Monolithically Integrated Wavelength Converter for Intra-Data Center Routing Applications

Fulong Yan, Wang Miao, Teng Li, Yoshinobu Maeda, Zizheng Cao, and Nicola Calabretta

Abstract—A wideband wavelength converter based on cross gain modulation has been demonstrated by using a monolithically integrated semiconductor optical amplifier and 12-channel distributed feedback lasers. Error-free operation unicast wavelength conversion of 10-Gb/s non-return-to-zero ON-OFF keying data payload has been demonstrated with 3-dB power penalty and around 0.5 dB extra penalty for transmission over 2-km single-mode fiber for intra-data center application. Performance of the wavelength converter multicasting operation of two channels has also been assessed by controlling the distributed-feedback lasers. Experimental results show 4.5 dB power penalty after multicasting wavelength conversion. The wavelength conversion of uni-/multi-casting operations would provide a compact, low power, and low-cost solution for wavelength routing-based intra-data center networking applications.

Index Terms—Cross gain modulation (XGM), semiconductor optical amplifier (SOA), data center, wavelength conversion, multicasting.

I. INTRODUCTION

A COMPANY with the thriving of various data center (DC) applications such as, multi-media video, MapReduce, the aggregation bandwidth needed in intra-DC are increasing hugely. In order to support a DC with scaling out number of servers (>10,000) and scaling up data rate (> 10 Gb/s), optical switching technology based on wavelength routing is a proper technology and is under consideration for the deployment in DC nowadays due to the flexibility and scalability [1]. Moreover, wavelength converter can efficiently improve the wavelength utilization, simplify the network management and reduce network congestion probability. Therefore, the efficient wavelength conversion of uni-/multi-casting has attracted lots of interests from both industry and academy. A typical application of the tunable distributed-feedback (DFB) laser in DC context is shown in Fig. 1. The ToRs in an intra-cluster are connected by a arrayed waveguide grating router (AWGR). There is a tunable laser assigned to each ToR, the transmitter inside the ToR send a signal light to the wideband wavelength convertor.

Fig. 1. The application of the device in data center context.

All-optical wavelength conversion of uni-/multi-casting are considered as key procedures for wavelength division multiplexing (WDM) and all-optical switching networks [2], [3]. Several semiconductor optical amplifier (SOA) based wavelength conversion techniques have been demonstrated in the last two decades. Wavelength conversion utilizing four-wave mixing (FWM) in an SOA is independent of the modulation format but it has issues of low conversion efficiency and generation of multiple sidebands. Conversion based on cross phase modulation (XPM) in the SOA is normally adopted in the interferometric structure, which has limited input dynamic range sensitivity to the power level [4]. The solution utilizing cross-gain modulation (XGM) effect in SOA has the advantages of simple implementation and insensitive to polarization. The principle of XGM is briefly described as follow. A strong beam of pump light with signal and a bunch of weak continuous probe light are simultaneously injected into the SOA. The input pump modulates the gain experienced by the probe light by saturating the SOA, therefore converting the signal carried by the pump light onto the probe light. Although the principle of wavelength conversion based on XGM has been extensively investigated [5]–[7], however, discrete devices result high power consumption and large volume. Besides the wavelength conversion based on discrete devices or integrated-SOA device without multicasting implementation, uni-/multi-casting wavelength conversion with SOA-integrated device have also been demonstrated in [8]–[11].

In this letter, we focus on wavelength conversion based on XGM in a monolithically integrated DFB laser array. Experimental results show the potential of this concept including the implementation of multicasting, which is desirable in data center network. The novel contribution is we demonstrate that error-free inverted wavelength conversion at data rates of 10 Gb/s can be realized in the customized low-cost SOA-integrated DFB laser. An advantage of this wavelength
TABLE I  
WAVELENGTH VARIATION RANGE OF EACH CHANNEL FOR THE DFB LASER

<table>
<thead>
<tr>
<th>Laser diode</th>
<th>Central wavelength</th>
<th>Laser diode</th>
<th>Central wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD1</td>
<td>1527.94</td>
<td>LD7</td>
<td>1549.486</td>
</tr>
<tr>
<td>LD2</td>
<td>1531.553</td>
<td>LD8</td>
<td>1553.015</td>
</tr>
<tr>
<td>LD3</td>
<td>1535.149</td>
<td>LD9</td>
<td>1556.663</td>
</tr>
<tr>
<td>LD4</td>
<td>1538.776</td>
<td>LD10</td>
<td>1560.289</td>
</tr>
<tr>
<td>LD5</td>
<td>1542.404</td>
<td>LD11</td>
<td>1563.809</td>
</tr>
<tr>
<td>LD6</td>
<td>1546.061</td>
<td>LD12</td>
<td>1567.371</td>
</tr>
</tbody>
</table>

converter is that it allows unicast as well as multicasting wavelength conversion using a single integrated DFB array of lasers. Results show that 3 dB/4.5 dB power penalty is observed for uni-/multi-casting wavelength conversion of the 40 nm broadband wavelength converter, respectively. While an extra 0.5 dB/1.5 dB power penalty is brought for uni-/multi-casting wavelength conversion after passing 2 km fiber. Therefore, the compact, low power and low-cost wavelength converter would provide a promising solution for wavelength routing based intra-data center networking applications.

II. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

The monolithically integrated DFB laser array has 12 channels with wavelength ranging from 1527.1 nm to 1568.9 nm (about 3.5 nm spacing), as shown in Table I. Each DFB laser has a slightly different grating pitch to diverse output wavelengths. The minimum value of the side mode suppression ratio (SMSR) is 35 dB, and the maximum linewidth (−3dB fullwidth) is 10 MHz. The wavelength of each channel can be tuned by changing the refractive index of the reflecting region tuned by changing its temperature. The allowed working temperature of the DFB laser is 10 ∼ 50°C. In order to cover the full wavelength range of 40 nm, the temperature of the DFB array can be tuned between 30 and 40 °C. Therefore, it is capable of providing the 50 GHz frequency space, 88-channel adjustable range that is accord with the ITU grid. And it is potentially capable of supporting wideband wavelength conversion with the total 40 nm bandwidth. The schematic of the chip is reported in Figure 2 and consists of an SOA, two thermo-electric coolers (TECs), two thermostats, and a wavelength monitor inside the DFB laser source. The maximum forward current of SOA is 350 mA, while the maximum gain around 20 dB is observed at wavelength of 1540 nm. The allowed working temperature of the SOA is 10 ∼ 50 °C. In the internal structure, the 12 DFB lasers are coupled by a multimode interference (MMI) coupler with splitting ratio of 1 × 12. The 1 × 12 splitter is achieved by cascaded 1 × 2 MMI. The SOA integrated on chip is used for light amplification and to perform the wavelength conversion based on XGM.

The DFB laser activates one channel or multi-channel for wavelength conversion of uni-/multi-casting based on the destinations of the signal. The converted channels after wavelength conversion are forwarded to the AWGR to the TORs destination.

In order to verify the feasibility of the deployment of the device in a DC context, the experimental assessment of the wavelength converter with uni-/multi-casting operation at 10 Gb/s are carried out. Figure 2 shows the experimental setup. Lighting up the laser diode (LD) 7 of the wideband wavelength converter as an example to show the process of the unicast wavelength conversion. The data signal was generated by a laser source that emits a continuous-wave (CW) light at 1545.8 nm (acting as the λ_{pump}) modulated by a 10Gb/s external modulator at with a non-return-to-zero-on-off keying (NRZ-OOK) 10Gb/s PRBS 2^{11} − 1 data stream. The modulated signal passed through port 1 of the circulator and is fed into the integrated SOA inside the wavelength converter. The XGM effect consists on the variation of the SOA gain in function of the input power. The increase of the power of the input signal causes a depletion of the carrier density in the SOA, and therefore the amplification gain is reduced. But the gain of SOA recovers rapidly to the original value when the pumping light intensity decrease. Therefore, the available gain is inversely changed with respect to the pumping signal polarity [12]. When another light with wavelength of λ_{probe1} generated by LD 7 is coupled into the SOA, the information carried on wavelength λ_{pump} are converted to wavelength λ_{probe1}, and the wavelength conversion featured with inverted polarity is realized. As MMI significantly attenuates the pumping light and the wavelength has been set apart, the pumping light has limited effect on the DFB LD operation. To filter out the residual pumping light, the converted wavelengths pass through an optical bandpass filter (OBPF) based on a 200 GHz arrayed waveguide grating (AWG) with 3 dB bandwidth of 1 nm. The converted signal power is divided in two parts. One part is fed into the optical spectrum analyzer (OSA) to visualize the optical spectrum, while the other part is fed into the the bit error rate (BER) tester.

III. EXPERIMENTAL RESULTS AND DISCUSSION

All of the 12 channels are experimented as probe signal to verify the wideband wavelength conversions while channel 7 and 9 are chosen to verify the multicasting wavelength conversion. First, during the unicast wavelength conversion experiment, the current of the SOA and each LD of the wideband wavelength converter is set as 80 mA and 50 mA, respectively. And the power of the pump light at the input of the SOA is 2 dBm. The spectra of the converted signals of four selected channels (LD1, LD4, LD8 and LD12) are measured at the output of the OBPF, as shown in Fig. 3 (a) to (d). From Fig. 3(a), it is observed that the power of channel 1 signal is 20 dB higher than the residue pumping light after wavelength conversion. And there is nearly no residue pump light when the signal pass through the AWG. Therefore, high performance of the wavelength conversion is obtained with low noise and high suppression. Similar results can be found in Fig. 3(b) − (d) for channel 4, 8 and 12.
Fig. 2. (a) Experimental set up, (b) schematic of the chip.

Fig. 3. Spectra of channel 1 (a), channel 4 (b), channel 8 (c), channel 12 (d) after wavelength conversion before and after the filter OBPF.

Fig. 4. BER for unicast wavelength conversion and back to back.

Fig. 4 shows the BER curves of the wavelength converted signals for LD 1, LD4, LD 8, LD12 and of the back-to-back signal as reference. The power penalty of wavelength conversion for LD 8 is around 3 dB as a result of the extinction ratio degradation. The performance differences between the up and down conversion and also spacing from the pump are due to a decreased XGM efficiency for up-conversion [13]. Besides, a large DC with distance variation of 2 km due to DC expansion is considered. The input power of the converted signal into the 2km single-mode fiber is 1 dBm, and a 10Gb/s photoreceiver is used for detection. Figure 4 also reports the BER of the wavelength converted signals after 2 km fiber transmission. An extra power penalty of around 0.5 dB was measured for those 4 channels.

Fig. 5 (a) shows eye diagram of back-to-back signal while (b) shows eye diagram of the the unicast wavelength converted signal of LD 7. As a comparison, Fig. 5 (c) shows the output converted signal of LD 7 from the wavelength converter after passing 2 km fiber. Fig. 5 (d) and (e) are the same results of LD 9. The performance of the converted signal of LD 7 and LD 9 only has tiny difference. The unicasting converted signal has almost the same quality before and after passing 2 km fiber. The scale of vertical axis are all 5 mw/div.

Multicast operation is further investigated for the LD 7 and LD 9. The current of the SOA is kept at 80 mA, while the current of the laser diodes of the two channels is set as 42 mA. The data signal was still at 1545.8 nm.

Figure 6 (a) and (b) show the spectra of the wavelength converted signals of LD 7 and LD 9 for multicast wavelength conversion operation, respectively. From Fig. 6 (a), it is also observed that after multicast wavelength conversion the power of channel 7 signal is 20 dB higher than the power of the pumping light. Similar results are obtained in Fig. 6 (b) for channel 9.
The BER curves of the multicast signals of LD 7 and 9 are shown in Figure 7. It is clearly shown in Fig. 7 that the power penalty of multicast compared with unicast wavelength conversion is about 1.5 dB. The extra power penalty for multicasting wavelength conversion results mainly from the residual crosstalk due to the limited performance of the OBPF. Besides, there will be an extra 1.5 dB after passing 2 km fiber for a large DC when it expands with distance variation of 2 km, and the input power of the converted signal into the 2 km fiber is 3.7 dBm.

Fig. 8 (a) and (b) show eye diagram of the multicasting wavelength conversion signals of channel 7 before passing 2 km fiber (a), of channel 9 after passing 2 km fiber (b) and of channel 9 before passing 2 km fiber (c), of channel 9 after passing 2 km fiber (d).

Fig. 8. Eye diagrams of the multicasting wavelength conversion signals of channel 7 before passing 2 km fiber (a), of channel 7 after passing 2 km fiber (b) and of channel 9 before passing 2 km fiber (c), of channel 9 after passing 2 km fiber (d).

The BER curves of the multicast signals of LD 7 and 9 are shown in Figure 7. It is clearly shown in Fig. 7 that the power penalty of multicast compared with unicast wavelength conversion is about 1.5 dB. The extra power penalty for multicasting wavelength conversion results mainly from the residual crosstalk due to the limited performance of the OBPF. Besides, there will be an extra 1.5 dB after passing 2 km fiber for a large DC when it expands with distance variation of 2 km, and the input power of the converted signal into the 2 km fiber is 3.7 dBm.

Fig. 8 (a) and (b) show eye diagram of the multicasting wavelength conversion signal of LD 7 from the wavelength converter before and after passing 2 km fiber, respectively. While the eye diagram of the multicasting wavelength conversion signal of LD 9 from the wavelength converter before and after passing 2 km fiber are shown in Fig. 8(c) and (d), respectively. It is observed that the signal of multicasting wavelength conversion gets a certain degree of deterioration when compared with the unicasting wavelength conversion signal.

IV. CONCLUSIONS

We have demonstrated all-optical wavelength conversion and multicasting operation at 10 Gb/s with an integrated-SOA DFB laser array with 12 channels. The experimental results show that 10-Gb/s NRZ-OOK format conversion can be achieved using the low-cost integrated DFB laser array with 3 dB and 4.5 dB power penalty for unicasting wavelength conversion and multicast wavelength conversion, respectively. When the signal passes a 2 km fiber, an extra 0.5 dB/1.5 dB power penalty is observed for the two cases, respectively. Therefore, the high performance XGM wavelength conversion of uni-/multi-casting provided by the integrated low-cost device is promising for wavelength routing in data-centers context.

REFERENCES