Scalable and Fast Optical Circuit Switch Exploiting Colorless Coherent Detection

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Abstract: We present a scalable and fast wavelength-routing switch employing colorless coherent detection. Some thousand port-count and a few microsecond switching time are realized by using a Silicon-Photonic tunable-filter-based local oscillator bank that enables colorless detection. © 2022 The Authors

1. Introduction

Datacenter-related traffic is increasing the rate of 25% per year and more than 75% of the traffic remains within data centers [1]. The explosive traffic demands raise a problem with the bandwidth and power consumption of intra data center networks. Electrical-packet and optical-circuit hybrid switching can overcome these issues by effectively offloading large flows from electrical switches to optical switches [2–4]. A high port-count optical switch plays a key role in creating the optical switching network since it enables single-tier networks with minimal latency and fewer optical interconnections [4]. The flat network substantially reduces (~75%) the number of optical transponders/links and switch power consumption compared to current multi-tier EPS networks [5]. To effectively attain high port-count optical switches, we have developed a scalable switch architecture that employs routing in the two dimensions of space and wavelength [6–8]. As the total port count is given by the product of two sub-switch port counts, a $1{,}600 \times 1{,}600$ optical switch is attained by combining 100 wavelengths and 16×16 space switches. Wavelength routing can be implemented using tunable laser diodes (TLDs) at transmitters, or tunable filters (TFs) or tunable local oscillators (LOs) at receivers. As TFs are simpler and more reliable devices than TLDs due to their passive nature, we adopt receiver side (TF-based) wavelength selection in this paper.

The substantial yearly reduction in cost, size, and power consumption of coherent transceivers portends their use in intra-data centers in the immediate future [9]. The switch bandwidth and port-count can be increased by using coherent optics that yield high spectral efficiency and receiver sensitivity. Coherent detection, however, needs widely and fast tunable LOs at the receiver for wavelength selection. Cost-effective tunable LO lights are available without using TLDs; wavelength bank can be combined with Silicon-photonic TFs (i.e., LO bank) [10]. This can eliminate TFs (and the resultant loss) in front of receivers, and thus colorless coherent detection further enlarges the available switch port count due to the improved loss budget. Caution is needed here on designing the optical switch due to self-beat interference (noise) from out-of-band channels [8] and power saturation in the colorless receiver.

This paper introduces a port-count scalable optical switch architecture based on a fast-tunable LO bank for coherent detection. Its design and verification are presented along with experiments on fabricated Silicon-Photonic TFs. The switch architecture realizes port-counts of over 1,000 and switching times of a few microseconds, which opens the way to creating future scalable and low power consumption intra data center networks.

2. Optical Switch Architecture based on LO Bank for Coherent Detection

Assuming an 18-dB receiver dynamic range according to the OIF arrangement [11], the maximum number of wavelength signals input to a coherent receiver is limited to 60 (= $10^{18/10}$) for 100-Gb/s DP-QPSK format. Tighter constraints on the receiver's dynamic range are imposed with high-order modulation formats such as DP-8QAM and DP-16QAM. Accordingly, even a coherent system needs a TF to prevent receiver power saturation when the channel number exceeds a certain limit [12]. Table 1 shows design examples of optical switch throughputs and port counts for different modulation formats, wavelength numbers (N), and space switch port counts (M), where colorless and filtered coherent systems (receivers), marked red and blue, respectively, are assumed. A tradeoff relation exists between available wavelength number (N)

Tab. 1. Achievable optical switch scale for each modulation format

Modulation format (SC: Single carrier, DC: Dual carrier)	Chanel speed [Gbps/ch.]	Number of wavelength, N (Channel spacing)	M=16		M=32	
			Switch port count	Throughtput [Tbps/switch]	Switch port count	Throughtput [Tbps/switch]
32Gbd SC DP-QPSK	100	117 (37.5 GHz)	1,872	187.2	3,744	374.4
32Gbd SC DP-8QAM	150		1,872	280.8	3,744	561.6
64Gbd SC DP-QPSK	200	58 (75 GHz)	928	185.6	1,856	371.2
32Gbd DC DP-QPSK			928	185.6	1,856	371.2
43Gbd SC DP-8QAM		88 (50 GHz)	1,408	281.6	2,816	563.2
32Gbd SC DP-16QAM		117 (37.5 GHz)	1,872	374.4	3,744	748.8
64Gbd DC DP-QPSK	400	32 (137.5 GHz)	512	204.8	1,024	409.6
43Gbd DC DP-8QAM		48 (100 GHz)	768	307.2	1,536	614.4
64Gbd SC DP-16QAM		58 (75 GHz)	928	371.2	1,856	742.4

and channel speed. Colorless coherent detection is possible when channel speed is higher than 400 Tb/s, while TFs are imperative in scaling the port count up more than 2,000 × 2,000 (M = 32). System performance analyses need to consider self-beat interference (noise) with colorless WDM reception; the design principle was presented in our previous paper [8].

Figure 1(a) depicts the $MN \times MN$ optical switch architecture utilizing a shared LO bank for coherent detection. The optical switch block consists of MN fixed-wavelength optical transceivers, M $N\times N$ wavelength aggregators-and-distributers, N $M\times M$ multicast switches (MCSs), and MN TF1s. By changing the state of the MCS and/or the passband of TF1, a signal is routed between arbitrary input and output ports without blocking. Wavelength selection is performed by tuning the LO wavelength sourced from an LO bank. In the shared LO bank, an optical comb or multiplexed N fixed-wavelength LD lights are broadcast by the two-stage distributer [10]. The target wavelength is extracted by TF2 and amplified by a compact and low-cost preamplifier with uncooled-LD pumping. Although relatively expensive EDFAs are placed on the optical switch and LO bank, the per-port cost can be reduced as multiple output ports share an EDFA. Figure 1(b) illustrates the Silicon-Photonic TF based on multistage asymmetric Mach-Zehnder interferometers (AMZIs). The k-th AMZI has FSR of $35/2^k$ nm to cover the C-band, and overall filter response is given by convoluting all AZMI responses. For 32-Gbaud WDM signals with more than 60 channels ($N \geq 60$), we have recently proposed a cooperative filtering scheme of transmission signals and LO channels [13]. For instance, the 8-stage AMZI is divided into the first 4-stage (TF1) and the last 4-stage (TF2). The scheme yields a 50% reduction in Silicon-Photonic TF chip size (or double the integration level) and more than 50% shorter response times than conventional multistage AMZIs. When number of wavelength channels (N) is less than 60, a silicon ring filter is a good candidate for TF2 [see Fig. 1(c)] for colorless detection due to its simple configuration with narrow-passband. For more details please refer to [6, 10, 13].

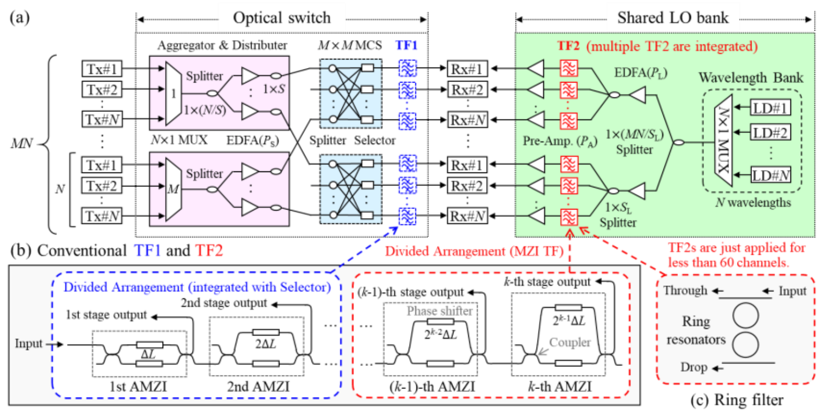

Fig. 1. (a) $MN\times MN$ optical circuit switch architecture based on tunable filters for coherent detection. Configuration of TFs based on (b) multistage AMZI and (c) ring resonator.

3. Widely and Fast Wavelength-tunable Silicon-photonic Filters

TFs are key enabler in creating scalable and fast optical switches and LO bank for coherent detection. We have so far developed a cascaded AMZI filter on a silicon chip [13]. The filter consists of eight AMZIs in conjunction with a 4 × 1 selector as illustrated in Fig. 2(a). They are monolithically integrated on a silicon-on-insulator wafer (top: 220 nm, buried oxide: 3 μm) by lithography and reactive ion etching. Figures 2(b) and 2(c) show photographs of the AMZI filter module and chip, respectively. The measured fiber-to-fiber insertion loss was 8.9 dB. As indicated in Fig. 2(d), the 3-dB bandwidths are 256 GHz, 66 GHz, 33 GHz, and 17 GHz after the 4-th, 6-th, 7-th, and 8-th AMZI, respectively. The phase shifters of each AMZI were thermo-optically activated to tune the passband wavelength. Figure 2(e) shows measured optical power transition, where turbo-pulse heater driving was employed to accelerate the tuning speed of the filter [14]. Thanks to turbo-pulse control, optical channels were switched within 5.8 μs for the four-stage AMZI filter. Regarding a silicon ring filter, 18-μs tuning speed for a signal with free spectral range (FSR) of 22 nm has been demonstrated [10]. However, further improvement is desired in terms of wavelength-tuning range and speed. In this paper, we newly fabricate a silicon ring filter with wider FSR and faster tuning speed. Figure 3(a) provides a schematic of the Silicon-photonic TF with ring resonators. The filter is designed with two identical arms, each of which uses double-ring resonator to expand FSR. A microscopic image of the fabricated filter chip is shown in Fig. 3(b). The footprint of the optical-filter chip is 1.4 × 0.5 mm^2. To cover the whole C-band (35 nm), the ring radius was designed to be approximately 20 μm less than that of the previous device (40 μm). Figure 3(c) depicts the measured transmittance spectra of the fabricated ring filter. The measured

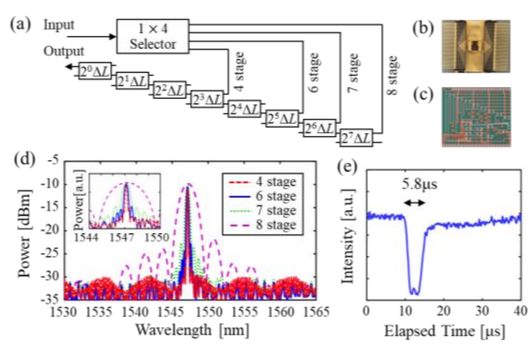

Fig. 2. Developed AMZI filter: (a) Structure. Photographs of the (b) module and (c) chip. (d) Measured spectrum of the filter. (e) Power transition with turbo pulse.

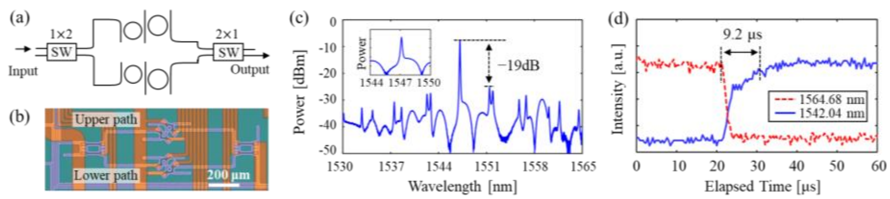

Fig. 3. Newly fabricated silicon ring filter: (a) Structure and (b) photograph of the fabricated filter chip. (c) Measured transmittance spectrum. (d) Power transition with turbo pulse.

3-dB bandwidth and FSR were 0.19 nm and more than 35 nm, respectively. Figure 3(d) plots measured power transitions with Turbo-pulse driving; the center wavelength of the passband was changed from 1,564.68 nm to 1,542.04 nm. A short switching time of 9.2 μs was recorded between the start of control and 90% of the optical output power level. A system validation of the developed silicon ring filter will be published elsewhere.

4. Proof-of-concept Experiment for 1,856 × 1,856 Optical Switching

We fabricated the multistage AMZI filters and confirmed the cooperative filtering scheme explained in Section 2. Figure 4 shows the experimental setup used to demonstrate 1,856 × 1,856 optical switching. The basic configuration is almost similar to that of Ref. [13]. The WDM transmitter emulated 116-channel × 32-Gbaud DP-QPSK signals spaced at 37.5 GHz. The test wavelength was set at 1547.116 nm. The transmitted signal passed through optical splitters, an EDFA, and a 16×16 MCS. The signal was then extracted by a multistage AMZI filter [see Figs. 2(b) and 2(c)] or WSS so as to limit the wavelength number incident on the coherent receiver. At the LO bank, 37.5-GHz-spaced 116-channel LO lights were supplied by the same procedure as the transmitter. The target LO channel among 116-channels was selected by a multistage AMZI filter or WSS for the coherent receiver. Finally, the received signal was coherently detected by mixing with the LO light in a coherent receiver. Figure 5 shows the measured bit error ratio (BER) versus EDFA saturation power (P_S) when the signal-side (TF1) AMZI stages were changed from 1 to 5, and accordingly LO side (TF2) AMZI stages were changed from 7 to 3. We achieved BERs under 1×10^{-3} at the EDFA saturation power (P_S) of ~20.5 and ~23.0 dBm for 3 stages and 4 stages, respectively. Smaller saturation power is needed when TF1 has fewer than 3 stages. This is because TF2 rejects the unwanted wavelengths and increasing the stage number increases the available power for the target LO channel. In terms of tuning speed, reducing the filter stages can shorten it since large cascade numbers yield large possible error in optimizing each AMZI response. According to the system requirements, we should determine the optimum filter combination by considering the tradeoff between system performance and switching speed.

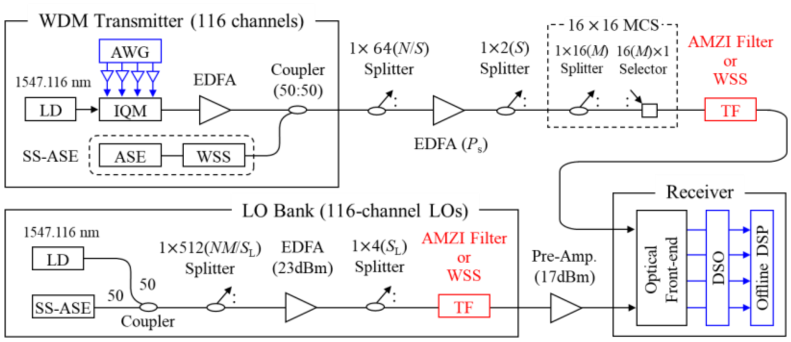

Fig. 4. Experimental setup for 1,856 × 1,856 optical switching.

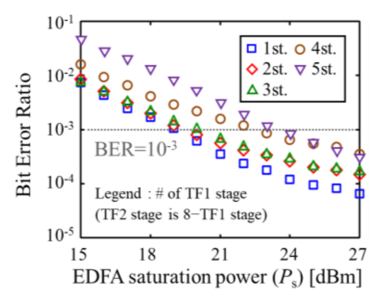

Fig. 5. Measured BER versus EDFA saturation power for different TF1 stage number, where 'st.' donates stage.

5. Conclusions

In realizing a scalable and fast optical switch, wavelength routing and coherent detection play a key role. A Silicon-Photonic TF is one of the important enablers. According to the switch port-count and channel speed needed, TF device selection and the configuration should be optimized to effectively create several thousand port-count optical switches. Different examples were analyzed and their performance was experimentally verified.

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