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Large-Scale and Fast Optical Circuit Switch Employing Coherent Detection Enabled with Hitless Cascaded-Silicon-Ring-Filter for Local Oscillator (LO) Wavelength Extraction from Laser Bank

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Abstract *We demonstrate a 1,856 × 1,856 optical circuit switch utilizing C-band tuneable local oscillators (LOs) for coherent detection. Hitless and fast (<14.8 μs) LO wavelength tuning is realized using a newly fabricated 8-cascaded silicon ring filter having wide free spectrum range (FSR) of >35 nm. ©2022 The Authors*

Introduction

High-port-count optical switches play an important role in overcoming the bandwidth bottleneck and power consumption limitation of intra-data centre networks [1–4]. Various studies have targeted optical switches with port counts of over one thousand [5–7]. We have already developed an optical switch architecture that combines the two independent dimensions of space and wavelength [7–9]: space switch port count (M) and the number of wavelengths (N) yields MN ports. Wavelength routing can be realized by tuning the optical source wavelength [7] (using tuneable laser diodes; TLDs) or receivers [9] (using tuneable filters; TFs). TFs are attractive since they are a simple, reliable and cost-effective device compared to TLD, and so this work adopts TFs.

Coherent detection enhances switch bandwidth and port-count through its high spectral efficiency and receiver sensitivity. Considering the year-by-year power, size, and cost reductions seen in commercial products [10, 11], it is expected to penetrate into intra-data centres in the not so distant future [12]. For coherent detection, fast and widely-tuneable local oscillators (LOs) are necessary at the receiver side of the optical switch. They can be cost-effectively realized as an LO bank formed that combines fixed-wavelength laser sources with TFs [13]. Silicon ring filters are promising candidates due to their compactness and narrow passband. High density integration is realized by cascading micro-rings in a single chip [14]. The prominent advantage of cascaded silicon ring filters is the reduced insertion loss (IL), as evident by the reuse of the Through-port outputs for other micro-rings without needing fibre-Si chip connection. However, the free spectrum range (FSR) of a ring filter is limited to less than 15 nm due to its minimum bend radius. In cascaded dynamic operation, each drop channel needs to be dynamically switched from one target wavelength to the other where *hitless wavelength tuning* [15, 16] that does not interfere with other channels is essential. In addition, the tuning time should be on the order of ten microseconds in data centre applications.

In this paper, we propose a large-scale optical switch that utilizes wideband and fast coherent signal tuning in an LO bank formed by cascaded silicon ring filters. An 8-cascaded second-order (Vernier) ring filter was developed that has 40-nm wide FSR. Hitless operation is achieved with fast tuning speed of under 14.8 μs; there is no signal distortions even with the dynamic operation of the other microrings. In a 1,856 × 1,856 optical switching experiment, we successfully demonstrate 256-Gbps DP-QPSK signal switching for all Drop ports of the fabricated 8-cascaded silicon ring filter. To the best of our knowledge, this is the first demonstration of a cascaded silicon ring filter that covers entire C-band.

Proposed optical switch based on LO bank

Figure 1(a) depicts our proposed $MN \times MN$ optical switch architecture [13] applying a new LO bank configuration for coherent detection. The signals generated by N fixed-wavelength transmitters are aggregated by an $N \times 1$ multiplexer (MUX). The N-channel WDM signal is broadcast to N paths by two-stage distributors; $1 \times (N/S)$ and $1 \times S$ splitters. After the first-stage distribution, an erbium-doped fibre amplifier (EDFA) compensates the splitter losses. One of the M distributed signal groups is selected by an $M \times M$ multicast switch (MCS) for space switching. At a receiver, the selected signal is coherently detected by using an external LO light served from an LO bank. The LO bank illustrated in Fig. 1(b) performs wavelength routing, using LO wavelength selection by Silicon-photonic TFs. N-wavelength LD lights are multiplexed (or optical comb), then distributed by a $1 \times (MN/S_L)$ splitter

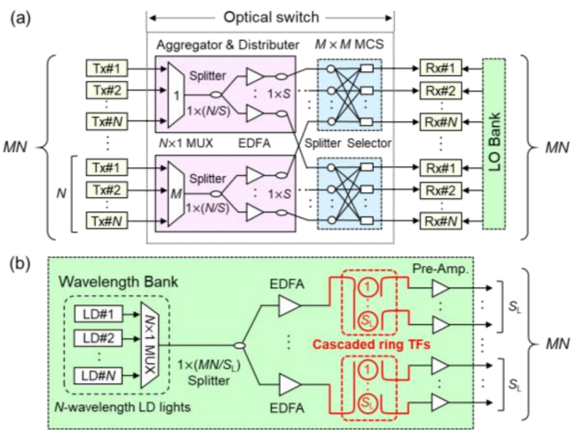

Fig. 1: (a) Proposed $MN \times MN$ optical circuit switch architecture based on LO bank. (b) Configuration of hitless and fast-tuneable LO bank for large-scale optical switch.

and amplified by an EDFA. The distributed optical combs are directed to cascaded ring TFs, where each filter section extracts one target wavelength. After boosting the TF output with a low-cost and compact preamplifier, the target channel serves as an LO light for coherent detection. Consequently, arbitrary *MN* input and output ports are connected by changing the state of the MCS and LO wavelength at the LO bank. Although the EDFA is a relatively expensive device, the per-port cost is reasonable as it is shared by plural output ports (S or S_L).

The previous study [13] implemented filter section by combining $1 \times S_L$ splitter and S_L silicon ring filters. For this paper, we develop a cascaded fast-tuneable silicon ring filter covering the entire C-band. Unlike the previous configuration, this eliminates excessive splitter loss and many interconnects between the splitter and TFs. For S_L = 8, the total fibre-to-fibre IL is reduced from 19.75 dB to 11.06 dB as measured in the experiments. For the MN = 1,856 scale LO bank, the reduced number of splitters is 232, and that of interconnect fibres is 1,856. The reductions become more prominent as the switch port count increases. Hitless operation is needed for cascaded ring filters, which is reported in next section.

Fabrication of 8-cascaded silicon ring filter

We fabricated a hitless and widely-tuneable filter by integrating 8-cascaded second-order ring resonators on a single silicon chip. As schematically illustrated in Fig. 2(a), each ring section consists of a bypass path and second-order ring resonator path, one of which is selected by Mach-Zehnder interferometers (MZIs) at both sides of the ring. In the ring resonator, the Vernier effect induced by the double-ring structure is employed to achieve wide FSR [17]. The resonance wavelength is thermo-optically tuned by activating heaters placed on the ring resonators. The tuning speed is accelerated by the introduction of the

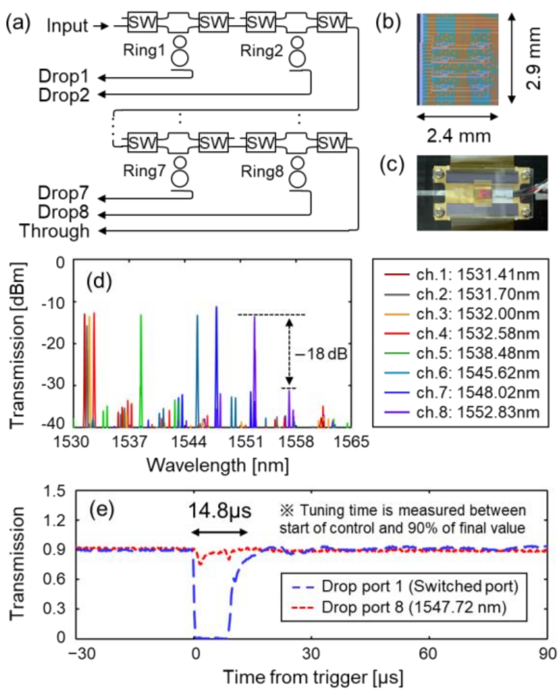

Fig. 2: Newly fabricated 8-cascaded silicon ring filter. (a) Structure. Photographs of the filter (b) chip and (c) module. (d) Measured transmission spectra from eight Drop ports. (e) Power transition observed at Drop ports 1 and 8.

Turbo-pulse heater control scheme [18]. Figures 2(b) and 2(c) show photographs of the 8-cascaded ring filter chip and module, respectively. The footprint of the optical filter is 2.4 × 2.9 mm^2. All components were designed to operate in transverse electric (TE) mode. The average fibre-to-fibre IL over the C-band (35 nm) was 11.06 dB, which includes 3-dB drop loss of the ring, 0.18-dB propagation loss between ring reconnectors, and 3.4-dB fibre coupling loss per facet.

Figure 2(d) presents the eight Drop-port responses measured by using an amplified spontaneous emission (ASE) light source and optical spectral analyser. Assuming the ITU-T 37.5-GHz grid on a C-band, we selected the eight Drop-port wavelengths (Ch.1–Ch.8) that yielded maximum IL of the optical filter (i.e., worst case). The average 3-dB bandwidth is 10.8 GHz with high side-band suppression of >18 dB. The FSR is larger than 40 nm by virtue of the Vernier effect. In addition to the 11.06-dB average fibre-to-fibre IL, an excess loss of ~5 dB (ch.2) is caused by thermal crosstalk from nearby devices. The dynamic switching performance is shown in Fig. 2(e), where the optical power transition was measured by changing the filtering wavelength from 1538.78 nm to 1538.48 nm at the Drop port 1. In the switching process, the initial wavelength (1538.78 nm) was disconnected by selecting the bypass using the input/output MZI switches. During the disconnection phase, the ring resonators are rapidly heated to retune to the target wavelength (1538.48 nm). The wavelength tuning is

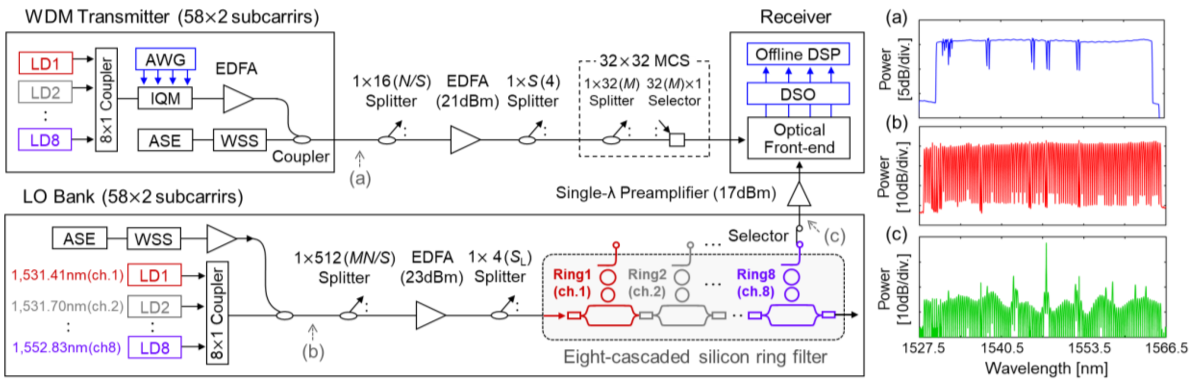

Fig. 3: Experimental setup of 1,856×1,856 optical switch with 32-Gbaud DP-QPSK signal ($M = 32$, $N = 58$, $S = 4$, and $S_L = 4$). Measured spectra at (a) WDM transmitter, (b) wavelength bank, and (c) Drop port 7 of fabricated 8-cascaded silicon ring filter.

complete by reconnecting the Through (Bypass) port to the Drop port. As indicated in Fig. 2(e), we achieved hitless wavelength tuning by keeping the temporal waveform almost unaffected during the other Drop-port operation. Wavelength tuning operation of the Drop port 1 can be completed very rapidly (≤15 μs), thanks to the Turbo-pulse heater driving. Here, the tested wavelengths yielded the longest (i.e., worst) tuning time in all channel combinations.

Experiments

The applicability of the fabricated silicon ring filter to a 1,856×1,856 optical switch ($M = 32$, $N = 58$) was verified using the experimental setup of Fig. 3. At the transmitter, the outputs of eight LDs were combined with an 8×1 optical coupler and then fed to a dual-polarization IQ modulator (DP-IQM) for data modulation. Their wavelengths were set to match those of Fig. 2(d). The DP-IQM was driven by an arbitrary waveform generator (AWG) with a sampling rate of 64 GSa/s to create 32-Gbaud DP-QPSK signals. The waveform had a root-Nyquist spectral shape after a root-raised-cosine filter with a roll-off factor of 0.1. The modulated signals were coupled with spectrally-shaped ASE (SS-ASE) light using a wavelength selective switch (WSS). This emulated 58 channels of 256-Gbps dual-carrier DP-QPSK placed on a 75-GHz grid [Fig. 3(a)]. The transmitted WDM signal was divided 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 before the receiver.

At the LO bank, 37.5-GHz-spaced 116-channel LO subchannels were emulated by coupling eight LD lights with an SS-ASE light [Fig. 3(b)]. The eight wavelengths were tuned to match those of the modulated signals (Ch.1–Ch.8). The multiwavelength LD light was divided by a 1 × 512 splitter and further distributed by a 1 × 4 splitter after an EDFA. The distributed LD lights were directed to the fabricated silicon ring filter with input power adjusted by an EDFA to 16 dBm. The filter

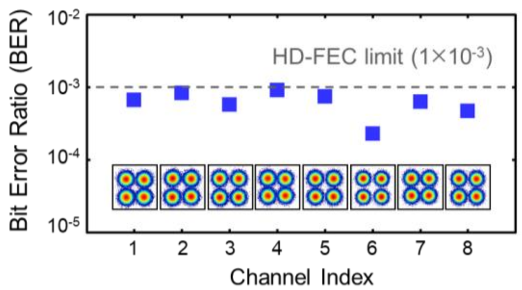

Fig. 4: Measured BERs and signals of eight channels.

extracted the target channel [Fig. 3(c)] and then sent to the receiver via a compact and low-cost preamplifier. At the receiver, the incoming signal was coherently detected by mixing with the LO light in an optical frond-end. No optical filters for the signal path were placed in front of the receiver (or after MCS) for colourless coherent detection. After the conversion into the electrical domain, the detected signal was analysed using a digital storage oscilloscope (DSO) followed by an offline digital signal processing (DSP).

Figure 4 plots the measured BERs against the channel index, together with the hard-decision forward error correction (HD-FEC) limit [19]. Successful colourless coherent detection of the eight signals was achieved with BERs below 1×10^{-3}. Those BERs were attainable despite the excess loss (<5 dB) at the Drop ports of the ring filter as observed in Fig. 2(d). The undesirable excess loss will be minimized by applying automatic thermal control [14, 20] and/or silicon waveguide layout optimization [21].

Conclusions

We experimentally demonstrated a 1,856×1,856 optical switch using an LO bank, enabled by wavelength selection via novel cascaded silicon ring filters. Wavelength channels were switched within 14.8 μs in a hitless manner.

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