学术期刊可以用微信做什么，快来看看！

微信自动应答服务平台

微服务
移动互联网时代的营销革命

简单快捷 • 高效互动 • 随时随地 • 广泛传播

微信扫一扫
开启智慧“微服务”
QPSK wavelength multicasting based on four-wave mixing in semiconductor optical amplifier

Jun Qin (秦军)1, Hongxiang Wang (王宏祥)1, Danshi Wang (王丹石)1, Min Zhang (张民)1, Yuefeng Ji (纪越峰)1, and Guo-Wei Lu (吕国伟)2

1State Key Laboratory of Information Photonics and Optical Communication, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China
2Institute of Innovative Science and Technology, Tokai University, Kanagawa 259-1193, Japan

Received June 4, 2014; accepted July 16, 2014; posted online October 24, 2014

We experimentally demonstrate one-to-five quadrature phase-shift keying (QPSK) wavelength multicasting based on four-wave mixing in bulk semiconductor optical amplifier. The input 25 Gb/s nonreturn-to-zero QPSK signal is successfully multicast to five new wavelengths with all information preserved. All the multicast channels are with a power penalty less than 1.1 dB at a bit error rate (BER) of 10−3. A characterization of the conversion efficiency in terms of pump and signal powers using the BER as figure of merit is also presented, the results indicate that the pump and signal powers should be optimized to eliminate the introduced deleterious nonlinear components.

OCIS codes: 060.0060, 070.4340, 190.4380.

doi: 10.3788/COL201412.110601.

In recent years, all optical wavelength division multiplexing (WDM) multicasting which can efficiently deliver a stream of information carried by one input wavelength to a number of output wavelengths has been regarded as an essential and important functionality in the next generation all optical transparent networks, especially with the emerging of the services such as high-definition TV and migration operations in data centers. Data delivering of streaming media or such as high-definition TV and migration operations network, especially with the emerging of the services such as high-definition TV and migration operations in data centers. Data delivering of streaming media or high-definition TV and data center migration operations are all characterized by delivering the information carried by a channel at certain input wavelength to a number of different output wavelengths which are just the functionalities of WDM multicasting. By employing the WDM multicasting technology, the network efficiency and throughput will be improved effectively[11], and with an all-optical way, the cost and energy consumption can be reduced significantly compared with the traditional electronic way.

During the past decade, multiple wavelength multicasting schemes have been extensively studied and demonstrated in various nonlinear devices including highly nonlinear fiber[2–6], silicon nanowire[7], and silicon waveguide[8]. But most of these schemes suffer from drawbacks such as high input powers, poor conversion efficiency (CE), and complicated system architecture. And, these works mainly involved with intensity modulated nonreturn-to-zero on-off-keying (NRZ-OOK) signal, return-to-zero (RZ) OOK signal, and differential phase-shift-keying (DPSK) signal. Adams et al.[5] discussed the multicasting of 16-ary quadrature amplitude modulation (16QAM) in silicon nanowire. However, a poor system performance was obtained (with a worst case power penalty of about 7.8 dB at the forward error correction (FEC) limit). The principle is not clear about the polarization state of the two pumps (parallel or orthogonal) and the other detailed parameters of the experiment (such as the CE and the optical signal-to-noise ratio (OSNR) of the output channels) are not given.

Quadrature phase-shift keying (QPSK) is an attractive data modulation format, by multilevel data encoding, its symbol rate is half the bit rate on the transmission line facilitating the improvement of the spectral efficiency. QPSK has been scheduled for use in the commercial 100 Gb/s Ethernet system, so the multicasting of QPSK signal will have more practical significance. As an obbligato device in optical signal processing, semiconductor optical amplifier (SOA) offers advantages in terms of integration potential, low power consumption, and high CE[9]. Four-wave mixing (FWM) in SOA has been proposed for wavelength multicasting as an efficient way[11], Contestabile et al.[11] demonstrated a scheme for multicasting an input signal to six output wavelengths employing three pumps with different states of polarization. However, the scheme suffers complexity in controlling the polarization state, low signal bit rate, and simply contraposing NRZ signal, and the results cannot be extended to phase modulated signals in a straightforward way[12]. On the other hand, the FWM based on dual-pump in SOA shows advantages in complexity, enhanced conversion...
Fig. 1. Operation principle of wavelength multicasting scheme based on FWM in SOA.
For the generated idlers at $\lambda_{i1}$ and $\lambda_{i2}$, there will be no information because of the absent participation of the original input QPSK signal in the FWM processes.

The frequency detuning between the pump and signal needs to be specified to avoid overlapping of the new generated idlers and reduce the cross talk between channels. The relationship of the frequency interval of the new generated idlers with the two pumps’ frequency spacing is shown in Fig. 1. With two pumps, five new multicast channels will be achieved, to obtain more multicast channels, more pumps are preferred to generate more FWM components.

The experimental setup for the 25 Gb/s QPSK WDM wavelength multicasting in SOA is shown in Fig. 2. The light sources of the input QPSK signal, the pumps, and the local oscillator (LO) at the coherent receiver are all with narrow linewidth of 100 kHz in order to reduce the added phase noise. On the signal branch, the light from an external cavity laser (ECL) at 1552.52 nm (193.1 THz) is modulated by a single inphase/quadrature (IQ) modulator with 23 GHz 3 dB bandwidth and 5 V half-wave voltage. The IQ-modulator is driven by two de-correlated two level driving electronics provided by pseudo-random binary sequence (PRBS) streams which are generated by an arbitrary waveform generator (AWG). The length of the PRBS stream is $2^{15} - 1$. An erbium-doped fiber amplifier (EDFA) is used to amplify the signal and a 1 nm optical band-pass filter (OBPF) is employed to filter out the out-of-band noise. The polarization controller (PC) is placed along the path between the EDFA and OBPF to adjust the polarization of the signal light to optimize the FWM efficiency. On the pump branch, two pumps at 1549.32 nm (193.5 THz) and 1550.12 nm (193.4 THz) are generated by two tunable ECLs. Then combined with a WDM multiplexer (MUX) together with the generated NRZ-QPSK signal is injected into the SOA through a 3 dB coupler. The two pumps are set copolarized with each other by properly adjusting the PCs to reduce the system polarization sensitivity. The SOA (CIP SOA-NL-OEC-1550) being used here is a commercially available device operating over the C-band which has a small signal gain of 34 dB, 6 dBm saturation output power, and typical 0.5 dB polarization-dependent gain value. The carrier recovery time of the SOA is typically 25 ps which does not cause any degradation to the multicast signals. The measured power for each pump before the MUX is 6 dBm. The power of the signal light before the coupler is $-4$ dBm. The total power in and out of the SOA are 5.75 and 13.93 dBm, respectively. The bias current of the SOA is set as 280 mA. At the output of the SOA, the new generated FWM terms are filtered by a 1–9 Finisar wavelength selective switch (WSS) (Finisar DWPF, Flexgrid) based on liquid crystals on silicon with variable bandwidth and then sent to a coherent receiver which includes a LO, an optical 90° hybrid, and two balanced photodetectors (BPDs) for detection and BER measurement. A variable optical attenuator (VOA) and EDFA will be used as pre-amplifier before the hybrid. After the BPDs, the data are sampled by a real-time storage oscilloscope operating at 80 GSa/s with 30 GHz electrical bandwidth (Tektronix MSO 73304DX). The captured data will be off-line processed through the digital signal processing method.

Figure 3 shows the spectra measured at the input and output of the SOA, the input NRZ-QPSK signal light and two pump lights are indicated by $\lambda_{i1}$ and $\lambda_{i2}$, and $\lambda_{s1}$ and $\lambda_{s2}$, respectively. At the output of the SOA, as analyzed above, five new generated idlers will preserve the information of the original QPSK signal, denoted by $\lambda_{i1} - \lambda_{i2}$, in Fig. 3. The idlers at $\lambda_{s1}$ and $\lambda_{s2}$ carry no information. At $\lambda_{s1}$ and $\lambda_{s2}$, two BPSK signals will be obtained. With our current experimental setup, by changing the frequency spacing between the signals and pumps, the output multicasting channels can be consistent with the ITU channels. Frequency detuning is another important factor that can influence the FWM CE. With a reasonable frequency detuning, a good CE can be achieved, whereas with too large frequency detuning, the CE will decrease obviously. In our experiment, the frequency detuning of $f_1$ to $f_2$ and $f_2$ to $f_3$ are 100, and 300 GHz, respectively. With the current frequency detuning, acceptable CE was achieved.

Figure 4 shows the BER performance of the multicast QPSK channels (including the output signal at $\lambda_{i1}$ for reference) as a function of the received power, the
back-to-back performance is also measured as a reference. From Fig. 4 we can see that the whole five multicast channels are all with low power penalties (from about 0.4 dB to less than 1.1 dB) at the BER of $10^{-3}$, their detailed performances including the wavelength, CE (defined as the ratio of the converted signal power to that of the input signal power), and power penalty at a BER of $10^{-3}$ are summarized in Table 1.

From Table 1 it can be seen that the power penalty is sensitive to the CE which directly influences the OSNR of the converted signal. When the CE of the generated idlers at $\lambda_{A2}$ and $\lambda_{A4}$ is larger than $-23$ dB, the power penalty is less than 0.6 dB. On the other hand, the power penalty of the idlers at $\lambda_{A1}$, $\lambda_{A3}$, and $\lambda_{A5}$ is larger than 0.7 dB because the CE is smaller than $-23$ dB. To further present the relationship between CE and input pump and signal powers in SOA, we give a characterization of CE using the BER as a figure of merit in the following.

Before the multicast signals were detected by the coherent receiver, we measured the spectra of the each wavelength at the output of the WSS, as shown in Fig. 5. The insets are the constellation and corresponding I and Q eye diagrams of the multicast QPSK signals after coherent detection and demodulation. The concentrated constellation and clear open eye proves the good quality of the multicast QPSK signal.

Figure 6(a) depicts the measured CE and BER as a function of the input signal power for the multicast channels at 1551.72 and 1546.12 nm when fixing the pump power at 6 dBm. It is obvious that the CE almost does not benefit from the increasing signal power, but when signal power is increasing it does help to drop the BER. However, when further increasing the signal power larger than $-4$ dBm, the increasing BER is obvious which is probably caused by the self-phase modulation introduced distortions. On the other hand, as Fig. 6(b) shows, when increasing the pump power it does make contribution to the CE. With a good CE, a sufficient OSNR will be obtained therefore resulting in a good BER performance. However, when the pump power is larger than 6 dBm, the added noise from cross-phase modulation (XPM) effects will distort the performance resulting in increasing BER. As discussed in Refs. [24, 25], the limited OSNR of the pump light will intensify the XPM effect resulting in a more severe performance degradation. Additionally, in-band cross talk due to high-order FWM, products can be particularly critical when the pump power is larger than 8 dBm. Figure 6 shows that not always with a high CE there will be a good BER performance but rather a compromise between the CE and the nonlinear noise. So, to eliminate the deteriorous components in the converted signal, the powers of the pumps and signals should be optimized. In our experiment, the optimal powers of the pump and signal are 6 and $-4$ dBm, respectively. The average CE of the five new generated QPSK channels is $-24.12$ dB when the BER is the best. In our experiment, the two pumps are set to be co-polarized with each other and parallel to the signal to maximize the FWM efficiency. Not all of the generated idlers from $\lambda_{A1}$ to $\lambda_{A5}$ will be polarization independent with the input signal, only $\lambda_{A4}$ and $\lambda_{A5}$ will be polarization insensitive. And when adjusting the polarization of the signal parallel to the pumps, a best FWM efficiency will be obtained for all the five channels. Orthogonal pumps scheme[22] and polarization diversity scheme with two independent circuits[26] can also be considered to reduce the polarization sensitivity.

In conclusion, we discuss a NRZ-QPSK wavelength multicasting based on FWM process in SOA. We experimentally demonstrate the one-to-five 25 Gb/s NRZ-QPSK signal WDM multicasting employing two pumps.

### Table 1. Multicast Channel Performance

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Estimated OSNR (dB)</th>
<th>CE (dB)</th>
<th>Power Penalty (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{A1}$</td>
<td>1546.12</td>
<td>16.1</td>
<td>$-28$</td>
</tr>
<tr>
<td>$\lambda_{A2}$</td>
<td>1546.92</td>
<td>21</td>
<td>$-22.4$</td>
</tr>
<tr>
<td>$\lambda_{A3}$</td>
<td>1547.72</td>
<td>18.7</td>
<td>$-23.4$</td>
</tr>
<tr>
<td>$\lambda_{A4}$</td>
<td>1551.72</td>
<td>19.5</td>
<td>$-22.8$</td>
</tr>
<tr>
<td>$\lambda_{A5}$</td>
<td>1553.33</td>
<td>16.8</td>
<td>$-24$</td>
</tr>
</tbody>
</table>
multicast channels are all compliant with the ITU grid. All the new generated QPSK channels are with a power penalty less than 1.1 dB at a BER of $10^{-3}$ and their respective constellation and eye diagram are presented. We also give a characterization of the CE in terms of input signal and pump powers using the BER as a figure of merit, the results indicate that the pump and signal powers need to be carefully controlled to avoid the performance distortion introduced by nonlinear effects. The SOA can be useful for WDM multicasting in the optical network for its integration potential, low power consumption, and high CE.

Fig. 5. Optical spectra of the multicast QPSK channels after the WSS at different wavelengths: (a) $\lambda_{\text{A1}}$, 1546.12 nm, (b) $\lambda_{\text{A2}}$, 1546.92 nm, (c) $\lambda_{\text{A3}}$, 1547.72 nm, (d) $\lambda_{\text{A4}}$, 1551.72 nm, (e) $\lambda_{\text{A5}}$, 1552.52 nm, and (f) $\lambda_{\text{A6}}$, 1553.33 nm. Insets: constellation and I/Q eye diagrams of the multicast signal on each wavelength.

Fig. 6. Measured CE and BER when (a) tuning input signal power with fixed pump power and (b) tuning input pump power with fixed signal power.

This work was supported by the National 863 Program of China under Grant Nos. 2012AA011302 and 2011AA010306.

References