students: Steve Chase, Lukas Chrostowski, Chih-Hao Chang, Jacob Hernadez, P. C. Ku, and Jeff Waite

USC Former and Current Students: J. Yoo, J.E. Leight, C. Kim, W. Shieh, E. Park, X.-P. Chen, B. Hoanca, K.-M. Feng, J.-X. Cai

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