Optimal design of grating-based wavelength division (de)multiplexers for optical network

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ABSTRACT

In this paper, we first review the working principle of grating-base wavelength division (de)multiplexers(WD(D)M)for optical networks. Then key device parameters for WDM multiplexers, including insertion loss, isolation, channel passband, wavelength accuracy, polarization-dependent loss and temperature sensitivity are provided to evaluate the performance for the devices. After that, issues regarding optical design of grating-based WD(D)Ms for commercial uses are addressed. Next, several grating-based WD(D)M structures are analyzed with the procedures to optimize design of grating-based wavelength division (de)multiplexers. Based on these designs and analyses, we give the procedures of optimal design of devices with experimental data .

Key Words: Wavelength division (de)multiplexing, optical networks, optical communication, optical interconnects, fiber optic, grating

1. INTRUDUCTION

Wavelength-division multiplexing (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[1]. 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 nm and 1550 nm fiber wavelength, and the mature of tunable solid state lasers, high speed detectors, Erbium-doped fiber amplifiers (EDFA's), 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[2-5].

WDM fiber-optic communications require high-performance multiplexers and demultiplexers with low loss, wide channel bandwidth, low crosstalk and low polarization dependence. 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[7]. Multiplexers and demultiplexers based on filters exhibit high insertion loss for devices with many channels[8]. Since a grating-based WDM device can offer the advantages of low cost for many channels, low loss, and llittle crosstalk, it has received much attention [6, 9-19]. In this paper, we will analyze the optimal design issues for grating-based WDM multiplexers/demultiplexers with experimental data. In Section 2, we briefly review the principle of grating-based WDMs and discuss the dispersion abilities of the devices. In Section 3, we provide the key parameters for WDM devices. Based on these parameters, the optimal design issues applicable to every variety of grating-based WMD are discussed with details of the experimental data. The design procedures for obtaining optimality in these grating-based WDMs are summarized in this section. At the end of the paper we offer our conclusions.

2. WORKING PRINCIPLES

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 Figure 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.

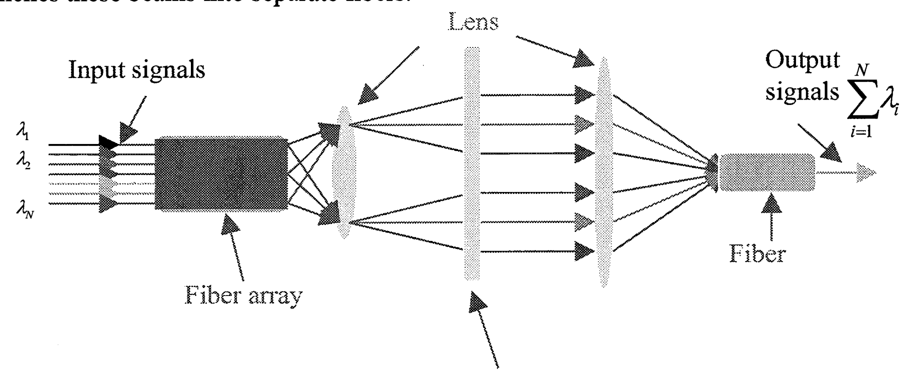


Figure 1. The diagram for the structure of the Czerny Turner typeWDM.

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.

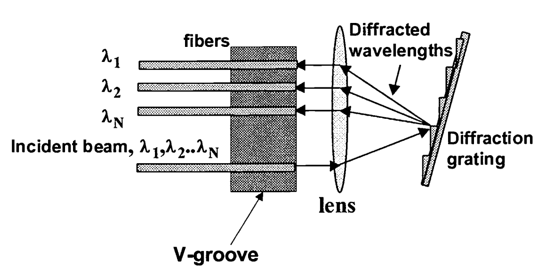


Figure 2. The diagram for the structure of the Littrow type WDM.

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[6, 10, 11, 17, 18, 19].

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. 20, and is

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

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

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

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

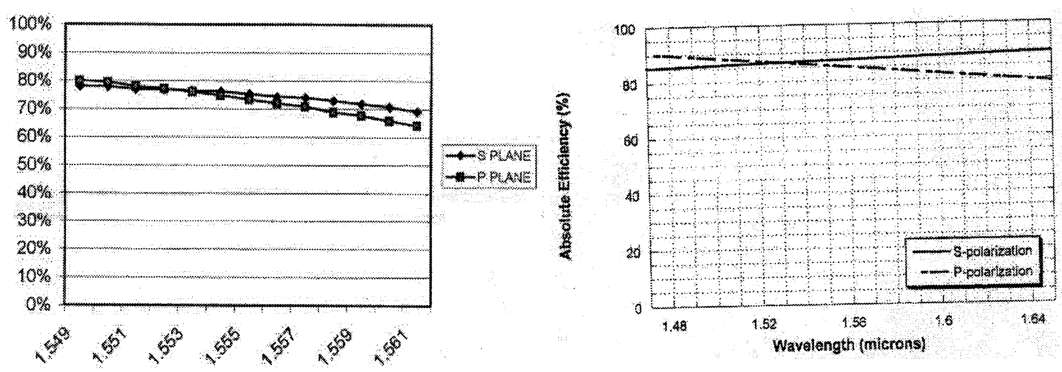
3. KEY PARAMETERS

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. This constrains the choice of (a)-(c) even though devices with channel spacing less than $50GHz$ 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 (d)-(h) above, 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

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. In our WDM multiplexer/demultiplexer design we use two types of high efficiency gratings to reduce the insertion loss and reach a wide passing bandwidth. Figures 3 (a) and 3 (b) show the respective efficiency spectra of the gratings for the DWDM and CWDM multiplexers/demultiplexers we have developed.



(a) (b)

Figure 3. The grating efficiency spectrum for WDM multiplexers/demultiplexers, (a) for DWDM and (b) for CWDM.

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

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

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. In all our multiplexer/demutiplexer 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. Figure 4 shows one of the surface/wavefront map of the gratings used in our WDM multiplexers/demultiplexers.

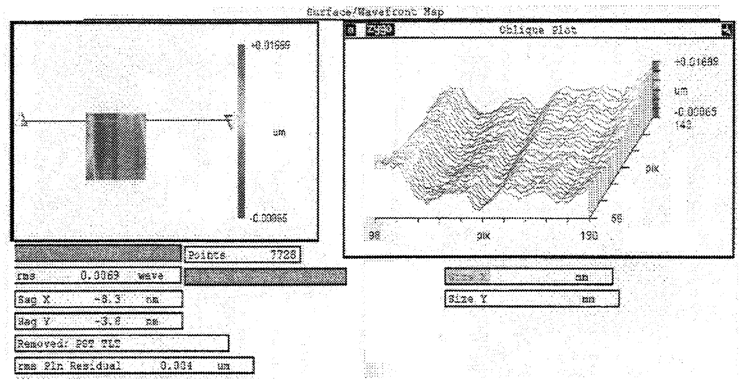


Figure 4. The surface/wavefront map of the gratings.

Figure 4 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 micron. 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 dB. Figure 5 shows the measured insertion loss for each channel in the 32 channel WDM multiplexer/demultiplexer.

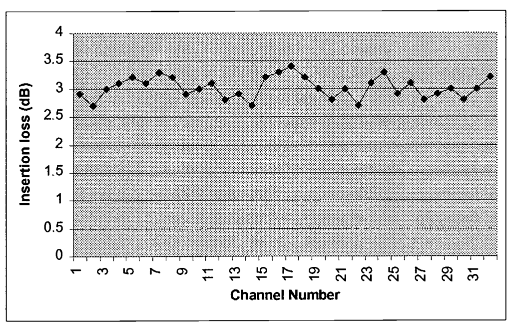


Figure 5. The measured data for insertion loss of a 32 channel WDM multiplexer/demultiplexer.

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 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. We used a ratio of four to develop the 8 channel multimode DWDM multiplexer/demultiplexer with 200*GHz* channel spacing. The isolation among channels is better than 40 dB.

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 and Fourier filtering technolgy[6]. This method has the cost of insertion loss and crosstalk among the channels. Figure 6 shows the defocusing effect on channel passpand of one demultiplexers developed in our lab. Another method reduces the ratio *b/d* of fiber spacing to the core of the output fiber. As mentioned in section 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[21]. 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.

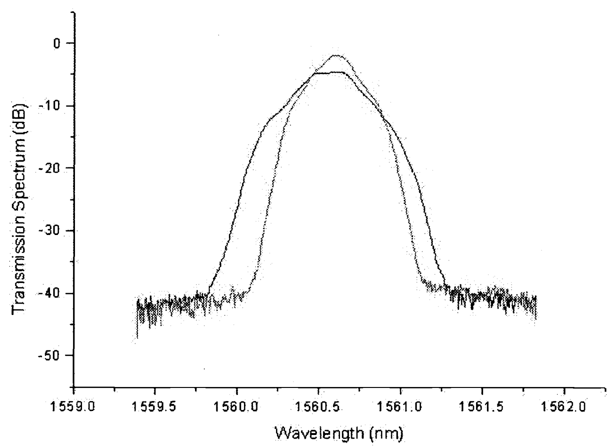


Figure 6. The experimental data for transmission spectrum of a demultiplexer for one channel, ... on focusing, ____Defocusing

3.4 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[18]. 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 gratings used in our WDM multiplexers/demultiplexers are almost polarization-insensitive in a certain wavelength range, especially in the C band. The PDL levels of all the WDM multiplexers/demultiplexers developed we have are less than 0.4 dB for all channels.

3.5 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. 12.) 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 central wavelength shift is used to indicate the channel stability and the insertion loss variation 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.

3.5.1. Central wavelength shift

The central wavelength shift of each individual channel can be found from the geometry of the multiplexer/demultiplexer and the grating equation, as in Equation (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[23]. The effect of temperature variations on wavelength shift is negligibly small[24]. 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 central wavelength shifting rate *(NCWSR)* for each channel is

$$\Gamma = \frac{1}{\lambda_c}\frac{\partial\lambda_c}{\partial T} = \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} = \alpha \qquad (4)$$

if we neglect the $\frac{dn}{dT}$ in air. Equation (4) shows that $\Gamma = \alpha$, which is the linear thermal expansion coefficient of the material for the grating. If the working temperature changes 50 degrees C, for a wavelength of 0.35 nanometer the central wavelength will shift 1.5 manometer if the linear thermal expansion coefficient of the substrate is 7×10^{-6} per centigrade, a typical value for most optical glass. For DWDM this shift is not permissible. In order to reduce this shift, low thermal expansion material is required.

3.5.2. 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 lateral 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 The lateral (horizontal) displacement rate can be found from grating equation (1), which is

$$\frac{\partial x}{\partial T} = -f\frac{1}{\cos^2(\theta_2-\theta_0)}\Gamma\lambda D(\lambda,\theta_2) \qquad (5)$$

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 (5) shows 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

$$\frac{\partial y}{\partial T} = -2R(\alpha_L - \alpha_M) \qquad (6)$$

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 insertion loss variations are within ±0.5 dB for all channels within a range of working temperatures from –5 to 65 degrees C. Figure7 shows the experimental data of the temperature variation effects on central wavelength shift and insertion variations of a demutiplexer we have developed. The data show that the channel is very stable.

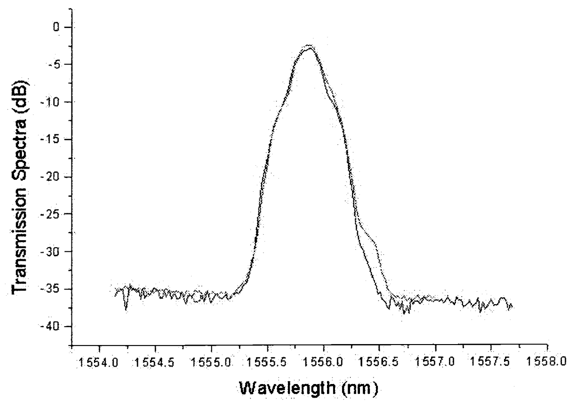


Figure 7. The experimental data for transmission spectrum of a demultiplexer for one channel, ... At -5 °C, _____ at 65°C

3.6. 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[18], 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 keeping in mind the cost-effectiveness of the methods. For optimal design, these tradeoffs must be carefully considered.

4. CONCLUSIONS

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

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