Wavelength division multiplexers/demultiplexers for high-throughput optical links

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ABSTRACT

Communication between computing systems is recognized as the main limitation to increasing 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 over a wide-wavelength region. In this talk, we review the working principles of wavelength division (de)multiplexers (WD(D)M) for optoelectronic interconnection in high-throughput optical links and address the optical design issues of WD(D)Ms. Several grating-based WD(D)M structures are analyzed. We report experimental data for several versions of WD(D)Ms which exhibit low insertion loss, high reliability, and low cost.

Key words: WDM, optoelectronic interconnect, optical interconnect, fiber optics, optical link, high throughput link

1.INTRODUCTION

There is a broad consensus that major discoveries in key sciences would be within reach if computers were far more powerful that today's conventional supercomputers. Only massively parallel processors are eligible to provide teraflops of computing power in 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 both through the use of large numbers of nodes and from fundamental improvements in hardware technologies and the communication among algorithms. In enhancement of the processing power of the node and the density of nodes in ULSI and massively parallel processing, the communication congestion may arise in electric interconnection for exchange information inter- and intra- nodes. The problems met by electric interconnection in ULSI and massively parallel processor have the following a few aspects:

A. The limitation of RC time constant

In order to enhance the density of devices integrated on a ULSI chip, all the dimensions, as well the voltage and currents on the chip are supposed to be scaled down by a factor α. It is obvious that the number of devices that can be placed on a chip of given size scale up by squared α. In addition, the power dissipation per device and the switching delay are decreased by a factor α. However, the RC time constant and the interconnect delay between the devices remain unchanged due to increase of the interconnect resistance and decrease of the distribution capacitance by the same factor α. So, it is clear that since gate delays decrease with scaling while interconnect delays remain constant with scaling, eventually the speed at which a circuit can operate is dominated by interconnect delays rather than device delays.

B. The problem of clock skew

Most computing architectures require synchronous operation of a multitude of devices, circuit and subsystems [1]. Synchronism is maintained by distributing to all parts of the system a timing signal, called the clock. One of the chief difficulties encountered in designing circuits and systems for high speed operation is the phenomenon called as 'clock skew', which means that different parts of the circuits or systems receive the same state of the clock signal at different time due to the different delay time for the same clock signal to be transferred to different parts.

C. Cross-talk

The number of transistors on integrated circuits (silicon circuit) has approximately doubled every 18 months for the past decades, and it currently looks likely that this trend will continue[2], perhaps, even for 15 years or more. Current electronic logic chips can have millions of transistors, and memory chips can have even more. For electrical interconnects, as density increases, the spacing between the lines decreases. When parallel electrical lines are placed closer together, they become more susceptible to cross-talk due to the capacitive and inductive coupling between them. The interline coupling increases with decreasing line spacing and is also a function of line length. And also as the system frequency is increased, the cross talk is severe [3].

D. Other problems related to electrical interconnects

Since electrical interconnections are dominated by problems of classical electromagnetics, such problems do not necessary scale well as semiconductor devices improve. They are connected with classical resistance and capacitance of lines and with Maxwell's equations. As ULSI circuits become larger and faster, the signals will leave the chip and emission loss will rise. In this case, other problems will arise, for example, the signal distortion, signal skew and reflections, impedance mismatch along transmission lines and high power dissipation due to the skin effect.

Optics, due to its inherent parallelism, can solve all the communication congestion problems met in electrical interconnection for ULSI and massively parallel processing. 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 over a wide-wavelength region, which will dramatically enhance the throughput of each link. In this paper, we will first briefly review the advantages of optical interconnects over electrical ones and address the issues of optical interconnects for high throughput optical link by wavelength division multiplexing (WDM) technology. Then will discuss the working principle of grating based WDM multiplexers /demultiplexers. Next we will discuss optimization design of WDM multiplexers /demultiplexers for this purpose. Finally, based on the design we have fabricated the WDM multiplexers /demultiplexers and give the experimental results.

2. THE SCHEME OF OPTICAL LINK S

2.1 Advantages of optical interconnects

There are many advantages or potential advantages of optical interconnections over electrical ones, for example, the freedom from capacitive loading effects for signal propagation speed, immunity to mutual interference effects, freedom from planar or quasi-planar constraints, and they have been exploited deeply [4, 5, 6,7]. Here are several aspects for optical interconnections. All of the potential advantages of optics in these regards come from the same fundamental difference between light waves and electromagnetic waves.

A. The much higher frequency of light over that of electromagnetic waves

Since the carrier frequency of light is much higher than any frequency at which we can modulate such modulation makes essentially no differences to the propagation of light. Therefore, there is no frequency-dependent loss and cross-talk when using light wave as the information carrier. Although there are some impedance mismatch loss (i. e. reflection) when light signals propagate in different materials, because the modulation bandwidth which is used is so narrow compared to the carrier, we can use very simple 'resonant impedance transformers', such as, anti-reflection coatings to eliminate the effects. There is no comparable simple impedance transformer, which can be used for broad band radio-frequency waves.

High frequency means short wavelength. Since the wavelength of light is so small, we can make waveguides that are much larger in cross sectional dimensions than those of the optical wavelength. As a result, we can guide the light waves entirely with dielectrics, and hence have low loss propagation. The small wavelength allows us contemplate information propagation along and off chips without the use of wave-guided devices. Optics therefore allows very large numbers of interconnections through 'free space'.

Such interconnections allow very global interconnect topologies in which all of the beams cross one another and also incidentally have little or no relative signal skew between the beams.

B.. Much larger photon energy of light over that of radio frequency electromagnetic waves

Since the photon energy of light is quite high, light is both generated and detected quantum-wise, not classically. For example, detection of light involves counting the number of photons, not measuring electrical field amplitudes. Detecting photons allows us to generate current or voltage without any direct electrical drive to the detector. In this case, we can avoid the problems of the impedance and high capacitance of electrical transmission lines, which would consume relatively large amounts of power to be driven.

2.2 optical interconnects for high-throughput optical links

Multiple wavelengths of light signals can pass over the same space with very little cross-talk. We may utilize different wavelengths of light as different interconnect channels to increase connectivity and bandwidth of processing systems by WDM. Recently, the availability of wavelength tunable VCSEL's and receiver arrays provides us the possibility to realize high-density wavelength tunable VCSEL based WDM interconnect network schemes[8]. 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 main problem in realizing a WDM system in this scheme is the manufacturability of a large number of channels. This is limited by the range of wavelengths of the VCSEL's that can be tuned in combination with other restricting optical parameters, such as diffraction limits, resolving distances and resolution of diffraction elements. This limits the number of channels to be exploited in a high-density optically-based fully-connect network.

In our approach, we use free space WDM technology combining fiber optic with that of WDM Laser array to realize multiplexing interconnects for high throughput links. Figure 1 shows scheme of the working principle of the demonstration of optical links between the processors in one direction. If we want

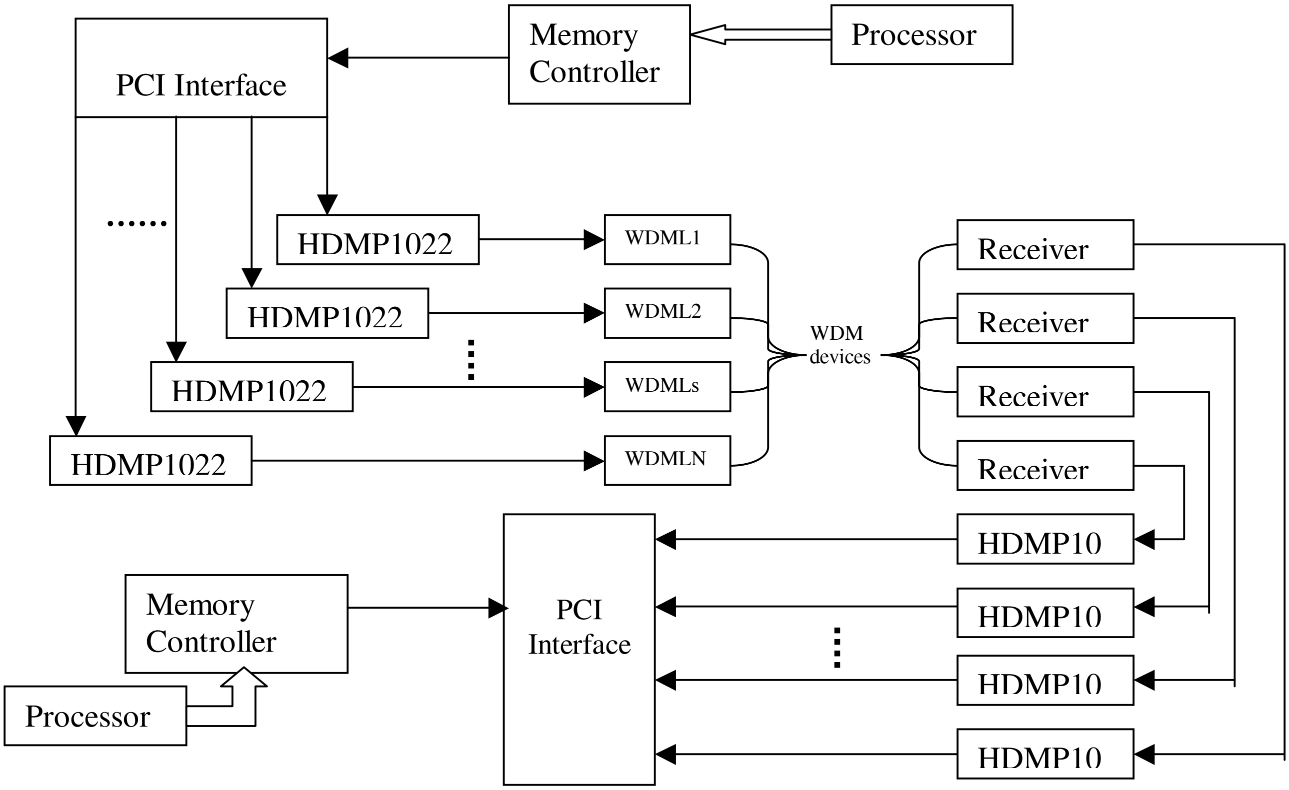


Figure1 scheme of the working principle of the demonstration of optical links between the processors bidirectional links we can use another similar systems. In this scheme, first S MHz*Kbit parallel signal from the PCI interface is divided into N S MHz*K/Nbit parallel signal and each of the four parallel signal is output to an HDMP-1022, where encoding and multiplexing are furnished. Then output from HDMP-1022 is input to N WDM lasers. The laser outputs are coupled to an optical fiber via a WDM. At the other end, another WDM is used to de-multiplex the N wavelengths and feed them to N photodetectors. The output from the photodetectors is fed to N HDMP-1024 chips where clock extraction, demultiplexing and decoding could be done. The parallel signals from the HDMP-1024 are feed back to another S MHz*Kbit PCI interface. PCI, HDMP1022, HDMP10, WDM laser and receiver are commercial. The WDM multiplexers /demultiplexers for optical links among the processors should have the bi-directional link ability and fit to multimode working environments. They are not commercially available. Since free space based WDM multiplexers /demultiplexers can meet the need. We chose grating technology to develop the WDM multiplexers /demultiplexers for optical links.

3. WORKING PRINCIPLES OFGRATING BASED WDM

Wavelength-division multiplexing (WDM) technology, by which multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical transmission medium, like optical fiber, is a useful means of making full use of the low-loss characteristics of optical fibers over a wide-wavelength region. Most wavelength division multiplexers (WDM) employ one of three technologies: arrayed waveguide grating (AWG), filter and dispersive element, primarily diffraction grating[6] . Although AWG technology is widely used for WDM devices, its strong temperature dependence often requires thermal regulation[9]. Multiplexers and demultiplexers based on filters exhibit high insertion loss for devices with many channels[10]. The devices based above two technologies have difficulties in applications of multimode and bi-directional transmission. They are not suitable in application of high throughput optical link in parallel processing and computing. Since a grating-based WDM device can offer these advantages and other advantages of low cost for many channels, low loss, and little crosstalk, it has received much attention [11-23]. We employed this technology to explore the WDM mulitplexer/demultiplexer for the application of high throughput optical link in parallel processing and computing.

In regard to the structure of grating-based WDM multiplexers/demultiplexers there are two main types: the Czerny-Turner structure, which has different lenses for input and output[16-20], and the Littrow structure, which has one common lens. Since Littrow WDM multiplexers/demultiplexers use fewer components they are more cost-effective. Most bulk grating-based WDM multiplexers/demultiplexers that have been developed recently employ a Littrow-type structure[11, 13, 14, 21, 22, 23]. Here we give the working principle of Littrow-type structured WDM multiplexer/demultiplexer.

To examine the operating principle of the Littrow structured grating-based WDM multiplexers/demultiplexers, we refer to the structure shown in Figure 2. 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, according to different wavelengths, and simultaneously reflected. Then the different wavelengths pass through the lens and are focused to their corresponding output fibers. Each wavelength is fed to one individual output fiber. This functions as a demultiplexer. When working in the reverse direction, the device serves as a multiplexer.

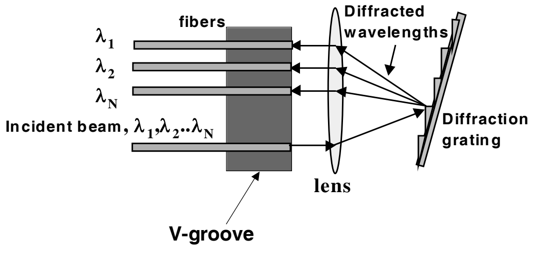


Figure 2. The diagram for the structure of the Littrow type WDM.

If we put two layers of fiber arrays, the devices can transmit WDM signal in bi-direction, that is, it can function as both mux and demux at the same time. Figure 3 shows the structure of devices.

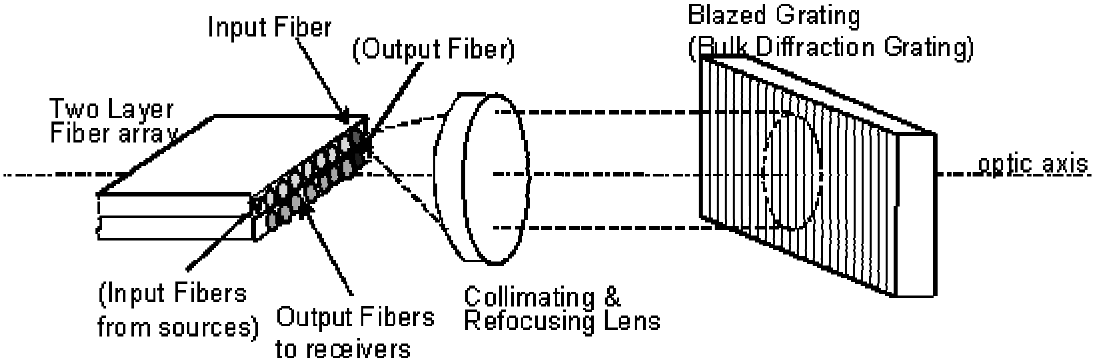


Figure 3. Scheme of double-duck of grating WDM multiplexer/demultiplxer

It is evident from the structure of the WDM that the core component in a diffraction grating-based WDM is the dispersive element, the grating, which separates the light signals of different wavelengths into different directions. How well it can separate light signals with a certain wavelength spacing depends on its dispersion ability. The dispersion can be accurately regarded as a diffraction process. A light beam of vacuum wavelength λ strikes the grating at angle θ_1. The light will be diffracted at the angle θ_2. The grating has a period of Λ. The grating equation may be found in Ref. 24, and is

$$\Lambda(n_3\sin\theta_2 \pm n_1\sin\theta_1) = m\lambda / n_3, \qquad m = 0, \pm1\ \pm2, \ldots \tag{1}$$

where n_1 and n_3 are the average refractive index of the medium in incident and diffraction space respectively. In the Littrow structured WDM, θ_1 and θ_2 are nearly equal in value and n_1 is equal to n_3. Here m represents the mth order for diffraction. Let θ_2 be the designed diffraction angle in the medium of refractive index n_3. Since the material dispersion $\frac{dn}{d\lambda}$ is negligibly small, the dispersion of the grating can be derived by differentiating Eq. (1), which gives

$$\frac{d\theta_2}{d\lambda} = \frac{m}{\Lambda n_3^{\,2}\cos\theta_2} = \frac{n_3\sin\theta_2 \pm n_1\sin\theta_1}{\lambda n_3\cos\theta_2} \tag{2}$$

Eq. (2) shows that large dispersion ability requires a large diffraction angle θ_2.

4. OPTIMIZATION OF DESIGN

Some of the key parameters are independent of the multiplexing/demultiplexing structure. An optimal design must take into account the following constraints: (a) nominal wavelengths or frequencies of each channel; (b) number of channels; (c) channel separation, in wavelengths or frequency; (d) passing bandwidth of each channel, or channel capacity; (e) insertion loss; (f) the transmission spectrum over the passing bandwidth of each channel; (g) isolation among channels, or the power level due to crosstalk; (h) polarization-dependent loss (PDL); (i) for passive devices, sensitivities due to ambient temperature, pressure, humidity variation, etc.; (j) return loss (RL); (k) the power damage threshold, or the maximum optical power for each channel; and (l) pulse-broadening of the device. Such other issues as physical geometry, weight, input/output interfaces, and greater or lesser cost depending on applications also directly affect the choice of design spaces.

WDM systems for telecommunication tend to use a $100GHz$ frequency grid centered at $193.1THz$ optical frequency, aiming at a $10Gbs$ capacity per channel, as recommended by ITU-T. Here in application of shorter-distance data communication, Much wider channel spacing can be used to reduce the size of the device and cost. For WDM lasers commercial viability, it is a good idea to select channel frequencies in ITU frequencies. For grating-based WDM multiplexers/demultiplexers these parameters are mostly determined by the dispersion ability of the grating, subject to the constraints of the physical size of the device. The loss spectrum of a passive device is generally sufficient to characterize the requirements (d)-(g) above, when appropriate out-coupling interfaces are taken into consideration. Material selection and engineering are also important elements by means of which the performance of the device is optimized. In practice, packaging issues should be considered along with the other criteria.

4.1 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 multi-wavelength 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 all range of the wavelengths used. The efficiency of coupling focused beams to fibers is another important factor affecting insertion loss. In order 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 conventional single-mode fiber and GI 62.5/125 multimode fiber. Since light signals travel in free space in grating-based WDM multiplexers/demultiplexers we can use a simple model to characterize the coupling from free space to output fibers for the devices. Suppose the transmission function of the *lth* output fiber centering at position (x_l, y_l) is $T_{F,l}(x, y)$, depending on the launching condition, 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 *lth* light signal with a wavelength of λ_l can be expressed as

$$\eta = \frac{\iint_{\Delta S} \mathrm{T}_{\mathrm{F,l}}(x,y) I_l(x,y)\,dxdy}{\iint_{-\infty}^{+\infty} I_l(x,y)\,dxdy} \qquad l = 1, 2, 3, \ldots N \qquad (3)$$

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 in order to obtain greatly qualified diffraction beams. Regarding to 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.

4. 2 Isolation

The quality of the diffracted beams plays an important role not only in the insertion loss but also in channel isolation. Using Equation (3) we can evaluate isolation among the channels if we substitute $T_{F,lk}(x, y)$, which is the transmission function of the *lth* output fiber centering at position (x_l, y_l) due to the *kth* light signal, for $T_{F,l}(x, y)$ and $I_{lk}(x, y)$, which is the intensity distribution of the focused beam of the *kth* light signal on the *lth* 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.

4. 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 technolgy[11] This method has the cost of insertion loss and crosstalk among the channels. Another method reduces the ratio *b/d* of fiber spacing to the core of the output fiber. As mentionedabove, a ratio that is too small will increase crosstalk 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 around 1.5[22]. 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.

4. 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. In order to reduce PDL in a grating-based WDM multiplexer/demultiplexer, we can use a polarization conditioning component, which conditions the input polarization, independent of orientation, for maximum diffraction efficiency of the grating[22]. 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.

4. 5. Other key parameters

Such other 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 degrees 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. The physical size and weight can be reduced by increasing the angular dispersion ability of the device. We can use a multi-pass through the grating for this reduction, as S. Bourzeix did[22], or we can 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 above, 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 with keeping in mind the cost-effectiveness of the methods. For optimal design, these tradeoffs must be carefully considered.

5. EXPERIMENTAL RESULTS

Considering all the factors discussed in Section 4 we designed and fabricated WDM multiplexer/demultiplexers for the applications of high throughput optical links. In order 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 duck 6-channel coarse WDM multiplexer/demultiplexers.

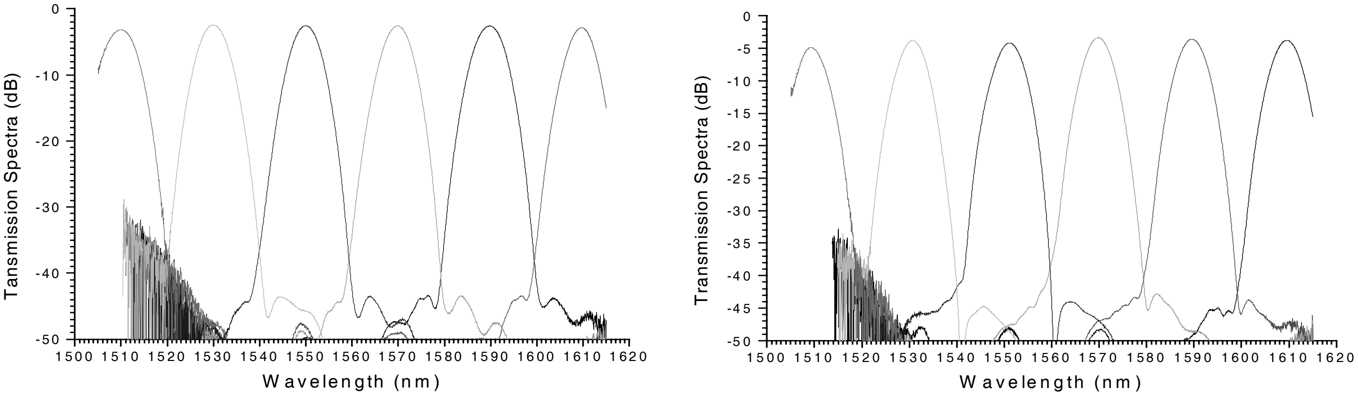


Figure 4. The transmission spectra of double-duck 6-Channel CWDM device, the left for one layer and the right for another

The channel spacing is 20 nanometer. The filtering characteristics of a WDM multiplexer/demultiplexer, i. e., the transmittance versus wavelength, provides almost complete information for the device. The temperature sensitivity of a multiplexer/demultiplexer can also be measured with its transmission spectra at static temperatures. Figure 4 shows the spectra of the device, The left is for one layer and the right for anther layer. This device can function as both a multiplexer and a demultiplexer simultaneously. In this case the system can realize bidirectional links by using one WDM device instead of two at one end . The signals noise in the spectra are due to the light signals from light source in the wavelength range is too weak. From the spectra we can see the insertion loss from one layer is in the neighborhood of 2.9dB and 4.2 dB from another layer. The channel uniformity is within 1 dB. Adjacent cross-talks are better than -40 dB. The PDL of the device is lees than 0.3 dB in all channels. 1-dB passband is larger than 3 nm.

In order to increase bandwidth of links we also develop 200 GHz channel spacing multimode WDM multiplexer/demultiplexer for high throughput optical link. Its transmission spectra is shown in figure 5.

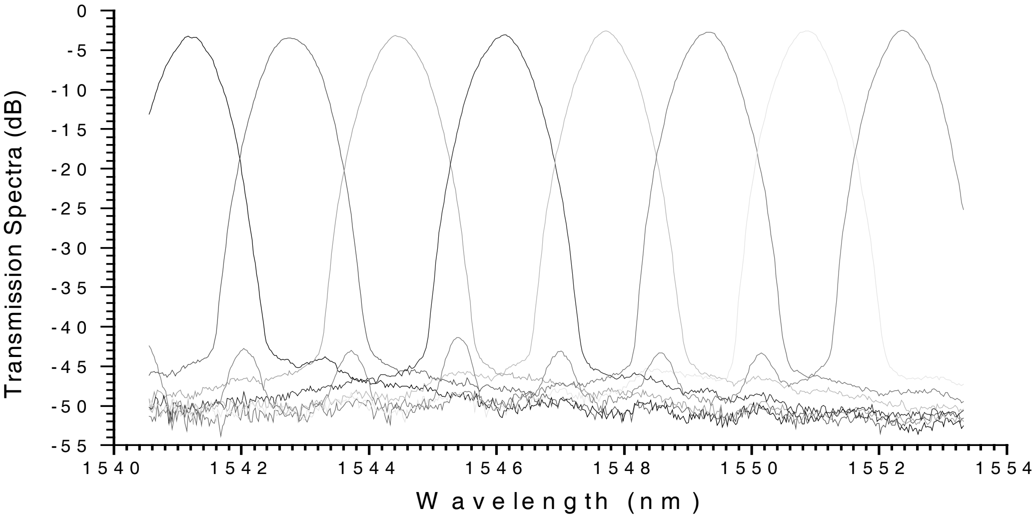
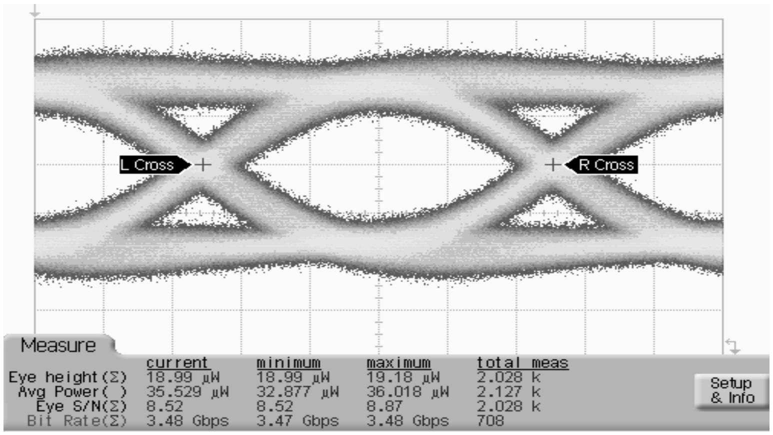


Figure 5. The Transmission spectra of 200 GHz multimode WDM Device

The performance parameters in the devices are following: Insertion loss: from 2.5 to 3 dB; Adjacent channel crosstalk: below –30dB; PDL: less than 0.5 dB; 1-dB passband: from 0.5 to 0.6 nm; The wavelength accuracy : ± 0.05 nm.



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              current       minimum       maximum       total meas
Eye height(Σ) 18.99 µW      18.99 µW      19.18 µW      2.028 k
 Avg Power( ) 35.529 µW     32.877 µW     36.018 µW     2.127 k
   Eye S/N(Σ) 8.52          8.52          8.87          2.028 k
  Bit Rate(Σ) 3.48 Gbps     3.47 Gbps     3.48 Gbps     708
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Figure 6. The eye diagram of the 200 GHz multimode WDM multiplexer/demultiplexer.

We also measured the performance of the device in high speed. Figure 6 shows the eye diagram of the 200 GHz multimode WDM multiplexer/demultiplexer. At bit rate of 3.5 Gbps from one channel the S/N is above 8.5, which correspondence the BER is less than 10^{-17}.

In this 8-channel WDM optical link system the all throughput can be 26 Gbps. If we choose 40-channel similar optical system the all throughput can reach at 140 Gbps.

6. CONCLUSIONS

In this paper, we first analyzed the communication problems met in high throughput links by electrical interconnects. Then we discussed the advantages of optical interconnects and proposed the a structure for high throughput optical links in massive parallel processing by using WDM technology to fully explore optical parallelism to increase the link throughput. We also explored the characteristics of WDM multiplexers /demultiplexers used in massive parallel processing links. The devices should have the ability of bi-directional transmittance and can be used in multimode environments. We found grating based multimode WDM multiplexers/demultiplexers can meet the needs. We also discussed 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, power-damage threshold. We follow with a set of analytical formulae to characterize these performance parameters with optimal design procedures for grating-based wavelength division (de)multiplexers in the application of massive parallel processing optical link. Based on the analyses and formulae, we have designed and developed a set of grating-based wavelength division (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 interconnect in high throughput links.

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