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Experimental Characteristics of Optical Crosspoint Switch Matrix and Its Applications in Optical Packet Switching

Nan Chi, *Member, IEEE*, Juan Jose Vegas Olmos, Kornkamol Thakulsukanant, Zhuoran Wang, Oliver Ansell, Siyuan Yu, *Member, IEEE*, and Dexiu Huang

Abstract—This paper presents the experimental results of the switching performances of the fast reconfigurable optical crosspoint switch (OXS) matrix. This paper demonstrates unicast optical packet switching for a 10-Gb/s payload at various modulation formats and a 155-Mb/s nonreturn-to-zero label. Reconfigurable time as fast as 2 ns is achieved because of the optimized control circuit and device fabrication. The power and wavelength dependence for the payload and the capability of multihop operation are investigated as well. The functionalities of the OXS acting as an optical switch and an optical buffer are demonstrated in the optical network node experiment. Very good switching property is obtained for the OXS, which clearly validates OXS as a potential technique for future high-speed Internet-protocol-over-wavelength-division-multiplexing networks.

Index Terms—Amplitude-shift keying, differential phase-shift keying (DPSK), integrated optoelectronics, optical crossconnect, optical packet switching.

I. INTRODUCTION

IN RECENT YEARS, we have seen a rapid movement toward data-centric communication network traffic. With the continuing growth of the Internet and the introduction of high-bit-rate wavelength-division-multiplexing (WDM) connections in metro and backbone networks, the current switching paradigm will not be able to use the available bandwidth efficiently, thereby increasing costs. Optical packet switching is a promising solution to transparently routing and forwarding packets independent of Internet protocol (IP) packet length and bit rate in the optical layer [1], [2]. Such optical packet switching networks require optical switch fabric to provide fast reconfiguration, high extinction ratio, low crosstalk, and good scalability [3].

Compared to all-optical switching, the electrooptic switching is technically more realistic while providing the necessary switching speed, which microelectromechanical system

(MEMS) and thermal switches cannot deliver [3]. It also provides the benefit of easier interfacing to network management functions, which is usually performed by a management layer in the electronics domain. The possibility of integration with other active devices such as semiconductor optical amplifiers (SOAs), detectors, and wavelength converters makes III–V-semiconductor-based optical switching solutions more attractive [4] compared to other material systems such as LiNbO₃.

We have in recent years worked on an optical crosspoint switch (OXS) matrix based on integrated active vertical coupler (AVC) as a promising switch fabric for future packet switching networks [5]–[9]. Exploiting the directional coupling between the passive waveguide (PW) in the bottom layer and the AVC in the upper layer, our OXS has several advantages such as the high switching-on speed (< 1.5 ns), compact size ($500 \times 500 \mu\text{m}^2/\text{switch}$), low crosstalk (< -50 dB), and high potential of port scalability [5], [6]. Several applications of OXS have been successfully demonstrated including 4×4 unicast switching [6], lossless multicast switching up to 2×4 [7], [8], and optical buffer based on recirculating loops [9], clearly validating the OXS as a promising switch fabric providing rich functionalities for future packet switching networks. However, so far, research on OXS has been focused on the packet switching for the nonreturn-to-zero (NRZ) payload, narrow wavelength range, and mostly on one-stage switching. Due to the carrier dynamics involved in the OXS devices, limitations such as data patterning and pulse distortion can become evident, therefore limiting the cascading of switches. This problem is also common to SOA-based switching fabrics. Further investigation on wider optical spectrum and multistage operation is necessary for the OXS.

In this paper, we present a detailed characterization of the switching properties of the OXS. We investigate the switching performance for various modulation formats, in particular, the differential phase-shift keying (DPSK) and return-to-zero DPSK (RZ-DPSK) formats. The power dependence and the feasibility of multihop operation are explored for the first time. This paper is organized as follows: The principle and structure of the OXS are presented in Section II. In Section III, we propose the switching properties for the OXS. The first time demonstration of cascaded optical packet switching and optical buffer is described in Section IV. This paper is concluded in Section V.

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Fig. 1. Schematic and photograph of the 4×4 crosspoint switch matrix. (a) Single switch cell in the ON state. (b) Single switch cell in the OFF state. (c) Packaged optical switch device (left) and a switch module (right).

II. PRINCIPLE AND STRUCTURE

The OXS matrix is fabricated in InGaAsP/InP semiconductor multilayers on an InP substrate. The matrix integrates 16 switch cells in a mesh structure (see Fig. 1). Each single cell involves two PWs crossing each other at a 90° angle. The PWs are made of wider bandgap material and have low loss at 1550 nm. The PWs form the signal input and output ports. Two AVCs are realized at the crosspoint by stacking on top of the PWs two active waveguides. For “active,” we mean that the waveguides have either significant loss or gain to the optical signal concerned. A total internal reflection mirror (TIRM) cuts vertically through the active waveguides and diagonally across the waveguides’ intersection, which allows the 90° redirection of the optical signal. When the AVCs are driven by carriers, which means that the switch cell is at the ON state, the light launched into the PW will be coupled to the active layer due to the refractive index (RI) matching. This light in the active layer is amplified by its gain, which is reflected by the TIRM to another AVC and coupled down to the PW as the output [see Fig. 1(a)]. The absence of carrier injection in the active layer will leave the switch cell in the OFF state, as illustrated in Fig. 1(b). The input light will simply pass through the PW due to the lack of RI matching. Strong optical absorption in the active layer helps to reduce signal leakage or crosstalk significantly. In this way, optical signals from the four input ports can be switched to the four output ports by triggering on the correctly selected switch cells. A finished 4×4 matrix is shown in Fig. 1.

The cell size is $500 \times 500 \mu\text{m}^2$. The structure has an intrinsic separate confinement heterostructure (SCH) upper active waveguide with $7 \times 75 \text{ \AA}$ unstrained InGaAs quantum wells (QWs) ($\lambda_{\text{PL}} = 1560 \text{ nm}$) and $60 \text{ \AA}$ Q1.3 barriers. The PW layer is Q1.2 and $0.7 \mu\text{m}$ thick. The spacing layer is $1.35 \mu\text{m}$ instead. The design requirement is the OFF state loss of $\sim 0.5 \text{ dB}$ per cell. A packaged device is shown in Fig. 1(c) with

Fig. 2. Experimental setup. ECL: external cavity laser. MZM: Mach-Zehnder modulator. PC: polarization controller. MZDI: Mach-Zehnder delay interferometer.

fiber ribbons for optical access and 1.27-mm pitch connection pins for electrical access. The thick connection pins are the thermoelectric cooler (TEC) current feedthroughs.

III. CHARACTERISTICS OF THE SWITCHING PROPERTIES

In this section, we provide the detailed investigation on the switching characteristics of the OXS by means of current dependence, wavelength, and injection optical power dependence, modulation formats, and cascability.

The experimental setup is shown in Fig. 2. The payload generator consists of an external-cavity laser at 1550 nm and two external Mach-Zehnder modulators (MZMs). The 10-Gb/s signal [pseudorandom binary sequence (PRBS) $2^{15} - 1$] is generated with an external MZM. Depending on the bias of the modulator, either an NRZ signal (which is biased at the half maximum) or a DPSK signal (which is biased at the null of its transmission) can be generated. Precoder for the DPSK format is not necessary in the experiment because the data is a PRBS pattern. The second modulator generates a 10-GHz RZ pulse train with 50% duty cycle. The modulator is biased at halfway point of its transmission curve and driven at the switching voltage with an ac-coupled bit rate (10 GHz) sine wave. The synchronous 155-Mb/s label signal is generated by a distributed feedback (DFB) laser at 1545 nm and combined to the payloads by a 3-dB coupler, thus realizing the optical packet in a wavelength labeling scheme. The labeling method is independent of the OXS, therefore; other optical labeling schemes such as subcarrier multiplexed labeling is compatible to our setup.

To perform the switching function, a fraction of the input packet is tapped for optoelectronic label processing. The remaining part of the packet is first label-erased by an optical bandpass filter and then input to the OXS. The 13-b label signal consists of a 4-b flag at the beginning, an 8-b address, and a 1-b flag at the end. The 8-b address describes the input and output port of the OXS, which is retrieved during the routing process. This address is then mapped to the switch-cell lookup table to find out which switch cells should be in the ON state in order to build up an appropriate optical path along the input and output. As soon as the corresponding element

Fig. 3. Transmission of all the 16 cells as a function of the cell drive current.

of the switching cell is logic 1, the control circuit will trigger the switching cell by injecting the required current. This 8-b address can define any subset of all the 16 switch cells to open at any time slot. After packet switching, the payload is detected by a preamplified 10-GHz receiver. When a DPSK or RZ-DPSK payload is employed, the DPSK or RZ-DPSK payload passes through a fiber-based stabilized Mach-Zehnder delay interferometer (MZDI) for phase demodulation.

A. Current Dependence for the Switch Cell

The transmission properties of the all the 16 switch cells have been measured and shown in Fig. 3. All data are normalized by the total insertion loss of about 18 dB, including polarization controller, chip coupling loss, and optical filter. The transmission is saturated when the injection current is 200 mA. An almost flat transmission curve is obtained when the current is around 200–250 mA, which means that in this operation range, the injection current does not need to be accurately controlled. When the device is in the OFF state (zero current), the measured on-chip leakage level is as low as -55 dB between all inputs and outputs, resulting in an extinction ratio of about 55 dB at 250 mA. Furthermore, no increase in leakage signal levels could be measured in all other outputs with any switch path in the ON state, confirming the excellent crosstalk suppression in the switch matrix.

In previous demonstrations, the turn-on speed for a cell from OFF state to ON state is shown to less than 1.5 ns [5]; this value is, however, measured at the chip level and not at the switching module level. In order to evaluate the dynamic reconfigurable time of the OXS module, we programmed the packet pattern so that the guard bands before and after the packet are continuous 1s, unlike the zero guard band in the conventional packet structure. In this way, a clear rising edge and trailing edge can be shown when the status of the cell alternates between ON and OFF states every two time slots, as shown in Fig. 4. The 10%–90% rise time and trailing time of the switching window, namely the switching speed for the OXS module, have been measured to be less than 2 ns (Fig. 4). Hence, the agility of the switch reconfiguration is guaranteed because the switch speed is short enough compared to the guard time.

Fig. 4. Measured waveforms of the switch cell A3D4. (a) Packet output. (b) Packet output when the guard band is logic 1. (c) Rising edge from OFF state to ON state. (d) Trailing edge from ON state to OFF state.

Fig. 5. Measured BER curves for the back-to-back signal (at 1550 nm) and after packet switching. The insets show the eye diagrams for NRZ-OOK signal, RZ-OOK signal, DPSK signal, and RZ-DPSK signal.

B. Switching Various Modulation Formats

So far, research on the OXS are mainly based on conventional ON–OFF keying (OOK) signal. It is envisaged, however, that impulse coding can outperform the NRZ coding [11] in transmission because RZ coding is more robust to fiber nonlinear effects and more resistant to the intersymbol interference introduced by bandwidth-limiting elements such as the transmitters and receivers. Recently, advanced modulation formats such as DPSK have attracted increased attention in order to enhance optical signal robustness to fiber nonlinear effects and to extend transmission distance [12]. It has also been proposed that the patterning-induced degradation in active devices can be alleviated by using the DPSK/RZ-DPSK format [13]–[16] due to its constant data pulse amplitude. Therefore, an RZ-coded signal and/or DPSK modulation can be an advantageous choice for the payload modulation format in next-generation networks.

For comparison, we measured the switching outputs for various modulation formats including NRZ-OOK, RZ-OOK, DPSK, and RZ-DPSK. The results are shown in Fig. 5. The single-stage switching penalty of all these modulation formats

Fig. 6. Simulated and measured static transfer function of the OXS cell.

are around 1 dB. Ideally, the length difference between the two arms of the MZDI DPSK demodulator should be 2 cm, which corresponds to a 100-ps delay. However, in practice, the length is slightly larger than 2 cm; therefore, the detected DPSK eye diagram has some intersymbol interference, as shown in Fig. 5, which results in a 0.6-dB penalty compared to the NRZ-OOK signal. However, for the RZ-DPSK signal, the penalty induced by the inaccurate delay of MZDI can be eliminated because the signal returns to zero at the border of the bit period. Almost the same sensitivities can be obtained for the RZ signal and the RZ-DPSK signal. It is worth noting that an even better sensitivity could be achieved for the RZ-DPSK signal if a balanced receiver is used in the setup. Thus, the feasibility of applying the advanced modulation formats to the OXS is demonstrated.

C. Wavelength and Input Power Dependence

Fig. 6 shows the simulated and the measured static transfer curve of the OXS cell. The simulation is carried out using the software Femlab3. The input saturation power of OXS is around 6 dBm, which is larger than that of SOA of usually less than -3 dBm [13]–[16]. When the chip input power of OXS is less than -1 dBm, the measured transfer function is approximately linear, which is well coincident to the simulation.

Fig. 7 shows the received sensitivity versus the input power. At low powers, the performance is degraded by the buildup of amplified spontaneous emission (ASE) noise from the amplifiers, but as the power is increased, the saturation of the switching cell in conjunction with pattern effect degrades the payload (see the inset eye diagrams of Fig. 7). Between these two extremes lies an optimum input power around -2–5.6 dBm, where the performance variation is less than 1 dB.

Fig. 8 shows the wavelength dependence of the OXS transmission for the RZ-DPSK payload. Error-free detection can be achieved in the whole C-band from 1535 to 1561 nm, with sensitivity penalty within 3 dB. It should be noted that the relatively large penalty at 1561 nm is due to the limitation of the optical bandpass filter utilized in the receiver. The output optical signal-to-noise ratio (OSNR) of four cells is also measured and shown in Fig. 8(b). All cells can realize an output OSNR larger

Fig. 7. Receiver sensitivity as a function of the input power.

Fig. 8. (a) Measured receiver sensitivity as a function of the wavelength. (b) Output OSNR (0.1 nm) versus wavelength.

than 35 dB (0.1 nm) for 0 dBm input power. The optimum range is around 1540–1555 nm due to the gain peak of the AVC.

D. Feasibility of Multihop Operation

The use of such kind of active optical switches is primarily limited by three factors [13], namely 1) the growth of ASE, 2) the pattern effect, and 3) the nonlinear intrapulse-phase distortions, which are caused by the low saturation energy, the gain recovery time comparable with the bit period, and by the nonlinearity of the devices. Conventional OOK signal could be susceptible to pattern effects due to above depletion and limited

Fig. 9. Cascaded switching setup. MZM: Mach-Zehnder modulator. PC: polarization controller. MZDI: Mach-Zehnder delay interferometer.

recovery time of the carrier density that results from the uneven dynamic data pulse pattern in the flow. With an increasing number of cascaded hops, the pattern effects become stronger, and the maximum propagation distance is limited by signal degradation. In contrast, DPSK has no data amplitude pattern and can therefore greatly reduce the pattern effect that suffer in the active device [13]–[16]. Hence, we can expect that the DPSK modulation format can benefit the multihop operation and extend the possible cascaded hops.

In order to investigate the cascability of the OXS, we implement the recirculating loop experiment, as shown in Fig. 9. The packet generator is similar as the setup in Fig. 2. The payload data stream is programmed to generate ten payloads at PRBS $2^7 - 1$ sequence. Before inputting to the OXS, the payload packets are amplified, filtered, attenuated, and polarization-adjusted because of the polarization-sensitive characteristic of OXS. The first is switched in to the recirculating loop by triggering the switching cell A4D2. The recirculations through the OXS are handled by the switch cell A2D2. The signal is output by switch A2D4. The optical power input to the OXS is maintained to be 4 dBm to avoid OSNR degradation. The erbium-doped fiber amplifier (EDFA) is necessary in the loop because the packaged OXS still has fiber-to-fiber transmission loss, despite a small on-chip signal gain, but can be eliminated in the future when a lossless OXS device becomes available. It should be noted that there is no fiber transmission link inserted in the loop in order to focus on the impairment caused by the OXS.

The output OSNR for the signal is in the order of ~ 35 dB (which is measured with an optical spectrum analyzer with 0.1 nm optical bandwidth). The extinction ratio of the back-to-back signal is larger than 12 dB, and for the switched signal, it is about 10 dB.

Fig. 10 shows the measured bit error rate (BER) curves for the OOK signal and DPSK signal for the back-to-back case and after multihop switching. It can be seen in Fig. 10 that the penalty for the OOK after nine hops is approximately 6.5 dB. The power penalty is due to both the spontaneous emission from the EDFA and the pattern effect of the switch. However, for the DPSK signal, the receiver penalty for the nine-hop switching is only 3.3 dB. Fig. 11(a)–(d) shows a

Fig. 10. Measured BER curves for the multihop switching of OOK signal and DPSK signal.

Fig. 11. Measured pattern for (a) four hops of OOK, (b) nine hops of OOK, (c) four hops of DPSK, and (d) nine hops of DPSK.

close-up look of the received packet after several recirculations within the OXS loop. Obviously, the OOK signal shows a strong pattern effect after more recirculation loops. For the long continuous 1s, the first bit of “1” would have an overshoot, and the power will gradually reduce for the subsequent 1s. The pattern effect also appears as the overshoot of a logic 1 after continuous 0s. The more switching hops, the worse the pattern effect. Therefore, the pattern effect is the main limiting factor for cascaded operation of the OXS when an OOK payload is deployed. In comparison, the DPSK signal maintains a very clear pattern after multiple loops, with very little distortion or signal degradation. The penalty is mainly induced by the noise accumulation. Therefore, it is clear that DPSK has a large advantage over OOK to improve the cascability of the OXS.

The phase noise generated from the OXS due to fluctuations of the carrier density could be a limiting factor for the DPSK signal. However, since each bit of the DPSK signal has an identical temporal intensity profile, the chirp (or phase variation) is identical from bit to bit [14]. Thus, the additional phase shift can be factored out after DPSK demodulation.

IV. APPLICATIONS IN THE OPTICAL NETWORK

In this section, we demonstrate the applications of the OXS in a network node acting as an optical time/space switch and

Fig. 12. Packet switching and buffering setup. MZM: Mach-Zehnder modulator. PC: polarization controller.

Fig. 13. Schematic of the optical buffer.

optical buffer for contention resolution. The experiment setup is shown in Fig. 12. The packet is generated and input to the first OXS for the pure packet switching. The label retrieving circuit will detect the label and do label processing. If there are two labels arriving simultaneously, i.e., a packet contention occurs, the switching control will trigger on the appropriate switching cell to let the packet input to the optical buffer.

Fig. 13 shows the schematics of the proposed optical buffer based on multiloop configuration and the OXS matrix [17]. In our proposal, the optical packets will input to the buffer from port A4 and output from D4. The other three input and output pairs of the OXS are, respectively, connected by different fiber delay lines. By selecting the switch cells, the input packets will be guided from the input port into the loops, transmitted in the loops, switched from one loop to another, or guided out from the buffer. Assume that the delay of the three loops are d_1 , d_2 , and d_3 , respectively, and the corresponding numbers of recirculation are n_1 , n_2 , and n_3 . The total delay T of the buffer can be given by

$$T = n_3 d_3 + n_2 d_2 + n_1 d_1 \quad (1)$$

where $d_3 = 10 \times d_2 = 100 \times d_1$ and $n_i = 1, 2, \dots$ ($i = 1, 2, 3$). In this way, decimal optical buffer satisfying is achieved. For instance, if the delays d_1 , d_2 , and d_3 are set to be 1, 10, and 100 ns, respectively (corresponding to the fiber

Fig. 14. Measured BER curves for packet switching and buffering. The inset figures show the waveforms for the switching output and the buffer input.

Fig. 15. Waveforms captured (a) at the input and (b) buffer size 1 μ s, (c) buffer size 2.1 μ s, and (d) buffer size 9 μ s.

of about 20 cm, 2 m, and 200 m), the buffer depths can be varied with a 1-ns step from 1 to 999 ns, when the circulation numbers n_i are limited to 9. Thus, the fine granularity and the large variable delay can be achieved simultaneously in this simple scheme. Sufficiently large delay is effective for resolving packet contention, whereas the fine granularity of the delay allows more efficient statistical sharing of the channel bandwidth among packets belonging to different source and destination pairs.

It is worth noting that to realize the same buffering function by other buffering schemes, either a large number of switches or a large amount of fibers for the delay lines are required. In our proposal, however, only one individual switch element and a small number of fibers are used; hence, the router management would be simpler, easier, and more stable. When a packet has entered a long fiber delay line, it cannot be switched out but will emerge only at the end of the fiber. However, because of the flexibility and fast switching speed of the OXS, it is feasible to reconfigure the switching cell and retrieve the packet from the buffer. Such delay variability is essential in time-critical applications where packets of information can be released from the buffer at will.

Fig. 14 shows the BER performance of the signal at different points of the setup. The inset figure shows the waveform output of the switch and input to the buffer. Fig. 15 shows the

time-domain measurements of different buffer configurations of 1, 2.1, and 9 μ s. The BER performance after optical switch is degraded by about 1 dB. The optical buffer introduces extra degradation. The overall penalty for optical switching and buffering for 9 μ s is 7 dB. Hence, packets arriving simultaneously to an optical node can be handled appropriately, i.e., switched or optically buffered. It is envisaged that a better performance can be obtained if the insertion loss and polarization-dependent loss can be further reduced for the OXS.

V. CONCLUSION

The performance of an OXS based on InGaAsP/InP semiconductor has been experimentally evaluated. The influence of injection current, modulation formats, signal input power, and wavelength on receiver sensitivity has been studied. Very good performance can be achieved in the whole C-band for the payload, and the output OSNR is larger than 35 dB at 0 dBm input power and 0.1 nm optical bandwidth. The pattern effect generated by the OXS is supposed to be the main factor limiting the multihop operation, however, it can be mitigated by deploying the DPSK modulation format. After passing through nine hops of switches, the DPSK signal has 3.3 dB penalty, which outperforms the OOK signal for 3.2 dB. Moreover, we demonstrated an optical network node with two OXSs performing as the optical switch and optical buffer. Our results clearly validate that OXS is a promising switch fabric/functionality for future packet switching networks.

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Juan Jose Vegas Olmos, photograph and biography not available at the time of publication.

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