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Scalable InP integrated wavelength selector based on binary search

Nicola Calabretta,* Ripalta Stabile, Aaron Albores-Mejia, Kevin A. Williams, and Harm J. S. Dorren

COBRA Research Institute, Eindhoven University of Technology, P. O. Box 513, NL-5600 Eindhoven, The Netherlands

*Corresponding author: n.calabretta@tue.nl

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We present an InP monolithically integrated wavelength selector that implements a binary search for selecting one from N modulated wavelengths. The InP chip requires only $\log_2 N$ optical filters and $\log_2 N$ optical switches. Experimental results show nanosecond reconfiguration and error-free wavelength selection of four modulated wavelengths with 2 dB of power penalty. © 2011 Optical Society of America

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High-speed and fast reconfigurable next generation optical networks are currently investigated to handle the ever increasing growth of Internet traffic. Fast reconfigurable wavelength selectors (WSs) that allow for operation on a large number of wavelength channels, with low cross talk and low optical signal-to-noise ratio (OSNR) degradation, and with fast dynamic response (in the order of nanoseconds) are essential subsystems for implementing reconfigurable WDM core and metro networks, optical packet switched networks, and ultrafast optical signal processing. Compact, low-power integrated solutions are also important for the WS scalability. Several tunable filter based WSs were investigated in [1–5]. However, high losses [1,3,5], low speed tuning [2], and narrowband operation [4] are critical issues. In [6], the high losses prevent practical utilization of the all-polymer WS based on electro-optic polymer switch array between two polymer arrayed waveguide gratings (AWG).

Lossless InP monolithically integrated AWGs in combination with optical switches based on semiconductor optical amplifiers (SOAs) were successfully demonstrated and applied to demonstrate fast optical packet switching [7]. However, the number of active components in the WS scales linearly with the number of channels N . In [8], a solution was demonstrated that scales as $2 \times \sqrt{N}$. However, for a large number of channels the number of switches still becomes substantial.

Here we present an InP monolithically integrated WS based on a binary search algorithm that requires only $\log_2 N$ switches to select N wavelengths. The optical switches are based on SOA technology that enables nanoseconds speed operation and lossless operation. Experimental results show error-free wavelength selection of four 10 Gb/s modulated signals at distinct wavelengths by using two optical switches with a power penalty of less than 2 dB.

The WS based on a binary search is schematically shown in Fig. 1(a). Half of the incoming channels are selected at each node according to the binary state of the node control. Thus, after the first node there will be $N/2$ channels remaining, then $N/4$ channels after the second node, and so on until one channel is univocally selected. The amount of required nodes and controls to select a distinct channel is $\log_2 N$. Without losing generality, Fig. 1(a) shows as an example the operation of the WS for eight wavelengths ($\lambda_1, \dots, \lambda_8$). The WS requires

three nodes, which is controlled by a binary control. For control signals “1 0 1” for the three nodes, the WS will select the λ_6 . At the first node $\lambda_5, \dots, \lambda_8$ are selected, at the second node λ_5 and λ_6 are selected, and at the third node λ_6 is selected.

The WS based on binary search algorithm can be effectively implemented in the optical domain, as shown in Fig. 1(b). Each of the $\log_2 N$ nodes selects half of the incoming channels by using a periodic filter (PF) and an optical switch. The PF spectrally divides half of the channels to output port 1 (black solid line) and the other half to the output port 2 (red dashed line). The optical switch forwards channels from either port 1 or 2 as instructed by the binary control. Note that the PFs at the i -th node have a free spectral range $\text{FSR}_i = \text{BW}_{\text{ch}} \times N/2^i$ with $i = 1, \dots, \log_2 N$, and BW_{ch} the channel bandwidth. This guarantees that the PF at the following node spectrally partitions half of the incoming channels to port 1 and the other half to port 2.

Figure 1(b) shows the WS operation with eight channels. Given “1 0 1” as binary controls, λ_6 is selected by the WS circuit. Indeed, at the first node the PF in combination with the optical switch selects $\lambda_5, \dots, \lambda_8$. At the second node, the PF with $\text{FSR}/2$ separates the λ_5, λ_6 at port 1 and λ_7, λ_8 at port 2 and the optical switch selects λ_5, λ_6 . At the third node, the PF with $\text{FSR}/4$ separates the λ_5 at port 1 and the λ_6 at port 2 and the optical switch selects λ_6 . The example in Fig. 1 employed eight channels and required $3 = \log_2 8$ optical switches and PFs. The

Fig. 1. (Color online) Operation of (a) the binary search algorithm, (b) the optical WS circuit, (c) transfer functions of the periodic filter with different free spectral ranges.

operation of the WS can be generalized to N channels by using $\log_2 N$ optical switches and PFs.

As a proof of concept, we have fabricated an InP monolithically integrated WS capable to select one out of four wavelengths. The PFs were implemented by using Mach-Zehnder interferometer (MZI) filters, and each of the two optical switches consists of two SOAs driven by two complementary electrical signals, as shown schematically in Fig. 2(a).

The InP monolithically integrated WS is shown in Fig. 2(b). It includes the optical switch 1, the PF2, and optical switch 2. The PF1 was not in the integrated chip. The chip is fabricated from a four quantum well active InGaAsP/InP epitaxy with a gain spectrum covering the range 1590–1620 nm. A three-step reactive ion etch is performed to define deep and shallow waveguides and to electrically isolate adjacent electrodes for the required operation. The total area of the integrated circuit is less than $4 \times 1 \text{ mm}^2$. The lengths of SOA₁, SOA₂, SOA₃, and SOA₄ are 2.6, 3, 1.6, and 1.6 mm, respectively. The MZI filter uses deep-etched waveguides. The waveguide filter arm lengths are 500 and 272 μm , respectively. Multimode interference couplers are employed as splitters and combiners.

The experimental setup employed to demonstrate WS operation with optical signals at different wavelengths is shown in Fig. 2. First, the static characterization of the WS chip has been performed. Lensed fibers were employed for coupling the light in/out of the chip. DC currents of 110 mA and 114 mA were applied to SOA₁ and SOA₃, and 27.3 mA and 20.2 mA to the two arms of the active filter. The input coupler current was 3.2 mA to optimize the contrast ratio while the output coupler current was 29.2 mA to provide gain. The SOA current at the chip output was 35 mA. The transfer function presents a periodicity of 3.2 nm. The -3 dB bandwidth of the MZI filter was 1.1 nm. The cross talk between channels spaced by 1.6 nm was around -16.5 dB . Cross talk and flattop passband can be further improved by using higher-order filters [9].

The static operation of the WS chip was tested by injecting four CW optical signals, $\lambda_1 = 1600.9 \text{ nm}$ and $\lambda_2 = 1602.5 \text{ nm}$ into port 1, and $\lambda_3 = 1604.1 \text{ nm}$ and $\lambda_4 = 1605.7 \text{ nm}$ into port 2, respectively (see Fig. 2). The optical switches in the WS chip have been electronically controlled to select a distinct CW wavelength. When optical switch 1 forwards the channels from output port 1 of the MZI filter, either λ_1 or λ_2 can be selected by the optical switch 2 according to the binary control. If the optical switch 1 forwards the channels from output port 2 of

Fig. 2. (Color online) (a) Schematic and (b) experimental setup of waveguide and electrode layout of the fabricated chip.

Fig. 3. Optical spectra recorded at the WS output for four different operations of the selector: (a) λ_1 , (b) λ_2 , (c) λ_3 , (d) λ_4 .

the MZI filter, either λ_3 or λ_4 can be selected by the optical switch 2. The four measured spectra at the chip output for the four combinations are shown in Fig. 3. Those static results clearly show the WS operation. The measured cross talk was lower than -16 dB , and the OSNR of the selected CW signals were larger than 30 dB . Scaling the WS operation to a larger number of channels will be limited by the OSNR degradation caused by the accumulated amplified spontaneous emission (ASE) noise of the SOAs in the chain. OSNR values exceeding 26 dB have, however, been measured after eight recirculating loops [10] indicating the possibility to scale to eight nodes the WS and thus to select one from 256 incoming wavelengths.

We have also investigated the time response of the WS chip. We fed a CW signal into the WS and we applied an electrical pulse with 5 V of amplitude and a rising and falling time of 2 ns to the optical switch. Figure 4 shows the photodetected output of the WS showing a rise time and fall time of around 4.6 and 3.2 ns (10% – 90% transitions), respectively. Electrical reflections are seen to lead to a dip in the time resolved gain 46 ns after the turn-on transient. This is expected to be eliminated by implementing high-speed drivers in close proximity to the chip.

To investigate the dynamic operation of the WS chip, we generated optical packets at $\lambda_1, \dots, \lambda_4$ by using an amplitude modulator driven by a 10 Gb/s pattern generator with a $2^{11} - 1$ pseudo-random binary sequence interleaved with

Fig. 4. Time response of the SOA of the optical switch.

Fig. 5. (a) Input packets. Complementary controls applied to (b),(c) SOA1, SOA2 of the optical switch 1; (d),(e) SOA3, SOA4 of the optical switch 2; (f)–(i) WS output traces for the wavelength λ_1 , λ_3 , λ_2 , and λ_4 , respectively.

512 bits sequence of zeros [see Fig. 5(a)]. This results in a packet guard time of 51.2 ns, which is sufficient to guarantee the response of the SOA to be flat with respect to the applied control, avoiding the dip 46 ns after turn-on. The colored packets were amplified, wavelength demultiplexed and decorrelated, before being fed into the WS chip. Two pairs of modulated signals λ_1 , λ_2 and λ_3 , λ_4 were fed into the two inputs of the WS, respectively. The optical power of each signal was -2 dBm at the input fiber lens. The output power was -13 dBm per channel. Assuming 6 dB/facet coupling losses, the chip losses are compensated by the SOAs. SOA₁, SOA₂, SOA₃, and SOA₄ of the two optical switches were driven by electronic control signals with 5.2 V, 5.1 V, 5.4 V, and 5.8 V, respectively. Note that most of the voltage is dropped across the 39 Ω matching resistor between the 50 Ω controller and the chip. By using a regular current source, the required voltage would be less than 1.5 V.

Figures 5(b)–5(e) show the control signals appropriately delayed to dynamically select one distinct wavelength at a time. Figures 5(f)–5(i) report the time-domain traces for each of the four wavelengths at the output of the WS. Those traces clearly show that according to the control pattern only the one optical wavelength packet is selected by the WS. The average extinction ratio was higher than 15 dB. The eye diagrams measured at the input and output of the WS chip are shown in Fig. 6. The eye diagram at the WS output is clearly open but it is slightly degraded due to cross-gain modulation in the SOA and noise. The bit error rate (BER) curves of the selected packets are reported in Fig. 6. The BER curve in back-to-back configuration is provided as reference. We also report the BER curve in static operation of

Fig. 6. (Color online) BER curves of the back-to-back and static selected wavelength at λ_1 , and of the dynamic packet selected operation. Inset, eye diagrams of the signal before and after the WS at λ_1 .

the WS recorded when only one wavelength (λ_1) is transmitted through the WS. Error-free operation with a power penalty of 0.5 dB was measured. Error-free operation is also obtained for the dynamic selection of the packets at different wavelengths with a power penalty of 1.7 – 2.1 dB, which is around 1.2 dB larger than the static case. The penalty is expected to be due to cross-gain modulation between the signals and ASE from the SOAs.

We have demonstrated a fast InP monolithically integrated WS based on a cascade of periodic filters and optical switches that requires $\log_2 N$ optical switches for selecting N wavelength signals. Experimental results show error-free wavelength selection of four modulated signals at distinct wavelengths with a power penalty of less than 2 dB.

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