Large-Scale and Fast Optical Circuit Switch for Coherent Detection Using Tunable Local Oscillators Formed with Wavelength Bank and Widely-Tunable Silicon Ring Filters

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Abstract *We demonstrate a 1,024×1,024 wavelength-routing optical switch with switching time under 18μs for 256-Gb/s DP-QPSK signals. Wavelength selection at the receivers is achieved by fast widely-tunable (22nm) local oscillators formed using a wavelength bank and newly fabricated silicon ring filters having 5.3-dB fibre-to-fibre insertion loss.*

Introduction

Increased bandwidth demands and the resultant power consumption of intra-data centre networks hinder the scaling out of present multi-tier electrical switching networks. Electrical-packet and optical-circuit hybrid switching can break the bandwidth and power barriers by effectively offloading large flows from electrical switches to optical switches [1, 2]. A single-tier fast and high port-count optical circuit switch can replace most of the multistage electrical switching networks and thus their innumerable optic-electric and electric-optic conversions. The flattened network reduces the number of optical transponders and interconnection links (by ~75%) which greatly simplifies network configuration and reduces electrical power consumption [2]. We have so far developed large-port-count optical switches by combining two different dimensions, space and wavelength [2-4]. For example, a combination of 32 × 32 space switches and 58 wavelengths yields the total port count of 1,856 × 1,856. Wavelength routing is implemented by tuning wavelengths at optical sources (tunable laser diodes; TLDs) or receivers (tunable filters; TFs). TFs are simpler and more reliable devices than TLDs, and hence we focus here on TF-based optical switches.

Coherent technologies are now commonly applied to inter-data centre networks [5]. The year-by-year power, size, and cost reduction [6] seen in commercial products portends their use in intra-data centres not so distant future. For coherent detection, a cost-effective and fast-tunable local oscillator (LO) is required at the receiver of the optical switch. It can be created with a wavelength bank and Silicon-photonic TFs. We have recently demonstrated a scalable and fast (3.5 μs [4]) optical switch for coherent signals using Silicon-photonic TFs composed of cascaded Mach-Zehnder interferometers (MZIs). On the other hand, a silicon ring filter forms simple configuration and is another candidate; 15-μs tuning speed for four channels spaced at 200 GHz has been demonstrated [7]. The current ring filter, however, has limited tunable range (<10 nm) and high insertion loss (>18 dB).

This paper proposes a high port-count optical switch that uses a fast and widely-tunable LO bank for coherent detection. First, we investigate available port count of the switch. Performance of the proposed LO bank, comprised of fixed wavelength LDs and newly developed Silicon ring filters, is analysed and optimized via numerical simulations. To prove feasibility, we fabricate a silicon ring filter that is tunable over 22 nm with an average fibre-to-fibre insertion loss of 5.3 dB. Using 32×256-Gb/s DP-QPSK signals, we conducted 1,024 × 1,024 optical switching experiments utilizing the developed LO bank. Fast switching time (<18 μs) is confirmed for the 32 channels (~22 nm).

Proposed optical circuit switch architecture

Figure 1(a) depicts the proposed $MN \times MN$ optical circuit switch architecture. The N-wavelength signals from fixed-wavelength transmitters are aggregated by an $N \times 1$ multiplexer (MUX) and then distributed by a $1 \times (N/S)$ splitter. After loss compensation by an erbium-doped fibre amplifier (EDFA), the signals are further distributed by a $1 \times S$ splitter. Although the EDFA is a relatively expensive device, the per-port cost can be reduced by sharing many wavelengths (N) and output ports (S). One of the M distributed signal groups is selected by an $M \times M$ multicast switch (MCS) for space switching. The signal incident on the receiver is coherently detected by using an external LO light served from an LO bank. Wavelength routing is performed by tuning the LO wavelength that extracts the target signal from the N wavelengths. After coherent detection, the received signal is demodulated by means of digital signal processing (DSP).

A remarkable feature of the proposed optical

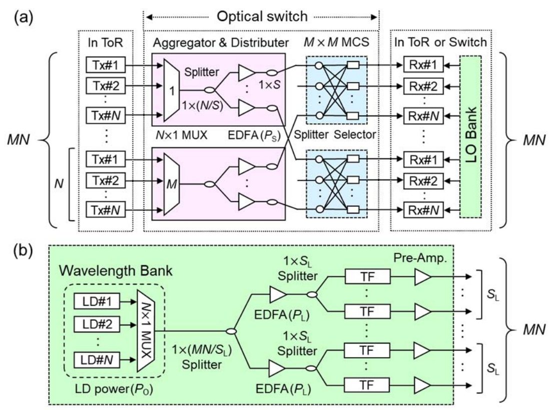

Fig. 1: (a) Proposed $MN \times MN$ optical circuit switch architecture based on LO bank. (b) Configuration of fast and widely-tunable LO bank for large-scale optical switch.

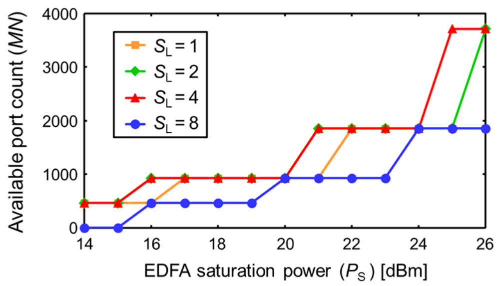

Fig. 2: Available port count calculated at $N = 58$ and $S = 4$ for different LO-side EDFA sharing numbers S_L.

switch is the LO bank supporting a huge number of output ports. Figure 1(b) illustrates one configuration of the LO bank. An optical comb or N-wavelength LD signals are multiplexed and the WDM channels are broadcasted via a two-stage distributor; $1 \times (MN/S_L)$ and $1 \times S_L$ splitters. After the first splitter, the loss is compensated by an EDFA, the cost of which is shared by multiple ports (S_L). After the second splitter, TF extracts the single target LO wavelength. The TF output is amplified by a compact and low-cost preamplifier with uncooled-LD pumping, and then launched into the receiver. Thus, MN continuous wave (CW) lights, each with arbitrary wavelength, are realized by using only N LDs: LO lights are cost-effectively produced. Port-dedicated components are the TF and preamplifier; the others are shared by many ports. TF cost can be reduced by integrating many of them on a single silicon chip.

Regarding the proposed switch configuration shown in Fig. 1, we analysed the available port count via numerical simulations. A transmitter generated 75-GHz-spaced 58-ch WDM signals modulated by 256-Gb/s dual-carrier DP-QPSK. EDFA sharing number for the optical switch is set at 4 [S = 4, Fig. 1(a)]. The performance of colourless coherent receiver was emulated by quantifying the front-end impairments [8]. For the LO bank, we assumed an LD output power of P_O = 8 dBm/LO and an EDFA saturation power of P_L = 24 dBm. The saturation power of the

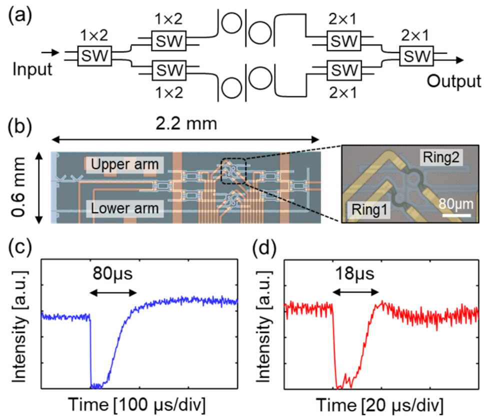

Fig. 3: Newly fabricated silicon ring filter. (a) Structure. (b) Microscopic image of the filter chip. Power transition after the preamplifier (c) without and (d) with turbo pulse.

preamplifier was set at 17 dBm. The other parameters were the same as those used in the previous work [4]. Figure 2 shows available optical switch port count versus switch-side EDFA saturation power (P_S) for different LO-side EDFA sharing numbers (S_L) [see Fig. 1(b)]. The bit error ratio (BER) target of 10^{-3} was set to meet the 7%-overhead forward error correction (FEC) limit. As the sharing number becomes larger ($S_L \geq 8$), available port counts are degraded due to the reduced LO output power. With small sharing ($S_L \leq 2$), the degradation in carrier-to-noise ratio due to excessive power loss stemming from the $1 \times (MN/S_L)$ splitter limits the optical switch scale. The best performance is observed at $S_L = 4$ and the port count of 1,856 is attained at $P_S = 21$ dBm.

Prototype fabrication of silicon ring filter

A widely-tunable TF was fabricated on a Silicon-photonic platform. Figure 3(a) illustrates the schematic of the Silicon-photonic TF with ring resonators. The filter is designed with two identical arms, each of which comprises two switch elements and one ring resonator. In the ring resonator, the Vernier effect induced by double-ring structure is utilized to expand free spectrum range (FSR) [9]. The resonance wavelength is tuned by applying an electrical current to heaters on the ring resonators. The turbo-pulse heater control scheme is employed to boost the tuning speed [10]. When a wavelength transition is requested, the input/output switches select a currently unused arm. The selected arm is rapidly heated by the Turbo Pulses, so that switching time is always determined by the heating up process, not the cool down one which takes longer time.

A microscopic image of the fabricated filter chip is shown in Fig. 3(b). The chip occupies the area of 0.6 mm × 2.2 mm, which is less than 1/6th that of our previous TF composed of cascaded MZIs [11]. The measured 3-dB bandwidth and FSR were 0.14 nm and 22 nm,

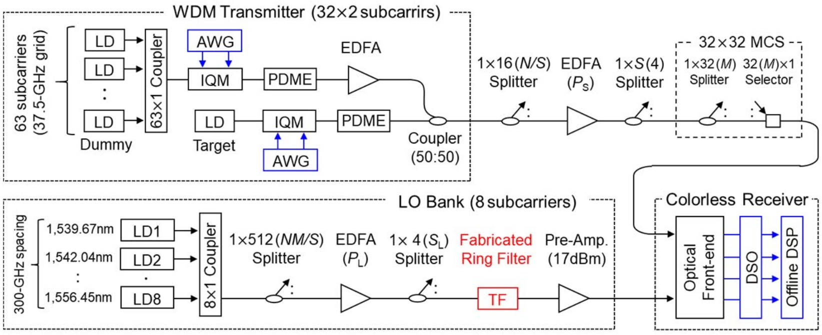

Fig. 4: Experimental setup under the condition of M = 32, N = 58, S = 4, and S_L = 4.

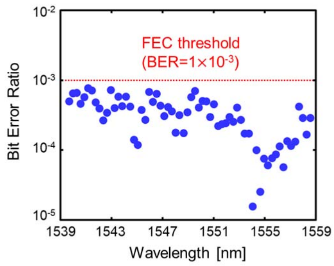

Fig. 5: Measured BERs for all 32×2 subcarriers.

respectively. The passband wavelength is tuneable in the C-band from 1,530 nm to 1,565 nm. The average fibre-to- fibre insertion loss over the C-band (35 nm) was 5.3 dB, which includes 1.9-dB on-chip loss and 3.4-dB coupling loss. The switching time was examined by passing two CW lights through the filter. Figures 3(c) and (d) show measured power transitions without and with the Turbo-pulse control, where the wavelength is changed from 1,530 nm to 1,565 nm. The switching time is reduced from 80 µs to 18 µs by Turbo-pulse control.

Experiments

The port count analyses shown in Fig. 2 assumed the entire C-band (35 nm, N = 58), however, the fabricated TF had the FSR of 22 nm (N = 32). Figure 4 shows the setup for the proof-of-concept experiment, where 32 × 256-Gb/s dual-carrier DP-QPSK signals were tested using a 32 × 32 MCS (M = 32); the emulated port count was 1,024 × 1,024. In the experiment configuration, however, the maximum EDFA output level and splitter ratios were set so that they could accommodate N = 58 when the TF FSR is expanded to 35 nm.

At the transmitter, 64 LDs were operated on a 37.5-GHz channel grid from 1,539.67 nm to 1,558.58 nm. The test and the other channels were separately modulated using two IQ modulators (IQMs). Individual 50-GSa/s arbitrary waveform generators (AWGs) drove the IQMs to generate 32-Gbaud QPSK signals. After polarization division multiplexing emulators (PDMEs), the PDM signals were combined at an optical coupler to form a 75-GHz-spaced 32-ch DP-QPSK WDM signal. The transmitted signal was split by a 1 × 16 splitter and amplified by an EDFA with saturation power of 21 dBm. The amplified signal was further distributed by a 1 × 4 splitter and delivered to a 32 × 32 MCS in front of the receiver. Owing to the limitation of available equipment, the LO bank was created with eight sets of sub-banks; each sub-bank was made of eight LDs. Thus 64 LO wavelengths were supplied to the receiver. The eight channels were aligned with 300-GHz spacing (4ch × 75 GHz). the EDFA gain was adjusted so that the per channel output power was same as that assumed for M = 32, N = 58, and S_L = 4. The worst crosstalk of –24 dB was measured from the extracted LO spectrum. At the receiver, the incoming signal was coherently detected using the LO light. The detected signal was sampled at a 50-GSa/s digital sampling oscilloscope (DSO) and demodulated by offline DSP. Thus, no optical filter was placed before the receiver, i.e. colourless coherent detection was performed.

Figure 5 plots the measured BERs for all 32 × 2 subcarriers. The results show the ensemble data with eight sets of LO sub-banks. All channels achieved the BER below the 7%-overhead FEC threshold of 1 × 10^{-3}. As a result, we have confirmed the feasibility of 1,024 × 1,024 (i.e. M = 32 and N = 32) optical switching with total throughput of 262.1 Tb/s. The demonstration emulated the optical splitter and amplifier parameters so that N = 58 is possible. A port-count of 1,856 will be achieved by expanding the TF FSR to 35 nm, which is our next step.

Conclusions

We have successfully demonstrated 262.1-Tb/s switch bandwidth (1,024 × 1,024 at 256 Gb/s) and switching times under 18 µs, using a newly fabricated silicon ring filter that creates an LO bank.

Acknowledgements

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