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Citation for published version (APA):

Calabretta, N., Soganci, I. M., Tanemura, T., Wang, W., Raz, O., Higuchi, K., Williams, K. A., De Vries, T. J., Nakano, Y., & Dorren, H. J. S. (2010). 1×16 optical packet switch sub-system with a monolithically integrated InP optical switch. In *2010 Conference on Optical Fiber Communication, Collocated National Fiber Optic Engineers Conference, OFC/NFOEC 2010* (pp. OTuN6). [5465273] Institute of Electrical and Electronics Engineers.

Document status and date:

Published: 30/06/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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1×16 optical packet switch sub-system with a monolithically integrated InP optical switch

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Abstract: We demonstrate a 1×16 optical packet switch sub-system for 160 Gbps RZ-OOK and 12 x 10 Gbps multi-wavelength DPSK packets. We show error-free operation with maximum penalties of 0.7 dB for 160 Gbps RZ-OOK and 0.6 dB for multi-wavelength DPSK packets.

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OCIS codes: (060.6719) Switching, packet; (200.4740) Optical processing; (130.7408) Wavelength filtering devices.

1. Introduction

Boosted by the traffic increase in the access networks future optical networks should handle hundreds of Tb/s data traffic [1]. High capacity optical links might carry ultrafast OTDM data packets or multi-colored optical packets with highly spectral efficient modulation formats, such as D(Q)PSK, OFDM, M-QAM. The increase of power consumption and dissipation as the required capacity increases will limit the scalability of current electronic circuit switching. Optical packet switch (OPS) sub-systems have potential to play an important role in future packet routers or computer interconnects. It is important that OPS sub-systems support router architectures that have large numbers of inputs and outputs (typically >1000). For this reason it is important to investigate OPS sub-systems that can address a large number of outputs, to reduce costs, power and the number of components. Apart from that, an OPS sub-system should be data-rate and data-format transparent, should have low insertion losses and introduce little latency. Moreover, photonic integration of optical switch is essential to reduce footprint and power consumption.

To realize such scalable OPS sub-systems, data format and data rate transparent label processing technique, which is capable to process a large number of labels, and photonic integrated switches with large number of ports should be realized. Despite the progress in the field [2-4], photonic switches based on those techniques do not support a large number of ports operating at high bit rate > 100 Gb/s due to the high insertion losses, power consumption and dissipation, optical signal-to-noise ratio reduction, footprint, and complexity of design and fabrication.

Here we demonstrate a data-format and bit-rate transparent 1×16 OPS sub-system that includes all the required functionalities, namely an all-optical label extractor, a switch controller, and a photonic integrated 1×16 optical switch. The photonic integrated switch has a maximum extinction ratio of 17 dB and only 7 dB on chip losses. We demonstrate error-free operation for 160 Gb/s OTDM RZ-OOK packets as well as for 120 Gb/s (12x10Gb/s) DPSK multi-wavelength packets at the expense of power penalties of 0.7 dB and 0.6 dB, respectively.

2. System operation

The schematic of the OPS sub-system is shown in Fig. 1. At the transmitter side, two types of payloads are generated. Firstly, we generate 160 Gb/s RZ-OOK payload by time-multiplexing 16 data-streams at 10 Gb/s consisting of modulated $2^{11}-1$ PRBS return-to-zero bits ($\lambda_p=1546$ nm) using a fibre-based interleaver. The optical pulses have duration 1.5 ps which corresponds to a -20 dB bandwidth of 5 nm. Alternatively, 12 channels with wavelengths between 1543.7 nm and 1548.5 nm (50 GHz spacing) were DPSK modulated by a pre-coded 10 Gb/s NRZ data sequence. A packet gate was used to make packets with 147.2 ns payload length and guard-band of 32 ns. The packets are equipped with address using in-band labels that have the same duration as the payload [5]. For the RZ-OOK packets the wavelengths of the labels are chosen to be within the -20 dB bandwidth of the payload (see Fig. 1a). For the DPSK multi-wavelength packets, we use the same label wavelengths, but they are spectrally located in the notches of the spectra of the DPSK multi-wavelength payload (see fig. 1b). This kind of in-band labelling has two advantages: firstly N labels allow for encoding 2^N addresses which makes that a relatively large number of ports can be addressed within the limited payload bandwidth. Secondly, in-band labelling allows for parallel and

Figure 1. Experimental set-up. Optical spectra of the OOK and DPSK packets: a-b) input packets, c-d) after the label extractor, e-f) after the switch. AWG: arbitrary waveform generator.

asynchronous optical pre-processing of the labels, which makes it easy to implement parallel electronic switch control without high speed clock recovery. This is essential for reducing latency and power consumption.

If an optical packet is input in the OPS sub-system, the labels are extracted by using four cascaded reflective fibre Bragg gratings (FBGs) with centre wavelengths that coincide with the centre wavelength of the labels. The 3dB bandwidth of the FBGs is 6 GHz, and the centre wavelengths are $L_1 = 1543.9$ nm, $L_2 = 1544.3$ nm, $L_3 = 1547.7$ nm and $L_4 = 1548.2$ nm. Thus four labels allow for addressing 16 outputs.

The labels that output the FBGs undergo opto-electronic conversion, and the corresponding label voltages are fed into the switch controller. The function of the switch controller is to map a combination of 4 control voltages into unique set of 24 analog output voltages that are required to control the electro-optical switch. The switch controller is based on an FPGA that contains a lookup table. Finally, the payload is fed into an integrated 1×16 electro-optical switch via a tapered lensed fiber. Details on the design and fabrication of the switch are reported in [6]. The switch shown in Figure 1 consists of an input waveguide, an input star coupler that divides the input light to an array of 24 waveguides with phase shifters, and an output star coupler that refocus the light from the waveguides to one of the 16 output waveguides. The total dimensions of the device are $4.5 \text{ mm} \times 2.6 \text{ mm}$. Switching is achieved by applying electrical signal (voltages $< 1.6 \text{ V}$) to the phase shifters to induce a beam steering to control at which output waveguide the light is re-focused. The static average extinction ratio is 18.6 dB, the on-chip loss is less than 7 dB, C-band (1530-1565 nm) operation with maximum wavelength-dependent loss of 0.8 dB, switching speed ~ 6 ns, and cross talk suppression ~ 17 dB.

3. Experimental results

Firstly, we investigated operation of the 1×16 OPS sub-system using RZ-OOK packets. We input a series of packets into the 1×16 OPS, with labels such that each consecutive packet is routed to the next port (see Fig. 2). The optical power of each extracted labels was -20 dBm. Fig. 2 shows the data traces at each output as well as eye-diagrams that show clear open eyes at each output. The optical power of the payload at the input of the 1×16 optical switch was 7 dBm (measured in the fiber). The optical power at the output of the 1×16 switch was -12 dBm. Assuming 2×6 dB of coupling losses per facet, the on chip loss is ~ 7 dB. The extinction ratio for each output was calculated to be in between 11 dB and 17 dB. A similar experiment was carried out for multi-wavelength DPSK packets. Figure 3 shows the corresponding data traces and eye diagrams at each output, for the channel with a wavelength of 1544.1 nm. This channel (spectrally located in between two labels) is most sensitive to distortion by the label extraction. We used similar average optical powers as for the OOK experiment, and we observed similar extinction ratios. At the receiver side, one packet out of 16 switched by the OPS is evaluated by BER analysis. This requires to set the error analyzer with a data-pattern that contains one packet and a series of zeros with duration of 15 packets ($2.7 \mu\text{s}$). This implies that we cannot use a long $2^{31}-1$ PRBS, but we employed a user-pattern based on $2^{11}-1$ PRBS for the packets and a series of zeros with duration of 15 packets. Figure 4 reports BER results only for output 11, which has the lowest extinction ratio. Thus, this channel shows the worst BER results. Panel a) reports results for 160 Gb/s RZ-OOK and panel b) shows results for the 12×10 Gb/s NRZ-DPSK. The 160 Gb/s RZ-OOK data were time demultiplexed to 10 Gb/s by using two cascaded electro-absorption modulators. The DPSK multi-wavelength channels were selected by a tuneable filter and demodulated by a 1 bit delay Mach-Zehnder interferometer. Figure 4 shows error-free operation with 0.7 dB penalty for 160 Gb/s RZ-OOK packets and 0.6 dB penalty for the 120 Gb/s NRZ-DPSK packets.

Figure 2. Outputs of the packet switch for 160 Gb/s OOK packets. Time scale of the eye diagrams is 5 ps/div.

Figure 3. Outputs of the switch for the DPSK channel at 1544.1nm. Time scale of the eye diagrams is 20 ps/div.

Figure 4. BER curves for a) 160 Gb/s RZ-OOK packets; b) 12x10 NRZ-DPSK packets.

3. Conclusions

We have demonstrated a data-format and bit-rate transparent 1×16 OPS sub-system by using a scalable and asynchronous label processing technique and a monolithically integrated electro-optical switch. Scalability of the number of ports and data rate of the switch is not limited by the OSNR degradation due to the large insertion losses, which determines a fundamental limit in case of broadcast and select switches. We have shown error-free operation for 160 Gb/s RZ-OOK and 12x10 Gb/s NRZ-DPSK at the expense of low penalties (< 0.7 dB), which indicates that use in large systems is possible.

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