Wavelength division multiplexers/demultiplexers for optical interconnects in massively parallel processing
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Autor: Feng Zhao, Yun Zhang, Jizuo Zou, Zhong Shi, Bipin Bihari,
Edward Frietman, Xuegong Deng, Jie Qiao, Zan Shi, Ray T. Chen
Bereitstellung: Dipl.- Ing. Björnstjerne Zindler, M.Sc.

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Feng Zhao
The University of Texas at Austin
PRC, MER 1606H
10100 Burnet Road
Austin, Texas 78758
E-mail: f.zhao@mail.mer.utexas.edu

Yun Zhang
Radiant Photonics, Incorporated
Kramer Lane
Austin, Texas 78758

Jizuo Zou
Zhong Shi
The University of Texas at Austin
PRC, MER 1606H
10100 Burnet Road
Austin, Texas 78758

Bipin Bihari
Radiant Photonics, Incorporated
Kramer Lane
Austin, Texas 78758

Edward Frietman
Delft University of Technology
Lorentzweg 1, 2628 CJ
Delft, The Netherlands

Xuegong Deng
Jie Qiao, MEMBER SPIE
Zan Shi
Ray T. Chen, FELLOW SPIE
The University of Texas at Austin
PRC, MER 1606H
10100 Burnet Road
Austin, Texas 78758

Abstract. Communication between computing systems is recognized as the main limitation to increase the speed of all-electronic systems beyond levels currently achieved in existing supercomputers. Optical interconnects hold great promise in eliminating current communication bottlenecks because of properties that stem from optics inherent parallelism. Wavelength-division multiplexing (WDM) technology, by which multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical transmission medium, is a useful means of making full use of optics parallelism in an application of interconnects for massive parallel processing. We first briefly review the bottlenecks of electrical interconnects in massively parallel processing. Then we discuss the advantages of optical interconnects and present our approach of optoelectronic interconnects in massively parallel processing by WDM technology. We then review the working principles of wavelength division (de) multiplexers [WD(D)M] for optical interconnects in massively parallel processing and address the optical design issues of WD(D)Ms. Finally, we report experimental data of WD(D)Ms for this application. The devices exhibit low insertion loss, high reliability, and low cost.
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Subject terms: wavelength division multiplexing; optoelectronic interconnect; optical interconnect; fiber optics; massively parallel processing; high throughput link.

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1 Introduction

Massively parallel processors can provide teraflops of computing power for solving problems containing trillions of data points and accessing terabytes of data. Such teraflop performance, derived from the product of the number of processing nodes and the processing power of each node, can be achieved by increasing the numbers of nodes, and fundamental improvements in hardware technologies and the communication among them. In enhancement of the processing power of the node and the density of nodes in ultra large scale integrated circuits (ULSI) and massively parallel processing, the communication congestion may arise in electrical interconnects for inter- and intra-nodal information exchange.[1,2] The problems met by electric interconnections in ULSI and massively parallel processors have a few aspects, such as RC time constant delay, clock skew and cross talk, and high power dissipation; especially when the system frequency is increased, these problems become severe[3] in massively parallel processing. The problems related to electrical interconnects are due to the fact that electrical interconnections are dominated by problems of classical electromagnetics, and such problems do not necessary scale well as semiconductor devices.

Optics has potential to solve all the communication congestion problems that exist in electrical interconnections for ULSI and massively parallel processing. Wavelength-division multiplexing (WDM) technology, which allows multiple optical channels to be transmitted simultaneously by transmitting different wavelengths through a single optical transmission medium, is a useful means of making full use of optics parallelism over a wide-wavelength region, which can dramatically enhance the throughput of each link. We review briefly the advantages of optical interconnects over electrical ones, and address the issues of WDM technology-based optical interconnects for massively paral-

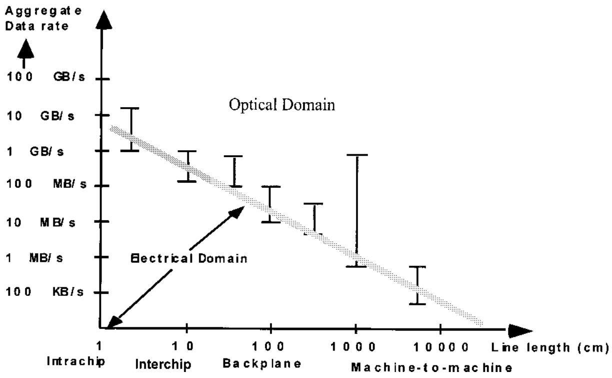


Fig. 1 The map of data rate and interconnect length.

lel processing. The working principle of grating-based WDM multiplexers/demultiplexers, design optimization, fabrication, and the experimental results are also discussed.

2 Optical Interconnects

In massively parallel processing the link distance ranges from a few to tens of meters. It is impossible to use electrical interconnects in these links at a high data rate (>100 Mbps) due to high radiation loss and sever crosstalk. Optics dominates the links in the range (see Fig. 1).[4,5]

There are many advantages of optical interconnections over electrical ones; for example, they are free from capacitive loading effects at high-signal propagation speeds, immune to mutual interference effects, and free from planar or quasiplanar constraints.[3,6–9] All of the potential advantages of optics in these regards come from the same fundamental difference between lightwaves and electromagnetic waves, which is the much higher frequency of light over that of electromagnetic waves used in electrical interconnects (see Ref. 2 in the details). In this case it brings the many advantages of optical interconnects, such as no frequency-dependent loss and cross talk when using lightwaves as the information carrier, and very large numbers of interconnections through "free space," in which all of the beams cross one another and also incidentally have little or no relative signal skew between the beams.

Multiple wavelengths of light signals can pass through the same space without any cross talk. WDM-based technologies utilize different wavelengths of light as different interconnect channels to increase connectivity and bandwidth. Recently, the availability of wavelength tunable VCSELs and receiver arrays provides us the possibility to realize high-density wavelength tunable vertical cavity surface emitting laser (VCSEL)-based WDM interconnect networks.[10] This wavelength tunable VCSEL-based WDM interconnect network can be constructed by placing a single wavelength tunable VCSEL and a number of receivers at every processing element (PE). The number of channels in such interconnects is limited by the range of wavelengths of the VCSELs that can be tuned in combination with other restricting optical parameters, such as diffraction limits, resolving distances, and resolution of diffraction elements.

In the approach presented in this work, the free-space WDM technology in conjunction with fiber optics and WDM lasers has been considered for realizing multiplexing interconnects for massively parallel processing. Figure 2 shows schematics of the working principle of the optical link demonstration between the processors. In this scheme, each of the N processors communicates with the PCI interface through a buffer. An M-bit parallel signal from the PCI interface is output to a (de)serializer, where encoding/decoding and multiplexing/demultipexing are furnished. Then output from the (de)serializer is input to the WDM

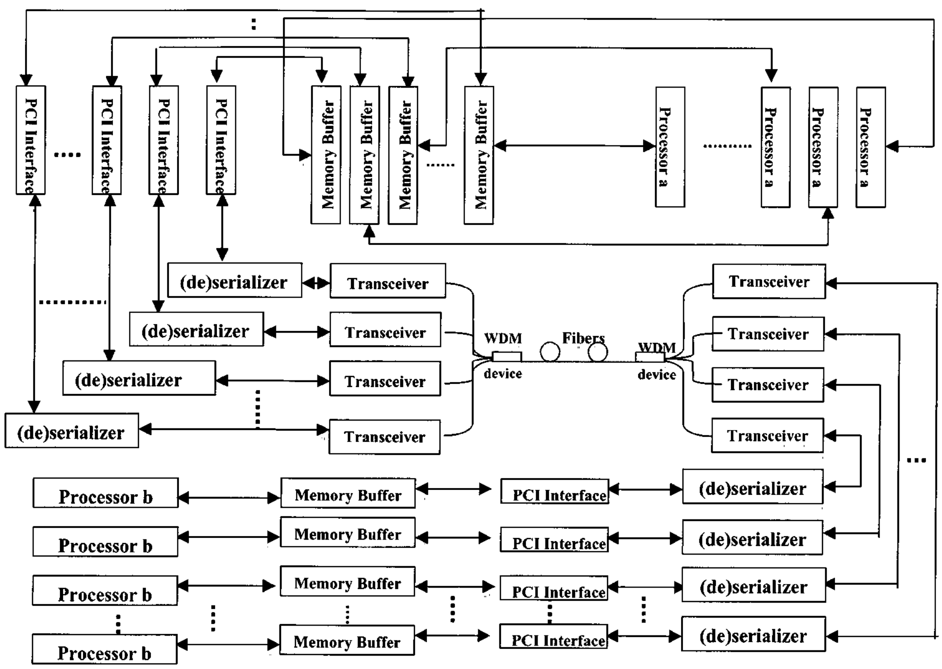


Fig. 2 Scheme of the working principle of the demonstration of optical links between the processors.

Table 1 The comparisons of the device performances based on the different technologies.

Technology	Flat top	Temperature control	Loss in high-count channel	Vibration stability	Bidirectional transmission	Multimode application
AWG	Possible	Yes	Low	Yes	Difficulty	Difficulty
Thin film	Yes	No	High	Yes	Difficulty	Difficulty
Blazed grating	Possible	No	Low	Possible	Yes	Yes

transceiver. The transceiver outputs are coupled to an optical fiber via a WDM. At the other end, another WDM is used to demultiplex the N wavelengths and feed them to the N transceivers. The outputs from the transceivers are fed to N (de)serializer chips, where clock extraction, demultiplexing, and decoding are done. The parallel signals from the (de)serializers are fed back to N M-bit peripheral component interconnect (PCI) interfaces. The signals go to the other N processors b through the buffer. PCI, (de)serializers, and WDM transceivers are commercially available. The WDM multiplexers/demultiplexers for optical links among the processors should have the bidirectional link capability and fit to multimode working environments. As mentioned at the beginning of this section, since the link distance is from a few to tens of meters, no optical amplifier is needed among the links. Since free-space-based WDM multiplexers/demultiplexers can meet the need, we chose grating technology to develop the WDM multiplexers/demultiplexers for this application.

3 Structure and Optimal Design of WDM Devices

3.1 *Structure of the WDM Device*

Most wavelength division multiplexers (WDMs) employ one of three technologies: arrayed waveguide grating (AWG), filters, and dispersive elements (primarily diffraction grating).[11–13] Although AWG technology is widely used for WDM devices, its strong temperature dependence often requires thermal regulation.[14] Multiplexers and demultiplexers based on filters exhibit high insertion loss for high counted devices.[15] The devices based on the two technologies mentioned before have difficulties in multimode and bidirectional transmission applications. They are not very suitable for application as high throughput optical links in parallel processing and computing. On the other hand, a grating-based WDM device offers several advantages such as low cost per channel, low loss, little cross talk, bidirectional transmission, and multimode features, for which it has received much attention.[16–24] Table 1 gives the comparisons of the device performances based on the different technologies mention before (for more information please Refs. 11–13). From the table we can see that only grating-based WDM devices are suitable in massively parallel processing applications.

Figure 3 illustrates the operating principle of grating-based WDM multiplexers/demultiplexers. An input fiber and multiple output fibers are arranged on the focal plane of the lens. Wavelength-multiplexed light signals from the input fiber are collimated by the lens and reach the diffraction grating. The light is angularly dispersed, reflected, and refocused by the same lens. The separating optical signals with the different wavelengths are coupled to corresponding output fibers. This functions as a demultiplexer. When working in the reverse direction, the device serves as a multiplexer. How well the device can separate the signals depends on the angle dispersion of the grating used (see the details in Refs. 11–13). If we put two layers of fiber arrays on the focal plane of the lens symmetrically about the optic axis, the devices can transmit WDM signals in bi-directions, that is, it can function as both mux and demux at the same time. Figure 4 shows the structure of the device.

3.2 *Optimal Design*

Optimal design of a WDM device must take into account the following constraints: 1. nominal wavelengths or frequencies of each channel; 2. number of channels; 3. channel separation, in wavelengths or frequency; 4. passing bandwidth of each channel, or channel capacity; 5. insertion loss; 6. the transmission spectrum over the passing bandwidth of each channel; 7. isolation among channels, or the power level due to cross talk; 8. polarization-dependent loss (PDL); 9. for passive devices, sensitivities due to ambient temperature, pressure, humidity variation, etc., 10. return loss (RL), 11. the power damage threshold, or the maximum optical power for each channel; and 12. pulse-broadening of the device. Other issues such as physical geometry, weight, input/output interfaces, and greater or lesser cost depending on the applications also directly affect the choice of design spaces.

WDM systems for telecommunication tend to use a 100-GHz frequency grid centered at 193.1-THz optical frequency, as recommended by the ITU Telecommunication Standardization Sector (ITV-T). Here in applications of shorter-distance data communication in massively parallel processing, much wider channel spacing can be used to

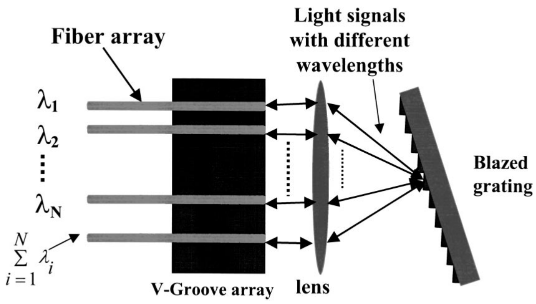


Fig. 3 The diagram for the structure of the grating-based WDM multiplexer/demutiplexer.

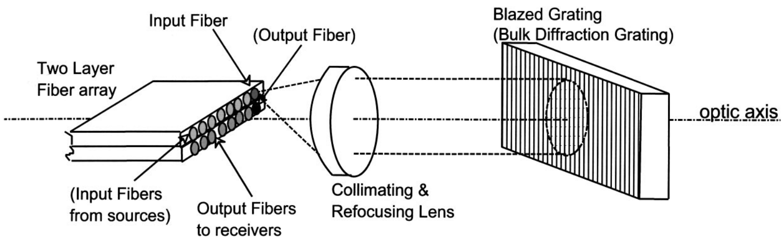


Fig. 4 The structure of dual deck WDM device for bidirectional transmission.

reduce the size of the device and cost. In view of the commercial availability of WDM lasers, it is a good idea to select channel frequencies from the International Telecommunications Union (ITU) standard frequencies. Extra attention must be provided while designing the device on the performance parameters, such as insertion loss, channel isolation, and PDL.

3.2.1 *Insertion loss*

The insertion loss comes from two main sources, the grating and the out-coupling interfaces that usually involve fibers. The grating also governs the total passing band of the device, while its diffraction efficiencies for the multiwavelength optical signals and the out-coupling loss to fibers predominate in accounting for the total loss occurring in the device. A wide passing bandwidth for the grating is necessary for a flat distribution of insertion losses among all the WDM/WDDM channels. And grating should have high diffraction efficiencies across the entire range of the wavelengths used. The efficiency of coupling focused beams to fibers is another important factor affecting insertion loss. To effectively couple the focused beam into output fibers, the numerical aperture (NA) of the beam should be no greater than that of the output fiber, which is respectively 0.14 and 0.28 for a conventional single-mode fiber and GI 62.5/125 multimode fiber. Since light signals travel in free space in grating-based WDM multiplexers/demultiplexers, one can use a simple model to characterize the coupling from free space to output fibers for the devices. Suppose the transmission function of the l'th output fiber centering at position (x_l, y_l) is $T_{F,l}(x,y)$, depending on the launching condition and characteristics of fiber used, and the intensity distribution of the focused beam on the fiber is $I_l(x,y)$. In that case, the transmittance, which is directly related to insertion loss, of the l'th light signalwith a wavelength of λ_l can be expressed as

$$\eta = \frac{\iint_{\Delta S} T_{F,l}(x,y) I_l(x,y)\,\mathrm{d}x\,\mathrm{d}y}{\iint_{-\infty}^{+\infty} I_l(x,y)\,\mathrm{d}x\,\mathrm{d}y} \quad l=1,2,3,\ldots N, \tag{1}$$

where ΔS is the area of the fiber core. The intensity distribution $I_l(x,y)$ is a function of grating efficiency, alignment condition, and the quality of the diffracted beam. The effect of misalignment and diffracted beam quality on the coupling loss is critical. Two main factors determine the quality of the beam. One is the lens; another is the flatness of the grating, both of which affect the wavefront of the beam. Diffraction-limited focal lenses are desirable to obtain greatly qualified diffraction beams. Regarding the coupling loss, the flatness of the grating surface plays an important role. The difference between the peak and valley on the surface of the grating should be less than 10% of the wavelength used.

3.2.2 *Isolation*

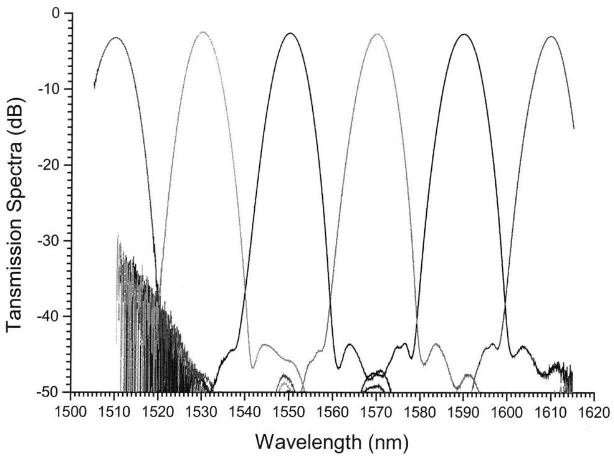
The quality of the diffracted beams plays an important role not only in the insertion loss but also in channel isolation. Using Eq. (1), one can evaluate isolation among the channels if one substitutes $T_{F,lk}(x,y)$, which is the transmission function of the l'th output fiber centering at position (x_l, y_l) due to the k'th light signal, for $T_{F,l}(x,y)$ and $I_{lk}(x,y)$, which is the intensity distribution of the focused beam of the k'th light signal on the l'th output fiber for $I_l(x,y)$. Generally, for a certain quality of diffracted beams, the larger the ratio of fiber spacing b to the core of the output fiber d, the better the isolation. However, the large ratio will reduce the passband of each channel in the device, as discussed in the next section.

3.2.3 *Channel passband*

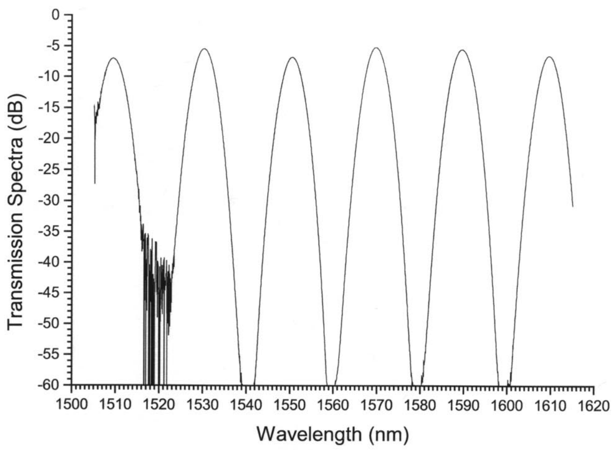
The channel passband is another critical parameter for WDM multiplexers/demultiplexers. A large channel passband allows large fluctuation of wavelengths of WDM sources due to the variation of temperature. For grating-based WDM multiplexers/demultiplexers, generally the transmission spectrum is Gaussian top-shaped. There are two ways to enlarge the channel passband. The first method uses defocusing and Fourier filtering technology.[15] This method has the cost of insertion loss and cross talk among the channels. Another method reduces the ratio b/d of fiber spacing to the core of the output fiber. As mentioned before, a ratio that is too small will increase cross talk among the channels. There is a tradeoff between passband width and channel isolation. In Littrow-structured WDM multiplexers/demultiplexers, if the imaging system is aberration free, the light spots of diffracted beams are almost identical in size to the cores of the fibers. In this case, the ideal value of the ratio would be about 1.5. There are three ways to reduce this ratio: by channel enlarging the fiber core, by stripping the fiber cladding, or by using a waveguide concentrator structure.

3.2.4 *Polarization-dependent loss*

Polarization-dependent loss (PDL) of a WDM multiplexer/demultiplexer due to random changes in the polarization of light signals is another issue of concern in a WDM networking system. To reduce PDL in a grating-based WDM multiplexer/demultiplexer, one can use a polarization con-



(a)



(b)

Fig. 5 (a) The transmission spectra of double-deck 6-Channel CWDM device from (a) one layer and (b) when working at multiplexing and demultiplexing simultaneously in a bidirectional mode.

ditioning component, which conditions the input polarization, independent of orientation, for maximum diffraction efficiency of the grating. This component also maintains the input polarization as it exits the device. The disadvantage of this method is that it increases the cost and difficulty in packaging the device. Another, more straightforward way to reduce PDL is to use polarization-insensitive grating.

3.2.5 *Other key parameters*

Other such issues as return loss, pulse broadening or bit rate, power damage threshold, physical size and weight, and cost also affect the design of devices. As a rule of thumb in fiber optics, a polished end angle of 8 deg will reduce the return loss to better than -40 dB for a single-mode device.[25] Since the grating-based WDM multiplexer/demultiplexer works on the principle of grating dispersion, when a light pulse passes through the device the pulse will be broadened. The pulse broadening can be reduced by contracting the device. Increasing the angular dispersion ability of the device can reduce the physical size and weight. One can use a multipass through the grating for this reduction,[23] or use grism (prism plus grating) instead of using only the grating as the dispersive element.

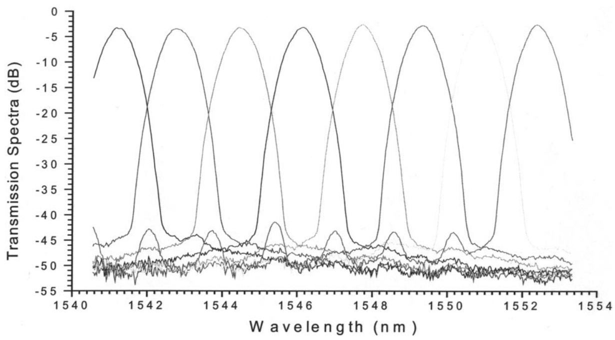


Fig. 6 The transmission spectra of a 200-GHz multimode WDM device.

In summary, a good WDM multiplexer/demultiplexer must optimize all the key parameters discussed previously, namely insertion loss, isolation among channels, polarization-dependent loss, return loss, power damage threshold, pulse broadening of the device, the physical geometry, weight, input/output interfaces, and sensitivities due to ambient temperature, pressure, humidity change, etc. For a passive structure, it is first of all necessary to balance the transmission spectrum of all the working channels with low loss. This is primarily determined by dispersion abilities, the linearity of out-coupling, and coupling losses. PDL, RL, and sensitivities to variability in the environment should be kept be as low as possible while keeping in mind the cost effectiveness of the methods. For optimal design, these tradeoffs must be carefully considered.

4 Experimental Results

Considering all the factors discussed in Sec. 3, we designed and fabricated WDM multiplexer/demultiplexers for the optical interconnects applications in massively parallel processing. To reduce the insertion loss and PDL, we first chose custom-designed high frequency blazed grating with high efficiency and wide passband to develop double deck six-channel coarse WDM multiplexer/demultiplexers. The channel spacing was 20 nm.

The filtering characteristics of a WDM multiplexer/demultiplexer, i.e., the transmittance versus wavelength, provides almost complete information of the device. Figure 5 shows the spectra of the device, Fig. 5(a) is for one layer and Fig. 5(b) for the spectrum of the device working as multiplexer and demultiplexer simultaneously. By employing this device, the system can realize bidirectional links by using one WDM device instead of two at one end. The signal noises in the spectra at low wavelength range are due to the light signals from the light source being too weak in that wavelength range. From the spectra we can see that the insertion loss from one layer is in the neighborhood of 2.9 dB, and it is 6.4 dB when working as a multiplexer and demultiplexer simultaneously. The channel uniformity is within 1 dB. Adjacent cross talks are better than -40 dB. The PDL of the device is less than 0.3 dB in all channels. 1-dB passband is larger than 3 nm. To increase bandwidth of links we also developed a 200-GHz channel spacing multimode WDM multiplexer/demultiplexer for high

Table 2 The measurement data for the multimode DMDM multiplexer/demultiplexer.

Channel number	1	2	3	4	5	6	7	8
Insertion loss (dB)	2.9	3.0	2.8	2.7	2.7	2.6	2.6	2.5
Channel Isolation (dB)	40	39	41	40	39	40	39	40
PDL (dB)	0.48	0.40	0.30	0.12	0.18	0.28	0.35	0.42
Central wavelength (nm)	1541.30	1542.91	1544.51	1546.11	1547.72	1549.33	1550.94	1552.56
Wavelength error (nm)	0.049	0.035	0.016	0.009	−0.005	−0.015	−0.030	−0.036
1-dB passpand (nm)	0.62	0.59	0.63	0.66	0.64	0.62	0.63	0.66

throughput optical links. Its transmission spectrum is shown in Fig. 6. The performance of devices is shown in Table 2.

We have also measured the high-speed performance of the device. Figure 7 shows the eye diagram of the 200-GHz multimode WDM multiplexer/demultiplexer working at 3.5 Gbps. At a bit rate of 3.5 Gbps from one channel, the signal-to-noise (S/N) is above 8.5, which corresponds to the bit error rate (BER) being less than 10^{-17}.

The eight-channel WDM optical link system can provide a throughput of 26 Gbps. If we choose a 40-channel similar optical system, the throughput can reach at 140 Gbps in one optical link.

5 Conclusions

We analyze the communication problems of electrical interconnects in the applications of massively parallel processing. Then we discuss the advantages of optical interconnects and propose a structure for high throughput optical links in massive parallel processing by using WDM technology to fully exploit optical parallelism to increase the link throughput. We also explored the characteristics of WDM multiplexers/demultiplexers used in massively parallel processing links. The devices should have the ability of bidirectional transmission and can be used in multimode environments. We found grating-based multimode WDM multiplexers/demultiplexers can meet these needs. We also discuss the optimal design of the devices and set several key parameters to characterize the performance of the grating-based WDM multiplexers/demultiplexers. These parameters are insertion loss, isolation among channels, polarization dependent loss, return loss, and power-damage threshold. We follow a set of performance parameters with optimal design procedures for grating-based wavelength division (de)multiplexers in the application of massively parallel processing optical links. Based on the analyses, we have designed and developed grating-based six-channel CDWM dual deck and eight-channel DMDM (de)multiplexers, which are reliable and cost effective with high performance. The experimental results show that the grating-based wavelength division (de)multiplexing devices are suitable for optical interconnects in massively parallel processing.

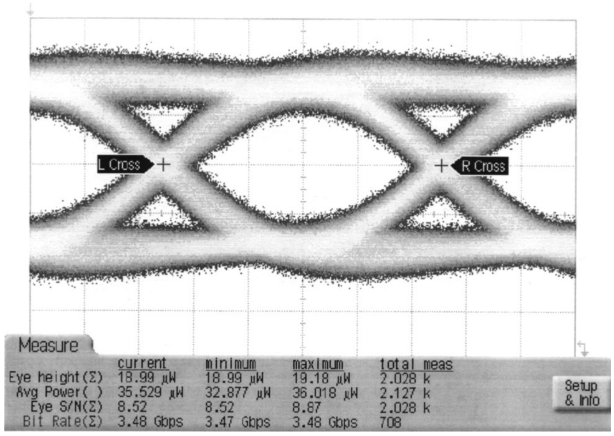


Fig. 7 The eye diagram of the multimode DWDM multiplexer/demultiplexer.

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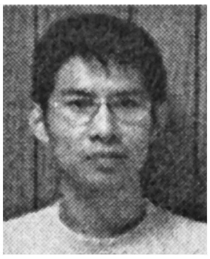
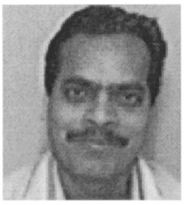
Feng Zhao was granted a PhD degree from the Department of Applied Physics, with a specialty in optics, from Harbin Institute of Technology, China, in 1991. He was an associate professor of physics at Harbin Institute of Technology, from 1993 to 1997. In 1997, he went to the Applied Science Faculty of Delft University of Technology, the Netherlands, to do research on optical networking and processing as a visiting professor. From 1998 to July 2002, he worked for the Microelectronics Research Center at the University of Texas at Austin as a research fellow. His research work in the past 20 years includes wavelength division multiplexing devices, polymer-based waveguide devices, optoelectronic interconnects, fiber-optic devices, optical interconnects, planar lightwave circuits, optical networking and processing, diffractive optical elements and holography, lasers, and high-speed optoelectronic device characterization. He has been selected as a committee member for several international conferences and has published more than 50 technical papers in these fields. He is a member of OSA, IEEE and the American Association for the Advancement of Science.

Yun Zhang was granted BS and MS degrees in physics in 1985 and 1988, both from JiLin University, China. She worked as an associate professor of applied physics at Harbin Institute of Technology, China, from 1997 to 1999. Since 2000, she has worked for Radiant Photonics as a research engineer. Her research interests include nonlinear optics, laser, optical interconnects, and fiber optics. She has published more than 20 papers in these areas.

Jizuo Zou received his BS and MS from Tsinghua University in China in 1991 and 1998, respectively. Currently he is a PhD student in the Electrical and Computer Engineering Department at the University of Texas at Austin. His current research topic is dense wavelength division multiplexers and glass integrated optics.



Zhong Shi received his BS degree in optics from Shandong University in 1994, and the MS degree in eletromagnetic field theories and microwave techniques from Beijing University of Posts and Telecommunications in 1997. He has been working toward his PhD degree at The University of Texas at Austin since 2000.



Bipin Bihari received his PhD in physics (laser spectroscopy) from the Indian Institute of Technology, Kanpur, India. Presently he is a senior scientist jointly at Omega Optics, Incorporated, Austin, Texas. He is the author or coauthor of more than 50 articles in refereed journals and conference proceedings. His areas of interest include optoelectronic interconnects, WDM for data-com applications, optical memories, polymeric waveguides and devices, molded waveguides, nanophase materials, and nonlinear optical properties of organic and inorganic materials. He has memberships in several professional societies, including ACS, MRS, and IMAPS. He has served as the session chair at several conferences organized by SPIE.

Xuegong Deng holds PhD degrees both in electrical and computer engineering from The University of Texas at Austin and in physics from the University of Science and Technology of China. He is a principal investigator and has been awarded two U.S. government-sponsored projects and has participated in several others. He authored more than 26 publications, has four U.S. patent applications, and three U.S. provisional patents pending. His research interests have been focused on fiber communications, diffractive optics, beam propagation in general systems, optical interconnections, and other applications of micro/nanoscale structures.

Jie Qiao received her PhD from the Department of Electrical and Computer Engineering, the University of Texas at Austin, in 2001. She joined Radiant Photonics, Incorporated, in January, 2001, where she engaged in the research, development, and prototyping of athermalized grating-based multiplexers/demultiplexers. She has published 15 technical papers, and holds two patent disclosures. She joined LNL Technology, Incorporated, in 2002. Her research fields include guided-wave optoelectronics, dense/course wavelength division demultiplexing, fiber optics, optical networks, optical interconnects, and optical communications.

Zan Shi received his BS and MS degrees in electrical engineering from Xi'an Jiaotong University of China in 1988 and 1991, respectively. After receiving his PhD degree in optical communication from Beijing University of Posts and Telecommunications in 1997, he was with China Telecom participating in the project management of China's communication backbone construction for a year. Then he spent three years at the University of Texas at Austin as a post doctor, and currently he is with Ultraphotonics, Incorporated. His interests include optical waveguides, photonic integrated circuits, nonlinear optics, WDM, and true-time-delay lines for phased array antennas.

Ray T. Chen received the BS in physics (1980) from the National Tsing Hua University in Taiwan, the MS in physics (1983), and the PhD (1988) in electrical engineering, both from the University of California. He joined the Department of Electrical and Computer Engineering at The University of Texas at Austin in 1992, and prior to that was a Director of the Electro-Optic Engineering Department at the Physical Optics Corporation in Torrance, California. His research group has been working on over 50 awarded research programs sponsored by many subdivisions of DOD, NSF, DOE, NASA, State of Texas and other private industries. The research topics cover guided-wave and free-space optical interconnects, polymer-based integrated optics, polymer waveguide amplifiers, graded index polymer waveguide lenses, active optical back planes, traveling wave electro-optic polymer waveguide modulators, optical control of phased array antennas, GaAs all-optical cross bar switches, holographic lithography, and holographic optical elements. Currently there are 14 PhD students and four postdoctoral students working on optical interconnect-related projects. He is a Fellow of SPIE and OSA. He was the recipient of 2000 UT Engineering Foundation Award for his contributions in teaching, research and service.

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