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Multichannel wavelength conversion of 50-Gbit/s NRZ-DQPSK signals using a quantum-dot semiconductor optical amplifier

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Abstract: We demonstrate simultaneous four-channel wavelength conversion of 50-Gbit/s non-return-to-zero differential quadrature-shift-keying signals with a channel spacing of 100-GHz using a quantum-dot semiconductor optical amplifier. Error-free operations with low-power penalties are successfully achieved with various channel configurations.

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1. Introduction

Multichannel wavelength converters (MWCs), which allow multichannel wavelengths carrying different data to be simultaneously converted from one to another, are expected to play an important role in enhancing the capacity and flexibility of future wavelength-routed optical networks that are based on a wavelength-division-multiplexing (WDM) transmission system. Moreover, one MWC would replace many single-channel wavelength converters, resulting in a smaller footprint and lower power consumption. MWCs exploit four-wave mixing (FWM) and second-harmonic generation in various kinds of nonlinear elements such as highly nonlinear optical fibers [1−4], semiconductor optical amplifiers (SOAs) [5−7], silicon waveguides [8], and periodically poled lithium niobate (PPLN) waveguides [9, 10]. In addition, a few practical applications of MWCs and their experimental use for optical packet switching have also been reported [11−13].

The use of SOAs allows the integration of the MWCs with other components, such as lasers and switches. Moreover, the switching energy required for the MWCs is much smaller than that required for the other kinds of nonlinear elements. However, the crosstalk induced among the input WDM channels by cross-gain modulation (XGM) in MWCs results in large quality degradation of the converted signals [5].

High spectral efficiency phase-modulated signals have attracted interest for use in long-haul, high-capacity WDM transmission systems [14]. The constant amplitude envelope of these signals would make it possible to use SOA-based MWCs without the degrading effects of XGM. In particular, non-return-to-zero differential quadrature phase-shift keying (NRZ-DQPSK) signal is one of the attractive modulation formats because, in this format, the symbol rate on the transmission line is half the bit-rate, facilitating the improvement of the spectral efficiency of WDM signals in the line.

Recently, optical signal processing using quantum-dot SOAs (QD-SOAs) has gained considerable interest, because of the unique properties of QD-SOAs, such as a higher and broader gain profile compared with that of common bulk/quantum-well SOAs [15]. Indeed, ultrahigh-speed wavelength conversion [16] and all-optical multicasting using XGM, which involves the replication of data over multiple wavelengths [17, 18] have already been reported. Moreover, single-channel wavelength conversions using FWM in QD-SOAs have also been demonstrated [19−21]. However, no demonstration of multichannel wavelength conversion using QD-SOAs has yet been reported.

In this work, we demonstrate the multichannel wavelength conversion of 50-Gbit/s NRZ-DQPSK signals with 100-GHz channel spacing using FWM in a QD-SOA [22]. In this
scheme, the induced channel crosstalk in the MWC was well-suppressed because of the constant envelope of the employed signal and the inhomogeneous broadening property of the QD-SOA gain. Consequently, we successfully achieved error-free, low power-penalty operation for various channel numbers and positions.

2. Experimental setup

The experimental setup for the MWC is shown in Fig. 1. Four-channel WDM signals were generated using four laser-diodes (LDs), each having a different wavelength. The channel spacing was 100-GHz, and the wavelengths of the signals were 1554.13 nm, 1554.94 nm, 1555.75 nm, and 1556.55 nm. In this experiment, the employed channel number and position were changed according to various channel configurations. The four-channel signals were combined using an optical coupler (OC) and modulated at a baud rate of 25-Gbaud (50-Gbit/s) using a DQPSK modulator; the modulator was driven by a pulse pattern generator (PPG) having a pseudorandom bit sequence (PRBS) with the bit pattern length of $2^{29} - 1$. It should be noted that the PRBS length was limited by the employed PPG and that the conversion performances of the converter used in this study did not have any dependences on the PRBS length. Polarization controllers (PC), at the output of each LD, and a polarizer (POL), at the input of the modulator, were employed to optimize the states of the polarizations (SOPs) of the signals injected into the modulator. The modulated data signals were amplified using an erbium-doped fiber amplifier (EDFA) and then filtered using a fiber Bragg grating (FBG) with a rectangular filter shape. The center wavelength and 3-dB bandwidth of the FBG were 1555.2 nm and 4.4 nm, respectively. To compare the conversion performance dependence on the bit pattern among the WDM signals in the MWC, the bit pattern was decorrelated using the dispersion in a 3-km standard single-mode fiber (SMF) with a dispersion of 17 ps/nm/km. In the following experiments, the SMF was inserted at the output of the WDM signal, as shown in Fig. 1. A pump signal source was generated using an external-cavity laser-diode with a wavelength of 1551.66 nm. The data and pump signals were combined using an OC and injected into the employed QD-SOA. The power of the injected WDM data signals and the injected pump signal was 1 dBm and 10 dBm, respectively. By using the PCs at the input of the OC, the SOPs were adjusted to obtain the highest QD-SOA gain of the data and pump signals. The MWC comprised the QD-SOA, an isolator (ISO), and an arrayed-waveguide grating (AWG), which was used for demultiplexing the WDM converted signals. The QD-SOA contained Stranski-Krastanow QDs and had a 5-mm-long active layer. The gain of the device was dominated by transverse electric (TE) mode. A gain bandwidth over 20 dB was measured for a bias current of 2.0 A and a gain bandwidth of 150 nm. The gain-saturated output power was approximately 10 dBm. In the experiments described below, the bias current and temperature were set as 2.0 A and 21°C, respectively. The converted signal was amplified using an EDFA, demodulated using a Mach-Zehnder interferometer (MZI), and converted into an electrical signal using a balanced photo-diode (BPD). The bit-error-rate (BER) of the signal was measured using an error analyzer (EA) synchronized with the PPG.
3. Experiments

3.1. FWM characteristics of QD-SOA

In order to evaluate the conversion performance on the basis of the FWM, we measured the relative FWM efficiency, which is defined as the power ratio of input signal to converted signal at the output the QD-SOA. Figure 2(a) shows the relative FWM efficiency for various detuning ranges from the pump wavelength. In this experiment, instead of the NRZ-DQPSK signals, we employed a single continuous-wave probe as the input signals. The pump wavelength was 1551.65 nm same as the setup, as shown in Fig. 1. The power of the pump and probe signals injected into the QD-SOA was set to 10 dBm and 1 dBm, respectively. In the case of negative wavelength detuning (long to short wavelength conversion), relative FWM efficiencies of higher than −30 dB were achieved within an 18-nm range. On the other hand, positive detuning (short to long wavelength conversion) exhibited lower efficiencies. These results were quite similar to those obtained in our previous work [20]. The reasons for the asymmetrical characteristics are also explained in that work. To evaluate the FWM efficiency dependence on the channel number, we measured the relative FWM efficiency for various bias currents and channel numbers, as shown in Fig. 2(b). The measured wavelength was set as 1555.75 nm. As shown in Fig. 2(b), there was no large variation of the FWM efficiency in all the cases, and high FWM efficiency could be preserved for the simultaneous four-channel operation at a current of 2.0 A. This result indicates that the converter enables us to realize simultaneous four-channel wavelength conversion.

![Fig. 2. (a) Relative FWM efficiency of the QD-SOA. (b) Bias current versus FWM efficiency with various channel numbers.](image)

![Fig. 3. Signal spectrum at the output of the QD-SOA in the case of four-channel wavelength conversion using 50-Gbit/s NRZ-DQPSK signals.](image)
Figure 3 shows the signal spectrum at the output of the QD-SOA in the case of four-channel wavelength conversion using 50 Gbit/s NRZ-DQPSK signals. The input channels are labeled as A, B, C, and D, whereas the corresponding wavelength-converted channels are labeled as A*, B*, C*, and D*, respectively. As shown in Fig. 3, undesired FWM components were observed around channel A* and the pump wavelength. They were mostly removed by the WDM demultiplexing process at the output of the MWC. In addition, it was observed that each converted channel had a high optical signal-to-noise ratio (OSNR) owing to the high FWM efficiencies of the employed QD-SOA. The measured average relative FWM efficiency was about −15.5 dB, which allowed us to obtain a high conversion performance.

3.2. Evaluation of channel-switching ratio

Figure 4 shows examples of the signal spectra at the output of the QD-SOA for various channel numbers and positions. As the channel number was increased, the extra signal components induced by the FWM process around the pump signal were increased. On the other hand, high OSNR was preserved at each converted channel in all channel configurations, as shown in Fig. 2(b).

In real wavelength-routed networks, arbitrary optical links are established, according to the data traffic. Then, the channel numbers and positions of the converted signals are switched on/off, and this switching has to be flexible. In such systems, the channel crosstalk, which coincides spectrally with the converted signal wavelength, will degrade the signal quality of the adjacent channel, and induce undesired signal components at the vacant channel positions. In particular, the residual signal components at the vacant channels result in critical degradation of the network performance. In order to quantify the degree of the crosstalk at the each vacant channel, we measured the channel-switching ratio, which is defined as the channel on/off ratio at each channel position, as shown in Fig. 5(a). Figure 5(b) shows the channel-switching ratio in the cases of three- and four-channel operations. As the channel number was decreased, the channel-switching ratio increased, because the FWM conversion efficiencies were little improved and the crosstalk among the channels was suppressed by reducing the input channel. In particular, this effect was clearly observed at the intermediate channels B and C. Nevertheless, in all the operations, a high channel-switching ratio of over 16.5 dB was successfully achieved. We think that the crosstalk was effectively reduced by a
combination of two factors: the low power of the WDM data signals injected into the QD-SOA and the reduction of the gain per wavelength due to the inhomogeneous broadening property of the QD-SOA gain.

Fig. 5. (a) Definition of channel-switching ratio. Solid (blue) line shows the signal spectrum at four-channel operation, while dotted (red) line shows the signal spectrum at three-channel operation. (b) Channel-switching ratio with various channel numbers and positions.

3.3. Multichannel wavelength conversion using 50-Gbit/s NRZ-DQPSK signals

Fig. 6. (a) BER characteristics for channel C. (b) Eye-patterns of the demodulated signals (c) Power penalties for various configurations.

To investigate the conversion performance and its dependency on the channel number and position, we measured the BER characteristics of the back-to-back (BtoB) and the converted signals. Figure 6(a) shows an example of the BER characteristics, measurements for which were performed on channel C for various channel numbers. Although the increase in the power penalty at BER = 10^{-9} with the increasing number of injected channels was greater for the converted channels compared to that for the BtoB signal, the obtained power penalties were less than 1.5 dB for all configurations. In the case of four-channel operation, small error floor was observed. Although similar small error floors of the other channels were also observed, the error-free operations with low power penalties were successfully achieved at all the channels. We also compared to the conversion performance dependence on the bit pattern by removing the 3-km SMF at the output of the WDM signals, as shown in Fig. 1. However, no difference of the power penalty was observed. Figure 6(b) shows the eye-patterns of the BtoB
and converted signals after demodulation. Clear and comparable eye-openings to the BtoB signal could be obtained for three- and four-channels configurations.

![Graph showing power penalties to the BtoB signal at the BER = 10^{-9} for various channel configurations.]

**Fig. 7.** Power penalties to the BtoB signal at the BER = 10^{-9} for various channel configurations.

To compare the signal quality of all the converted channels for various channels numbers and positions, we measured the power penalties of the BtoB signal at BER = 10^{-9} for various configurations, as shown in Fig. 7. In all the channels, the power penalties increased with the number of the channels. In particular, the power penalties were rapidly increased in the case of four-channel operation, because the channel crosstalk was also drastically increased by the large interaction among the four-channel signals without vacancy of channel positions for the MWC. In addition, the penalties strongly depended on the position of the channel, and channel A and D had larger power penalties than the intermediate channels, B and C. We think that the large power penalties depended on the channel positions. In the conversion D to D*, the wavelength hopping was larger than those of the other channels, and resulted in the large degradation of the signal quality due to the low conversion efficiency. In the conversion A to A*, the signal degradation was mainly due to the high FWM crosstalk, which generated during the multichannel FWM in the QD-SOA around the pump wavelength, and the crosstalk was larger than those of the other channels. In this work, the BER measurement showed a power penalty of less than 4.0 dB for all configurations. To reduce the power penalties, especially in the case of four-channel operation, it will be useful to broaden the channel spacing.

**4. Summary**

We have demonstrated, for the first time, simultaneous wavelength conversion of 4 × 50-Gbit/s NRZ-DQPSK signals by means of FWM in a single QD-SOA. In all the channel configurations, the measured power penalties at the BER = 10^{-9} were less than 4.0 dB, and high channel-switching ratios were obtained with 100-GHz narrow channel spacing.

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