40-Gbit/s RZ-DPSK Wavelength Conversion Using Four-Wave Mixing in a Quantum Dot SOA

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Abstract: We demonstrate, for the first time, all-optical wavelength conversion of 40-Gbit/s RZ-DPSK signal using four-wave mixing in a quantum dot semiconductor optical amplifier. We achieved error-free operations with high conversion performances.

OCIS codes: (230.1150) All-optical devices; (230.5590) Quantum-well, -wire, and -dot devices.

1. Introduction

Quantum dot semiconductor optical amplifiers (QD-SOAs) have attracted much attention, since the QD-SOAs have been predicted to be superior to bulk or quantum-well SOAs (QW-SOAs) in many merits, in terms of higher gain, faster recovery time, and wider gain bandwidth [1]. These characteristics will be useful for not only amplification but also all-optical signal processing.

All-optical wavelength conversion (AOWC) is an essential technology in wavelength-division-multiplexing (WDM) systems for avoiding wavelength blocking and improving the utilization efficiency of the signal wavelength. AOWCs using various kinds of nonlinear elements have been studied so far. In particular, the use of integratable elements such as semiconductor optical amplifiers (SOAs) [2], silicon waveguides [3], and chalcogenide glass chips [4] will be very useful for comprising monolithic circuits with small foot print and realizing low-power switching operation. Recently, a few applications such as simultaneous multiwavelength 40-Gbit/s AOWC [5] and 160-Gbit/s AOWC using cross-gain-modulation [6] have been reported using QD-SOAs at 1.55-μm wavelength region.

In AOWCs, an attractive function is transparency to modulation format, since advanced modulation formats will play an important role in future photonic network. For example, differential phase-shift keying (DPSK) provides 3-dB improvement of receiver sensitivity compared to conventional on-off keying (OOK) formats [7]. Therefore, four-wave mixing (FWM), which can preserve both phase and amplitude information of the optical signal, is very useful for AOWC to provide strict transparency in modulation format.

In this work, we report an AOWC of 40-Gbit/s return-to-zero (RZ)-DPSK signal using FWM in a single QD-SOA at 1.55-μm wavelength region, for the first time. To achieve this, we use a QD-SOA at 1.55-μm and investigate the FWM conversion efficiencies in wide detuning range between the input data and pump wavelengths. We successfully demonstrated error-free operations with high conversion performances of 10-Gbit/s and 40-Gbit/s RZ-DPSK signals. The obtained conversion performances were superior to the previously reported ones of the FWM-based AOWCs using common SOAs.

2. Experimental setup

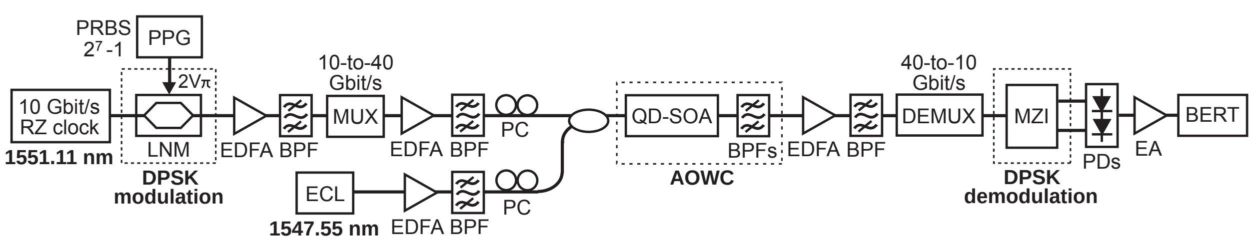

Fig. 1. Experimental setup for 40-Gbit/s AOWC using a single QD-SOA.

The experimental setup for AOWC is shown in Fig. 1. As a transmitter, a 10-Gbit/s RZ clock, which consists of external-cavity laser-diode (ECL) and an optical comb generator, was employed. The generated pulse train was filtered by a tunable bandpass filter (BPF) with the bandwidth of 0.55 nm to broaden the pulsewidth to 6.8 ps. The center wavelength of the pulse train was 1551.11 nm. To generate a RZ-DPSK data signal, the pulse train was modulated by a $LiNbO_3$ modulator (LNM) and a pulse pattern generator (PPG) with $2V_\pi$ peak-to-peak voltage and

2^7-1 pseudorandom bit sequence (PRBS) data. A continuous-wave (CW) pump signal was generated by an ECL with the wavelength of 1547.55 nm. After the data and pump signal amplifications by erbium-doped fiber amplifiers (EDFAs) with the following BPFs, the 10-Gbit/s RZ-DPSK data signal was multiplexed to a 40-Gbit/s signal by using a fiber-based optical time-division-multiplexing (OTDM) multiplexer. The amplified data and pump signals were combined by an optical coupler, and injected into a QD-SOA. Polarization controllers (PCs) at the input of the coupler were employed not only to obtain highest gain in the QD-SOA, but also to match with the state of the polarizations (SOPs) of the data and pump signals. The wavelength converter consists of a single QD-SOA and dual-stage cascaded BPFs, which removes the original data and pump signals. The employed QD-SOA was commercially available (QD Laser, Inc.) 5-mm long device with Stranski-Krastanow QDs, and optimized for broadband operation. The gain was transverse electric (TE) mode dominated. In this experiment, the operating forward current and temperature were set to 2.0 A and 25°C, respectively. After passing through the QD-SOA, the converted signal by means of the FWM process in the QD-SOA was filtered out using the dual-stage cascaded BPFs with the 3-dB bandwidth of 1.0 nm. The amplified 40-Gbit/s signal was demultiplexed to 10-Gbit/s signal by an electro-absorption modulator (EAM)-based demultiplexer, demodulated by a delayed Mach-Zehnder interferometer (MZI), and detected by a balanced photodiodes (PDs). The bit-error-rate (BER) characteristics of the amplified electric signal by an electrical amplifier were measured by a bit-error-rate tester (BERT) to evaluate the conversion performance of the wavelength converter.

3. Characteristics of QD-SOA

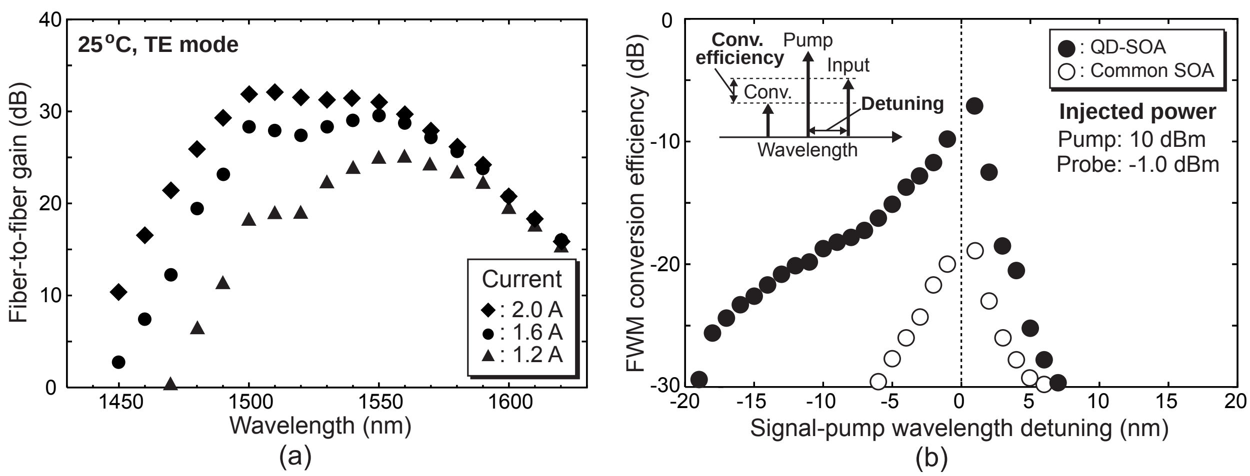

Fig. 2. (a) Gain characteristics of the QD-SOA for various forward currents. (b) FWM conversion efficiencies of the common SOA and QD-SOA.

Figure 2(a) shows the gain characteristics of the employed QD-SOA in the operating wavelength range between 1450 nm and 1620 nm. As the forward current became larger, the gain band and its peak wavelength were shifted to short wavelength side. When the current was set to 2.0 A, the gain peak wavelength and its small signal gain were 1510 nm and 32.09 dB, respectively. The available bandwidth with over 20 dB gain was about 150 nm. The 3-dB saturation output power at the wavelength of 1550 nm was approximately 10 dBm. The QD-SOA was employed in the following experiments.

To show the advantage of QD-SOA in the process of the FWM, we measured the conversion efficiencies, defined as the ratio between the input probe signal power and the converted signal power, of the QD-SOA and common SOA. Figure 2(b) shows the FWM conversion efficiencies with changing the input signal-pump wavelength detuning. In this experiment, we employed a CW probe as an input signal instead of a data-modulated signal. The injected pump and probe signal powers into the common SOA or QD-SOA were set to 10 dBm and −1.0 dBm, respectively. Compare to the common SOA, the QD-SOA had much higher conversion efficiencies in a wider pump detuning range. Moreover, more than −30 dB conversion efficiencies could be achieved within 20 nm negative detuning as shown in Fig. 2(b), despite the injected probe power into the QD-SOA was quite low (−1.0 dBm) compared with the previous FWM demonstrations using common SOAs [8]. This means that the AOWC using FWM in QD-SOA enables us to operate at a much lower-power switching operation than common SOA. On the other hand, the positive detuning had lower FWM conversion efficiencies, because of the destructive interferences of nonlinear process. Although symmetric high conversion efficient AOWC in a QD-SOA was previously reported [9], our employed QD-SOA had the asymmetric conversion efficiency as shown in Fig. 2(b).

4. Experimental results

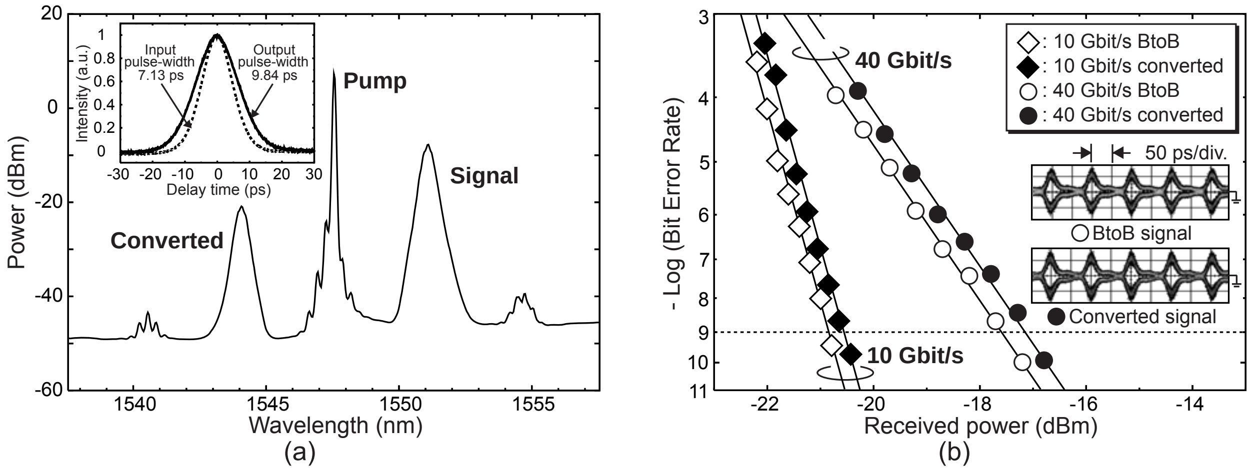

Fig. 3. (a) Signal spectra at the output of the QD-SOA in the AOWC. The inset shows the 40-Gbit/s RZ-DPSK pulse trace of the converted signal. (b) BER characteristics of the AOWC. The insets show the demodulated eye-patterns of the demultiplexed 40-Gbit/s BtoB and converted signals.

Figure 3(a) shows the signal spectra at the output of the QD-SOA in the AOWC. The injected CW pump signal and the average 40-Gbit/s RZ-DPSK data signal powers were 10 dBm and −1.0 dBm, respectively. As shown in Fig. 3(a), high output optical signal-to-noise ratio (OSNR) component of the converted signal was clearly observed at the wavelength spacing between pump and converted signals of 3.56 nm, which was enough to remove residual signal components by a conventional BPF at the output of the QD-SOA. The measured conversion efficiency was −13.11 dB. The inset shows the autocorrelation traces of the signals at the input and output of the QD-SOA. The measured pulse-widths were 7.13 ps and 9.84 ps, respectively. Although the pulse-width was little broadened by passing through the QD-SOA, larger waveform distortion due to self-phase modulation were hardly observed.

To evaluate the conversion performances of the AOWC, the BER characteristics of the back-to-back (BtoB) and converted signals at the bit-rates of 10-Gbit/s and 40-Gbit/s were measured as shown in Fig. 3(b). Owing to high conversion efficiency and wide detuning range in the FWM process, the obtained power penalties at the BER=10^{-9} at the bit-rates of 10-Gbit/s and 40-Gbit/s were 0.35 dB and 0.56 dB, respectively. The penalties were much smaller than that of the previous work using a common SOA and an 80-Gbit/s differential quadrature phase-shift keying (DQPSK) signal having the same baud-rate [8]. The insets show the demodulated eye-patterns of the 40-to-10 Gbit/s demultiplexed BtoB and converted signals. As shown in the obtained low power penalty of 0.56 dB, quite similar eye-patterns with clear eye openings could be obtained. These results show that higher bit-rate operation using a shorter pulse train will be expected. These results indicate the feasibility of the QD-SOAs for high speed DPSK wavelength conversion using FWM.

5. Conclusions

We experimentally demonstrated all-optical wavelength conversion based on FWM in a QD-SOA using 40-Gbit/s RZ-DPSK signal. The obtained results showed that the converter had high conversion performances with the power penalty of less than 0.6 dB, owing to high FWM conversion efficiency in wider detuning range. Moreover, the conversion performance at a low injected signal was much superior to that of common SOA.

6. References

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