Fully Packaged Dense Wavelength Division Demultiplexer for Optical Networks

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Abstract

A fully packaged dense wavelength division demultiplexer (DWDDM) by using dispersion-enhanced volume holographic grating and V-grooved silicon fiber array is demonstrated. The device demultiplexs eight optical channels, namely at wavelengths of 1549 nm to 1563 nm every 2 nm respectively. The system insertion losses are -5.68 dB, -5.6 dB, -5.40 dB, -5.3 dB, -5.68 dB, -5.59 dB, -5.58 dB, -5.49 dB respectively. Typical adjacent cross-talks among these eight channels are less than -35dB. Epoxy and UV curing are used for fixing most parts of the optical components, which ensures the low cost of the devices. The trade-off between getting smaller physical packaging size and linear dispersion ability at different wavelength is addressed.

Keywords: DWDDM, Volume holographic grating, Photo polymer films, Optical network, Dispersion

1. Introduction

Dense Wavelength Division Multiplexing (DWDM) systems are key elements for increasing the transmission bandwidth of optical communications and sensors. The use of DWDM systems allows the already installed point-to-point networks to greatly multiply their capacity without additional optical fibers. An important future of dense WDM is that discrete wavelengths from an orthogonal set of carriers which can be separated, routed, and switched without interfering with one another, as long as the total light intensity is kept sufficiently low[1-3]

For optical network at wavelengths of 1330 nm and 1550 nm, investigations have been focusing on arrayed waveguide gratings (AWG) [4-6] and Bragg grating [7-8]. In this letter, an eight channel fully packaged dense wavelength division demultiplexer (DWDDM) is presented which uses a dispersion-enhanced DWDDM structure by employing a novel grating design[9]. By using a path-reversed substrate-guided-wave configuration working at a center wavelength of 1555 nm. This demultiplexer is compact in size and more cost-effective compared with the counterparts made out of the other methods.[4-8]

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2. Grating working principle and structure

A path-reversed photopolymer-based substrate-guided holographic grating is used for demutiplexing 8 wavelengths with 2 nm separation. The choice of wavelengths and wavelength channel spacing is depend upon the requirement of the parallel optical interconnect system built by Jet Propulsion Lab.

Figure 1 shows the schematics of the eight channel DWDDM device and the geometric structure of the path-reversed substrate-guided-wave optical interconnection. The grating dispersion ability for the first order forward diffraction can be derived from grating equation [10], which gives:

$$\frac{d\theta_{diff}}{d\lambda}=\frac{\sin\varphi}{\Lambda\cos\theta_{diff}}=\frac{n(\sin\theta'_2+\sin\theta_2)}{\lambda\cos\theta_{diff}} \qquad (1)$$

where φ is the slanted angle of grating, Λ is the grating period, θ_2 and θ_2' are, respectively, the incident angle and the diffraction angle of the optical signals in the grating region at a center wavelength of λ (in the air). n is the average refractive index of the grating region. θ_{diff} is the designed diffraction angle in the air of refractive index n_3.

The diffracted multi-wavelength signals are coupled into a silicon V-grooved fiber array with a 62.5 um diameter core, a 125 um diameter cladding, and a 250 um channel to channel spacing. The linear angular dispersion among different wavelengths is highly demanded to get balanced coupling efficiency. Since the grating angular dispersion equation (1) is not an exact linear function, there is a small deviation from the designed diffraction position to the real diffraction position. Therefore, it is much easier to get high and balanced coupling efficiency if we could choose our wavelengths in the linear region of the dispersion equation (eq.1). The condition for getting linear angular dispersions among different channels can be found by the following equation:

$$\frac{d^2\theta_{diff}}{d\lambda^2}=\frac{\sin(\theta_{diff})}{\cos^3\theta_{diff}\Lambda_y^{\ 2}} \qquad (2)$$

In equation (2), Λy = Λ/sin(Φ), it is the grating period projected in the direction vertical to the grating normal. When diffraction angle in the air is zero, The best angular dispersion linearity can be achieved. Diffraction angle at different wavelength is:

$$\theta_{diff(\lambda)}=\arcsin(\lambda/\Lambda_y-n\times\sin(\theta_2)) \qquad (3)$$

The diffraction angle difference between a specific wavelength and the center wavelength is:

$$\Delta\theta_{diff(\lambda)} = \theta_{diff(\lambda)} - \theta_{diff(center\text{-}\lambda)} \tag{4}$$

Channel spacing between specific wavelength and center wavelength:

$$\Delta d_{(\lambda)} = f \times \tan(\Delta\theta_{diff(\lambda)}) \tag{5}$$

The simulation result of channel spacing deviation at two different incident angles and diffraction angles is shown on Table 1. For incident angle of 60° in the grating, diffraction angle of 0° in the air, (ie: 60° / 0° structure), we can get coupling balance, but the dispersion ability is only 0.0485 degree per nanometer. For incident angle of 60° in the grating, diffraction angle of 60° in the air, (ie: 60° / 60°) grating structure, the dispersion ability is 0.1600 degree per nanometer, which is 2.3 times larger than that of 60° / 0° structure. The biggest deviation of channel spacing for 60° /60° structure grating structure is 24.08 um, most of them are smaller than 6 um. The core size of multimode fiber is 62.5 um, so this shift is tolerable. There exists a trade-off between the dispersion ability and the dispersion linearity. We select a grating structure with a grating period Λ of 694 nm, a diffraction angle θ_{diff} of 60° in air and an incident angle θ of 60° in the grating. This structure can provide a relatively large dispersion and bandwidth, like, $d\theta_{diff} / d\lambda = 0.16^{\circ}/\mathrm{nm}$. The beveled edge provides a way to overcome the limitation of the critical angle of the waveguiding substrate and to enhance the dispersion of the holographic grating. For our device, the spacing of the diffracted beams on the focal plane of lens are not uniform and their position shift accordingly, which can be compensated by tuning the wavelength slightly.

3. Experiment

The demonstrated system is shown in Figure1 which illustrates the layout of the design and packaging of our devices. A collimator with single mode fiber and FC fiber connector, a computer optimized achromatic lens, a V-grooved silicon fiber array and their holders are integrated on a 4.3 inch by 2.7 inch base plate. The lights coming from WDM lasers are transposed to a collimator by a single mode fiber, and are diffracted by a 60° / 60° holographic grating. Diffracted beams outside of grating vary almost linearly with the deviation of eight input wavelengths. A lens is used to focus the beams down to diffraction limited spots which can be coupled into a eight channel V-grooved silicon multi-mode fiber array with a 250 um channel spacing.

To maintain precision and accuracy during the packaging, the V-grooved fiber array is installed on a specially designed gripper whose position can be controlled by a position system with six degrees of freedom including X, Y, Z translation, rotation, peach, and yaw. For X,Y,Z translation stages, the translation resolution is 0.5 um. The resolution of goniometer used for the rotation of V-grooved fiber array is 6 arcsec resolution. The resolution of tilt for both peach and yaw is 5 arcsec. Because IR is invisible, it becomes critical to locate the exact position of focal point of lens. First of all, We couple the center wavelength 1555 nm to the 4th channel of v-grooved fiber array which is the designed coupling channel for center wavelength. The smallest insertion loses and balanced crosstalks to the two neighbor channels can be reached by adjusting X, Y, Z translation stage. At this time, the focal point of the lens is immediately on the front face of V-grooved fiber array when operating at the center wavelength. Tightly focused beams may thermally damage the end of the fiber. Secondly, we couple light with wavelength of 1553 nm and 1557 nm to the two neighbor channels, namely, the 3rd channel and the 5th channel. The rotation and yaw freedoms are used for keeping v-grooved array flat and its axis at the same direction as the optical axis. After we get the smallest insertion losses and balanced crosstalks for the two channels, we continue to couple channel 2, channel 6, channel 1 and channel 7, and so on. Because WDM laser source usually contain a spectral width depending on the laser cavity structures and the operating conditions [11], Laser wavelength shift is also present when the laser is internally modulated [12]. Dispersion nonlinearities will limit the wavelength range and channel spacing. It is observed that there is a little shift for the coupled wavelength compared to the designed. The fully packaged device is shown in Figure 2.

Two terms are defined here. Insertion loss is defined as the power loss from WDM laser to the output of the silicon V_grooved fiber array including the loss of input signal mode fiber, collimator, holographic grating, lens and silicon V-grooved fiber array. Crosstalks are the power ratio among a specific channel with its neighbor channels when only the specific channel is activated. The measured crosstalks of the DWDDM system are listed in Table 2. The typical value of crosstalks is less than –35dB which is good enough for optical communications network. The typical insertion loss of this system is 5.6dB. The insertion loss is mainly due to using a home made holographic grating which is polarization sensitive. The diffraction efficiency of the holographic grating is 40% for TE mode, which is due to the fixed index modulation and film thickness provided by DuPont photopolymers (DuPont Holographic Materials, Wilmington, Delaware, USA)[13-14]. Figure 3 gives the measured diffraction efficiencies (circles) of the +1 order forward diffraction of the grating as a function of wavelength under s-polarization, which are matched with the simulation results (solid lines) by the rigorous coupled wave analysis (RCWA). Because this grating is made in our lab in a very short time period, we certainly can get high diffraction efficiency and polarization non-sensitive grating from outside. (The absolute diffraction efficiency of grating made by American Holographic Inc is 91.2% for both TE and TM mode, The diffraction efficiency of Gratings made by Optometrics USA, INC can be 72.5% and polarization insensitive). The insertion losses can be decreased significantly down to –2.5 dB to –3 dB if we use these gratings in the future.

Figure 4 shows the output spectrum from the eight-channel V-grooved fibers when input wavelength are 1549 nm, 1551nm , 1553 nm, 1555 nm, 1556 nm, 1558 nm, 1560 nm, 1562 nm. Under practical environment, the working wavelengths of DWDDM devices are most probably slightly different with the designed, which may result from the precision of semiconductor laser or grating. This is actually implies our work actually have potential application. We use epoxy and UV curing to permanently fix all the optical components together with their mounts. There is no observed component displacements after UV curing of epoxy.

summary

The designed DWDDM employs dispersion enhance volume holographic grating and V-grooved multi-mode fibers array with 250 um spacing to demultiplex optical signal to eight-channel, namely at wavelength of 1549 nm , 1551 nm, 1553 nm, 1555 nm, 1557 nm, 1559 nm, 1561 nm, and 1563 nm. The insertion losses of these channels are -5.68 dB, -5.6 dB, -5.40 dB, -5.3 dB, -5.68 dB, -5.59 dB, -5.58 dB, -5.49 dB respectively. The typical cross-talk is –35dB. The cross-talks among all the channels are less than –31dB which can be confirmed by experiment result. Most parts of the DWDDM device are off-shelf optical components which can ensure the cost is effectively low. All the components are permanently fixed with epoxy and UV cured, which make the device is robust and rigid.

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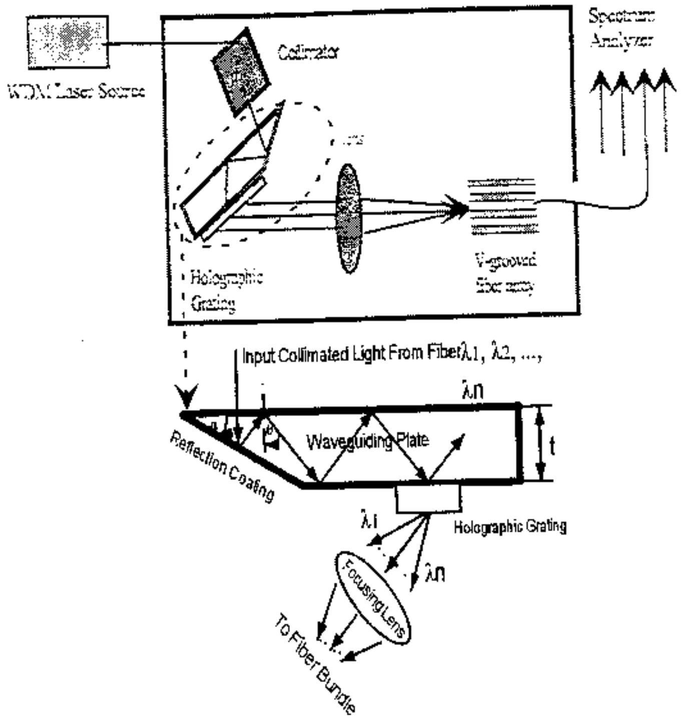

Figure 1 (a).

Figure 1. (b)

Figure 1 Schematic of an eight channel DWDDM device and the Geometric Structure of a path-reversed substrated-guided-wave interconnected scheme

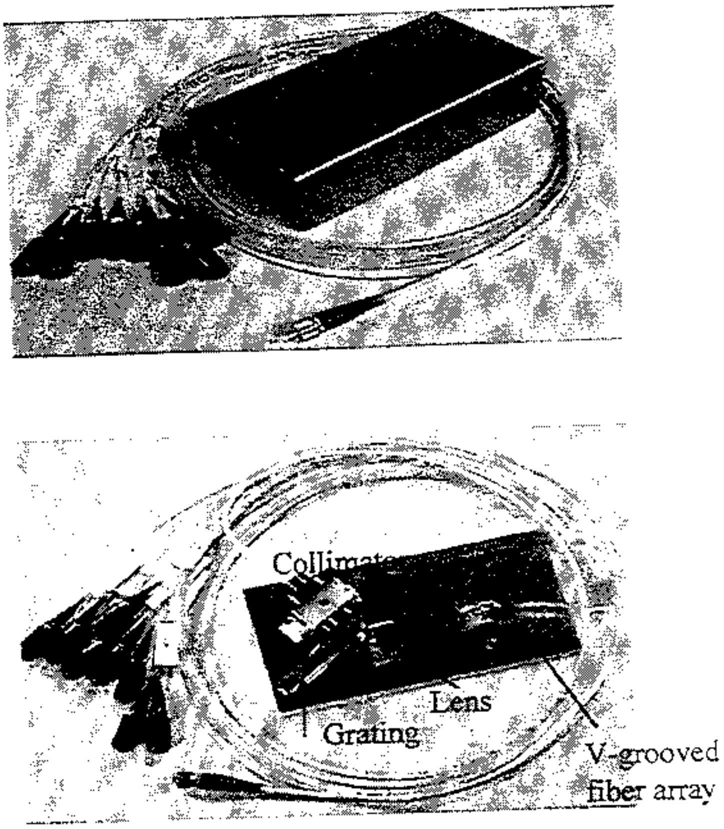

Figure 2 (a) Fully packaged 8 channel DWDDM device

(b) Inside setup of the packaged device

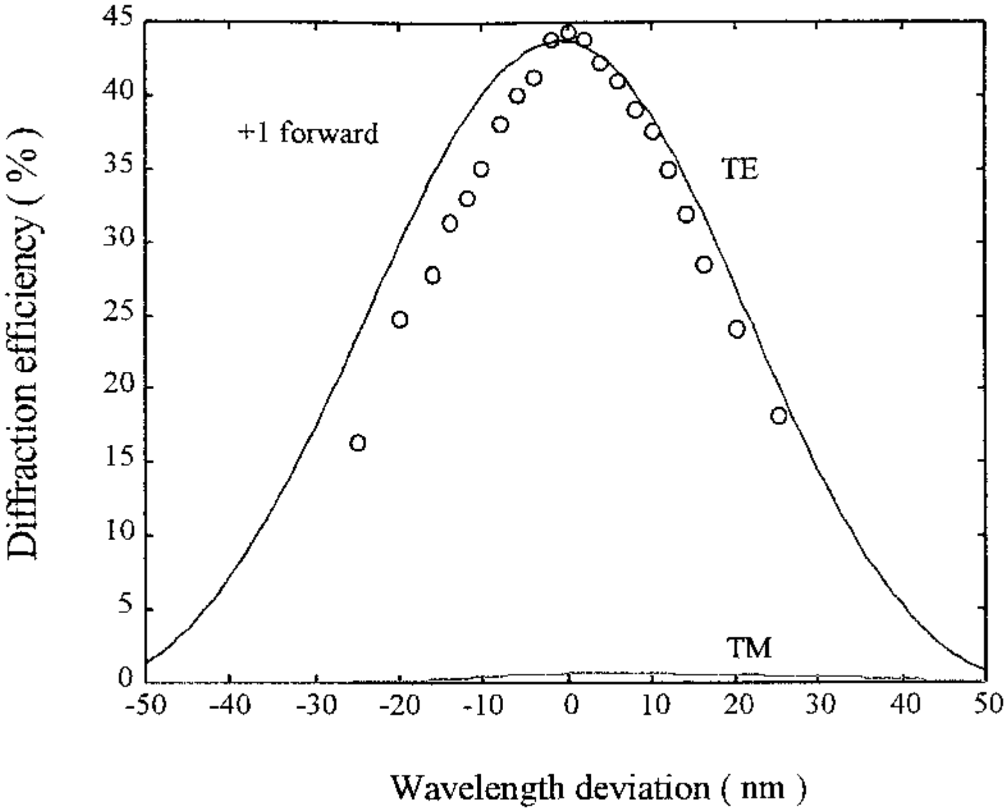

Figure 3 Grating efficiency measurement

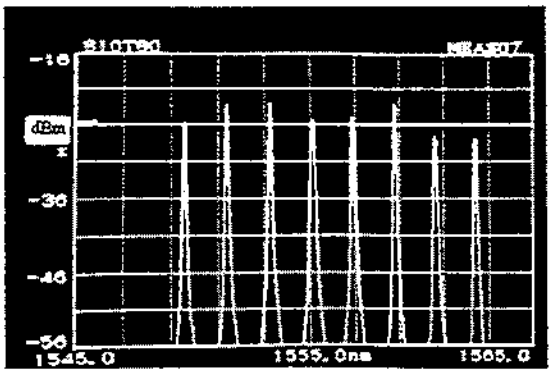

Fig. 4 output spectrum from an eight channel V-grooved fiber array

Wavelength (nm)		1549	1551	1553	1555	1557	1559	1561	1563
Expected spacing to center wavelength		-750	-500	-250	0	250	500	750	1000
Spacing to center wavelength (um) at two different structure	60°/60° structure	-725.92	-486.09	-244.15	0	246.43	495.24	746.52	1000.37
	60°/0° structure	-746.05	-497.36	-248.68	0	248.68	497.36	746.05	994.75
Deviations of spacing(um)	60°/60° structure	-24.08	-13.91	-5.85	0	-3.57	-4.76	-3.48	0.37
	60°/0° structure	-3.94	-2.63	-1.32	0	-1.32	-2.63	-3.94	-5.25

Table 1 Spacing deviation for two different grating structure

Channel # & Wavelength (unit: nm)	1	2	3	4	5	6	7	8
1 (1549.45)	-5.68	-35.72	-40.80	-44.91	-45.82	/	/	/
2 (1551.37)	-43.12	-5.6	-36.3	-42.0	-46.6	/	/	/
3 (1553.20)	-42.2	-40.7	-5.40	-36.6	43.2	/	/	/
4 (1555.10)	-46.9	-42.9	-41.0	-5.3	-40.3	-43.27	-47.49	/
5 (1556.86)	/*	/	-41.7	-40.1	-5.68	-38.5	-46.1	/
6 (1558.79)	/	/	-41.9	-41.9	-38.3	-5.59	-40.1	-45
7 (1560.62)	/	/	-43.6	-43.5	-42.3	-33.5	-5.58	-39.2
8 (1562.65)	/	/	/	/	/	-39.9	-31.7	-5.49

Note: " / " means the crosstalks are not deectable

Table 2 Insertion losses and crosstalks of the packaged device