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Four-channel coarse WDM for inter- and intra-satellite optical communications

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Abstract

A polymer volume grating-based four-channel coarse wavelength division multiplexer (WDM) for inter- and intra-satellite optical communication application is reported for the first time. This compact four-channel WDM device working at 0.83, 1.06, 1.34 and 1.55 μm is designed to build a complete optical link between two satellites, where wavelengths of 0.83 and 1.55 μm are used for data stream channels, 1.06 and 1.34 μm are used for inter- and intra-satellite connection. It is for the first time reported that a WDM device can cover such a large wavelength range in a single substrate. For transverse electric (TE) wave, the channel efficiencies at 0.83, 1.06, 1.34 and 1.55 μm are 55%, 40%, 35% and 45%, respectively. Channel efficiencies for transverse magnetic (TM) waves are 20% lower than those of TE waves on average. Wavelength shifts due to Doppler effect, temperature variations and radiation effects in space can be adequately accommodated.
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The concept of space-based, free space optical communications among satellites was developed in the early 1960s [1]. However, there was no system demonstration coming into reality until 2001 by ASTRIUM [2] due to the complexity of ultra-precise beacon acquiring, tracking and pointing technology. For data rates above 1 Gbps, optical inter-satellite links (ISLs) outperform conventional RF links in terms of high data rate, huge transmission capacity, low power consumption, small size and light weight. While Space–ground links have been, and will continue to be dominated by RF links due to severe atmosphere and weather interference at optical frequencies, global optical backbone networks, i.e., space-based optical ISLs are believed to be the future replacements of their microwave counterparts [3]. Inter-satellite optical communication requires three wavelengths to complete the simplest point-to-point data transfer between two satellites. One laser beam is used as an information carrier, the second laser beam is used as a tracking and pointing beacon, and the third laser beam works for intra-satellite communication. A lot of the earlier work was done based on 0.8 μm technologies with which the research about the free space optical communications started [4]. However, current plans call for continuous investigations of medium bit-rate (300 Mbps) systems using 0.8 μm technology and new investigations of high-rate (1.2 Gbps) systems using 1.5 μm technology, which is now available due to terrestrial fiber systems development [5,6].

Coarse wavelength division multiplexing (WDM) technology, which is developed for storage access networks (SANs), finds its great potential for applications in the space-based optical communication system. The data bit-rate independence of the WDM technology

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[7] makes it even more attractive in space-based application because it permits excellent upgrading compatibility of the current on-board network. In this paper, a coarse photopolymer grating-based WDM device is proposed and developed. Our proposed four-channel CWDM device which covers both 0.83 and 1.55 μm data stream channels works properly in the current optical satellite medium bit-rate systems based on 0.8 μm technology and its good performance can also be maintained in the future high bit-rate system using 1.5 μm technology. This broad-band four-wavelength CWDM is designed to provide two data streams at 0.83 and 1.55 μm, an inter-satellite tracking channel at 1.06 μm, and an intra-satellite communication channel at 1.34 μm.

The schematic and the real device picture of the four-channel CWDM device using four photopolymer-based holographic gratings in conjunction with substrate-guided waves are shown in Fig. 1. An aluminum-coated beveled edge is used to couple optical signals into the wave-guiding plate with a bouncing angle larger than the critical angle of total internal reflection (TIR) of the glass substrate [8]. Four volume holographic gratings are recorded to provide surface-normal fan outs for four different wavelengths, i.e. 0.83, 1.06, 1.34 and 1.55 μm. Independent zigzag guided beams of their designated wavelengths are selectively coupled out from one of the four outputs at their Bragg angles. The wavelength separation and channel spacing for our CWDM can be designed depending on different requirements to the targeted applications. In this work, a beveled edge is designed at the input end to maximize the coupling of the optical signal into the glass substrate. The beveled edge is coated with aluminum film with reflection efficiency higher than 99%. Wedge angle is designed at 22.5° to router normal incident signals into the wave-guiding plate shown in Fig. 1(b) with a TIR bouncing angle at 45°. In this work, 4 mm thick optically flat glass plate is used as the wave-guiding plate for all four wavelengths. To facilitate the output coupling and packaging, physical separation of the adjacent channels is designed to be 8 mm. The total length of this device is 4 cm.

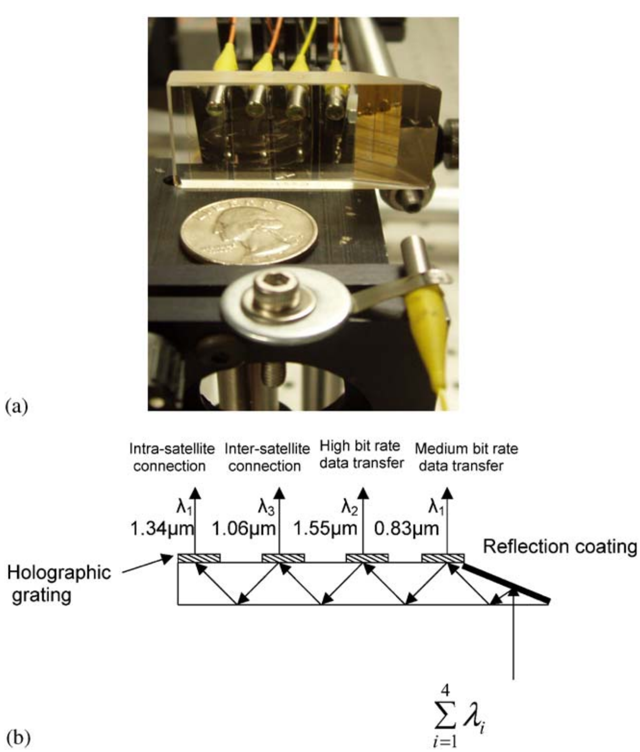

Fig. 1. Four-channel CWDM device using four photopolymer-based holographic gratings in conjunction with substrate-guide waves: (a) device picture; (b) geometric structure.

Diffraction efficiency of a transmission volume grating can be simulated by using couple mode theory [9]. For TE mode, the diffraction efficiency is given by

$$\eta = \sin^2(\upsilon^2 + \xi^2)^{1/2}/(1 + \xi^2/\upsilon^2), \tag{1}$$

$$\upsilon = \frac{\pi \Delta n d}{(c_R c_S)^{1/2}}, \tag{2}$$

$$\zeta = -\Delta\lambda K^2 d/8\pi n c_{Ss}, \tag{3}$$

$$c_R = \cos\,\theta, \quad c_S = \cos\,\theta - \frac{K}{\beta}\cos\,\varphi,$$

$$K = \frac{4\pi n}{\lambda_0}\cos(\varphi - \theta), \quad \beta = \frac{2\pi n}{\lambda}.$$

In Eqs. (2) and (3), θ is the designed incident angle for holographic grating which is 45° for all wavelengths, λ_0 is the designed channel wavelength, φ is the slant angle of volume grating, n is the average refractive index modulation of the recording medium (DuPont HRF 600X001-20 photopolymer), which is close to 1.51. Δn is the maximum index modulation of the photopolymer which can be controlled by exposure dosage. Signal beams at λ_0 can be coupled out efficiently through their correspondent holographic gratings, which are designed to satisfy Bragg condition at 0.83, 1.06, 1.34 and 1.55 μm, respectively. The thickness (d) of HRF 600X001-20 photopolymer is 20 μm. For TM mode, most equations above are valid except a change on υ to υ', which becomes

$$\upsilon' = -\upsilon\,\cos\,2(\theta - \varphi)$$

In principle, 100% channel efficiency can be achieved if Δn is optimized to the required values for different channels. In our design, index modulations of 0.018, 0.023, 0.028 and 0.031 for TE mode and 0.026, 0.032, 0.04, 0.045 for TM mode are required to achieve 100% efficiency for channels at 0.83, 1.06, 1.34 and 1.55 μm. The simulation results are shown in Fig. 2. It is clear that 100% channel efficiency can be achieved for each channel if the index modulation is chosen properly. It is

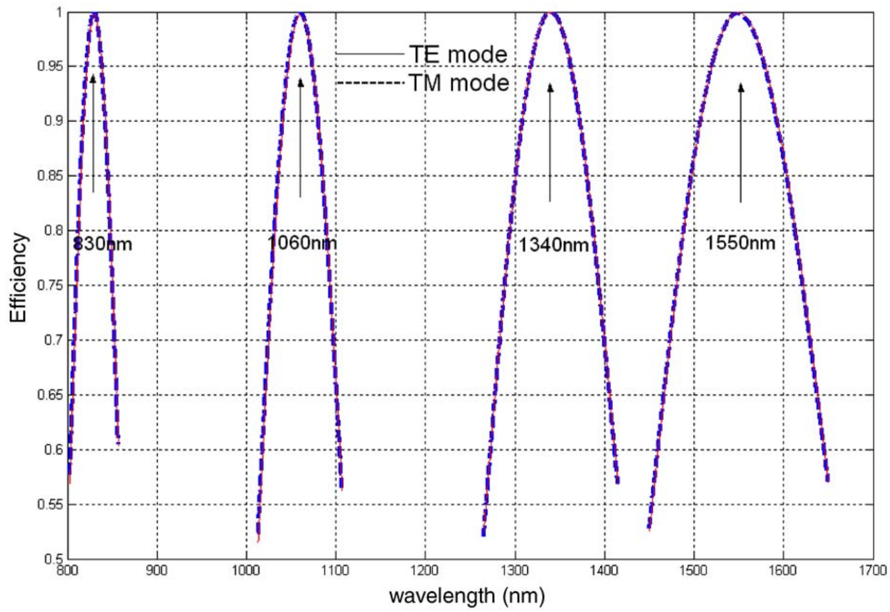

Fig. 2. Simulation results of diffraction efficiency versus wavelength for both the TE and TM waves at incident angle of 45°, for photopolymer films with thickness of 20 μm. Refractive index modulations (Δn) of 0.018, 0.023, 0.028, 0.031 for TE mode and 0.026, 0.032, 0.04, 0.045 for TM mode are used for channels at 0.83, 1.06, 1.34 and 1.55 μm, respectively.

also seen that four wavelengths at 0.83, 1.55, 1.06 and 1.34 μm can be easily separated by the designed CWDM. Any wavelength selective device used on-board of a satellite must be able to accommodate the wavelength shifts due to Doppler effect, temperature variations and radiation effects in space [10]. Therefore, wide bandwidth is always preferred for a WDM in space-based optical application. It is shown by simulation that 3 dB bandwidth of the volume holographic grating increases when designed incident angle decreases for surface normal channels. We design the grating incident angle at 45° by taking both bandwidth and TIR condition into consideration.

Four slanted volume holographic gratings are fabricated independently using the two-beam interference method [11]. 532 nm line from a 5 W Verdi laser is employed in the recording of the holographic gratings. All these four volume gratings have the same slant angle at 22.5° (with respect to the direction of surface normal), which forms the same diffraction angle for different optical signals with the same incident angle. However, their grating periods are quite different. To satisfy Bragg condition for each channel wavelength, gratings with periods of 0.72, 0.92, 1.16 and 1.35 μm are made for 0.83, 1.06, 1.34 and 1.55 μm, respectively.

The four-channel CWDM fabricated is shown in Fig. 1. The dimension of this device is 40 mm × 20 mm × 5 mm. The scaling capability of this device makes it promising in space-based application where reduction in the mass and volume to be boosted into orbit is always a big concern. Fig. 3(a) shows an experimental demonstration of a four-channel CWDM operating at 0.83, 1.06, 1.34 and 1.55 μm. The image is taken by an infrared camera under the randomly polarized input optical signals. A TV lens with focal length of 25 mm is used to enable the responding area of camera to accommodate all the four fan outs. It is seen from Fig. 3 that four channels are completely separated while good mode qualities are maintained. Diffraction efficiency of each channel is plotted in Fig. 3(b). This device is polarization sensitive. For TE wave, channel efficiencies at 0.83, 1.06, 1.34 and 1.55 μm are 55%, 40%, 35% and 45%, respectively. With the achievable maximum refractive index modulation of recording medium fixed, the difference in the efficiency for each channel can be simulated by couple mode theory [9]. A comparison between the experimental and theoretical simulation results indicates that the maximum index modulation of the recording medium achieved in our experiment is 0.012–0.14. For TM wave, channel efficiencies are 45%, 30%, 25%, 30%, respectively. The polarization dependence of the diffraction beam is due to the different boundary conditions between the TE and TM waves, which can be analyzed in details by couple mode theory [9].

In summary, a new application of CWDM for optical ISLs is reported. A four-channel CWDM is designed and then fabricated particularly for the applications in both current medium bit-rate (300 Mbits/s) system based on 0.8 μm technology and future high bit-rate (1.2 Gbits/s) system based on 1.5 μm technology. This broad-band four-wavelength CWDM provides two data streams

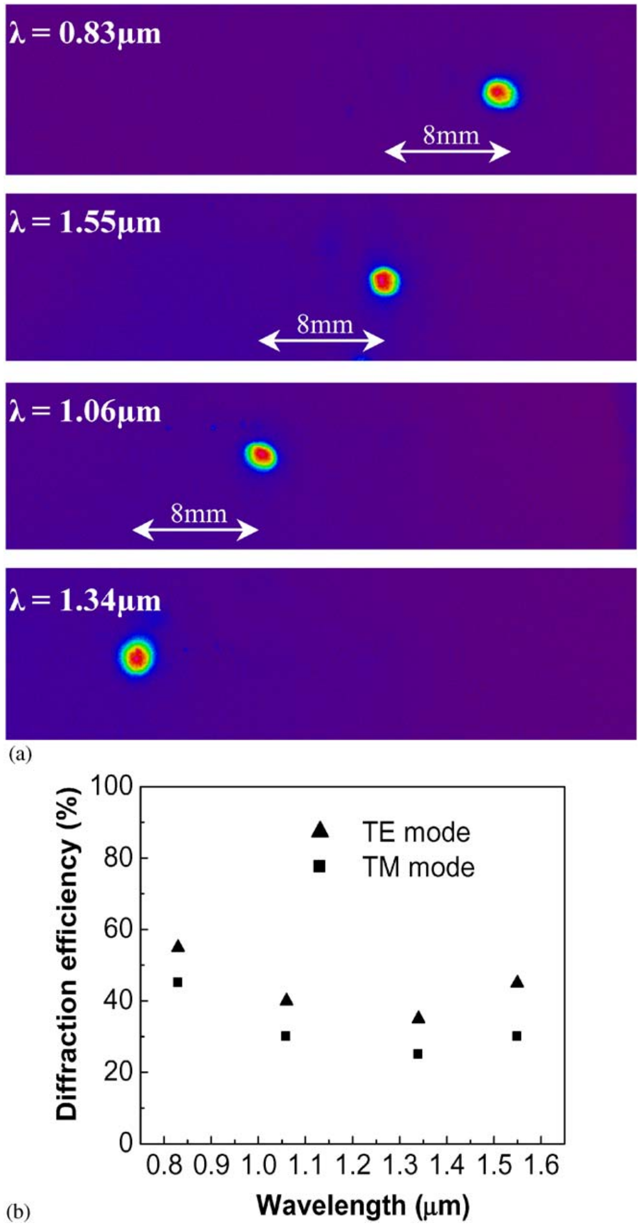

Fig. 3. (a) IR images of the light spots for CWDM working at 0.83, 1.06, 1.34 and 1.55 μm; (b) measured diffraction efficiency of each channel for both the TE and TM waves.

channels at 0.83 and 1.55 μm, one inter-satellite tracking channel at 1.06 μm, and one intra-satellite communication channel at 1.34 μm. A multilayer structure of holographic grating based WDM device which covers channels from 780 to 1550 nm was reported previously [12]. However, it is for the first time that a WDM device is designed and fabricated to cover such a large wavelength range in a single substrate. Surface-normal fan outs and 8 mm physical separation between adjacent channels are designed to facilitate the output coupling and packaging. The features of small size and light weight make this CWDM device quite attractive for space borne applications due to the requirements of low weight and volume.

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