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Adaptive multi/demultiplexers for optical signals with arbitrary wavelength spacing

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Abstract: We propose and demonstrate the principle of a novel adaptive wavelength division multiplexer/demultiplexer structure based on Opto-VLSI processing. By driving an Opto-VLSI processor with an appropriate phase hologram, optical signals of arbitrary wavelengths from different input fiber ports can be multiplexed into a common output fiber port. In addition, wavelength division multiplexed channels of arbitrary wavelength spacings can also be demultiplexed and dynamically routed into arbitrary output fiber ports. A proof-of-principle 1×3 adaptive multiplexer/demultiplexers is experimentally demonstrated.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2340) Fiber optics components.

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1. Introduction

Dense wavelength-division-multiplexing (DWDM) technology is popularly used to increase the transmission bandwidth of optical communication systems, where high-performance multi/demultiplexers with wide channel passband, low crosstalk, and low polarization dependence loss, are needed. Future optical communication systems require adaptive optical devices, such as tunable lasers, variable optical attenuators, reconfigurable add/drop multiplexers, and adaptive multi/demultiplexers. Furthermore, fiber optic technologies have widely been applied to various areas such as fiber sensors, optical instrumentation and testing,

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and microwave photonic systems, where adaptive multi/demultiplexers are crucial for the effective processing of optical signals.

Different multi/demultiplexers designs have recently been reported, including the use of free-space diffraction gratings [1, 2], fiber Bragg gratings [3], and arrayed waveguide gratings [4]. However, these designs only enable the multi/demultiplexing of wavelength channels with fixed wavelengths, bandwidth, and channel spacings, thus having limited reconfigurability. Liquid crystal (LC) devices have long been developed for wavelength-division multiplexing. A liquid crystal and grating based cross-connect 1×2 switch has been reported, which can switch independently eight wavelength channels that are 4 nm apart [5]. More recently, a wavelength-selective switch (WSS) based on a Liquid Crystal on Silicon (LCOS) switching element has been reported, which enables the demultiplexing WDM channels into 9 fiber ports [6]. Microelectromechanical systems (MEMS) employing micromirrors have also been explored for adding flexibility to signal demultiplexing and routing in WDM systems [7, 8].

In this paper, we propose and experimentally demonstrate the principle of a novel structure of an adaptive wavelength multi/demultiplexer based on the use of an Opto-VLSI processor. Using computer-generated phase holograms uploaded onto an Opto-VLSI processor, wavelength channels with variable and arbitrary channel spacings can be multiplexed and steered into a common output fiber port. In addition, multiplexed wavelength channels with variable and arbitrary channel spacings can be demultiplexed and steered into any specific fiber ports. A proof-of-concept 1×3 adaptive WDM multi/demultiplexer structure is developed, demonstrating multiplexing and demultiplexing of three WDM channels of arbitrary wavelengths over the C-band.

2. Opto-VLSI processor

The Opto-VLSI processor is a diffraction element capable of steering/shaping an incident optical beam electronically without mechanically moving parts [9]. An Opto-VLSI processor comprises an array of liquid crystal (LC) cells driven by a Very-Large-Scale-Integrated (VLSI) circuit, which generates digital holographic diffraction gratings (e.g. blazed gratings) of arbitrary pitches, thus achieving arbitrary beam deflection/multicasting. A transparent Indium-Tin Oxide (ITO) layer is used as the second electrode, and a quarter-wave-plate (QWP) layer is deposited between the LC and the aluminum mirror to accomplish polarization-insensitive operation. The voltage level of each pixel can individually be controlled by using a few memory elements that select a discrete voltage level and apply it, through the electrodes, across the LC cell. The diffraction angle, α_m, for the Opto-VLSI processor is given by:

$$\alpha_m = \arcsin\left(\frac{m\lambda}{d}\right) \tag{1}$$

where m is the diffraction order (here only first order is considered), λ is the vacuum wavelength, and d is the grating period.

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3. Structure of the Opto-VLSI-based adaptive multi/demultiplexer

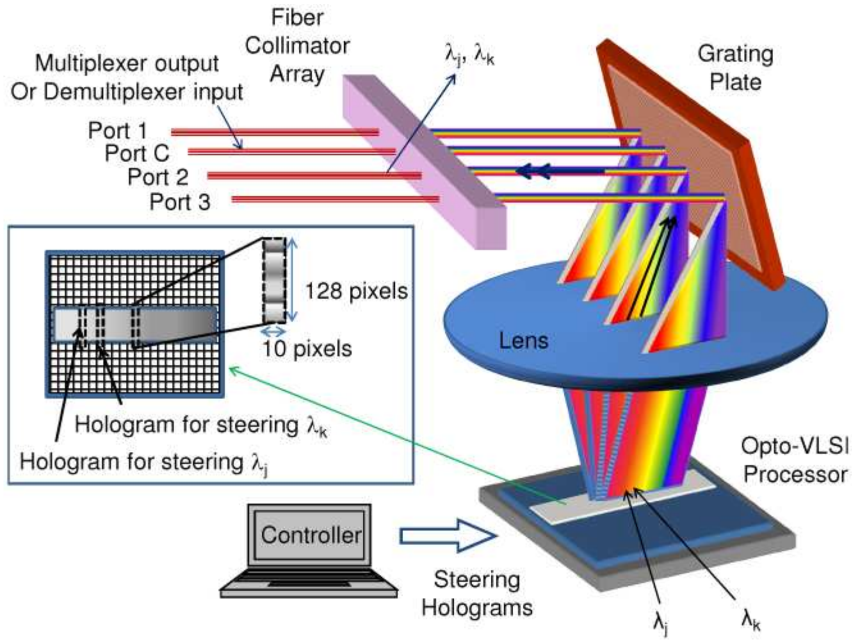

Fig. 1. The proposed adaptive multi/demultiplexer structure.

The proposed adaptive multi/demultiplexer is illustrated through an experimental setup in Fig. 1. The fiber collimator array provides the input and output ports. In the multiplexing mode, arbitrary wavelength channels are input through Port 1, Port 2, and Port 3, and the multiplexed signal is routed to Port C. The input wavelength channels are collimated, and diffracted by a grating plate with 1200 line/mm along different directions, and mapped, by the lens, onto the active window of the Opto-VLSI processor. According to Eq. (1) the wavelength channels illuminating the different pixel blocks of the Opto-VLSI processor can be either independently steered and coupled into Port C of the fiber collimator array with minimum attenuation, or deliberately steered "off-track" so that they are partially coupled into Port C, leading to arbitrary and independent optical attenuation for all wavelength channels (as illustrated in the inset of Fig. 1). Note that, by reconfiguring the hologram uploaded onto the Opto-VLSI processor, any of the wavelength channels can also be steered and coupled into any port other than Port C. The demultiplexing mode is the reverse process of multiplexing, but has a similar principle, where Port C serves as the input fiber port for an input WDM multiplexed signal, while the demultiplexed channels are routed to the other collimator ports.

When the wavelength of an input port changes, the corresponding collimated optical beam is diffracted through the grating plate along a different direction, and mapped onto a different pixel block, whereon an optimal phase hologram is uploaded to optimally steer the new collimated optical beam and couple it into the desired output fiber port.

4. Experiments and results

In the experiments demonstrating the multiplexing mode, three tunable lasers (Agilent) were used to supply three arbitrary input wavelength channels. The spacing between the fiber collimator elements was 1 mm. A 256-phase-level two-dimensional Opto-VLSI processor having 512×512 pixels was used for optical beam steering. A Labview software was specifically developed to appropriately partition and drive the pixel blocks so that any wavelength channel illuminating the active window of the Opto-VLSI processor can

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independently be steered and coupled into Port C. By optimizing the size and the phase profile of each pixel block, optimum optical beam steering was achieved corresponding to maximum optical power coupling into the fiber ports, and hence minimum insertion loss for each wavelength channel.

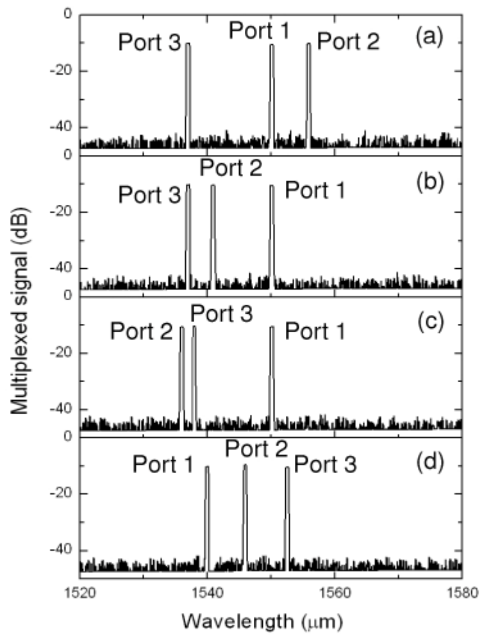

Fig. 2. Multiplexing operation of the proposed adaptive multi/demultiplexer

Figure 2 shows some experimental scenarios for the multiplexing operation of the proposed adaptive multi/demultiplexer. In the scenario corresponding to Fig. 2(a), the wavelength channels λ1=1550.12 nm, λ2=1556.06 nm, and λ3=1537 nm, were input through Port 1 (we call Channel 1), Port 2 (Channel 2), and Port 3 (Channel 3), respectively. The three channels, whose wavelength values were randomly set, were mapped onto the different pixel blocks on the Opto-VLSI processor. By independently and simultaneously uploading optimized phased holograms to the corresponding pixel blocks, each wavelength channel was coupled into Port C. The multiplexed signal, shown in Fig. 2(a), was monitored by an optical spectral analyzer. In the scenario corresponding to Fig. 2(b), the wavelength of Channel 2 was changed to λ2=1541 nm and the others were not changed. Hence, the optical beam associated to Channel 2 was mapped onto a different position on the pixellated surface of the Opto-VLSI processor, while those corresponding to Channel 1 and Channel 3 were unchanged. In this case, the phase hologram responsible for steering Channel 2 to Port C was shifted to the pixel block where λ2 was mapped. The measured multiplexed signal at Port C is shown in Fig. 2 (b), which indicates that the three channels were successfully multiplexed. More complex multiplexing operations were demonstrated in the scenarios corresponding to Fig. 2(c) and Fig. 2(d), where two and three wavelength channels were changed, in comparison to the WDM profile shown Fig. 2(b). By applying appropriate phase holograms to the corresponding illuminated pixel blocks, the three wavelength channels were successfully multiplexed, as illustrated in Fig. 2(c) and Fig. 2(d), respectively.

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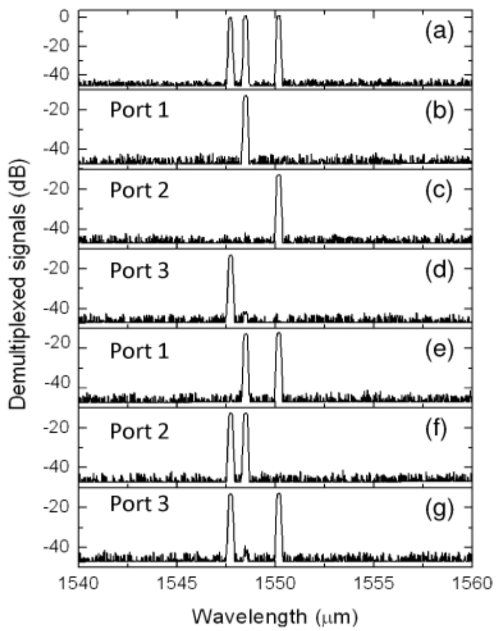

Fig. 3. Demultiplexing scenarios demonstrating the principle of the Opto-VLSI-based multi/demultiplexer.

To demonstrate the demultiplexing capability of the Opto-VLSI-based multi/demultiplexer, we first multiplexed three wavelengths ($\lambda1$=1547.71 nm, $\lambda2$=1548.51 nm, and $\lambda3$=1550.12 nm) using an arrayed waveguide grating (AWG), which produced fixed and "irregular" channel spacings. The multiplexed signal, shown in Fig. 3(a), was input from Port C, and the optical beams associated with the three wavelength channels were mapped onto different pixel blocks on the active window of the Opto-VLSI processor. By uploading appropriate phase holograms onto the three pixel blocks, their corresponding optical beams were steered to specific output ports, thus demonstrating the demultiplexing operation. Some demultiplexing scenarios are shown in Figs. 3(b, c, d) where multiplexed signals monitored from Port 1, Port 2, and Port 3, demonstrating the demultiplexing of wavelength channels with unequal spacings. Note that, more than one wavelength channel can be steered and coupled into any output port by simply reconfiguring the phase holograms applied onto the associated pixel blocks. The three scenarios shown in Figs. 3(e, f, g), demonstrate the ability to switch $\lambda2$ and $\lambda3$ into Port 1, $\lambda1$ and $\lambda2$ into Port 2, and $\lambda1$ and $\lambda3$ into Port 3, respectively. The insertion loss of the multi/demultiplexer was around 12 dB.

This relatively large insertion loss was mainly due to (i) the lens reflection loss; (ii) the grating plate loss; (iii) the coupling loss of the collimator array, and (iv) diffraction loss and insertion loss of the Opto-VLSI processor. In addition, the insertion loss can be partially attributed to imperfect optical alignment and imaging error caused by the aberration of the lens. This insertion loss can further be reduced to around 6 dB through using high-quality optical components and improving the alignment of the imaging system. Note that the large port spacing of the collimator array used in this experiment limited the number of input/output ports. However, by reducing the spacing between the fiber collimator elements to around 0.5 mm, an 8-port demulti/multiplexer can practically be realized according to the maximum beam steering angle that our Opto-VLSI processor could achieve.

5. Conclusion

A novel Opto-VLSI-based adaptive optical multi/demultiplexer structure capable to dynamically multiplexing and demultiplexing arbitrary wavelength channels has been

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proposed and experimentally demonstrated. Proof-of-concept experimental results have demonstrated that arbitrary wavelength channels launched into different input ports can be multiplexed and routed into an output fiber port, and a WDM signal composed of arbitrary wavelength channels can be demultiplexed and routed to arbitrary output fiber ports. This adaptive multi/demultiplexer structure has potential applications in optical communications, fiber optics, optical signal processing, microwave photonics, and optical sensing.

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