WDM Polymer Substrate Mode Photonic Interconnects for Satellite Communications

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Abstract

WDM is an enabling technology for future satellite communications to increase capacity of bandwidth and network efficiency. Polymer based substrate mode optical interconnects is advantageous over its competing technologies, such as waveguide and free space approaches, in terms of insertion loss, robustness, and packaging. In this paper, we will describe polymer substrate mode photonic interconnects and their reconfiguration functions for separation of coarse and dense wavelength channels.

1 Introduction

Optical satellite communications are considered to be the enabling technology to meet the increasing data traffic demand [1-3]. Compared with RF satellite communications, they use much smaller antenna aperture size and consume less power. Furthermore, since the carrier frequencies are very high, wavelength division multiplexing (WDM) can be employed to dramatically increase the capacity of optical transmission and to achieve dynamic and efficient networking. Figure 1 gives an example of WDM satellite communication networks. This inter-satellite data networking capability can improve real time global connectivity, reduce dependence on ground relay sites, and enhance the survivability by shared redundancy. A newly formed program by DOD, called Transformational Communications (TC), aims at these purposes [4,5]. By use of WDM technology, two way communications between satellite and ground stations, satellite-to-satellite, aircraft and ground stations, aircraft-to-aircraft, and ship-to-ship become secured, non-blocking and free of delay.

With tremendous data traffic incoming and outgoing at various light colors, the satellite has to have the capability in handling and processing of the photonic signals without any delay. On the other hand, due to the limitation of space and power supply in the satellite, the photonic signal processing unit needs to be compact, lightweight, and low power consumption. This remains a challenge for researchers. We propose an integrated solution by using the polymer based photonic interconnects with the concept of "system-on-a-chip". In the architecture, as shown in Figure 1 (right), the photonic interconnects is surface mounted with the system chip. Incoming WDM signals from different satellites can be

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directly coupled into the system chip without any intermediate optical-electrical (OE) and electrical-optical (EO) conversions. By doing so, the data processing speed increases dramatically and the size of the system become more compact compared with current approaches [3]. In cooperating with reconfigurable digital grating processors (DGP) the system can achieve both power and wavelength management.

In this paper, section 2 will review the substrate mode photonic interconnects. In section 3, experimental results on CWDM and DWDM substrate mode photonic interconnects will be demonstrated. Reconfiguration functions of power management of wavelength management will be addressed in experiment. Section 4 includes a discussion for potential applications.

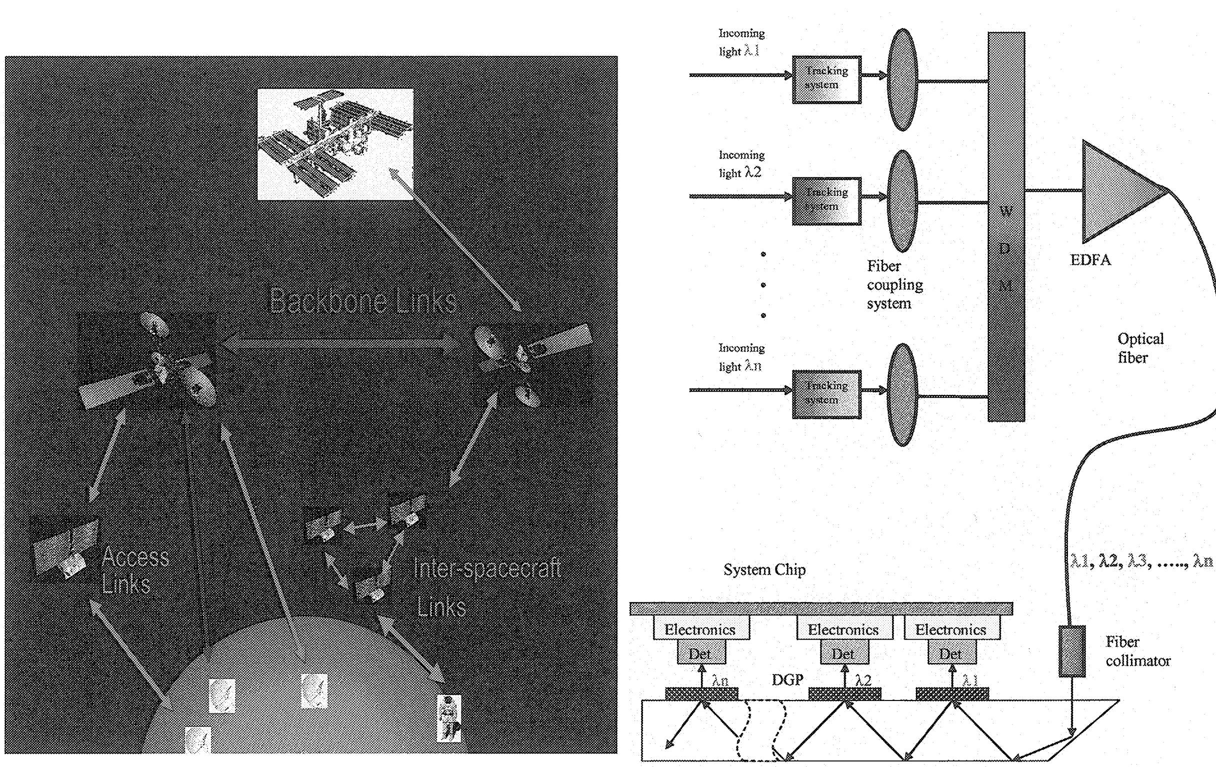

Figure 1 Schematic diagram of WDM satellite communications (left) and
Substrate mode WDM photonics interconnects (right)

2. Substrate Mode Photonic interconnects

Optical interconnection has been widely agreed to be one of the most important alternatives to overcome the bottlenecks of electrical interconnects caused by electromagnetic interference, parasitic capacitance, and inductance coupling.[6, 7] For practical optical interconnections, precise alignment of the device components is required along with mechanical robustness and temperature stability. Free space optical interconnects using conventional optomechanical technology are vulnerable to mechanical and environmental perturbations. Consequently, various planarized implementations were proposed to fold three-dimensional (3-D) optical systems into a two-dimensional (2-D) geometry and integrate them onto a single substrate with the light signals traveling inside the substrate.[8-13] By integrating photopolymer holographic optical elements (HOEs) with the designed diffraction efficiencies on planar waveguiding plates, substrate-guided wave optical interconnects were proposed and energy-equalized fanout distribution has been solved.[10, 11] Optical correlator and Fourier transformation were demonstrated by Reinhorn and his colleague using substrate-guided wave optical interconnects.[12, 13] In this paper, we extend the application of photonic inyterconnects to satellite communications.

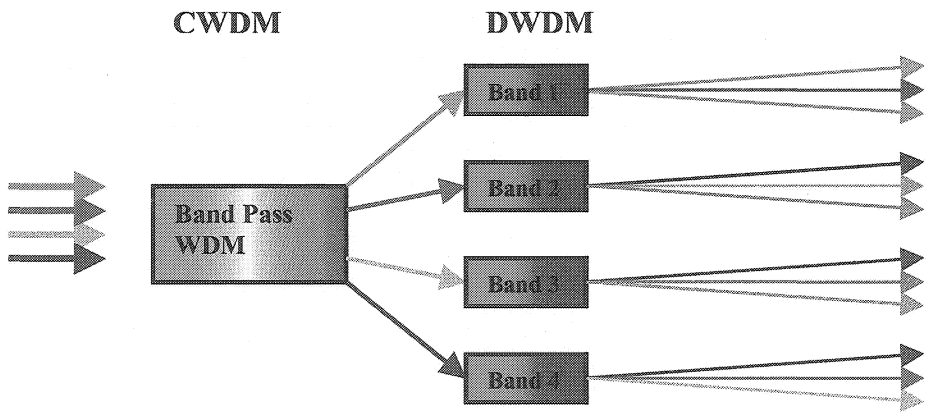

Figure 2 Scalable WDM photonic interconnects for satellite communications

As shown in Figure 1, the input signals are coupled into the substrate with a grating or micro mirror coupler, zigzagged within the substrate, and then coupled out of the substrate at the desired destination by the DGP. Reconfigurable functions of switching, power management, and wavelength management can be incorporated into various prototypes accordingly. The size of the interconnects are adjustable by using different substrates and the number of the interconnected entities are designed based on the system requirement. Figure 2 shows a conceptual example of scaling the wavelength bands (CWDM) and channels (DWDM) by integrating several substrate mode photonic interconnects together. One of the substrate mode photonic interconnects works as a CWDM to separate different signal bands, such as 850 nm, 1060 nm, 1310 nm, and 1550 nm. Then a series of DWDM photonic interconnects can be used to further de-multiplex dense wavelength channels within each band.

The advantages of the substrate mode photonic interconnects are

- Robust planar platform for integration of both active and passive components
- Insensitive to mechanical and environmental perturbations
- Low propagation losses
- Less complicated fabrication processes
- Compatible with surface mount technology
- Relaxed alignment and packaging requirements
- Low cost

3. Polymer Based Substrate Mode WDM Photonic Interconnects: Experimental Results

3.1 CWDM and DWDM Photonic Interconnects

Principles and fabrication methods of photopolymer based holographic gratings have been intensively studied and can be found in references 9-16. In this section, we will focus on experiment and package of a coarse WDM and a DWDM. Reconfiguration functions of power management and wavelength management will also be addressed.

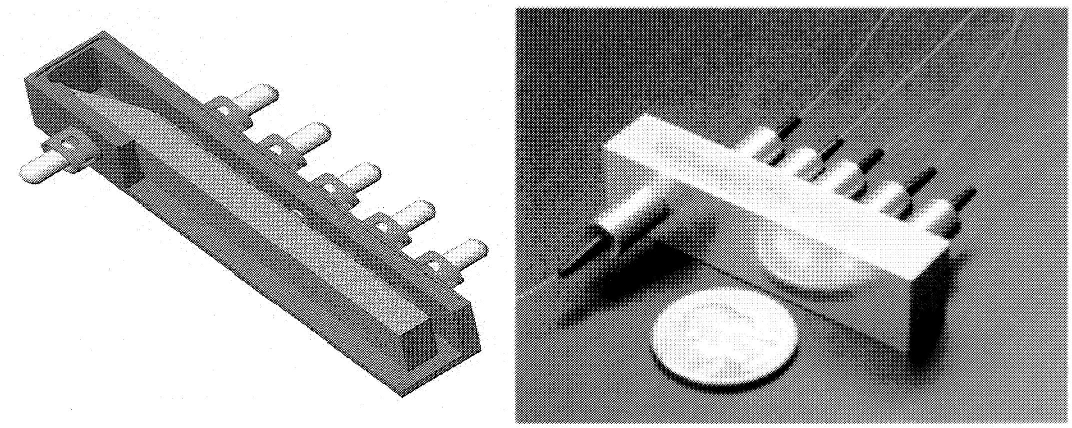

Figure 3 A packaged polymer coarse WDM photonic interconnects (right) and its assembly drawing (left)

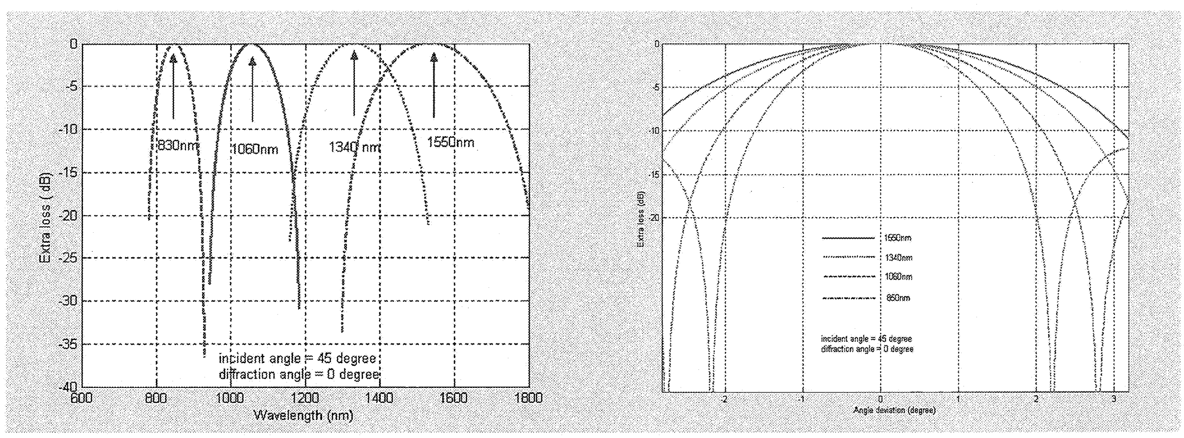

Figure 4 Wavelength and angular tolerance of a CWDM photonic interconnects

Figure 3 shows a diagram of CWDM using substrate mode photonic interconnects. Photopolymer based grating processors are used to de-multiplex four optical signal bands (850 nm, 1060 nm, 1340 nm, and 1550 nm) and coupled back into fibers. Figure4 shows the wavelength and angular dependence of the four grating couplers used to couple out the four wavelength bands. It turns out the 3 dB bandwidths can from 60 nm at 850 nm to 250 nm at 1550 nm. These gratings are less sensitive to angular deviation. We have packaged a CWDM interconnects device, which is shown in Figure 3 (right). The extra packaged losses are less than 0.4 dB.

After separating the signal bands, DWDM substrate mode photonic interconnects can be integrated with each separated band to further de-multiplex fine wavelength channels. One of the approach we are engaging is depicted in Figure 5. The surface-normal incident laser beams with different wavelengths are coupled into the glass substrate by a volume holographic grating. Different bouncing angles for different wavelengths are achieved by the dispersion effect of holographic grating. After one zigzag guided bouncing, surface-normal outputs of different wavelengths is realized by twice coupling with the same grating. Wavelength separation and channel spacing can be designed precisely according to the specific requirement in the application. In Figure 5, L is the distance between the input and output of central wavelength designed for grating after one zigzagged bounce. $\Delta\lambda$ is the signal wavelength channel separation, $\Delta L1$ and $\Delta L2$ denote distances from the nearest channel and second nearest channel to the central channel, respectively. It is clearly shown that the larger the diffraction angle the greater the angular dispersion. Thus more dense channels could be achieved for larger diffraction angles by considering the physical channel spacing limitation set by collection method.

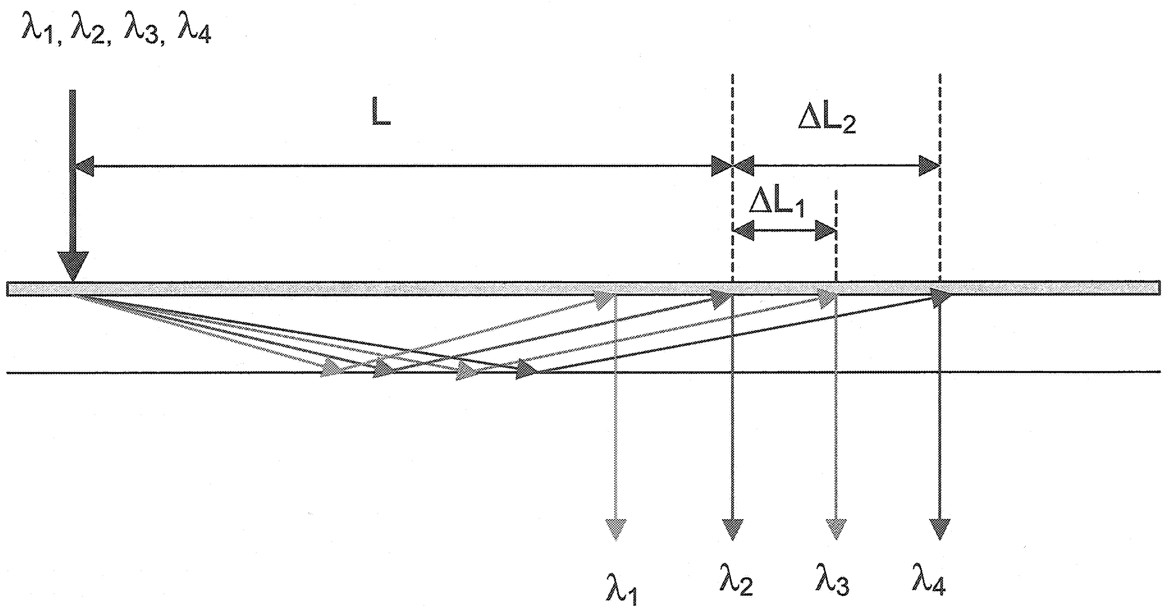

Figure 5 Structure of four-channel surface-normal WDDM device using photopolymer-based substrate-mode holographic grating photonic interconnects.

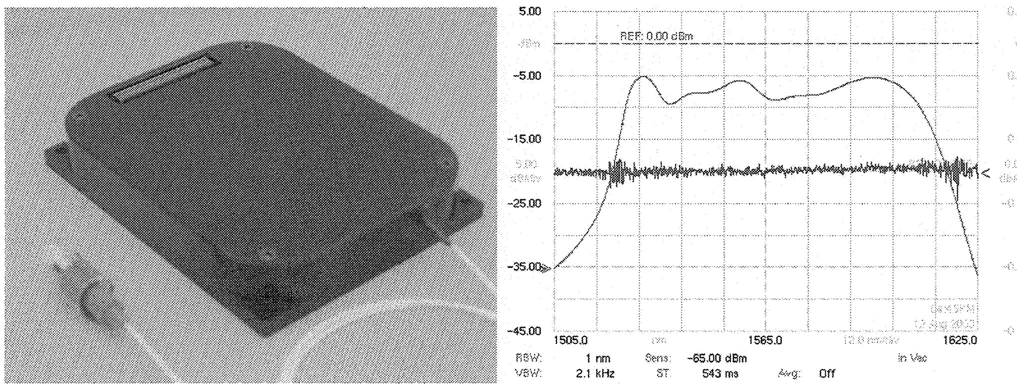

Figure 6 Broadband ASE source module and spectrum stability over 15 minutes

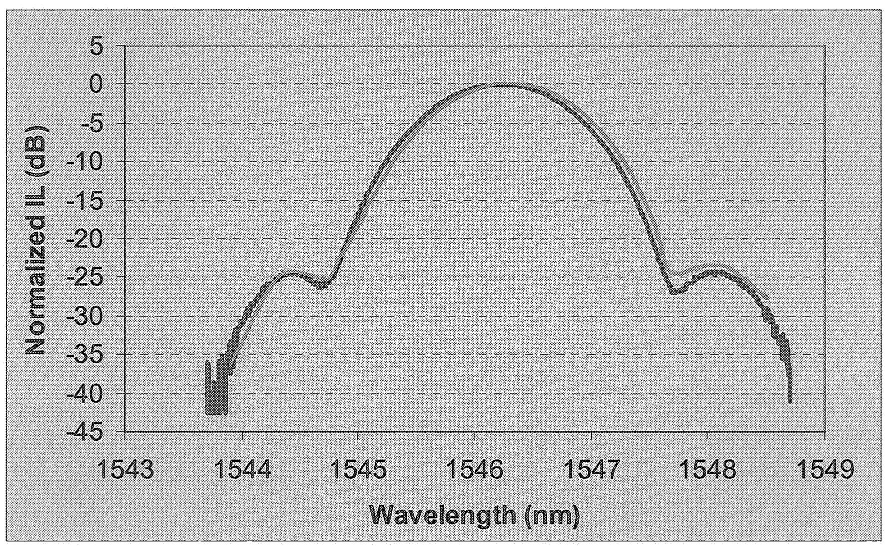

Figure 7 A comparison of spectra taken by a tunable laser and the ASE broadband source

One challenge for testing and packaging a DWDM interconnects is related to the cost and time. Conventional methods use either tunable laser or multi-wavelength lasers to monitor the alignment and packaging process. It is costly and time consuming. We used a broadband ASE source and use it to simultaneously monitor the performance of all WDM channels. Figure 6 shows such a module built up by PolarOnyx, Inc., Sunnyvale, CA, and its over 85 nm (C+L bands) performance. It has been used to compare with a tunable laser. Figure 7 shows there is no difference between the measurements. A device has been made and tested. Figure 8 gives the experimental setup and the output spectra by using the ASE module. It is very convenient to use the broadband to test and align the optics with the gratings. All the channels are simultaneously shown in the OSA. This helps significantly reduce the labor and time. Figure 9 shows the spectra of the four channels WDM interconnects and Figure 10 shows the wavelength and angular tolerance. Compared with those of CWDM, the DWDM is more sensitive to the wavelength and angular change. Currently, the ILs can be controlled within 1.5 dB. Investigation is carrying on in our lab to further improve the efficiency of gratings and reducing the packaging IL.

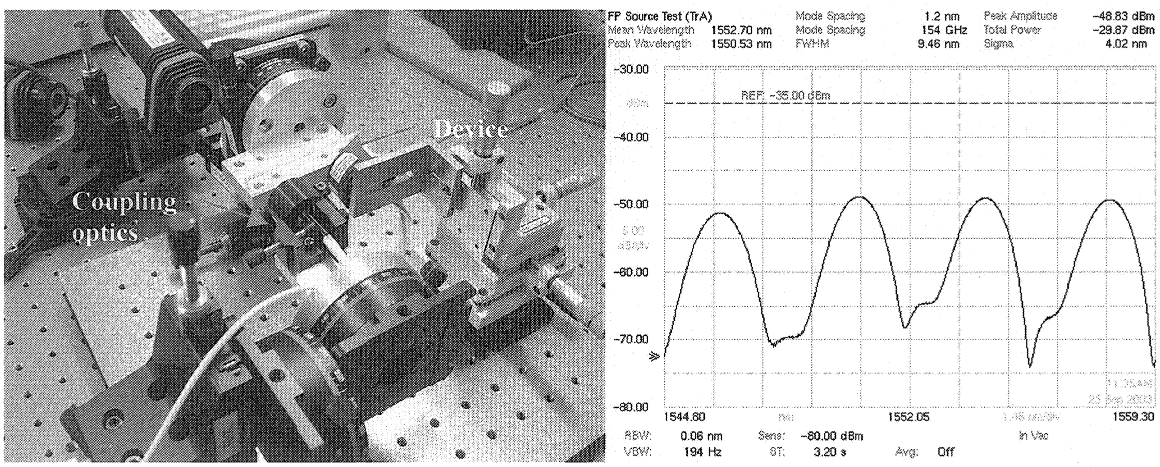

Figure 8 Package setup and output spectra of a dense WDM polymer photonic interconnects

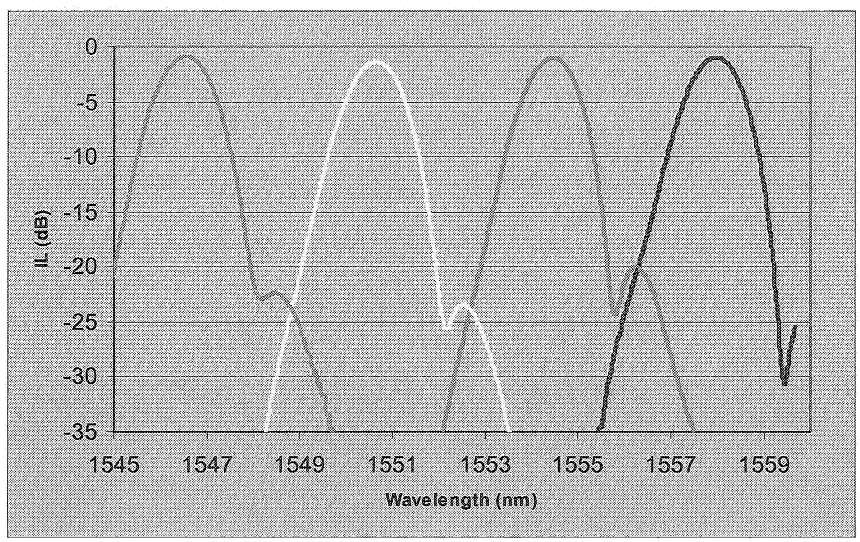

Figure 9 Output spectra for a four channels DWDM polymer photonic interconnects, individually taken by using the broadband ASE source.

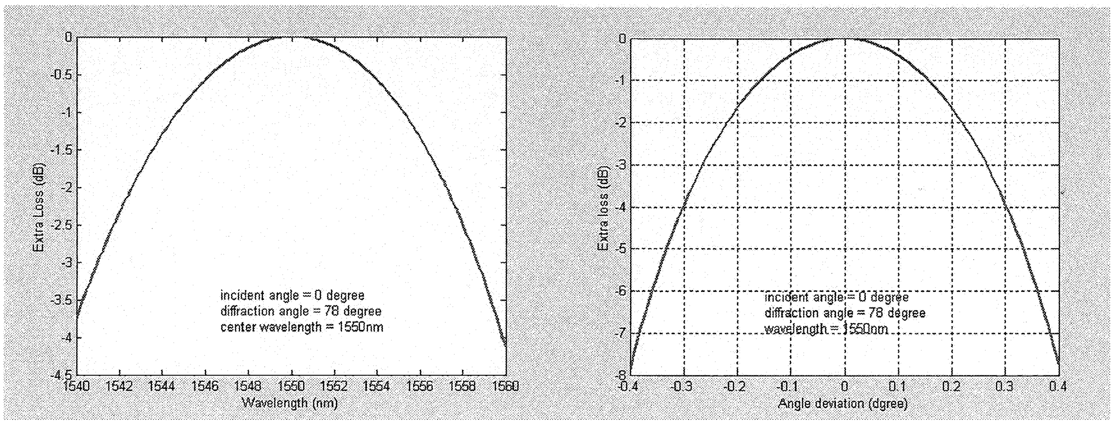

Figure 10 Wavelength and angular tolerance of a DWDM photonic interconnects

3. 2. Reconfigurable function

Digital grating processor is the key component for achieving reconfiguration of the photonic interconnects. Figure 11 gives an example of doing power management function. Figure 12 shows a photograph of the experimental setup and Figure 13 demonstrate the performance of the reconfigurable optical interconnects for wavelength coupling, switching, and power management. Two of the DGPs were tuned by applying different voltages to the capability of switching and power management. The positions of the DGPs are illustrated in Figure 13 by arrows. From Figure 13, we can see that the DGPs work well to switch ON and OFF. Power management can be done by applying voltages between ON and OFF. For visualization purpose, operating wavelength is used at 633 nm. Experiment at 1550 nm was also shown similar results. 10 ms switching time has been achieved in our experiment.

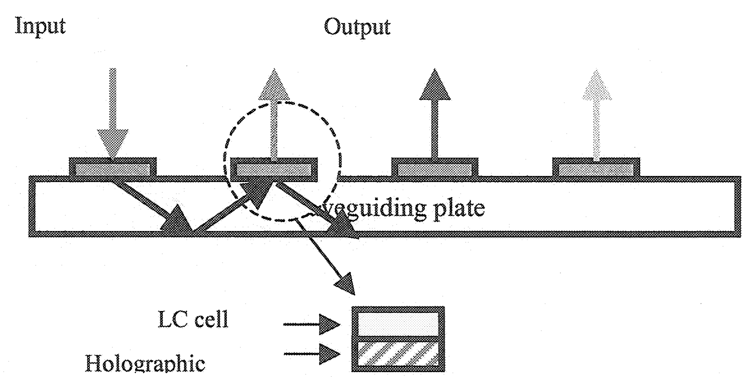

Figure 11 Reconfigurable substrate mode optical interconnects with polymer holographic grating processor integrated with LC cells for power management

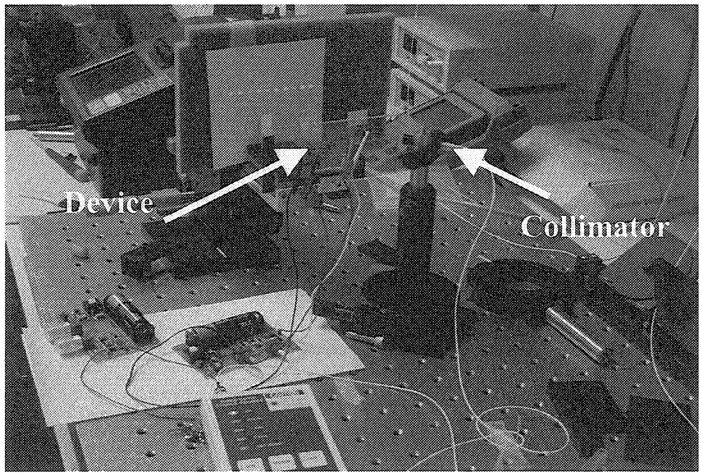

Figure 12 Experimental setup for a reconfigurable optical interconnects

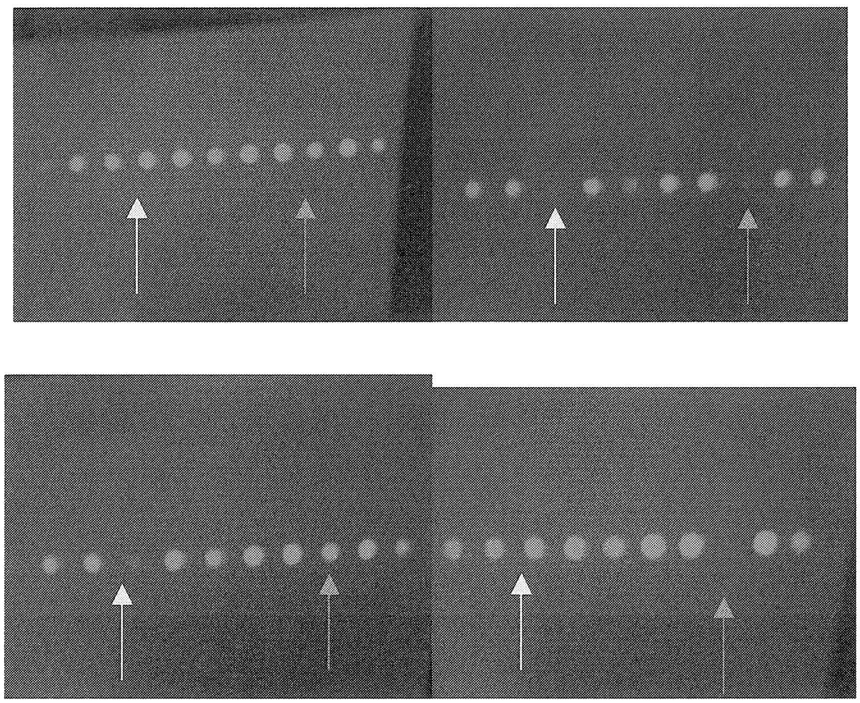

Figure 13 Experimental results for two of the reconfigurable elements (yellow and blue arrows). Top left: two ONs. Top right: two OFFs. Bottom left and bottom right: one ON and one OFF alternatively.

Figure 14 shows an electrode type DGP for achieving wavelength management. If the grating is designed to operate at one wavelength with variable diffraction efficiency, it can be used for spatially reconfigurable optical interconnects. By adjusting efficiency of each individual digital grating processor, the power level of the fanout beams of the optical interconnects can be equalized. On the other hand, if the grating is designed in a way that its diffraction efficiency is very sensitive to wavelength of input signal, the photonic interconnects will work as a wavelength selective interconnects. Moreover, if the grating processor has a large wavelength dependent dispersion, it will operate as a reconfigurable WDM photonic interconnects.

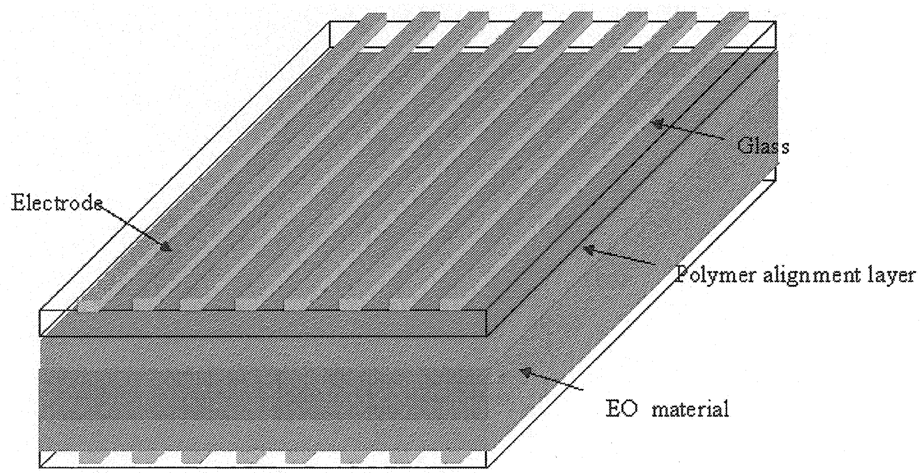

Figure 14 A DGP structure

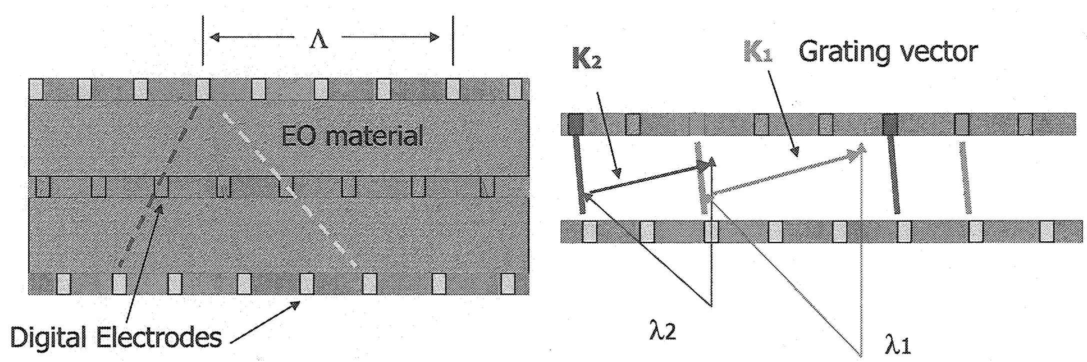

Figure 15 A schematic diagram of a digital grating processor configuration to achieve (a) different slanted angles; (b) different grating periods.

Figure 15 shows that electrodes of the DGP are addressable. By applying voltage to different electrodes, it can be configured to have different slanted angles as shown in Figure 15(a) to phase match optical signals with different input and output angles, and/or configured to have different grating periods to have different responding wavelengths of signals. Recently, we have modified the theory of electrodes for multi-layer design [17]. Our current model is able to do design and optimization for multi-layer structures of electrodes. Figure 16 and 17 gives an example of the simulation results.

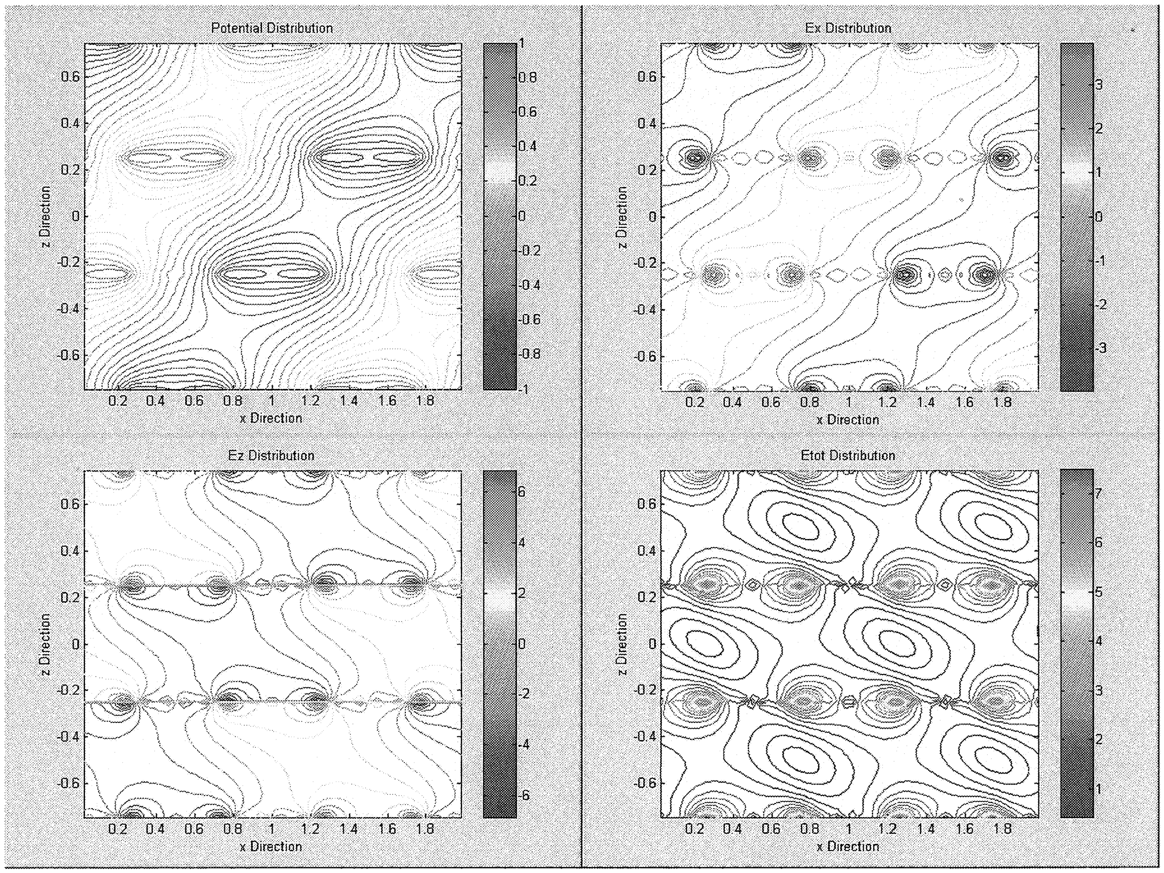

Figure 16 An example of potential and electrical fields distributions for a triple layers of electrodes

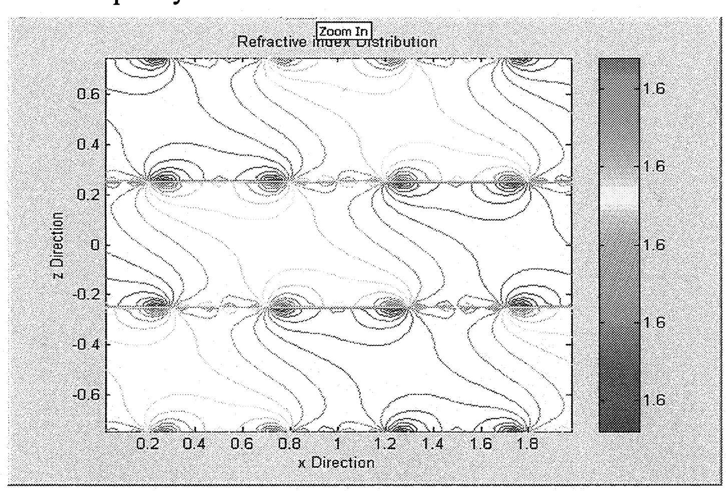

Figure 17 Refractive index modulation in the multi-layer electrodes

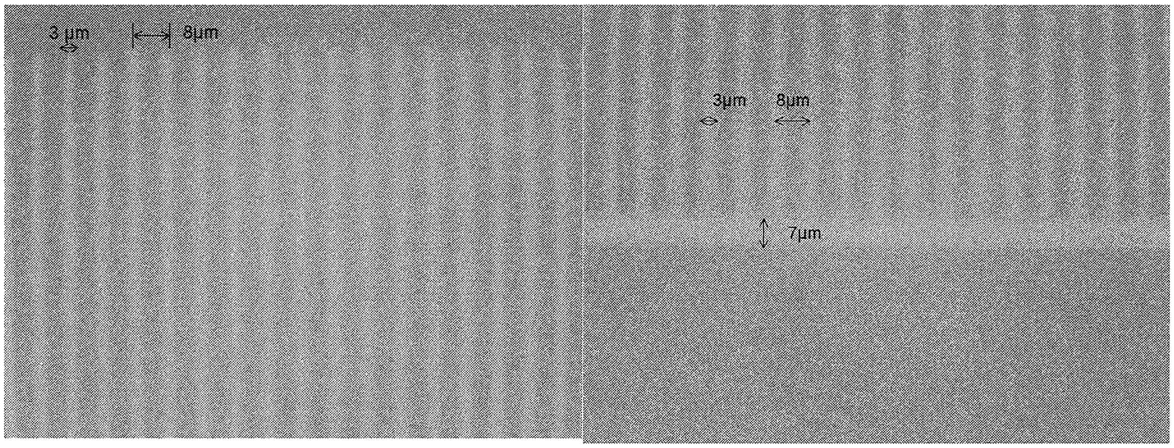

Figure 18 Electrode images

Fabrication of the electrode type DGP has been done. Figure 18 shows that minimum width of 2 mm of electrodes has been achieved in our lab with an excellent etching. The electrodes were sandwiched and injected LC. The diffraction pattern changes when addressing different electrodes. This proves the potential usage of wavelength switching and selecting. More experimental results will be reported in our future publications.

4. Discussion

In summary, we have described polymer WDM substrate mode photonic interconnects for satellite communications. A CWDM interconnects was demonstrated to separate signal bands of 850 nm, 1060 nm, 1340 nm, and 1550 nm. DWDM photonic interconnects were further used to de-multiplex channels with narrow channel wavelength spacing. Reconfiguration functions of power management and wavelength management were achieved experimentally. By providing such critical functions, the polymer substrate mode photonic interconnects is a promising approach to future WDM satellite communications in achieving high capacity and scalability and intelligent and dynamic connectivity. Other applications include dynamic WDM fiber telecommunication networks and WDM photonic interconnects for high speed computers (chip-to-chip optical interconnections).

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