Cost-effective ROADM Using Wide-bandwidth Silicon Tunable Ring Filter for Drop Operation

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Abstract: We develop a ROADM using an 8-channel integrated polarization-insensitive, wide-bandwidth silicon tunable ring-filter for signal drop. A 75-GHz-spaced 60-channel 200-Gb/s DP-QPSK signal is transmitted over 640 km (8 span × 80 km) without any penalty. © 2024 The Authors

1. Introduction

Reconfigurable optical add/drop multiplexers (ROADMs) are widely deployed in communication networks, as their colorless signal drop capability is essential for network operation. The wavelength selectivity is provided by tuning local oscillator (LO) frequency in the coherent receiver, which acts as a narrow optical bandpass filter to select the desired wavelength channel. However, the maximum number of wavelength channels input to a coherent receiver is limited by the receiver's dynamic range, which is determined by the ratio of the per-channel signal power to the total input power [1]. To meet the OIF requirement (18-dB receiver dynamic range [2]), the maximum number of wavelength channels incident on a coherent receiver is limited to 63 (= $10^{18/10}$) channels for a 100-Gb/s DP-QPSK signal. The requirement becomes even more stringent for coherent transmission using higher symbol rates (≥64 Gbaud) and/or higher order modulation formats (e.g., DP-8QAM and DP-16QAM). In addition to this dynamic range limitation, colorless coherent receivers also suffer degraded performance due to self-beat interferences from out-of-band (OOB) channels [3]. As a result, even a coherent system needs an optical tunable filter to reject undesired wavelength signals when the channel count or dynamic range exceeds the design bounds. Until now, microelectromechanical system (MEMS) filters or $M \times N$ wavelength selective switches (WSS) [4] have been used to meet this need. The silicon photonics platform offers high-density integration, mass productivity, and superior reliability, leading to greater cost-effectiveness. A silicon ring filter is simpler and more compact [5] than a Silicon-photonic multistage Mach-Zender interferometer (MZI) filter [1]. The filter's bandwidth needs to be wide enough that it can accommodate, for example, a 60-GBaud signal on a 75/100-GHz frequency grid [6, 7]. So far, the development of silicon ring filters for this application has been constrained, since wide optical filtering bandwidths (above 50 GHz) require a small ring radius [8, 9], which results in high radiation and bending losses.

In this paper, we demonstrate a cost-effective ROADM by utilizing a newly-fabricated silicon ring filter that offers polarization insensitivity and gridless frequency tunability. Eight-array ring resonators are monolithically integrated on a chip in the double-ring (Vernier) racetrack structure, enabling small (≤6 μm) ring radii and broad (>35 nm) free spectrum range (FSR) while holding the ring filter insertion loss (IL) under 5 dB. The filter achieves broad passband bandwidth, larger than 65 GHz, and tuning times under a few tens of microseconds. Experiments verify the performance of the 8-integrated silicon ring filter, and no filter penalty was observed for 15-Tb/s (60 × 64-Gbaud DP-QPSK signals) C-band WDM transmission over a 640-km fiber spanning eight ROADMs.

2. ROADM Architecture Employing Gridless Tunable Optical Filters

Figure 1 depicts a broadcast-and-select (B&S) or route-and-select (R&S) ROADM node configuration which is divided into two main blocks; one is for express switching and the other for add/drop operations. The WDM signals incoming to the ROADM are delivered to the drop part by an optical splitter in the B&S (splitter-WSS) node or a WSS in the R&S (WSS-WSS) node. The add optical channels are combined at the output WSS with optical through-channels and launched into outgoing fibers. To drop channels from the node, a multicast switch (MCS) is used consisting of $1 \times M$ optical splitters and $M \times 1$ selectors. The selector selects one of the $1 \times M$ optical splitters that is dedicated to one of the incoming fibers, and the signals are fed to a receiver. An optical tunable filter is set before the receiver to select the target channel from the dropped WDM signals. Coherent receivers can, in general, eliminate optical filtering devices when the LO wavelength is tuned to the target channel. However, practical limits exist on the input power dynamic range [2] and the common mode rejection ratio (i.e., suppression of mixing products from the same wavelength channels) [3] of the coherent receiver. To keep the receiver input power and signal quality acceptable, unwanted OOB signals must be filtered out prior to coherent reception [1]. In the R&S configuration, the input-side WSS can limit the maximum number of channels to be dropped to within the input power limit of the receiver, we note that this restriction may degrade fiber utilization efficiency of the network. This situation becomes worse as the recent bandwidth expansion to the C+L band has increased the number of channels in a fiber. Thus, a gridless tunable optical filter is an important device to attain high performance for the large channel-count WDM systems offering

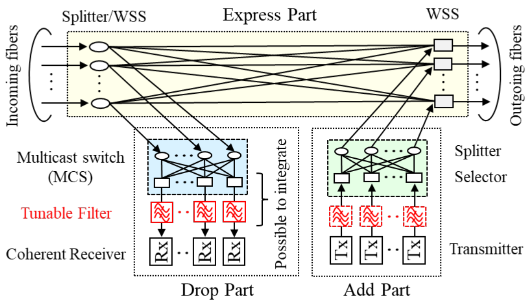

Fig. 1. ROADM architecture using optical tunable filters.

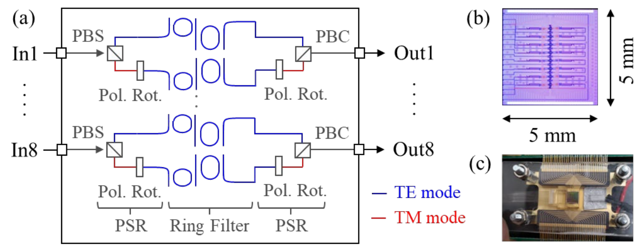

Fig. 2. (a) Schematic illustration of 8-port silicon ring filter with on-chip polarization diversity. Photographs of the filter (b) chip and (c) module. PBS: Polarization Beam Splitter, PBC: Polarization Beam Combiner.

ultra-dense and multiband WDM transmission. When the optical filters are integrated together with the $M \times 1$ selectors on a single silicon chip [1] the size and insertion loss can be minimized, which will be our next development.

3. Integrated 8-array Silicon Ring Filter with Polarization Diversity

We fabricated a polarization-insensitive optical filter that integrates eight sets of micro-ring resonators on a single silicon chip. As schematically illustrated in Fig. 2(a), each filter has a pair of polarization splitter-rotators (PSRs) and two identical second-order ring resonators on each arm for polarization diversity. The filter can handle arbitrary input polarization as the PSRs convert the incoming light of random polarization into two identical polarizations (TE mode), each of which is processed by an individual TE-mode circuit. Each resonator has a racetrack ring structure [9] that yields strong confinement to reduce the coupling and bending losses. The small ring radius of approximately 6 µm is designed as having a 3-dB filter passband larger than 65 GHz. Wide FSR (>35 nm) operation is achieved by the Vernier effect employing the double-ring resonators with different radii. The passband center wavelength can be continuously tuned from 1,530 nm to 1,565 nm in a gridless manner, as the resonant frequency is thermo-optically controlled using heaters around both ring resonators. Figures 2(b) and 2(c) show microscope images of the 8-port silicon ring filter chip and module, respectively. The footprint of the filter chip is 5×5 mm^2, which is less than 1/36 of the previously developed tunable filter composed of multistage MZIs [1]. Assuming the ITU-T 75-GHz grid for the C-band, we measured 3-dB bandwidth and side-mode suppression ratio (SMSR) for all sixty channels at drop port 1, as plotted in Fig.3(a). The average 3-dB bandwidth was larger than 65 GHz across the C-band (35 nm) with side-mode isolation of more than −11 dB. An example spectrum yielded by a silicon ring filter turned to 1,547.516 nm (ch.30) is shown in Fig. 3(b). The averaged fiber-to-fiber IL over the sixty channels was 24 dB, indicating a 4-dB/facet chip-to-fiber coupling loss and 16-dB on-chip loss including 5-dB IL of the ring filters and 11-dB excess loss of the PSRs. The unexpected excessive on-chip loss of 10 dB or more that stems from PSR fabrication error will be removed, as suggested by our previous work [10]. All eight ring filters exhibited polarization dependent loss (PDL) of less than 1.8 dB over the C-band. Figure 3(c) displays the measured temporal waveforms from output port 1 when the drop signal was switched from 1530 nm to 1565 nm. Measured switching time was short at less than 40 µs (transition time between 90% power levels), which well satisfies the ROADM switching time requirement (≤10 ms) [11].

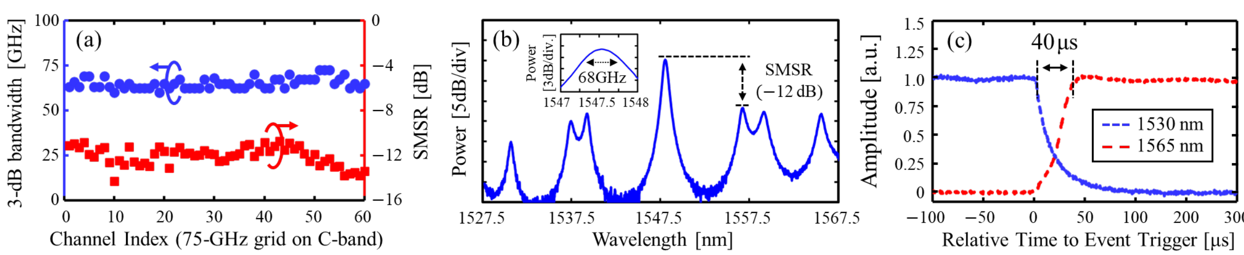

Fig. 3. Measured Drop-port responses from the filter port 1. (a) Channel dependency of 3-dB bandwidth and side-mode suppression ratio. (b) Transmission spectrum near the resonant wavelength set at 1547.5 nm (c) Switching transients of the filter from 1,530 nm to 1,565 nm.

4. Experiments

The fabricated silicon ring filter was tested using a recirculating loop system emulating cascaded B&S ROADM nodes. Figure 4 illustrates the setup of the loop experiment for 60-channel WDM transmission. At the transmitter, sixty laser diodes (LDs) were tuned to a 75-GHz frequency grid (1,530.334 nm – 1,565.700 nm) and divided into two groups, target and dummy channels. Both were independently modulated using two distinct IQ modulators (IQMs), each driven by four $2^{15}-1$ pseudo-random bit sequence outputs by an arbitrary waveform generator (AWG) operating at 128 GSa/s. The modulated signal was 64-Gbaud DP-QPSK shaped by a root-raised-cosine filter with roll-off factor of 0.1. The target and dummy channels were spectrally multiplexed by a WSS, resulting in a 15.36-Tbps (60-channel × 256-Gb/s DP-QPSK) WDM signal with 75-GHz channel spacing [Fig. 4(a)]. The transmission experiment was

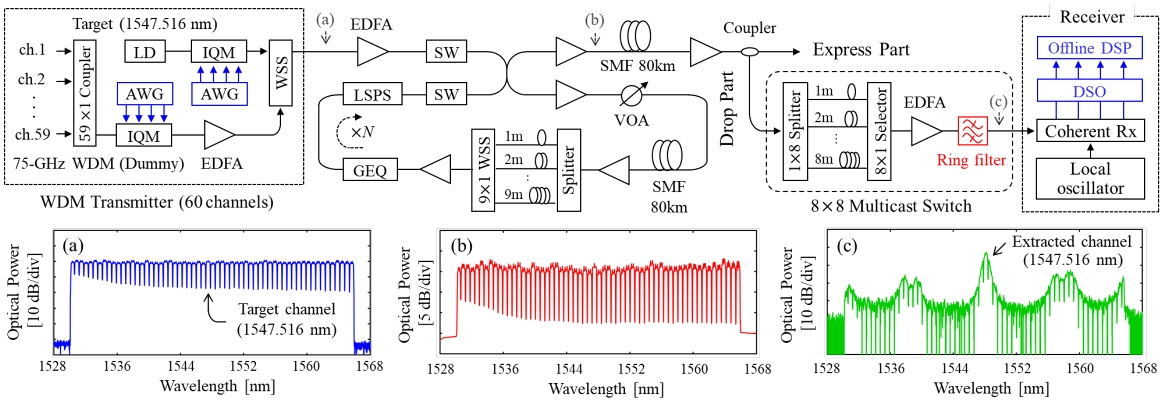

Fig. 4. Experimental setup for evaluation of fabricated 8-port silicon ring filter in ROADM node. Measured optical spectra after (a) WDM transmitter, (d) one round trip, and (c) silicon ring filter when turned to 1547.516 nm (ch.30).

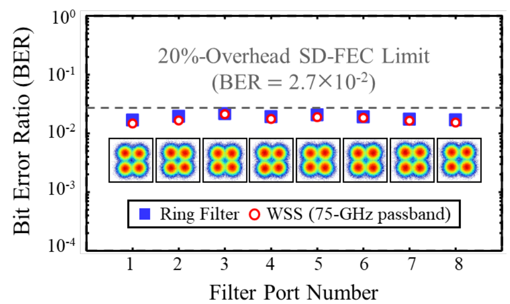

Fig. 5. Measured BERs for different ports and filters.

performed using a recirculating loop with 80-km circumference, consisted of an 80-km single mode fiber (SMF) having a span loss of 16 dB and flexible-grid WSS for 75-GHz grid filtering. After each span of fiber, optical signals were passed through a 1 × 9 optical splitter and 9 × 1 WSS to emulate joint impact of in-band crosstalk from express parts at a B&S ROADM. The configuration passed the target channel (75-GHz passband centered at 1,547.516 nm) through WSS input port 1 while the other WSS input ports rejected the target channel in the eight splitter outputs (75-GHz stopband centered at 1,547.516 nm) equipped with arbitrary length fiber delay lines. The span and loop losses were compensated by EDFAs including a gain equalizer (GEQ) to flatten the gain response. A loop synchronous polarization scrambler (LSPS) was placed at the end of the loop to evenly distribute polarization dependent effects. After the desired number of circulations [Fig. 4(b)], the WDM signal was transmitted over an 80-km SMF outside the loop and then routed to a drop part (i.e., 8 × 8 MCS) through an optical splitter. The 8 × 8 MCS incorporated a 1 × 8 optical splitter and 8 × 8 Silicon-photonic switch [12] acting as an 8 × 1 optical selector; the dropped signal was broadcast to the 8 splitter output ports and one of the 8 port signals was selected. The channel under test (ch30; 1,547.516 nm) was filtered at each port of the fabricated 8-port silicon ring filter [Fig. 4(c)], and then coherently detected by mixing with LO light in an optical front-end. The received signal was sampled at 256 GSa/s using a digital storage oscilloscope (DSO) and then processed by offline digital signal processing (DSP).

Figure 5 plots the measured bit error ratios (BER) for different filter ports after seven 80-km loops. For comparison, BERs when WSS (75-GHz passband and identical loss to that of each ring filter) was used instead of the silicon ring filter are also shown. All eight filters produced BERs better than 20%-overhead soft-decision forward error correction (SD-FEC) limit (BER = 2.7×10^{-2} [13]), with almost no penalty compared to the WSS filtering case. As evident from prior work [6, 14], the passband narrowing effect is negligible (<0.5-dB Q-penalty) for 64-Gbaud DP-QPSK transmission on 75-GHz frequency grid in ROADM nodes. We achieved 60-channel WDM transmission over 640-km of SMF and eight ROADMs, with hardly any filtering or crosstalk penalty attributed to the fabricated 8-port silicon ring filter. The optical power launched into each span was held constant at –9 dBm/channel, which is known to be non-optimum, but was enforced by the available EDFA output power in the experiment. Our numerical simulation showed that the expected reach is 2,000 km for DP-QPSK and 600 km for DP-16QAM at optimal launched powers.

5. Conclusions

We fabricated a compact 8-port silicon ring filter with wide (~65 GHz) passband, and experimentally validated its applicability by transmitting 60-ch. × 64-Gbaud DP-QPSK signals over 640 km with eight ROADM nodes. An improvement in both size and loss (e.g., at least 10 dB) will be gained with the monolithic integration of the Silicon-Photonic selector and filter, and removing the unexpected excess loss observed in PSR.

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