

Reliable grating-based wavelength division (de)multiplexers for optical networks

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Abstract. We first review the working principle of grating-based wavelength division (de)multiplexers [WD(D)M] for optical networks. We also address issues regarding optical design of grating-based WD(D)Ms for commercial uses. Next, several grating-based WD(D)M structures are analyzed. Based on these designs and analyses, we develop several versions of highly reliable WD(D)Ms, from coarse to dense, with low insertion loss and low cost. Last, we present the experimental data for these WD(D)Ms. © 2001 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1385328]

Subject terms: wavelength division (de)multiplexing; optical networks; optical communication; optical interconnects; grating.

Paper APC-14 received Nov. 11, 2000; revised manuscript received Jan. 26, 2001; accepted for publication Jan. 29, 2001.

1 Introduction

Optical communication devices and interconnection networks constitute the backbone of the information super-highway. To enhance communications throughput, higher speed optoelectronic devices need to be implemented. Tunable solid state lasers, high speed detectors and external modulators for cable TV and long-haul telecommunications,^{1,2} and laser diode arrays for computer-to-computer interconnects^{3,4} are some of the most successful products. To further enhance the bandwidth promised by optics, there are a number of competing and plausible technologies.⁵⁻⁹ Time-division multiplexing (TDM), frequency-division multiplexing (FDM), optical solitons, optical code-division multiple access (CDMA), and wavelength-division multiplexing (WDM) are becoming the leading candidates for the next-generation telecommunication network. Data networks with WDM¹⁰ have experimentally demonstrated terabit-per-second transmission.

WDM technology, by which multiple optical channels can be simultaneously transmitted at different wavelengths through a single optical fiber, is a useful means of making full use of the low-loss characteristics of optical fibers over a wide-wavelength region. The concept of using WDM to increase the transmission capacity of a telecommunication network appeared about two decades ago.¹¹ However, the real push for deployment and commercialization of WDM only recently became a reality. Breakthroughs such as openings of low-loss windows around 1300- and 1550-nm fiber wavelength, and the maturing of tunable solid state lasers, high speed detectors, erbium-doped fiber amplifiers (EDFAs), and external modulators make fiber the world-

wide primary communication medium. The proliferation of data networks, especially the Internet, has resulted in abrupt continuous demands for communication bandwidth and speed. Besides its capability to efficiently exploit the huge bandwidth of single mode fibers, WDM is promising for constructing different levels of transparency to optical transmissions, i.e., independent of data bit rate, modulation format, or protocol, which permits excellent upgrading and backward compatibility of the current network. This makes WDM the key technology for tomorrow's developments in data, voice, imaging, and video communications.¹²⁻¹⁵

WDM fiber-optic communications require high performance multiplexers and demultiplexers with low-loss, wide-channel bandwidth, low crosstalk, and low polarization dependence. Most WDMs employ one of three technologies: arrayed waveguide grating (AWG), filter and dispersive element, or primarily diffraction grating.¹⁶ Although AWG technology is widely used for WDM devices, its strong temperature dependence often requires thermal regulation.¹⁷ Multiplexers and demultiplexers based on filters exhibit high insertion loss for devices with many channels.¹⁸ Since a grating-based WDM device can offer the advantages of low cost for many channels, low loss, and little crosstalk, it has received much attention.^{16,19-29} We analyze the optimal design issues for grating-based WDM multiplexers/demultiplexers with experimental data. In Sec. 2, we briefly review the principle of grating-based WDMs and discuss the dispersion abilities of the devices. In Sec. 3, we provide the key parameters for WDM devices. Based on these parameters, the optimal design issues applicable to every variety of grating-based WDM are discussed with details of the experimental data. The design procedures for obtaining optimality in these

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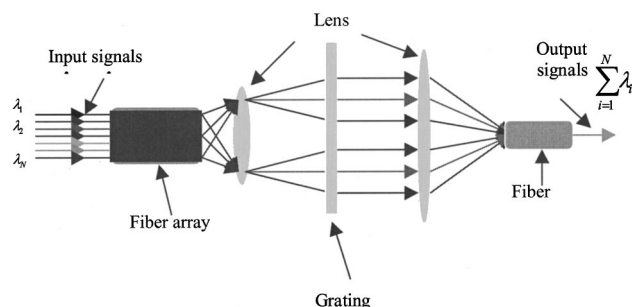


Fig. 1 The diagram for the structure of the Czerny-Turner type WDM.

grating-based WDMs are summarized in this section. At the end we offer our conclusions.

2 Dispersion Abilities of Grating-Based WDM Multiplexers/Demultiplexers

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, and the Littrow structure, which has one common lens.

The structure for the Czerny-Turner type WDM is shown in Fig. 1. Light signals with different wavelengths from different channels are launched into a fiber array. The light signals from the fiber array are collimated in different directions by a lens, and the grating diffracts these beams in a given direction. Another lens focuses the light beams into a single fiber. This operates as a multiplexer. When the directions are reversed, the device functions as a demultiplexer, in which light signals with different wavelengths traveling in a single fiber are collimated by a lens and guided in different directions by a grating. Another lens launches these beams into separate fibers.

To examine the operating principle of the Littrow structured grating-based WDM multiplexers/demultiplexers, we refer to the structure shown in Fig. 2. 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

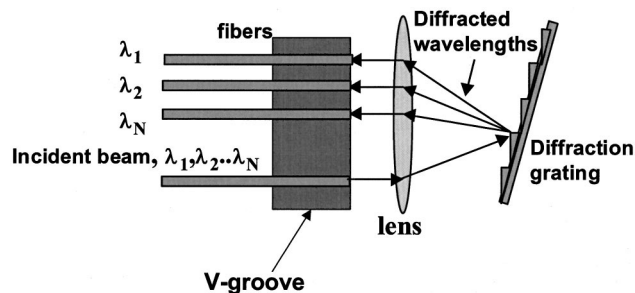


Fig. 2 The diagram for the structure of the Littrow-type WDM.

to one individual output fiber. This functions as a demultiplexer. When working in the reverse direction, the device serves as a multiplexer.

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.^{16,20,21,27–29}

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. 30, and is

$$\Lambda(n_3 \sin \theta_2 \pm n_1 \sin \theta_1) = m\lambda/n_3, \quad m = 0, \pm 1, \pm 2, \dots, \quad (1)$$

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 m 'th order for diffraction. Let θ_2 be the designed diffraction angle in the medium of refractive index n_3 . Since the material dispersion $dn/d\lambda$ is negligibly small, the dispersion of the grating can be derived by differentiating Eq. (1), which gives

$$\frac{d\theta_2}{d\lambda} = \frac{m}{\Lambda n_3^2 \cos \theta_2} = \frac{n_3 \sin \theta_2 \pm n_1 \sin \theta_1}{\lambda n_3 \cos \theta_2}. \quad (2)$$

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

3 Key Parameters for WDM Multiplexers/Demultiplexers

Some of the key parameters are independent of the multiplexing/demultiplexing structure. An optimal design 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 crosstalk; (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. 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 100-GHz frequency grid centered at 193.1-THz optical frequency, aiming at a 10-Gbs capacity per channel, as rec-

ommended by ITU-T. This constrains the choice of (1) to (3) even though devices with channel spacing less than 50 GHz have been developed. Much wider channel spacing for shorter distance data communication may be a good compromise for operational and economic reasons. 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 (4) through (10), when appropriate out-coupling interfaces are taken into consideration. In the remaining part of this section, we discuss these terms in detail with experimental data obtained in our efforts to optimize the design for grating-based WDM multiplexers/demultiplexers. 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.

3.1 Insertion Loss

3.1.1 Main factors to affect the loss

The filtering characteristics of a multiplexer/demultiplexer, i.e., the insertion loss versus wavelength, provide almost complete information for the device. The temperature sensitivity of a multiplexer/demultiplexer can also be measured with its loss spectra at static temperatures. 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.

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, 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 l 'th 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 l 'th light signal with a wavelength of λ_l can be expressed as

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

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 cou-

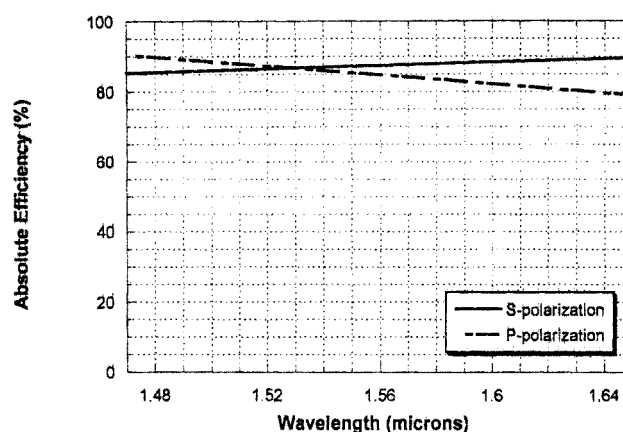


Fig. 3 The grating efficiency spectrum for WDM multiplexers/demultiplexers.

pling 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. In all our multiplexer/demultiplexer designs from CWDM to DWDM, and from the single mode module to the multimode module, the lenses used are diffraction limited. As to the coupling loss, the flatness of the grating 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.

3.1.2 Parameters for gratings

As discussed in the last section, grating parameters, especially diffraction efficiency, passband, and surface flatness, play an important role in the performance of multiplexer/demultiplexer on insertion loss. When customer-designed gratings are used in the devices, the parameters for gratings need to be specified. These parameters, to mention a few, are free aperture, grating area, substrate dimensions, substrate material, nominal surface figure, wavefront flatness on the grating surface, groove frequency, groove alignment, diffraction efficiency, and passband. In our WDM multiplexer/demultiplexer design, we use custom-designed high efficiency gratings to reduce the insertion loss and reach a wide passing bandwidth. One of the gratings we used is high frequency grating. The frequency of the grating is 600 1/mm. We used a first order diffracted beam of wavelength of 1.55 μm . Figure 3 shows the respective efficiency spectra of the grating. The data in Fig. 3 show that the grating has high efficiency with a large wavelength range. Figure 4 shows the surface/wavefront map of the grating. Figure 4 also shows the maximum difference between the peak and valley on the surface of the grating to be less than 2% of the wavelength, which is 1.55 μm .

3.1.3 Insertion losses of the devices

We have used our specially designed lenses and grating to develop 4-channel single mode CWDM, 8-channel multimode DWDM, and 32-channel DWDM multiplexers/demultiplexers. The insertion losses for all of these modules of WDM multiplexers/demultiplexers are less than 3.5

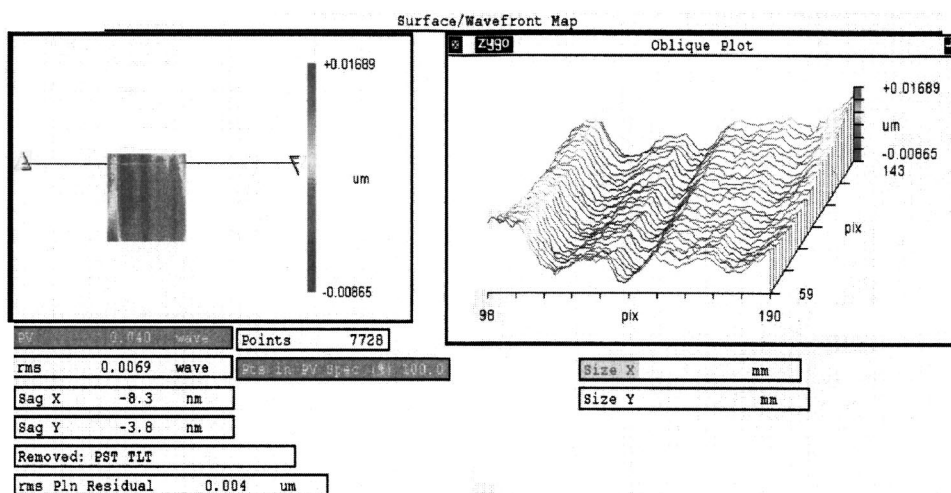


Fig. 4 The surface/wavefront map of the gratings.

dB. Figure 5 shows the measured insertion loss for each channel in the 32-channel WDM multiplexer/demultiplexer.

3.2 Isolation

The quality of the diffracted beams plays an important role not only in the insertion loss but also in channel isolation. Using Eq. (3), we can evaluate isolation among the channels if we substitute $T_{F,lk}(x,y)$, 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 reduces the passband of each channel in the device, as discussed in the next section. We used a ratio of 4 to develop the 8-channel multimode DWDM multiplexer/demultiplexer with 200-GHz channel spacing. The isolation among channels is better than 40 dB. Figure 6 gives the transmission spectrum for each channel in the DWDM multiplexer/demultiplexer.

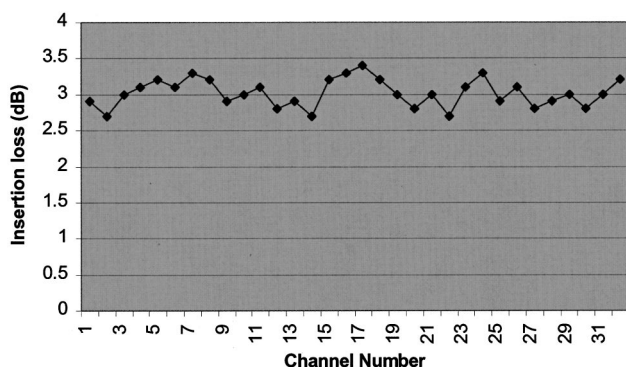


Fig. 5 The measured data for insertion loss of a 32-channel WDM multiplexer/demultiplexer.

3.3 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.¹⁶ This method has the cost of insertion loss and crosstalk among the channels. Few researchers use this procedure to develop grating-based WDM multiplexers/demultiplexers. Another method reduces the ratio b/d of fiber spacing to the core of the output fiber. As mentioned in Sec. 3.2, 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 1.5.³¹ There are three ways to reduce this ratio: by enlarging the fiber core, by stripping the fiber cladding, or by using a waveguide concentrator structure, as shown in Fig. 7.

To enlarge the fibers we can choose either a thermal expansion fiber³² or Fourier filtering technology. We used thermal expansion fibers to explore 4-channel single mode CWDM multiplexers/demultiplexers, in which the channel 3-dB passband is approximately 5 nm. Figure 8 shows the measured transmission spectrum of the device.

3.4 Wavelength Accuracy

In a typical multiplexer/demultiplexer, optical signals of different wavelengths, dispersed by the grating, will be routed to individual output ports—usually optical fibers. A simple way to accomplish this discrimination of different wavelengths involves focusing the diffracted beams to linearly spaced fibers permanently fixed in V-grooves. The horizontal positioning accuracy of the fibers in commercially available arrays can be as low as $0.3 \mu\text{m}$. One of the advantages of such an arrangement is that it eliminates necessary multiple alignments for individual fibers by simulta-

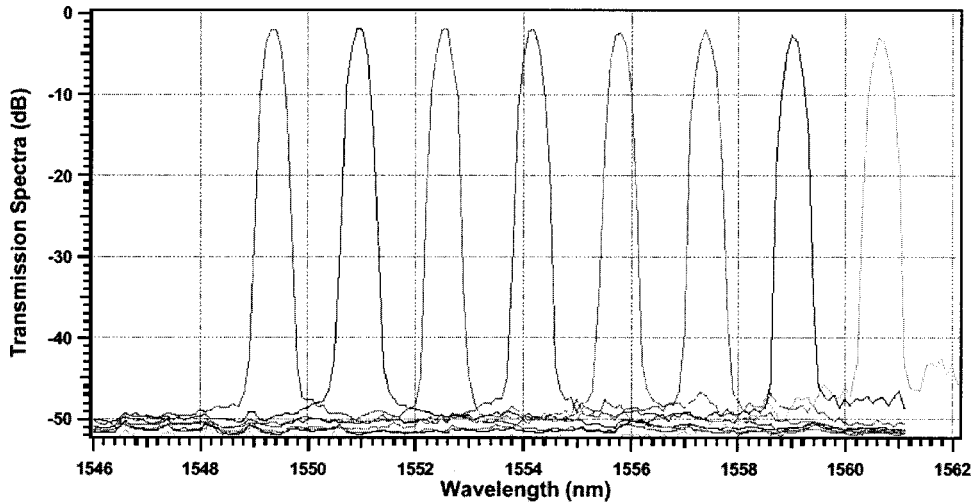


Fig. 6 The experimental data for transmission spectrum of an 8-channel multimode DWDM multiplexer/demultiplexer.

neously coupling out all the channels, thus improving the throughput. However, this imposes additional constraints on the structures, such as tradeoffs between good wavelength accuracy and the size of the device. Equation (2) shows that a larger diffraction angle results in a smaller size for the device and in worse wavelength accuracy, due to the nonlinearity of angular ability $D(\lambda, \theta_2)$, if a linearly spaced fiber array is used (see Ref 26). The following equation describes the nonlinearity of the angular ability of the grating.

$$\frac{dD(\lambda, \theta_2)}{d\lambda} = \frac{d^2\theta_2}{d^2\lambda} = \frac{(n_3 \sin_2 \pm n_1 \sin \theta_1)^2 \sin \theta_2}{\lambda^2 n_3^2 \cos^3 \theta_2} \quad (4)$$

There are two ways to solve this problem. One is to use a prism to linearize the dispersion of the diffracted beams.²⁸ This method introduces an extra component which must be aligned, complicating the packaging. Another is to use custom-designed V-grooves with nonlinear fiber spacing. We employed the second method to design our WDM multiplexers/demultiplexers. For our DWDM multiplexer/demultiplexer, the wavelength accuracy is within 0.1 nm for all channels. Table 1 shows the measured data for the 8-channel multimode DWDM multiplexer/demultiplexer.

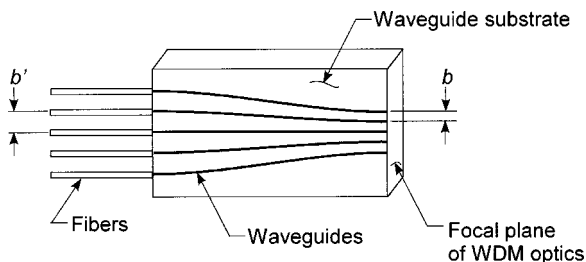


Fig. 7 WDM waveguide concentrator structure to reduce (b/d) ratio.

3.5 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, we can use a polarization conditioning component, which conditions the input polarization, independent of orientation, for maximum diffraction efficiency of the grating.²⁸ 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. Figure 3 shows that the difference of diffraction efficiencies in *S*-polarization and *P*-polarization is less than 5% in a whole C-band, which gives PDL less than 0.3 dB. This kind of grating is almost polarization insensitive in a working wavelength range. The PDL levels of all the WDM multiplexers/demultiplexers we have developed are less than 0.4 dB for all channels.

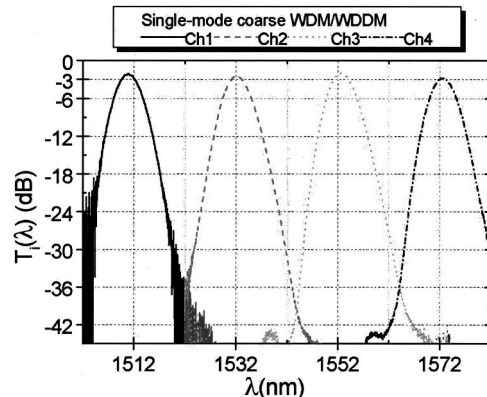


Fig. 8 The experimental data for the transmission spectrum of a 4-channel single mode CWDM multiplexer/demultiplexer.

Table 1 The measured data for the 8-channel multimode DWDM multiplexer/demultiplexer.

	Ch#1	Ch#2	Ch#3	Ch#4	Ch#5	Ch#6	Ch#7	Ch#8
Insertion loss (dB)	-2.9	-3.1	-2.9	-2.3	-1.8	-2.4	-2.3	-2.7
Cross talk isolat. (dB)	47.8	47.6	48.0	48.0	46.0	45.7	44.6	44.4
Center wave. (nm)	1560.70	1559.00	1557.40	1555.80	1554.15	1552.7	1550.95	1549.35
Wavelength error (nm)	0.09	0.02	0.04	0.05	0.02	0.03	0.02	0.02

3.6 Temperature Sensitivity

Here only static temperature sensitivity is considered, i.e., there is no temperature gradient across the device. (For theoretical considerations in more general cases see Ref. 22.) We use two parameters to characterize temperature sensitivity, namely, the central wavelength shift (CWS) of each individual channel, and the insertion loss variation (ILV), while the working temperature is changing. The CWS is used to indicate the channel stability and the ILV is a good benchmark of signal strength. For field deployment, both CWS and ILV should be as low as possible across the working temperature range.

3.6.1 Central wavelength shift

The CWS of each individual channel can be found from the geometry of the multiplexer/demultiplexer and the grating equation, as in Eq. (1). From the structure of grating-based WDM multiplexers/demultiplexers, we can see that changes in the sizes of the baseplates and focal lengths due to the temperature variations affect only the insertion loss of the devices. The V-grooves for holding the fiber array are customarily made of silicon, the linear thermal expansion coefficient of which is 2.33×10^{-6} per centigrade degree.³³ The effect of temperature variations on wavelength shift is negligibly small.³⁴ The major factor causing a central wavelength shift is the change in grating period due to variation of temperature. For the fixed incident and out-going angles in a Littrow-structured device, the normalized CWS rate (NCWSR) for each channel is

$$\Gamma = \frac{1}{\lambda_c} \frac{\partial \lambda_c}{\partial T} = \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} = \alpha, \quad (5)$$

if we neglect the dn/dT in air. Equation (5) shows that $\Gamma = \alpha$, which is the linear thermal expansion coefficient of the material for the grating. If the working temperature changes 50°C , for a wavelength of $1.5 \mu\text{m}$, the central wavelength will shift 0.35 nm if the linear thermal expansion coefficient of the substrate is $7 \times 10^{-6}/\text{C}$, a typical value for most optical glass. For DWDM this shift is not permissible. To reduce this shift, low thermal expansion material is required. For this grating we chose a zero-expansion glass as the substrate. Figure 9 shows the measured data of the central channel wavelength shift for the 8-channel WDM multimode multiplexers/demultiplexers when the working temperature changes from 0 to 65°C . The experimental data show this shift to be very small.

3.6.2 Insertion loss variations

For constant incident wavelengths, which is the case for each channel of the multiplexer/demultiplexer, the insertion loss variations depend on the angular deviations, on the quality variations, and on the shifts in vertical direction of the diffracted beams. All three variables are due to working temperature variation. The effects of angular deviation can be found from grating Eq. (1), which is

$$\frac{\partial \theta_2}{\partial T} = -\frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \frac{n_3 \sin \theta_2 \pm n_1 \sin \theta_1}{n_3 \cos \theta_2} = -\Gamma \lambda D(\lambda, \theta_2). \quad (6)$$

The lateral (horizontal) displacement rate due to angular deviation can be expressed as

$$\frac{\partial x}{\partial T} = -f \frac{1}{\cos^2(\theta_2 - \theta_0)} \Gamma \lambda D(\lambda, \theta_2), \quad (7)$$

where f is the effective focal length of the coupling lens or lens system, and θ_0 is the angle between the optical axis and the normal of the grating. Equations (6) and (7) show that low thermal expansion material is required to reduce the lateral spatial shifts of diffracted beams for certain wavelengths.

The vertical spatial shift rate can be found from geometrical layouts of Littrow-structured WDM multiplexers/demultiplexers, which is

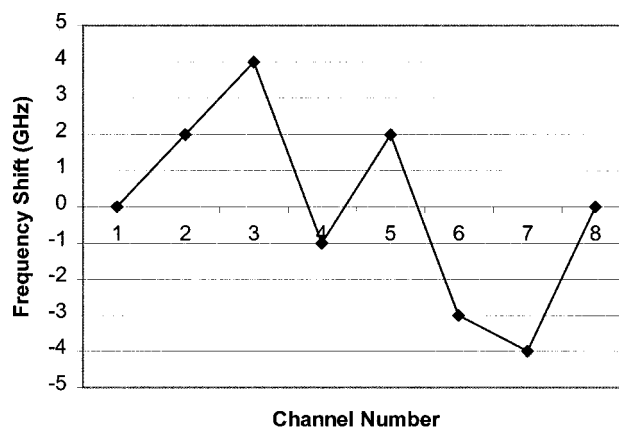


Fig. 9 The measured data of channel central wavelength shift for the 8-channel multimode WDM multiplexers/demultiplexers, with working temperatures varying from 0 to 65°C .

$$\frac{\partial y}{\partial T} = -2R(\alpha_L - \alpha_M), \quad (8)$$

where $2R$ is the diameter of the lens, α_L is the linear thermal expansion coefficient of the lens, and α_M is the linear thermal expansion coefficient of the holder for the V-groove fiber arrays. Therefore, for good thermal performance in WDMs, it is important to match the coefficients of expansion of the supports with those of the focusing optics. The differential expansion in the vertical direction is directly proportional to the lens diameter, so that thermal problems become severe for large lenses unless the expansion coefficients of the lens elements are nearly equal to each other and to that of the support. In all our WDM multiplexers/demultiplexers, the ILVs are within ± 0.5 dB for all channels within a range of working temperatures from 0 to 65°C.

3.7 Other Key Parameters

Other issues such 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.³⁵ 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 multipass through the grating for this reduction, as S. Bourzeix did,²⁸ 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 before, 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 as low as possible, keeping in mind the cost effectiveness of the methods. For optimal design, these tradeoffs must be carefully considered.

4 Conclusions

We discuss a set of 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, pulse broadening of the device, the physical geometry, weight, input/output, and sensitivities due to ambient temperature, pressure, humidity variation, etc. Effects on the performances of the devices due to various factors are analyzed and confirmed by experimental data. We follow with a set of analytical formu-

las to characterize these performance parameters with optimal design procedures for athermalized grating-based wavelength division (de)multiplexers. Based on the analyses and formulas, we have designed and developed a set of grating-based wavelength division (de)multiplexers, which are reliable, athermalized, and cost effective with high performance.

Acknowledgments

The authors would like to give their special thanks to Radiant Photonics Inc., Austin, Texas. This research was partially supported by BMDO, Army SSDC, Center of Optoelectronics Science and Technology (COST), DARPA, Office of Naval Research, AFSOR, and ATP.

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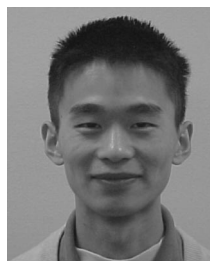


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