Wavelength division multiplexers/demultiplexers for optical interconnects in massively parallel processing

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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 severe3 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-
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 severe crosstalk. Optics dominates the links in the range (see Fig. 1).

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. 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. 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/demultiplexing are furnished. Then output from the (de)serializer is input to the WDM...
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 mentioned 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.

![Fig. 3](image-url)

**Figure 3** The diagram for the structure of the grating-based WDM multiplexer/demultiplexer.

![Table 1](table-url)

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Flat top</th>
<th>Temperature control</th>
<th>Loss in high-count channel</th>
<th>Vibration stability</th>
<th>Bidirectional transmission</th>
<th>Multimode application</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWG</td>
<td>Possible</td>
<td>Yes</td>
<td>Low</td>
<td>Yes</td>
<td>Difficulty</td>
<td>Difficulty</td>
</tr>
<tr>
<td>Thin film</td>
<td>Yes</td>
<td>No</td>
<td>High</td>
<td>Yes</td>
<td>Difficulty</td>
<td>Difficulty</td>
</tr>
<tr>
<td>Blazed grating</td>
<td>Possible</td>
<td>No</td>
<td>Low</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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 (ITU-T). Here in applications of shorter-distance data communication in massively parallel processing, much wider channel spacing can be used to
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 signal with a wavelength of \(\lambda_l\) can be expressed as

\[
\eta = \frac{\int_{-\Delta S}^{\Delta S} T_{F,l}(x,y) I_l(x,y) \, dx \, dy}{\int_{-\Delta S}^{\Delta S} I_l(x,y) \, dx \, dy} \quad l = 1, 2, 3, \ldots, N, \tag{1}
\]

where \(\Delta S\) 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 \(T_{F,l}(x,y)\), 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 \(I_l(x,y)\), 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-

Fig. 4 The structure of dual deck WDM device for bidirectional transmission.
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. 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, or use grism (prism plus grating) instead of using only the grating as the dispersive element.

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...
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 ratio (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.

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References

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