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All-Optical Data Vortex Node Using an MZI-SOA Switch Array

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Abstract—We propose and demonstrate a new structure of a Data Vortex switch node for all-optical routing of wavelength-division-multiplexing (WDM) 10-Gb/s optical packets. The proposed node consists of two Mach–Zehnder interferometers with integrated semiconductor optical amplifier: an optical AND gate and a high-speed optical switch. In the experiment, WDM 10-Gb/s data packets are successfully routed with 1-dB power penalty at a bit-error rate of $10^{-5}$.

Index Terms—Data Vortex switch, Mach–Zehnder interferometers with integrated semiconductor optical amplifier (MZI-SOA), optical header processing, optical packet switching.

I. INTRODUCTION

The current and upcoming increase in Internet traffic and the growth of new and diverse kinds of services are calling for higher rates and flexibility that current networks cannot offer. Optical packet switching has emerged as a solution for these demands by means of increasing the network throughput, efficiency, transparency, and flexibility [1]. In order to meet these promising expectations, high-speed signal routing and switching is required. Currently, hybrid electrooptical configurations are used to process the header information due to the immaturity of photonic technologies to perform those operations. Moreover, operations easily performed in the electrical domain such as header processing and packet buffering are still challenging to be realized all-optically. Therefore, solutions need to be searched in order to realize the so called all-optical packet switching.

A new packet routing architecture called the Data Vortex [2], [3] was proposed that is uniquely free of an optical buffer and enables a simple routing strategy for large scale low latency packet switch fabrics. So far, several researchers [3]–[5] have reported on the operation of Data Vortex switch structures. In their approaches, an electrical decision circuit to perform header processing was employed. Especially at higher bit rates, however, electrical signal processing may introduce latency and suffer from limited switching speed.

In this letter, we propose a new structure for a Data Vortex switch node with full all-optical operation. All-optical self-routing decisions are realized by using an optical AND logic operation implemented by a Mach–Zehnder interferometer with integrated semiconductor optical amplifier (MZI-SOA) switch. To verify the feasibility of the proposed idea, an experimental demonstration was performed. In the experiment, wavelength-division-multiplexing (WDM) 10-Gb/s data packets are successfully routed with 1-dB power penalty at bit-error rate (BER) of $10^{-5}$.

II. PRINCIPLE OF OPERATION

The proposed all-optical Data Vortex switch node is shown in Fig. 1, which consists of two MZI-SOAs [6]. The upper and lower MZI-SOA act as an AND optical logic gate and an optical switch, respectively. The switch node has six optical ports: two input ports, from an outer cylinder (North input) and from the same cylinder (West input), respectively; two output ports, to an inner cylinder (South output) and to the same cylinder (East output); a control input port from an inner cylinder; and a control output port to an outer cylinder [3]–[5].

A WDM scheme was used to carry the payload and header of the optical packet. Since the packet switching is done independently with respect to the wavelength, WDM technology can be used to increase the network capacity. In addition, encoding the header bits by WDM substantially simplifies the routing strategy at each node. In a WDM packet encoding scheme, each wavelength channel carries a single header bit on a time slot, and each cylinder in a Data Vortex switch decodes a specific header bit in a binary tree fashion. Because of that, passive wavelength filtering can be implemented in the nodes to perform the routing operations [3].

If a WDM encoded optical packet comes into the proposed switch node, a portion of the signal is tapped into the upper
MZI-SOA. Then, the single header signal is extracted by the optical bandpass filter (BPF) with a specific wavelength which is uniquely dedicated to a particular cylinder. The extracted header signal interacts with the control signal from an inner cylinder node according to AND logic operation. This output signal of this upper MZI-SOA controls the switching function of the lower MZI-SOA gate. The output signal of the upper MZI-SOA is only “on” when both control and header signals are of “1”-state, resulting in routing of the input packet signal to the inner cylinder node. In the case of the output of the upper MZI-SOA being “off,” the input optical packet remains in the same cylinder.

III. EXPERIMENT AND RESULTS

Fig. 2 shows the experimental setup. The setup consists of two parts: the optical packet generator and the proposed Data Vortex switch node. In the packet generator, two signals [10-Gb/s optical clock (1552.52 nm) and laser diode (LD1) (1557.36 nm)] were used for the payload and a continuous-wave LD2 (1554.13 nm) was used to carry the header information. The electrical data of the payload and header bits were generated by the same pulse pattern generator (PPG1). The packet length was 16 ns, including 2.4-ns guard time. In the experiment, the payload and header were modulated with the same intensity modulator to simplify the temporal alignment between the payload and header signals. The control signal generated separately was delayed to align it with the extracted header signal at the upper MZI-SOA.

To emulate packets propagating across multiple node hops, a recirculating configuration was used for the switch node. Therefore, the signal from the (S)outh output port was connected to the (N)orth input with two time slot delays. A fiber Bragg grating next to the (S)-output was used to eliminate the control signal from the (S)-output due to the copropagation configuration employed in the lower MZI-SOA. The (E)ast deflection output port is directed to an erbium-doped fiber amplifier (EDFA) followed by a filter for wavelength selection, a 10-Gb/s receiver, and a BER tester (BERT).

To verify successful routing functions, we examined the signal traces at each input and output port. Fig. 3(a) shows the initial input sequence. We programmed an initial bit sequence to be “001100 100011 001100 110011 000000 000000” and this pattern was repeated continuously. The last 12 “0s” among the whole bits were inserted to distinguish the given sequence from the next sequence. The packet sequence shown in Fig. 3(a) tends to be biased upward because two payloads and the header signal were modulated by the same electrical bit sequence and detected at the same photodetector which acts as a broadband radio-frequency (RF) power combiner.

As mentioned previously, a portion of the input packet signal was tapped and sent to the upper MZI-SOA to perform the header processing. For the header processing, the filter bandwidth should be narrow enough to select the proper header wavelength assigned to this cylinder. In the experiment, a BPF with a 3-dB passband of 0.3 nm was used. Fig. 4(a) shows the optical spectrum of the extracted header signal. Although there are residual signal peaks from the two payload signals, it has enough extinction ratio to avoid substantial crosstalk at the output of the MZI-SOA.

The extracted header signal interacted with the control input signal according to the AND logic operation. That is, the only “on” bits at the output of the upper MZI-SOA shown in Fig. 3(c) are those when both the header and control bit are simultaneously “1.” Fig. 4(b) shows the output spectrum of the upper MZI-SOA. As compared with the control input signal, the output spectrum has some amplified spontaneous emission (ASE) noise from the SOAs inside the MZI-SOA switch. The small peak on the left side of the output spectrum is the header signal which is reflected at the SOA end facet. The input packet
signal heading to the lower MZI-SOA was routed to either the same or to the inner cylinder node in accordance with these control output bits.

Results of the routing are shown in Fig. 3(d) and (e). The bits in Fig. 3(e) are the output to the (S)outh port at the lower MZI-SOA. Each “1” bit comes out only when the control signal from MZI-SOA is “on.” As mentioned previously, the signals from the (S)outh port are used for the recirculating input signal to the (N)orth port. Fig. 4(d) shows the optical spectrum of the (S)outh port. As shown in the figure, the control signal was filtered out and only the payload and header signals are there. Figs. 3(d) and 4(c) show the deflected signal at (E)ast port. As mentioned above, only the 10-G payload signal was selected to monitor the routing function and to measure BER performance. The recirculated signal from the (S)outh port was combined with the initial input packet and then reapplied to the switch node. The result is shown in Fig. 3(f). The amplitude of the routed packet is not even and somewhat noisy. This is due to the suboptimal input optical power level to the MZI-SOA. This causes variations in the switching conditions of MZI-SOA, which need to be optimized to keep the same switching performance. Consequently, each bit showed different switching performance.

Fig. 5 shows the BER performance of the single-path routed signal at (E)ast and (S)outh output ports. The power penalty at each output port is approximately 1 dB at a BER of $10^{-9}$. The penalty comes from the additional ASE noise of the MZI-SOA and crosstalk between two output ports. This power penalty is acceptable as just a single function block. However, more optimization is needed to apply this structure to large-scale networks.

We have proposed and demonstrated a full all-optical Data Vortex switch node. All-optical self-routing decisions are performed as AND logic operation in an MZI-SOA switch between an optical header and control signal. The output of this AND operation controls all-optically a second MZI-SOA and in this way all-optical packet routing is achieved. In the experiment, WDM 10-Gb/s data packets are successfully routed with 1-dB power penalty at BER of $10^{-9}$. We believe the new node structure is promising as a fundamental building block for future large-scale OPS networks with its integratability onto a single chip and its scalability to operate at very high processing rate due to its switching speed.

IV. CONCLUSION

We have proposed and demonstrated a full all-optical Data Vortex switch node. All-optical self-routing decisions are performed as AND logic operation in an MZI-SOA switch between an optical header and control signal. The output of this AND operation controls all-optically a second MZI-SOA and in this way all-optical packet routing is achieved. In the experiment, WDM 10-Gb/s data packets are successfully routed with 1-dB power penalty at BER of $10^{-9}$. We believe the new node structure is promising as a fundamental building block for future large-scale OPS networks with its integratability onto a single chip and its scalability to operate at very high processing rate due to its switching speed.

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