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Feng Xiao

*Edith Cowan University*

Budi Juswardy

*Edith Cowan University*

Kamal Alameh

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Yong Tak Lee

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# Novel broadband reconfigurable optical add-drop multiplexer employing custom fiber arrays and Opto-VLSI processors

Feng Xiao, Budi Juswardy, and Kamal Alameh

Centre for MicroPhotonic Systems, Edith Cowan University, Joondalup, WA, 6027, Australia  
[k.alameh@ecu.edu.au](mailto:k.alameh@ecu.edu.au)

Yong Tak Lee

Gwangju Institute of Science and Technology, Department of Information and Communications, Gwangju, Korea.  
[ytlee@gist.ac.kr](mailto:ytlee@gist.ac.kr)

**Abstract:** A reconfigurable optical add/drop multiplexer (ROADM) structure based on using a custom-made fiber array and an Opto-VLSI processor is proposed and demonstrated. The fiber array consists of  $N$  pairs of angled fibers corresponding to  $N$  channels, each of which can independently perform add, drop, and thru functions through a reconfigurable Opto-VLSI beam steerer. Experimental results show that the ROADM structure can attain an average add, drop/thru insertion loss of 5.5 dB and a uniformity of 0.3 dB over a wide bandwidth from 1524 nm to 1576 nm, and a drop/thru crosstalk level as small as -40 dB.

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**OCIS codes:** (230.2090) Electro-optical devices; (090.1970) Diffractive optics.

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## 1. Introduction

The explosive growth in demand for the transmission capacity and network is leading to an urgent need for flexible, cost-effective optical components. The challenge for dense wavelength division multiplexing (DWDM) technology is being extended from developing long-haul point-to-point links to building out flexible automatically switched optical networks [1]. Reconfigurable optical add-drop multiplexers (ROADMs) are attractive components in DWDM systems because they can handle the vast data traffic capacity and control the optical channels for optimum network performance [2, 3]. A ROADM is a device that can dynamically add, block, pass or redirect modulated infrared (IR) and visible light beams of various wavelengths in fiber optic systems that employ WDM. It is used to remotely reconfigure, add and drop capacity at each node, which allows for network upgrades without affecting in-service traffic and helps minimize operational expenditures, especially in the metro/regional environment.

Several techniques have been developed for realizing dynamic add/drop multiplexing [4, 5, 6], such as wavelength blocker (WB) [7], wavelength selective switches (WSS) [8], and planar-lightwave-circuit (PLC) ROADM [9, 10]. Each technology has various tradeoffs among bandwidth, flexibility, channel isolation, switching times, reliability, integration, and cost. High cost is the main factor preventing ROADMs from wide application in current communication systems.

In this paper, we propose and demonstrate a novel ROADM structure employing custom fiber arrays and Opto-VLSI processors. The opto-VLSI processor can be programmed to generate multiphase steering holograms to adaptively steer wavelength channels, thus achieving add, drop, and thru operations. Proof-of-concept experiments demonstrate that a high-performance ROADM can be achieved with high flexibility, cost-effectiveness, broad bandwidth, large wavelength numbers, high channel isolation, and relatively simple structure.

## 2. Opto-VLSI processor

An Opto-VLSI processor consists of an array of electro-optic cells independently addressed by a Very-Large-Scale-Integrated (VLSI) circuit to generate a reconfigurable, reflective digital holographic diffraction grating capable of steering and/or multicasting an optical beam. Figure 1 shows a typical layout and a cell design of a multi-phase Opto-VLSI processor. It comprises a VLSI circuit, evaporated aluminum, a quarter-wave plate (QWP), liquid crystal (LC), Indium-Tin Oxide (ITO) and a glass. ITO is used as the transparent electrode, and evaporated aluminum as the reflective electrode. The quarter-wave plate (QWP) layer between the liquid crystal and the VLSI backplane is responsible for polarization insensitivity (polarization dependent loss for optical beam steering is as low as 0.5 dB [11]). The ITO layer is generally grounded and a voltage is applied at the reflective electrode by the VLSI circuit below the LC layer to generate digital phase holograms for optical beam control. Some specific memory elements that store a digital voltage value are assigned to each pixel. This device is electronically controlled, software configurable, and polarization independent. It is a cost effective solution because of the high-volume manufacturing capability of VLSI chips as well as having capability of controlling multiple incident beams in one compact Opto-VLSI module, and very reliable since beam steering/multicasting is achieved with no mechanically moving part.

The deflection angle for the Opto-VLSI processor,  $\theta_m$ , is given by [11]:

$$\theta_m = \arcsin\left(\frac{m\lambda}{d}\right) \quad (1)$$

where  $m$  is the diffracted order (usually only the first order is considered),  $\lambda$  is the vacuum wavelength, and  $d$  is the grating period.

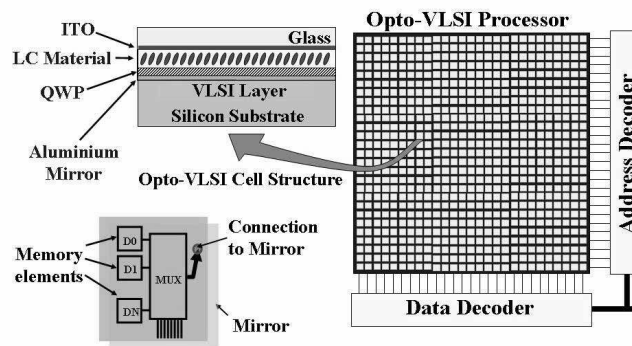


Fig. 1. Opto-VLSI processor structure

### 3. ROADM architecture

The structure of the reconfigurable optical add-drop multiplexer is shown in Fig. 2. The WDM signal launched at the input-port are routed, through a circulator, to an N-channel arrayed waveguide grating demultiplexer (AWG 1) where each output port dedicated to a wavelength channel (from  $\lambda_1$  to  $\lambda_N$ ) is connected to a corresponding optical fiber of the following fiber array. The fiber array consists of  $N$  pairs of optical fibers. Each pair consists of an upper fiber (connect to AWG 1) and a lower fiber (connect to AWG 2). The angle between the upper and lower fibers is  $\theta$ , which is optimized to minimize the insertion loss and crosstalk. A lens array is used to collimate the divergent beams from the upper optical fibers. The collimated beams illuminate different pixel blocks on the Opto-VLSI active window which is tilted at an angle  $\phi$  with respect to the lens array. When a blank hologram is used, the collimated beam from an upper optical fiber is placed in such a way so that the reflection from the Opto-VLSI falls onto the area between the upper and lower optical fiber pairs. By employing an appropriate hologram into the Opto-VLSI processor, the collimated beam is independently steered and coupled to either the upper fiber (for thru operation) or the lower fiber (for drop operation). All dropped wavelengths are multiplexed via AWG 2 and sent to the drop-port through a circulator. The added wavelengths launched at the add-port propagate along the same paths of the dropped wavelengths but in the opposite directions, where they are steered by the Opto-VLSI processor, coupled to the upper fibers and multiplexed via AWG 1 to reach the thru port.

The 1-D ROADM structure shown in Fig. 2 can easily be extended to a 2-D structure by using a 2-D large-area Opto-VLSI processor in conjunction with a 2-D custom fiber array, and a 2-D microlens array. This will dramatically decrease the cost per channel and extend the capability of add, drop, and thru operation.

### 4. Experiments and results

In order to demonstrate the principle of the ROADM, a custom-made fiber array was fabricated with the angle between the upper and lower fiber pairs being  $1.5^\circ$ . Generally, the larger the angle between the fiber pairs, the lower the crosstalk between the upper and lower fibers, and the larger the insertion loss for the thru and add/drop operations. The tradeoffs between the two parameters (loss and crosstalk) was minimized by optimizing the angle between the upper and lower fibers of the custom fiber array. Figure 3 shows the experimental setup, where add, drop and thru operation were investigated. A tunable laser source with a range from 1524 nm to 1576 nm was used in the experiment. Two optical spectral analyzers were employed to monitor the thru-port (OSA 1 in Fig. 3) and drop-port (OSA 2), respectively. A 2 mm diameter lens with a focal length of 5 mm was used to collimate the light from the upper fiber at 1mm diameter, and

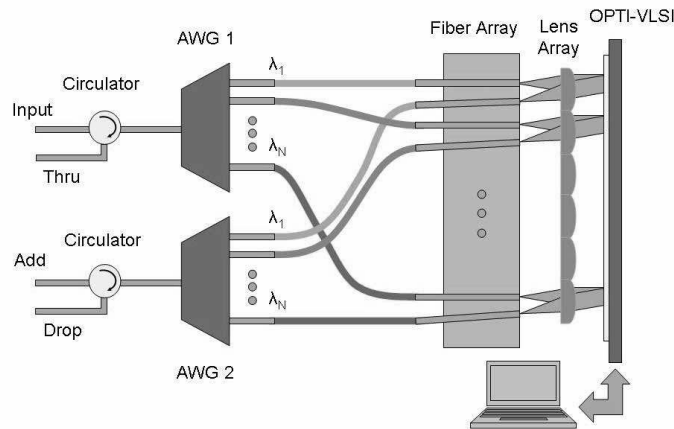


Fig. 2. Novel ROAD structure employing AWGs, a custom-made fiber array, and an Opto-VLSI processor for optical beam steering.

the collimated beam was launched onto the active window of the Opto-VLSI processor. The 1-D, 256-phase-level Opto-VLSI processor used in the experiments has  $1 \times 4096$  pixels with  $1 \mu\text{m}$  pixel size and  $0.8 \mu\text{m}$  dead spacing between adjacent pixels. A Labview software was developed to generate optimized phase holograms that steer the incident beam along desirable directions.

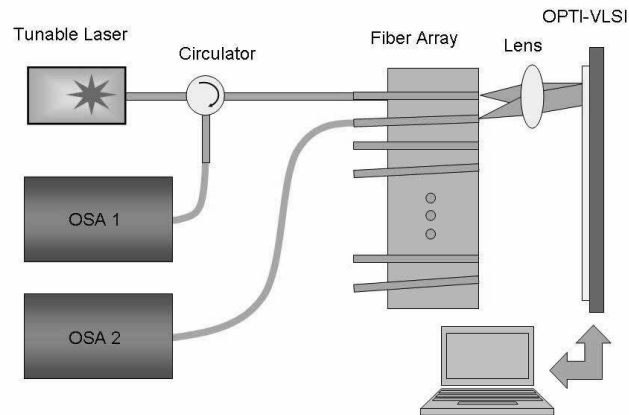


Fig. 3. Experimental setup for demonstrating the concept of the ROAD structure shown in Fig. 2.

When no phase hologram applied, the Opto-VLSI processor acted like a mirror. Before the appropriate phase hologram was uploaded, the Opto-VLSI processor was slightly tilted so that the reflected collimated beam is focused onto an area between the upper and lower fibers (called zeroth-order spot). In the experiment, the zeroth-order direction has an angle of  $0.61^\circ$  with respect to the upper fiber, and  $0.89^\circ$  with respect to the lower fiber. Two phase holograms were

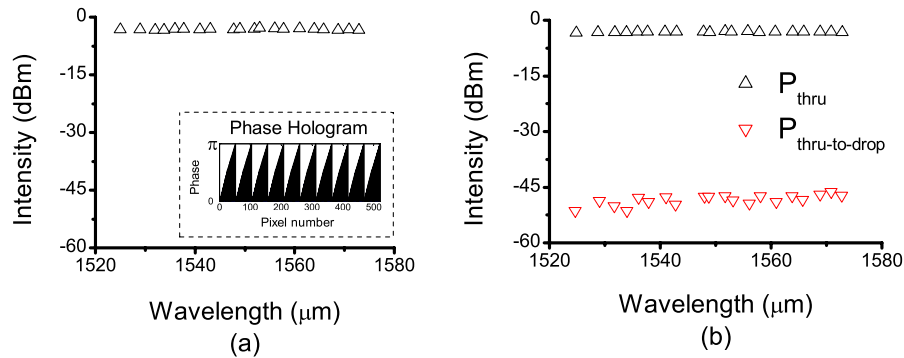


Fig. 4. (a) Measured transmission versus wavelength for drop operation, and phase hologram used for channel dropping. (b) Transmission and crosstalk versus wavelength for the thru operation.

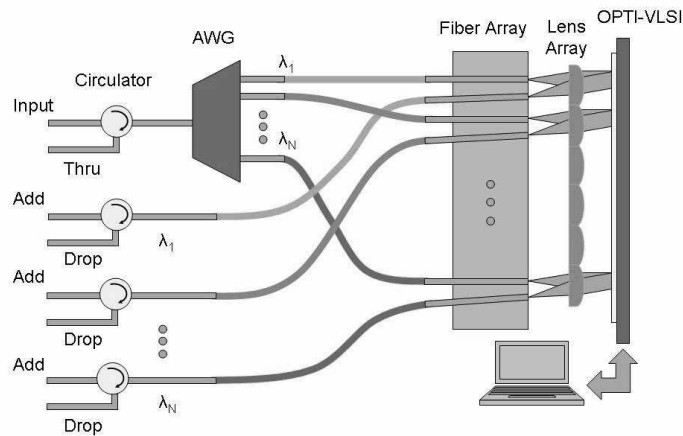


Fig. 5. A ROADM structure with multiple add/drop ports.

generated and optimized for steering and coupling the incident collimated beam to either the upper fiber (thru) or the lower fiber (drop). The transmission versus wavelength for the drop operation is shown in Fig. 4(a). Also shown in the same figure is the phase hologram used for dropping all channels over the wavelength span. Figure 4(b) shows the transmission and crosstalk versus wavelength for the thru operation. The laser power launched into the fiber array was +2 dBm. As shown in Fig. 4, the drop and thru optical power levels were from -2.9 dBm to -3.4 dBm, exhibiting a uniformity of  $\pm 0.3$  dBm. Therefore, the measured insertion loss for drop/thru operation was about 5.5 dB. Figure 4(b) shows that the thru-to-drop crosstalk was below -40 dBm.

This device has high flexibility for wavelength port assignment because each wavelength channel can be routed from AWG 1 via an optical fiber and mapped onto an appropriate pixel block dedicated to add or drop that particular wavelength channel. Note that in Fig. 2 all the drop channels are multiplexed and routed to a single output port and all the add channels are launched from a single Add port. However, the structure can be modified so that each channel

is dropped/added through a dedicated fiber port, as illustrated in Fig. 5. Note that the add, drop, and thru signal levels can be balanced by simply reconfiguring the steering phase holograms of the Opto-VLSI processor. Note also that, by using a 2-D opto-VLSI processor, one can increase the number of channels significantly. For example, by using a 2-D 8192x80 pixel Opto-VLSI processor, a 128-channel ROADM can be realised.

## **5. Conclusion**

We have proposed a ROADM structure based on a custom fiber array and an Opto-VLSI processor. Experiments have shown a high drop/pass isolation level less than -40 dB, more than 50 nm bandwidth with uniformity of  $\pm 0.3$  dB, and an insertion loss as small as 5.5 dB. This ROADM structure exhibits high flexibility, broad bandwidth, high channel isolation, cost-effectiveness, high reliability, and compact size, and has the potential to meet the requirements for high optical performance in reconfigurable optical networks.