Multi-deck structure WDM devices for optical networks

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ABSTRACT

Wavelength division multiplexing (WDM) and demultiplexing (WDDM) devices are considered to be one of the key elements in optical networks. WDM device by using conventional, such as thin film filter and AWG based devices, can only be used as one device either multiplexing or demultiplexing. Here we propose a novel structure for WDM device, ehic is based on free-space diffraction-grating multiplexer/demultiplexer technology. By using multi-deck fiber arrays one device can function as both multiplexers and demultiplexers simutaneouly. In this paper we will give the structure and working principle for such device. We will also discuss the optical design issues. Finally we will present our experimental results. The devices can be used for bi-directional transmissions and optical transceivers in optical networks.

Keywords: WDM, fiber optics, optical networks, optical communications, grating, diffraction efficiency, free space optics

1. INTORDUCTION

The tremendous growth of the Internet and other data, image, voice services is driving the need for more and more bandwidth in networks. The bandwidth of one single-mode optical fiber is about 25 THz in the 1.5 μm band alone. Optical networks, having optical layer as the dominant technology for transport, becomes a key technology to fulfill the demands for bandwidth.

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. 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.

Wavelength division multiplexing (WDM) and demultiplexing (WDDM) devices are considered to be one of the key elements for enhancing the transmission bandwidth of optical communications and sensor systems. During the past 20 years, various types of WDMs and WDDMs have been proposed and demonstrated.[1-7] Most wavelength division (de)multiplexers employ one of the three technologies: arrayed waveguide grating (AWG), filter, and dispersive element (primarily diffraction grating).[8-9]

Conventional filters made of dielectric thin films and fiber Bragg gratings are not suited to high-channel-count muxes/demuxeses because they filter light in a serial manner and so must be used in combination with other technologies such as interleavers and circulators, which can cause high insertion loss and increased system costs.

With advances in waveguide photonic integrated circuits, muxes/demuxes based on planar arrayed waveguide gratings (AWGs) and etched Echelle gratings have potential use in DWDM networks. These devices process optical signals in a parallel fashion, which is preferred for high-channel-capacity networks. However, the devices based on AWGs are temperature-sensitive.

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Photonic Integrated Systems, L. A. Eldada, A. R. Pirich, P. L. Repak, R. T. Chen, J. C. Chon, Editors, Proceedings of SPIE Vol. 4998 (2003) © 2003 SPIE · 0277-786X/03/$15.00

Free-space diffraction-grating (FSDG) muxes/demuxes, which employ bulk diffraction gratings and discrete optical components to carry out parallel light processing, can address many of the performance weaknesses of planar AWG devices. The most importantly, the FSDG-based WDM devices can be made as multi-deck devices, which function as multi-muxes/demuxes. Therefore, multi-deck devices can dramatically reduce the WDM system costs. In this paper we first introduced multi-deck WDM devices based FSDG technology. In the following sections, we will first give the working principle of multi-deck WDM muxes/demuxes. Then we will discuss the optimal design of such device. After that we will give the applications of the devices with experimental results. Finally we end the paper with the conclusions.

2. THE STRUCTURE & WORKING PRINCIPLE

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,[10-11] and the Littrow structure, which has one common lens. Since Littrow WDM multiplexers/demultiplexers use fewer components they are more cost-effective.[12]

To examine the operating principle of the Littrow structured grating-based multi-deck WDM multiplexers/demultiplexers, we refer to the structure shown in Figure 1 for double deck device as an example.

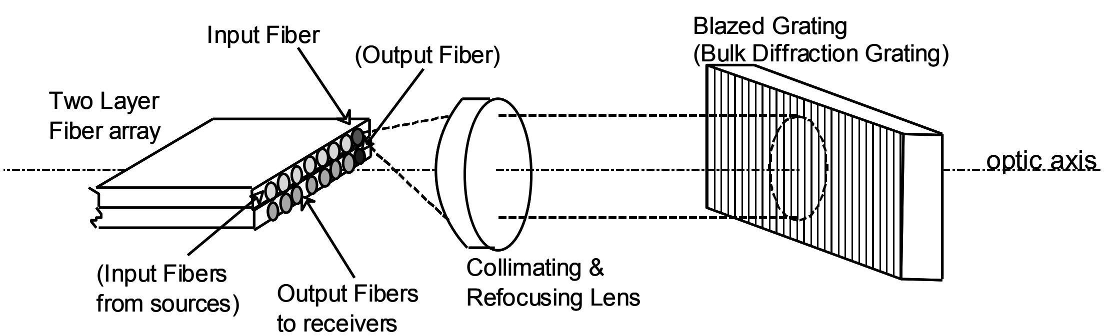


Figure 1. Scheme of double-deck of grating WDM multiplexer/demultiplxer

In a double-deck device, two layers of fiber arrays are arranged on the focal plane of the lens symmetrically about the optic axis. Wavelength-multiplexed light signals from the input fiber in upper layer are collimated by the lens and incident on the diffraction grating. The light is angularly dispersed and reflected (demultiplexed) simultaneously, according to different wavelengths. Then the diffracted wavelengths pass through the same lens and are focused to their corresponding output fibers in lower layer. Each wavelength is fed to one individual output fiber and sent to the receiver. In reverse process, the laser signals from WDM laser sources in transceivers are coupled into fibers in the upper layer according their wavelengths. These signals are then collimated by the same lens and reach the same diffraction grating, get diffracted into one angle (multiplexed) and reflected. The multiplexed wavelengths pass through the lens and are focused onto a single input fiber in the lower layer, and are sent to optical transmitter.

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 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. 13, and is

$$\Lambda(n_3\sin\theta_2 \pm n_1\sin\theta_1) = m\lambda / n_3\,, \qquad m = 0, \pm 1 \pm 2, \ldots \tag{1}$$

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. 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 .

3. OPTIMIZATION OF DESIGN

An optimal design of WDM device 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 100*GHz* frequency grid centered at 193.1*THz* optical frequency, aiming at a 10*Gbs* capacity per channel, as recommended by ITU-T. This constrains the choice of (a)-(c) 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. 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.

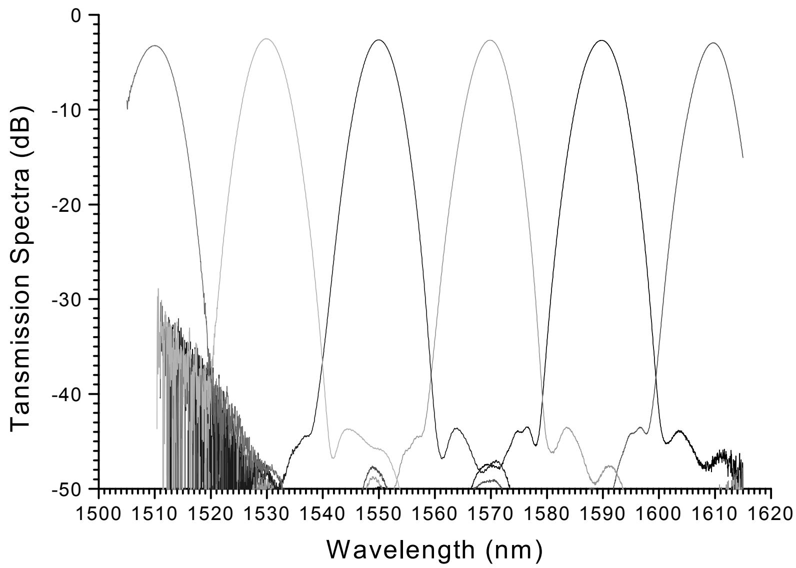
In summary, a good WDM multiplexer/demultiplexer must optimize all the key parameters discussed above, namely, insertion loss, isolation among channels, polarization-dependent loss, return loss, power damage threshold, pulse broadening of the device, the physical geometry, weight, input/output interfaces, 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.

To optimize design of free-space diffraction-grating (FSDG) muxes/demuxes all the factors mentioned above should be taken into account. How to optimize these parameters can be found in Ref. 14.

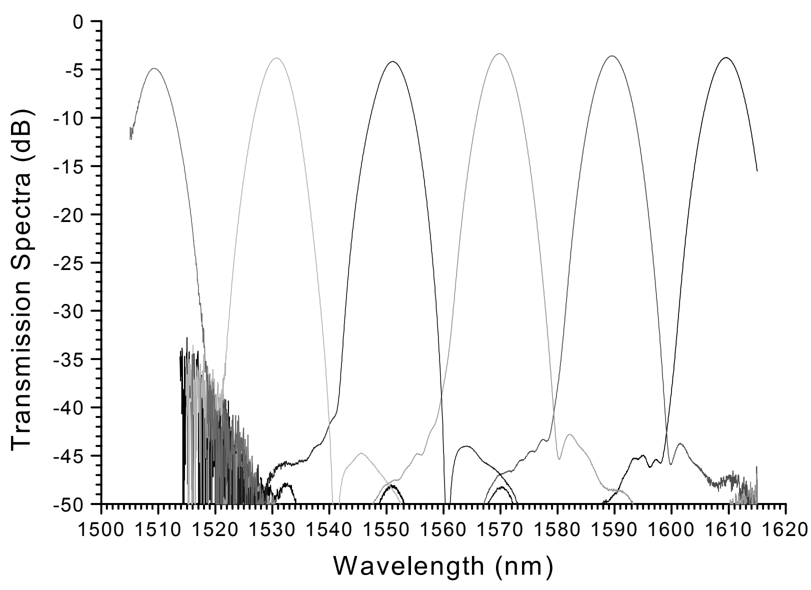
4. APPLICATIONS & EXPERIMENTAL RESULTS

4.1 6-channel double-deck device for bi-directional transmission application

Considering all the factors mentioned in Section 3 we designed and fabricated 6-channel double-deck WDM multiplexer/demultiplexers for the applications in bi-directional transmission. In order to reduce the insertion loss and PDL, we first chose custom-designed high frequency blazed grating with high efficiency and wide pass band to develop the devices. The channel spacing of this 6-channel double-deck WDM device is 20 nanometers. The filtering characteristics of a WDM multiplexer/demultiplexer, i. e., the transmittance versus wavelength, provide almost complete information for the device. Figure 2 shows the spectrum of the device, the (a) is for one layer and the (b) 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 signal noise in the spectra is due to the light signals from light source in the wavelength range used in the measurement is too weak. The performance in one deck is given in table 1 in the detail.



(a)



(b)

Figure 2. The transmission spectra of double-deck 6-channel WDM device, (a) for one layer and (b) right for another

Table1. The measured data for the performance of the 6-channel double-deck WDM device in one deck.

Channel Number	1	2	3	4	5	6
Central Wavelength (nm)	1509.6	1529.8	1535.0	1570.1	1590.4	1610.6
Wavelength Error (nm)	-0.4	-0.2	0	0.1	0.4	0.6
Insertion Loss (dB)	2.9	2.6	2.4	2.5	2.6	2.8
Channel Isolation (dB)	44	45	46	45	44	46
1-dB Passband (nm)	3.1	3.0	2.9	3.0	3.1	3.0
PDL (dB)	0.3	0.2	0	0.1	0.2	0.3

For comparison, we also measured the spectra of the devices when multiplexed signals pass through two decks simultaneously, which is illustrated in figure 3. From the spectra we can see that the insertion loss is 6.4 dB when working as multiplexer and demultiplexer simultaneously. The channel uniformity is within 2 dB. Adjacent cross-talks are better than -40 dB.

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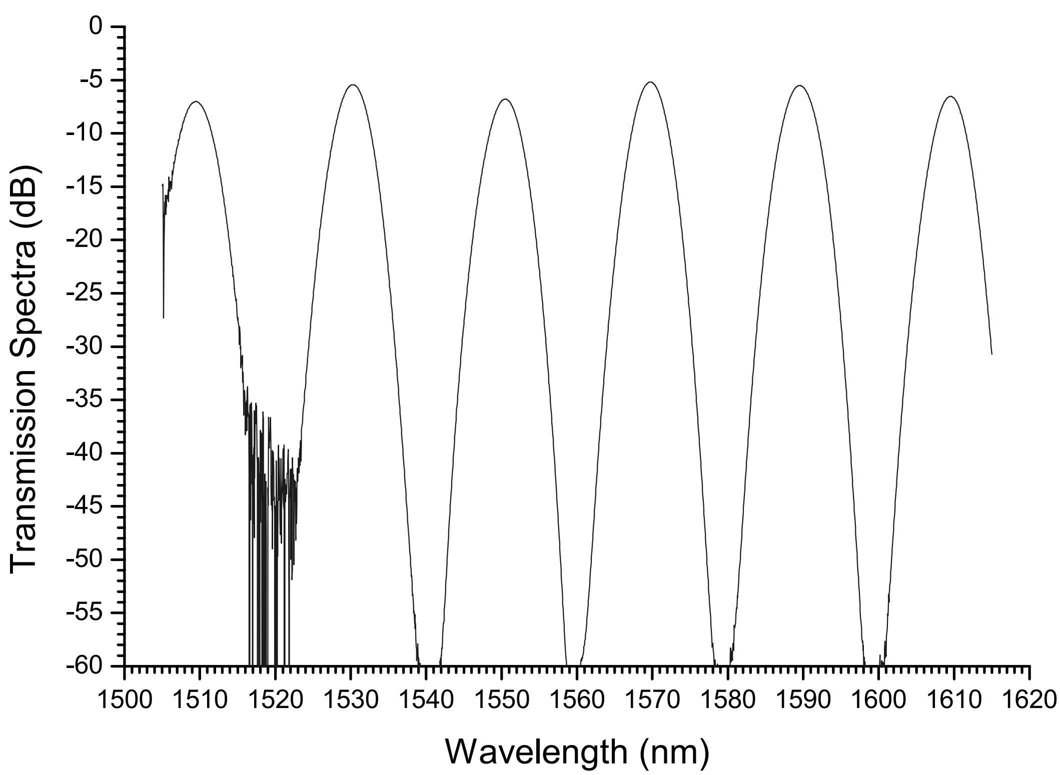

Figure 3. The transmission spectrum of double-deck 6-Channel CWDM device when working at multiplexing and demultiplexing simultaneously in bi-directional mode.

We also measured high-speed performance of the device. Figure 4 shows the eye diagram of this 6-channel WDM multiplexer/demultiplexer working at 12.3 Gbps. From the figure we can see the eye is still open at 12.3 Gbps.

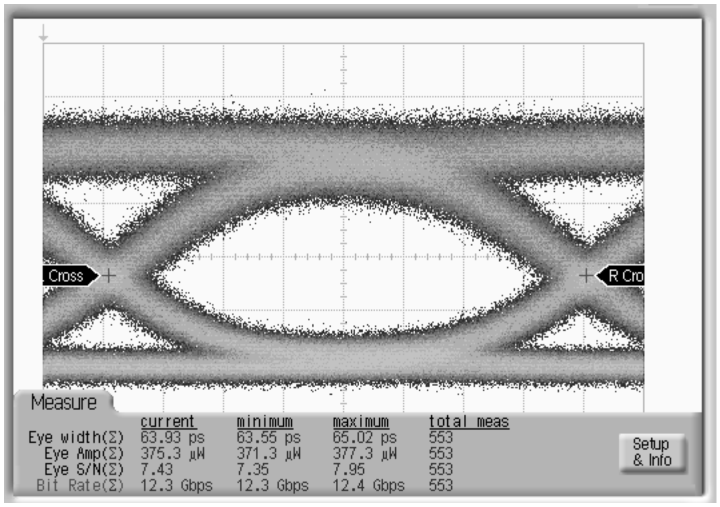

Figure 4. The Eye Diagram of Dual-Deck 6-Channel DWM device at 12.3 Gbps

4.2 Enhanced channel-pass-band ultra-dense WDM device

Channel pass-band is critical parameter for WDM networks. A large channel pass-band allows large fluctuation of wavelengths of WDM sources due to the variation of temperature. In addition, in most long-haul networks, the light must be multiplexed and demultiplexed many times, thus requiring multiplexer/demultiplexer to be cascaded in series. A wide pass-band is needed to accommodate wavelength inaccuracies in the dense WDM device caused by manufacturing. We can dramatically increase the bass-band of dense WDM multiplexer/demultiplexer and make ultra-dense WDM device by combination of inter-leaver and multi-deck dense WDM device. Figure 5 shows the working principle for such a device.

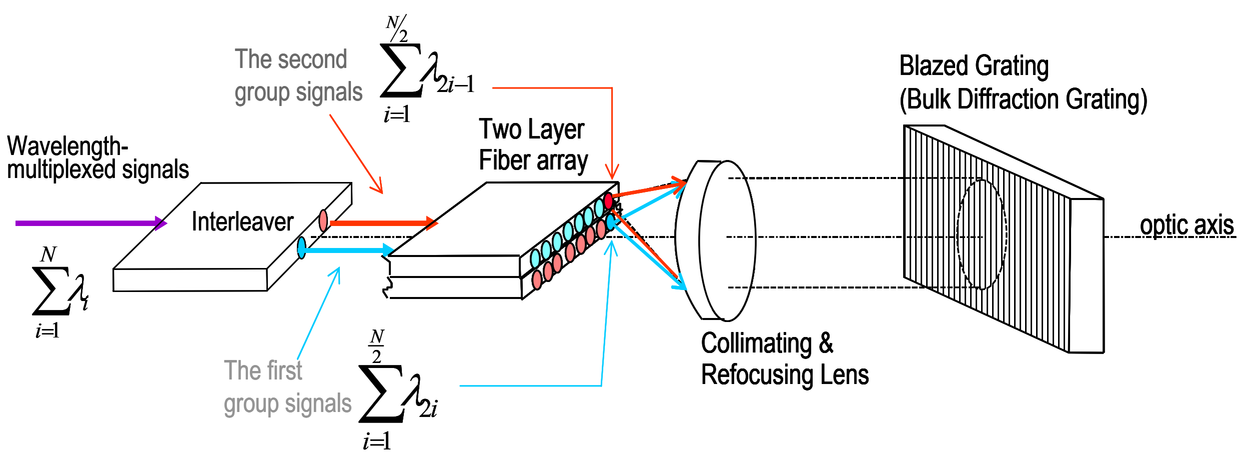

Figure 5. Scheme of enhanced channel-bass-band WDM multiplexer/demultiplxer by combination of interleaver and double-deck WDM device

This devices works as the following: Wavelength-multiplexed light signals are fed into an interleaver. They are divided into two groups with interleaving wavelengths, that is, the light signals whose sequence-numbers of are even in one group and others are in another group. Two groups of light signals are sent to different layer fiber arrays in the multi-deck WDM devices.

We designed and fabricated 100 GHz WDM devices by using an interleaver and a 200-GHz double deck WDM multiplexer/demultiplxer. The transmission spectrum of the device is shown in Figure 6.

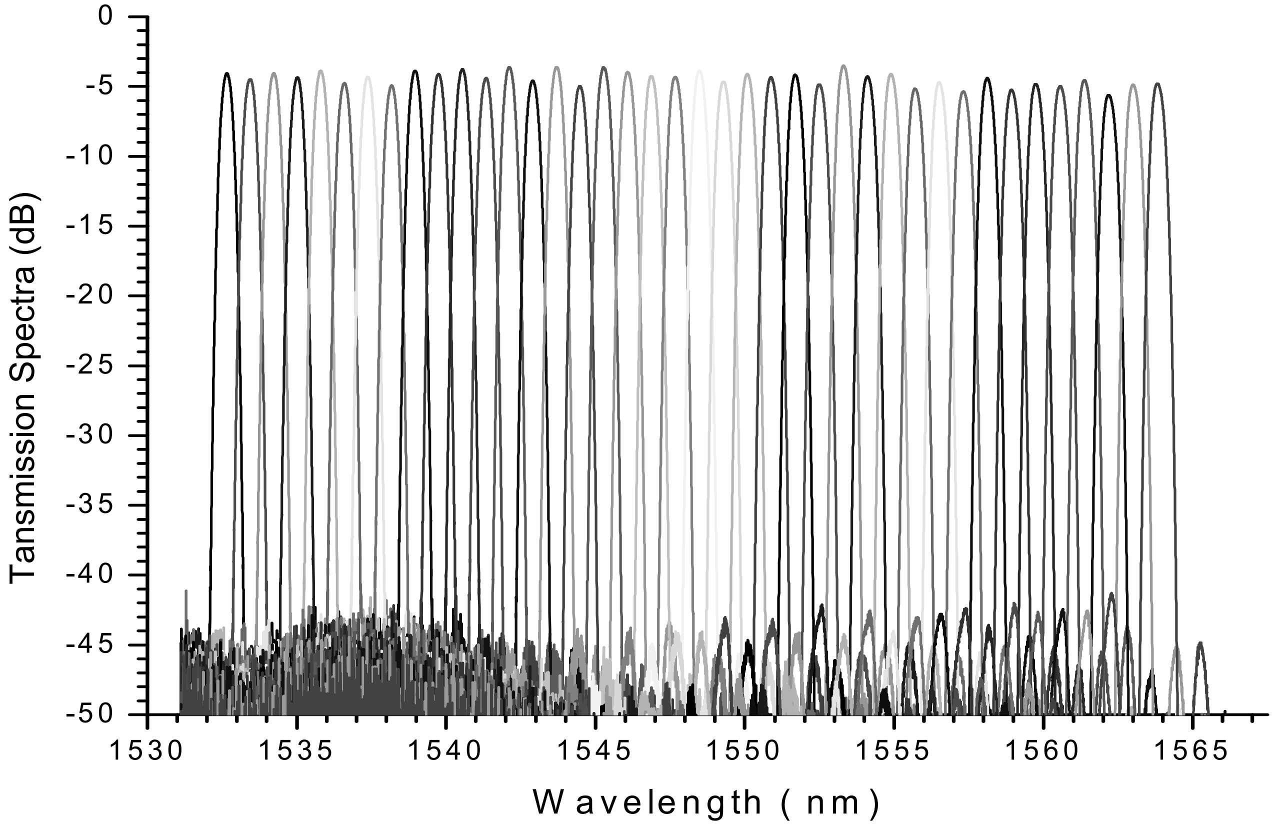

Figure 6. The transmission spectrum of 100 GHz WDM devices

5. CONCLUSIONS

As dense wavelength division multiplexing is becoming a preferred technique for increasing the information-carrying capability of optical networks by making full use of the huge bandwidth available in optical fibers, multi-deck WDM multiplexer/de multiplexer makes the technology more attractive. Here, we fist proposed and demonstrated a multi-deck structure WDM device based on free-space diffraction-grating multiplexer/demultiplexer technology, which processes optical signals in a parallel fashion. The device functions as multiple WDM multiplexers/demultiplexers. As discussed in previous sections only free space grating technology can provides the chance for multi-deck WDM device without adding extra components for processing optical signals. The proposed multi-deck WDM devices can function as multiple WDM devices and performs as a single-deck device does. It is very is cost-effective, low-payload, and easy to be integrated in optical networks.

ACKNOWLEDGEMENTS

This research was partially supported MDA, Army SSDC, Center of Optoelectronics Science and Technology (COST), DARPA, Office of Naval Research, AFSOR, and ATP. The authors would like to give their special thanks to them.

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