Passive single-mode wavelength-division (de)multiplexers for short-link multi-wavelength applications in field environments

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ABSTRACT

We construct a passive grating-based wavelength-division (de)multiplexer (MUX/DMUX) for single-mode-fiber networks. The MUX/DMUX has almost identical bi-directional filtering characteristics on optical signals at wavelengths around 1550nm. With total insertion loss less than 3dB and an enlarged passing band of each channel, the encapsulated device exhibits very stable performance under temperature variation and is immune from mechanical vibration. The insertion loss of this device changes about 1dB at temperatures from 25^oC to 60^oC, while the center wavelength of each channel drifts about $8.3\times10^{-4} nm/(nm\cdot^o C)$. Better results are expected with further optimization on the design. The device successfully demultiplexes $2^{31}-1$ PRBS signals up to 3.5Gb/s per channel in an emulated amplifier-free local-area networks (LAN's) and metropolitan-area networks (MAN's) transmission. It is plausible the cost-effective MUX/DEMUX is an excellent candidate to meet 10Gb/s all-optical multi-wavelength short-link applications.

Keywords: Wavelength-division multiplexers/demultiplexers; environment stability; passive device; diffractive optics; LAN/WAN applications; all-optical multi-wavelength networks; optical communication

1. INTRODUCTION

It is unarguable that wavelength-division multiplexing (WDM) has becoming the most fast-paced developing technology for next generation all-optical networks. In long-haul networks, telecommunication giants such as AT&T and Sprint already begin deploying this maturing technology.[1-4] Terabit per second transmission experiments demonstrated on data networks by using WDM advocate a precursory model for data, voice, imaging, and video communications.[5-9] However, the image and rationale for using WDM in short links such as local-area networks (LAN's) and metropolitan-area networks (MAN's/WAN's) are not so crispy sharp. One of mainly disputable issues is whether there exists such demand on communication bandwidth as well as the cost for such a possible deployment. Given the evolutionary of personal computing and its undeniable impacts on the society, the answer to the demand question is obvious. Besides, progresses on passive optical networks (PON) and passive devices are maturing, constituting a strong proponent to minimize the amortized equipment costs and to maximize

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the market volume. Among these components, passive wavelength-division (de)multiplexers (MUX's/DMUX's) are the key PON elements.

Facing drastically different challenges to its long-haul counterparts, WDM in LAN's or WAN's exhibit distinct requirements on the MUX's/DMUX's. On one hand, dense WDM (DWDM) already gain unanimous recognition as the best path to network evolution by packaging and unpacking a large number (for example, 40) of signals separated about $0.8nm$ or less in wavelength around $1.55\mu m$. DWDM takes advantage of the high performance fibers, fast-tunable highly stable semiconductor lasers, high-speed detectors, Erbium-doped fiber amplifiers (EDFA's), wide-band external modulators, and other ultra-fast electronics. On the other hand, LAN's and MAN's are likely to minimize or even to eliminate amplifiers. The lasers in the transmitters or transceivers drift in a much wider range. For example, the thermal coefficient of typical commercial distributed feedback (DFB) lasers is about $7.5\times10^{-2} nm/^{o}C$, hurting any current DWDM scenarios. It is not easy, and perhaps not necessary, to meet the stringent DWDM requirements in LAN and MAN environment, despite that recent efforts in developing $1.55\mu m$-quantum-cascaded resonant-tunneling (QCRT) lasers that seems promising to eliminate active temperature controllers from the lasers.[10,11] In comparison, coarse WDM (CWDM) is gaining momentum. Bigger channel spacing as large as $20nm$ in wavelength and a channel-number count of $4\sim16$ is seeing an acceptable tradeoff between economy and technological efforts.

In Section 2, we present a passive grating-based MUX's/DMUX's for single-mode-fiber CWDM networks. A series of parameters of the device are measured. We examine its bi-directional transmission characteristics in Section 3 where experiments are explained by simulation. Stability data of the encapsulated device are presented thereafter. Finally, we test the device by emulating an amplifier-free LAN/WAN transmission and try to establish a power budget for the MUX's/DMUX's.

2. PASSIVE GRATING-BASED WAVELENGTH-DIVISION DEMULTIPLEXERS

Passive grating-based MUX's/DMUX's have very simple structures and are inherently robust. These well-designed devices work in a range of ambient environments without active temperature control. This is one of the key features for field deployment of the device over the other scenarios such as arrayed-waveguide gratings (AWG) [12,13] and micro-optics technique[14]. Following the optimal design criteria outlined in Ref. 15, we constructed a four-channel MUX/DMUX for CWDM network. The grating based MUX/DMUX works in littrow configuration. The nominal center wavelengths of the four channels are $1512nm$, $1532nm$, $1552nm$ and $1572nm$, respectively. The MUX/DMUX interfaces with single-mode fibers that are linearly spaced in silicon V-groove and terminated with SC connectors. Thus, the device can be used in any SMF networks.

One problem in the grating-based SMF MUX/DMUX is the passing bandwidth of each channel. A rule of thumb on estimating this figure of merit is the "filling ratio," namely, the quotient of the diameter of the fiber $2R_f$ to the fiber spacing s. Three major methods have been proposed to improve this number. The first method relies on reducing the cladding of the SMF, for example, via chemical etching, which suffers from the uniformity problem. SMF of down to $25\mu m$ in outer diameter was made[16]. The second advocates discrete micro-lens arrays aligned in front of the fibers. The lenslet effectively forms an image of the fiber's core comparable in size up to half the fiber spacing[17]. However, quite amount of effort has to be allocated to the alignments of the discrete components, which is tricky and may be a big hurdle for mass production. The last one resorts to waveguide concentrators that is one of the most flexible and important methods for planar integrated optical circuits (PIOC's). [17] It is advantageous to PIOC's yet suffer the same problem as the lenslet array method when coming to the packaging of the MUX/DMUX.

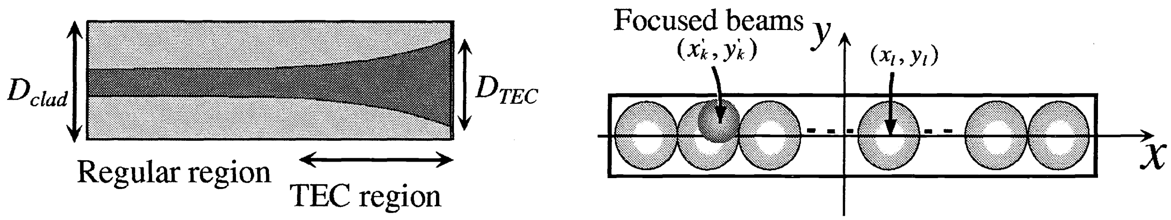

Figure 1: *Left*: Schematic illustration of a thermally-expanded-core (TEC) fiber. The mode field diameter (MFD) at one end of the TEC fiber is $D_{TEC} = 40\mu m$ while maintaining cladding diameter $D_{clad} = 125\mu m$ both at the regular region and at TEC region of the fiber. *Right*: End view of the TEC fibers in a silicon V-groove and the coordinate conventions.

To alleviate the filling-ratio problem, we packaged five thermally expanded core (TEC) fibers in silicon V-groove. The structure of the TEC fiber is illustrated in Fig. 1. The nominal value of the mode-filed diameter of each TEC fiber is $40\mu m$, corresponding to a filling ratio about 31.5%. Thus, $6.3nm$-wide passing band at $3dB$ point of each channel is expected.

The MUX/DMUX consists of only a few components, namely, a bulk blaze grating, a single diffraction-limited lens, a V-groove where five linearly spaced TEC fibers are packaged, and the mechanical housings. The groove's spatial frequency of the first-order littrow grating is $600l/mm$, while its diffraction efficiencies for both TE- and TM-polarized light is about 80% covering the interested wavelength range of the MUX/DMUX. Shown in Fig. 2, the diffraction-limited point-spread function (PSF) of the focusing lens is essential for satisfactory performance of the MUX/DMUX. In Fig. 2, two nonlinear fitting curves are used to simulate the diffraction effects of lens. Their corresponding parameters are listed in Table 1. Therefore, diffraction will bring about $16\mu m$ broadening to the focused spots in the MUX/DMUX.

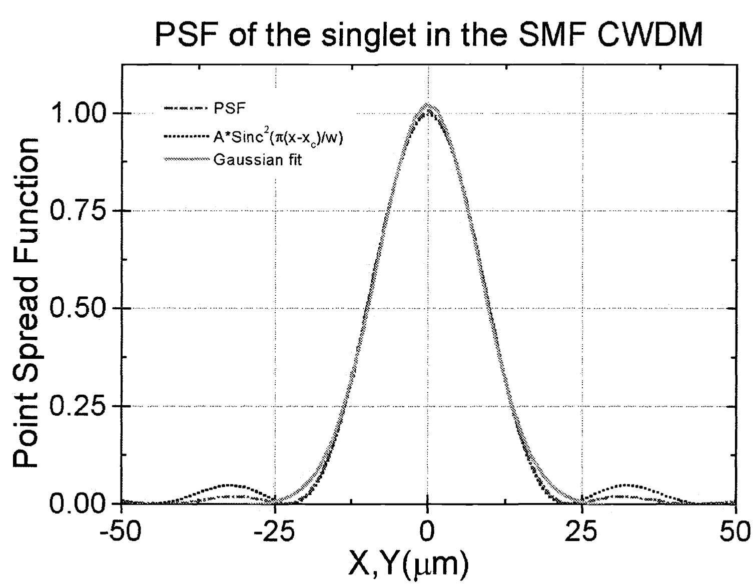

Figure 2:Point-spread function (PSF) of the singlet lens in the CWDM and two fitting curves, namely, $PSF = A\ (\sin(t)/t)^2$ with $t = \pi(x - x_c)/w$ and Gaussian $PSF = y_0 + \frac{A}{w\sqrt{\pi/2}}\exp[-2(\frac{x - x_c}{w})^2]$.

Table 1: Nonlinear curve fitting of the PSF of the singlet in the CWDM.

Parameters/STD	$PSF = A\ [\frac{\sin(\pi(x-x_c)/w)}{\pi(x-x_c)/w}]^2$	$PSF = y_0 + \frac{A}{w\sqrt{\pi/2}}\exp[-2(\frac{x-x_c}{w})^2]$
A	$0.995 \pm 6.9\times10^{-4}$	21.06 ± 0.0263
$x_c(\mu m)$	$3.0\times10^{-5} \pm 4.7\times10^{-5}$	$0.0294 \pm 5.92\times10^{-3}$
$w(\mu m)$	$22.52 \pm 1.0\times10^{-5}$	16.36 ± 0.0180
y_0		$-3.70\times10^{-3} \pm 5.80\times10^{-5}$

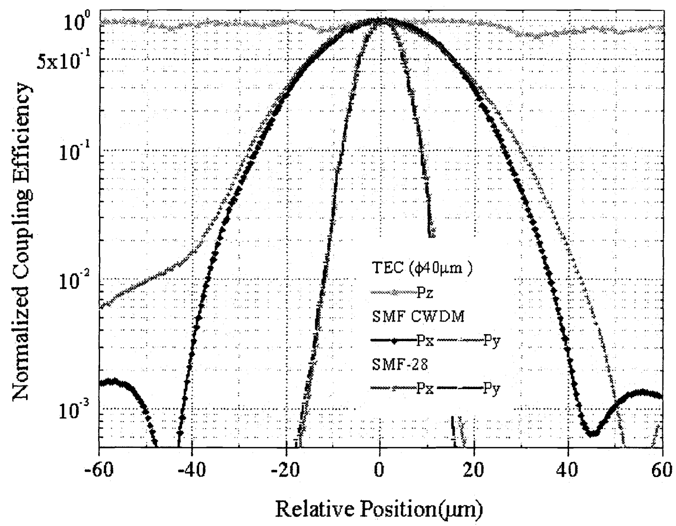

Figure 3: Transmitted power vs misalignmnets along $x-$ and $y-$directions of the V-grooved fibers for standrard single-mode fibers(e.g., SMF-28) and the TEC fibers in the CWDM device. It is clear that the MFD of the TEC is $D_{TEC} \approx 30\mu m$. The tolerance long the optical aixs of the TEC fiber in the CWDM is also shown ("**Pz**").

The device was packaged and encapsulated after careful alignment. One advantage of using TEC fiber is the highly alleviated tolerance for alignment, especially along the optical axis of the MUX/DMUX, as shown in Fig. 3. In Fig 3, the coupling losses along three-translation axes of the V-groove relative to the focal plane of the lens are compared with those for single-mode fibers (SMF-28). It is clear that TEC fibers are about three times insensitive to the misalignments in $x-$ and $y-$ direction. The measured MFD of the TEC fibers is $D_{TEC} \approx 30\mu m$, compared with the nominal value of $40\mu m$. This reduction in MFD directly comes from the unperfection of the packaging process of the TEC fibers for this MUX/DMUX. Polishing of V-groove end cuts off a section of the TEC region of the fiber. Thus, the expected passing bandwidth is limited to about $5nm$, as one may infer from the transmission spectra of the device in DMUX mode in Fig. 4. As one can see, the total insertion loss of each channel is less than $3.0dB$.

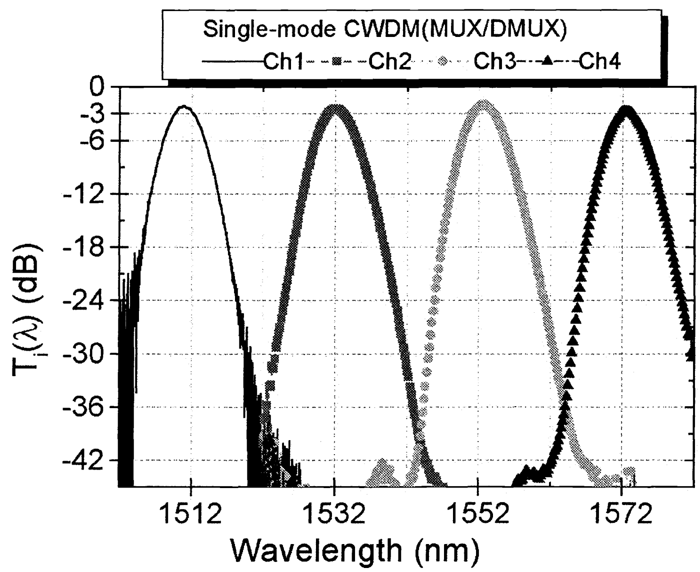

Figure 4: Transmission spectra of the 4-channel single-mode-fiber compatible coarse WDM. (in DMUX mode). The insertion loss of every channel, including the connector loss, is less than $3.0dB$. The passing band at $3.0dB$-point is about $5nm$.

The CWDM was tested against environmental temperature and mechanical variations. We use two normalized parameters to characterize the stability of the device, namely, the center-wavelength shift (CWS) and the insetion-loss varation (ILV). One may refer to Ref. 18 for a detailed analysis of these parameters for grating-based MUX/DMUX. Here we only present the experimental results in Figs. 5. The ILV is about 1dB at temperatures from 25^oC to 60^oC, while the CWS of each channel drifts about $8.3\times10^{-4} nm/(nm\cdot^o C)$. Better results are expected with further optimization on the design.

3. BI-DIRECTIONAL TRANSMISSION PROPERTIES OF THE MUX/DMUX

The transmission spectra in Fig. 4 were obtained by using a calibarted wide-band light source that incooperates atomic spontaneous emissions (ASE's) of erbium atoms in silica fiber. The ASE source is very stable and covers the same wavelength range as that of a typical EDFA. It may be obvious that the grating-based WDM should work either as a multiplexer or demultiplxer. However, little experimental data is presented in literature to verify such a claim. In this Section, we detail on such an investigation.

The transmission spectrum of the l^{th} channel of a grating-based MUX or DMUX may be modeled as a super-Gaussian profile taking the following form

$$T_l(\lambda) = B_{0,l}\cdot\exp\left[-\log_{10}(2)\cdot\left|\frac{\lambda-\lambda_{c,l}}{\sigma_l}\right|^{n_l}\right] + N_l(\lambda), \qquad l = 1,2,3,\ldots N_w \tag{1}$$

where $2\sigma_l$ represents the $3dB$ passing bandwidth (FWHM), $B_{0,l}$ is the maximum transmission of the channel, whereas the profile steepness factor $n_l \approx 2$ and $N_l(\lambda)$ is the noise in the channel. In our device, the noise floor is less than $-35dB$, we will negelect it unless we talk about crosstalks among the optical channels. The center wavelength of the channel $\lambda_{c,l}$ is determined by the following grating equation

$$\Lambda_t(\sin(\theta_i) - \sin(\theta_{o,l})) = m\lambda_l, \; l = 1,2,3,...N_w \tag{2}$$

with Λ_t for the period of the grooves along the grating surface, m the diffraction order, and θ_i and $\theta_{o,l}$ the input and diffraction angles of the beams by the grating. Eq. (2) implicitly states that the MUX and DMUX have the same value of the $\lambda_{c,l}$. However, the FWHM of the device in MUX mode differs to that in DMUX mode since the dispersion abilities are slightly different [15,18]. Differentials of MUX transmisson to that of DMUX,

$$\delta T_l(\lambda) = T_l^{(MUX)}(\lambda) - T_l^{(DMUX)}(\lambda), \tag{3}$$

is used as a figure-of-merit to characterize bi-directional transmission of the CWDM.

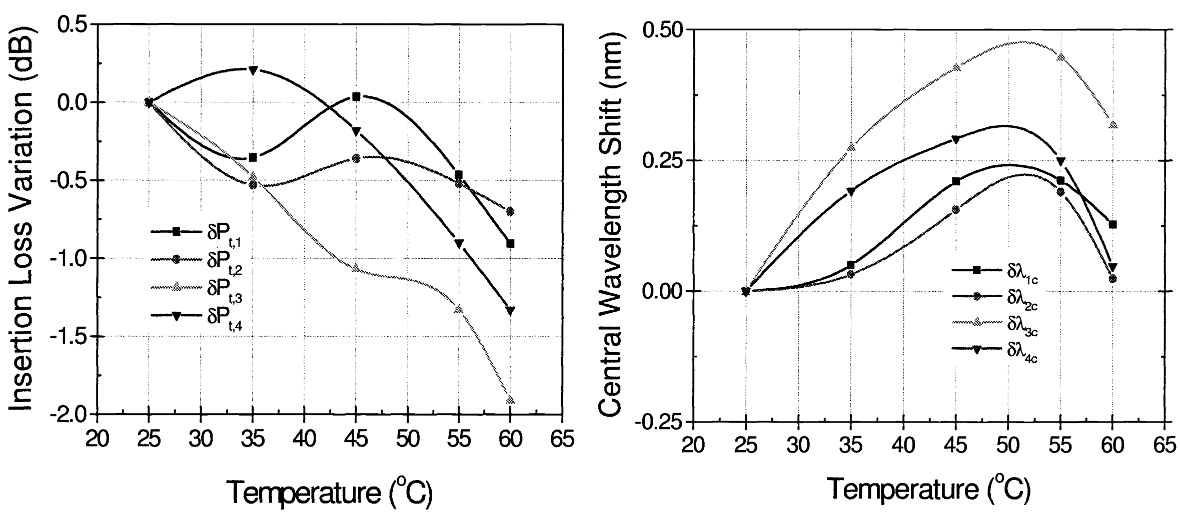

Figure 5: Measured insetion-loss variaiton (ILV) (*left*) and center-wavelength shift (CWS) (*right*) of each channel of the CWDM.

The simulated transmission spectra of the CWDM in MUX mode by using Eqs.(1)-(2) is shown in Fig. 6 , while $\delta T_l(\lambda)$ under perfect alignment is plotted in Fig. 7. The nonvanishing values of the curves clearly demomstrate differences among the dispersion abilities for MUX and DMUX. In Fig. 8, we show the measured curves of the $\delta T_l(\lambda)$ of the packaged device. The behavior of the curves in Fig. 7 and in Fig. 8 could be qualitatively explained by the misalignment of the grating. As depicted in Fig. 9, even a slight deviation of the grating angle as small as $1.75 \times 10^{-4}\, rad.$ from the designated value may account up to noticable slopes on the transmisson curves in Fig. 9. The overall rolling off on the curves in Fig. 8 might come from the misalignment of the fiber array. However, it is hard to determine the accurate amount of the misalignment with our simplified model due to possibly complicated movements of the components in the device.

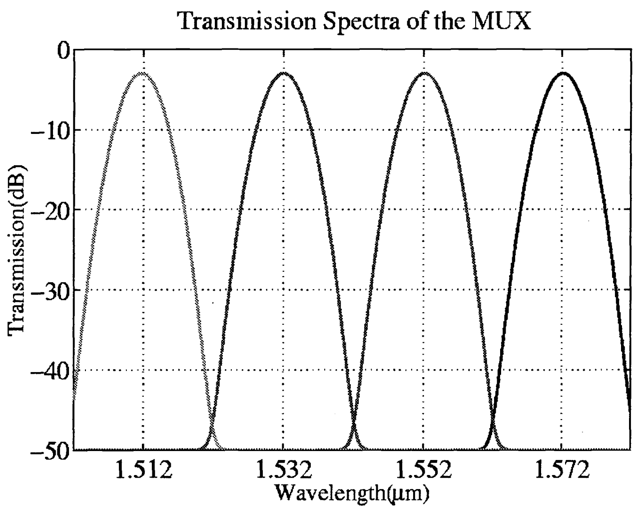

Figure 6: Simulated transmission spectra of the CWDM in MUX mode.

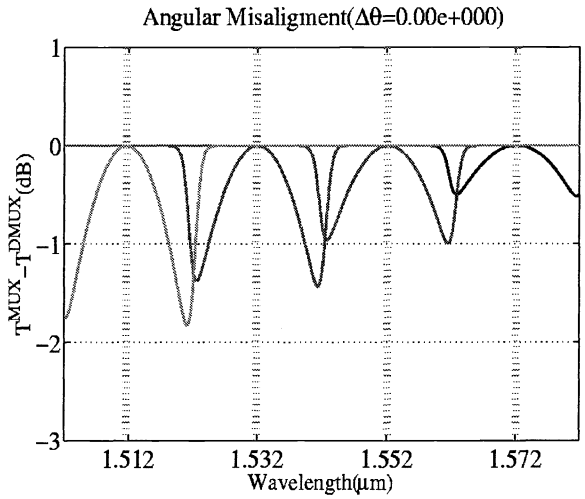

Figure 7: Simulated $\delta T_l(\lambda)$ of the CWDM under perfect alignment.

Some preliminary measurements were conducted on the CWDM with a pseudo-random binary sequence (PRBS) signals. We used the HP8133A delivering $2^{23}-1$ PRBS signal to a $LiNbO_3$ modulator that modulates a narrow-linewidth external-cavity CW laser. The output of the laser is passed to the CWDM whose output was measured with a high speed oscilloscope (HP 83480A/83487A). The device successfully tramismitted up to $3.5Gb/s$ NRZ PRBS signal that is the maximum from HP8133A. The eye diagram for the third channel is presented in Fig. 10. Our simulation indicates a much higher data rate per channel for this device. Quite a portion of the eye-closure is due to reflections of microwave signals from the modulator, as is evident from Fig. 10. The measured power margin for error-free transmission ($BER < 10^{-12}$) indicates that the device can be used with standard single-mode fiber links over $10km$ at $3.125Gb/s$ per channel. More comprehensive tests are underway.

4. CONCLUSION

We constructed a high-performance passive CWDM. The grating-based MUX/DMUX could be used in single-mode-fiber networks transmitting optical signals at wavelengths around 1550nm. The device has excellent insertion loss (<3dB) and enlarged passing bandwidth, which is bi-directionally nearly identical. The encapsulated device exhibits stable performance under temperature variation and is immune from mechanical vibration. We successfully use the device to demultiplex $2^{23}-1$ PRBS signals up to 3.5Gb/s per channel in an emulated amplifier-free local-area networks (LAN's) and metropolitan-area networks (MAN's) transmission. It is plausible the cost-effective MUX/DEMUX is an excellent candidate to meet 10Gb/s all-optical multi-wavelength short-link applications.

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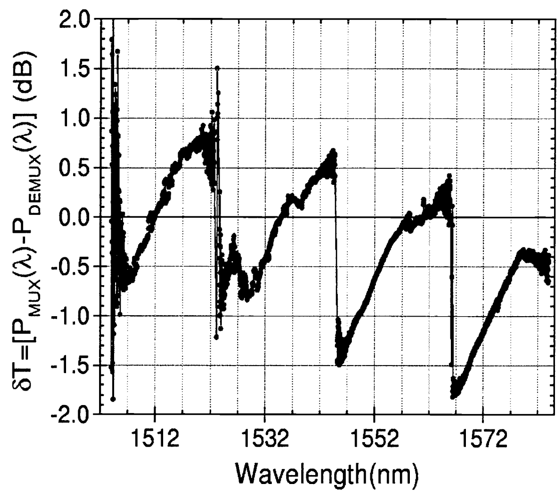

Figure 8: Measured $\delta T_l(\lambda)$ of the CWDM.

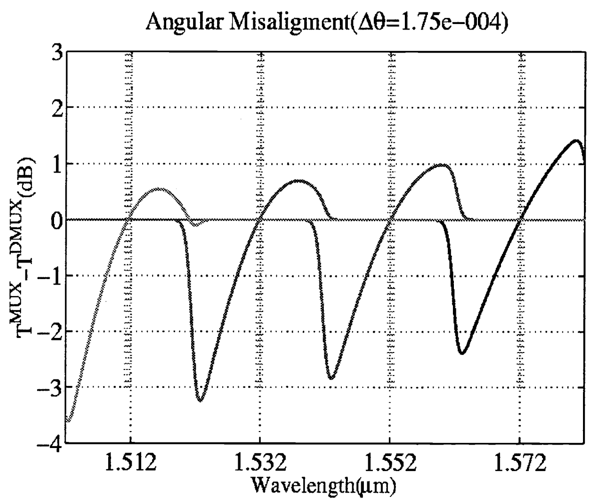

Figure 9: Simulated $\delta T_l(\lambda)$ of the CWDM if the grating is angularly misaligned $1.75\times10^{-4}\,rad$.

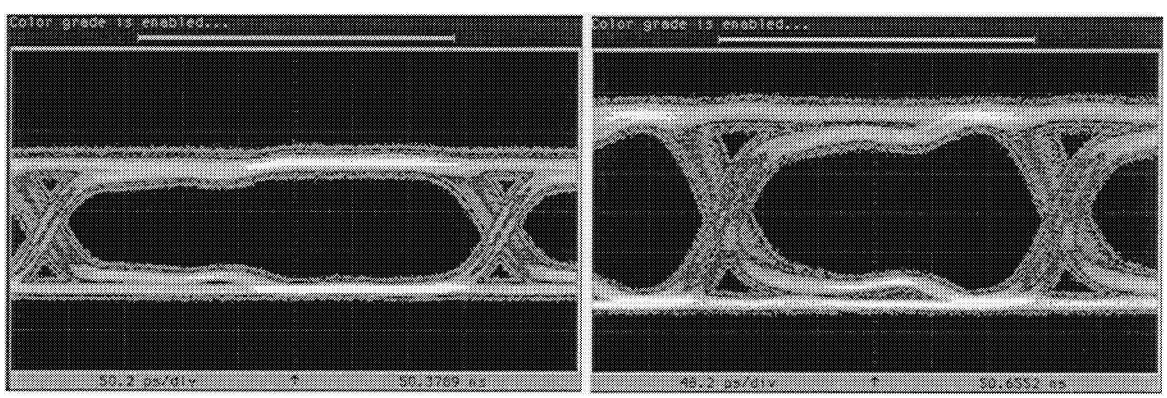

Figure 10: Measured eye diagram of the third channel of the CWDM. The wavelength was tuned to the center wavelength of the channel and the output of the HP8133A was set to $2^{23}-1$ PRBS NRZ at $2.5Gb/s$ (left) and $3.5Gb/s$ (right), respectively.

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