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Ultrahigh-speed and widely tunable wavelength conversion based on cross-gain modulation in a quantum-dot semiconductor optical amplifier

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Abstract: We present ultrahigh-speed and full C-band tunable wavelength conversions using cross-gain modulation in a quantum-dot semiconductor optical amplifier (QD-SOA). In this study, we successfully demonstrated error-free 320-Gbit/s operation of an all-optical wavelength converter (AOWC) using the QD-SOA for the first time. We also demonstrated full C-band tunable operation of the AOWC in the wavelength range between 1535 nm and 1565 nm at a bit rate of 160-Gbit/s.

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Introduc

All-optical wavelength converter (AOWC) will be a key device for wavelength-routed optical networks based on wavelength-division-multiplexing (WDM) transmission systems [1, 2]. In AOWCs, ultrahigh-speed operation is one of the attractive features for future Ethernet applications based on optical time-division multiplexing (OTDM) transmission systems [3]. Indeed, ultrahigh-speed operation of an AOWC has been demonstrated using different nonlinear elements such as highly-nonlinear fibers [4], periodically-poled LiNbO$_3$ waveguides (PPLNs) [5, 6], silicon waveguides [7], chalcogenide glasses [8], and semiconductor optical amplifiers (SOAs) [9−14]. In particular, AOWCs using nonlinear effects in SOAs will be useful for producing monolithic circuits with a small footprint and achieving low-power switching [9]. Previous demonstrations of AOWCs using other types of SOAs, containing bulk or quantum-well (QW) gain layers, have resulted in conversion at speeds as high as 320-Gbit/s [13] or broadband 300-nm-wide operation [14], but no single device has been shown to achieve both ultrahigh-speed and tunable operation, which fully covers the available wavelength region for an OTDM system.

Quantum-dot semiconductor optical amplifiers (QD-SOAs) have attracted much attention, as they have been shown to be superior to common SOAs in terms of the key attributes needed for an AOWC, such as improved gain, faster recovery time, and broader gain
Recently, a number of high-speed demonstrations highlighting the potential advantages of using QD-SOAs for AOWCs were reported. Four-wave mixing (FWM) can offer higher conversion efficiency over a wider bandwidth, which is needed for AOWCs, in comparison with a common bulk/QW-SOA [16–18]. Indeed, we have successfully demonstrated error-free operation of an AOWC at a bit rate of 320-Gbit/s [19]. However, it was difficult to achieve widely tunable operation. In the AOWC, the available wavelength range was severely limited because the signal spectra of the 320-Gbit/s input and converted signals with the large wavelength spacing required for the FWM process had to be within the available wavelength range. Another promising approach is to use cross-gain modulation (XGM) in a QD-SOA [20–23]. An AOWC using XGM has also been demonstrated up to broadband operation covering the S/C/L-bands [20] and 160-Gbit/s operation assisted by an optical filter [22]. However, no experimental demonstration of the XGM-based AOWC beyond 160-Gbit/s operation has been reported so far, and the performance reported at 160-Gbit/s was not quantified in terms of the bit-error-rate (BER) and tunability.

In this work, we present ultrahigh-speed and widely tunable wavelength conversion by means of XGM using a QD-SOA [24]. First, we demonstrate low power penalty full C-band wavelength-tunable operation of return-to-zero on-off keying (RZ-OOK) signal at a bit rate of 160-Gbit/s. Next, we demonstrate error-free 320-Gbit/s wavelength conversion by means of XGM in a QD-SOA. Here, we show that QD-SOAs show superior performance in comparison to common SOAs, due to different gain and index dynamics, in particular, a stronger blue chirp. The device we used had a gain recovery of 85% within 10 ps, while the remaining 15% was completely recovered within approximately 100 ps. Consequently, the device introduces strong blue-chirp, which, when properly exploited, leads to ultrahigh-speed operation and low receiver power penalties. We believe that these are only possible because of the much broader gain bandwidth that QD-SOAs have compared to common SOAs.

This paper is organized as follows. Section 2 describes the gain characteristics of the QD-SOA we used. The experimental setup is explained in Section 3. In Section 4, an experimental demonstration of widely tunable operation of the AOWC is presented for 160-Gbit/s followed by a demonstration of ultrahigh-speed operation of the AOWC at 320-Gbit/s. Finally, Section 5 concludes this work.

2. Gain characteristics of QD-SOA

![Fig. 1. (a) Fiber-to-fiber gain characteristics of the QD-SOA. (b) ASE spectra with various bias currents. (c) An example of gain response of the QD-SOA at a repetition rate of 10-GHz.](image)

Figure 1 shows the gain characteristics of the employed QD-SOA. The QD-SOA we used had InAs dots grown on InGaAsP and was a 5-mm long device with Stranski-Krastanov QDs. The device was dominated by transverse electric (TE) mode gain. As shown in Fig. 1(a), the bandwidth for which over 25 dB gain was measured for a current of 2.0 A was 100 nm, which is much broader compared to that of a common SOA. Here, the signal power injected into the QD-SOA was −30 dBm, while the gain-saturated output power was about 10 dBm. Figure
The remaining 15% occurring in approximately 100 ps. These unique characteristics were due to a combination of the different gain recovery times, based on various carrier responses such as fast part with 85% of the gain recovery occurring within less than 10 ps and the slow part with 15% occurring in approximately 100 ps. These unique characteristics were due to a combination of the different gain recovery times, based on various carrier responses such as spectral-hole burning and carrier heating. Similar characteristics were also observed with a different QD-SOA demonstrated in the previous work [22].

3. Experimental setup

![Experimental setup diagram]

Fig. 2. (a) Experimental setup. MLFL: Mode-locked fiber laser, PPG: Pulse pattern generator, LNM: LiNbO₃ modulator, MUX: Multiplexer, ECL: External-cavity laser-diode, EDFA: Erbium-doped fiber amplifier, BPF: Bandpass filter, PC: Polarization controller, OC: Optical coupler, ISO: Isolator, PMF: Polarization-maintaining fiber, POL: Polarizer, DEMUX: Demultiplexer, PD: Photo-diode, EA: Error analyzer.

The experimental setup is shown in Fig. 2. As a pulse source for the 320-Gbit/s or 160-Gbit/s transmitter, a 40-GHz, 1.8-ps pulse width, mode-locked fiber laser (MLFL) was employed. The generated pulse train was modulated by a LiNbO₃ modulator (LNM) driven by a pulse pattern generator (PPG) with a 2³⁻¹ pseudorandom bit sequence (PRBS) data signal. The PRBS length is limited by the physical delays in the employed OTDM multiplexer. The generated data signal was compressed using the pulse compressor, which consisted of a 150-m-long highly nonlinear fiber (HNLF). The HNLF had a zero dispersion of 1590 nm, dispersion slope of 0.029 ps/nm/km at 1550 nm, and nonlinear coefficient of 20 W⁻¹km⁻¹. The compressed data signal with 1.2-ps pulse width was multiplexed to 320-Gbit/s and 160-Gbit/s using the OTDM multiplexer. To adjust the power injected into the QD-SOA, the generated signal was amplified using an erbium-doped fiber amplifier (EDFA) followed by a bandpass filter (BPF). A CW probe signal was generated using a wavelength-tunable external-cavity laser diode (ECL). The amplified data and the probe signals were combined using an optical coupler (OC) and injected into the QD-SOA. The injected powers were optimized to obtain the best conversion performance for each operation. By using polarization controllers (PCs) at the input of the OC, the states of the polarizations of the input data and probe signals were adjusted to obtain the highest gain of the data and pump signals in the QD-SOA. The AOWC comprised the QD-SOA, an isolator (ISO), a conventional two-cavity-type BPF with a 3-dB bandwidth of 5 nm (Koshin-Kogaku Co., Ltd.), two PCs, a polarization-maintaining fiber (PMF) with a 1.8 ps differential delay, and a polarizer (POL). The operating principle is
explained as follows. The converted signal is obtained by modulating the CW probe signal by XGM. The slow trailing edge of the converted signal induced by the slow gain recovery time of the QD-SOA is suppressed by the BPF with the passband blue-shifted by 5.0 nm from the center wavelength of the CW probe signal. The blue-shift filtering extracts the ultra-fast chirp dynamics and results in a fast response at the trailing edge of the converted signal [12, 22]. Finally, the polarity of the converted signal is inverted using the delayed-interferometer, which consists of the PCs, PMF, and POL in the AOWC. In the previous AOWC using the common SOA, a special filter had to be required additionally for the 320-Gbit/s operation [13]. On the other hand, it should be noted that our AOWC using the QD-SOA required only one common BPF, because the small slower tailing edge was effectively suppressed by the stronger blue chirp, compared to the common SOA. After passing through the AOWC, the converted signal was amplified and demultiplexed to a 40-Gbit/s signal using an OTDM demultiplexer (DEMUX). For 160-Gbit/s operation, an electro-absorption modulator (EAM)-based DEMUX was employed because the EAM could operate with a wide bandwidth, which covered the C-band, whereas a nonlinear optical loop mirror (NOLM)-based DEMUX, which consisted of a 125 m long HNLF, was employed for the 320-Gbit/s operation because the operating speed had to be much faster than the EAM-based DEMUX. The HNLF had a zero dispersion of 1558 m, dispersion slope of 0.029 ps/nm²/km at 1550 nm, and nonlinear coefficient of 20 W⁻¹ km⁻¹. The demultiplexed 40-Gbit/s signals were converted into electrical signals using a photo-diode (PD), and the BER characteristics were measured by an error analyzer (EA).

4. Experimental results

4.1. Ultrafast gain recovery of QD-SOA assisted by an optical filter

![Figure 3. 160-Gbit/s XGM signal spectra before (red, dotted line) and after (blue, solid line) the blue-shift filtering at the output of the QD-SOA and the shape and position of the employed BPF for the blue-shift filtering (green, dashed line). The insets show the eye-patterns of the 160-Gbit/s XGM signals before (upper) and after (bottom) the blue-shift filtering.](image)

As mentioned in the previous section, to achieve ultrafast gain dynamics in the QD-SOA, the blue-shift filtering technique was utilized at the output of the QD-SOA. To confirm the improved gain dynamics, we investigated the temporal gain recovery time of the 160-Gbit/s XGM signal with and without the blue-shift filtering. Figure 3 shows the 160-Gbit/s XGM signal spectra before (red, dotted line) and after (blue, solid line) the filtering at the output of the QD-SOA. The spectrum represented by the dashed line is the shape and position of the BPF employed for the blue-shift filtering in this experiment. The wavelength of the input data
and CW probe signals was 1540 nm and 1560 nm, respectively. The center wavelength of the BPF was blue-shifted by 4.2 nm. As indicated by the dashed line in Fig. 3, the employed BPF was not a common Gaussian-shape filter because the BPF had a two-cavity configuration. Indeed, the top part of the filter shape was little flatter and the side slopes were sharper, compared to a common Gaussian filter. However, no significant differences in the ultrafast dynamics of the QD-SOA were observed. The power injected into the QD-SOA of the input data and probe signals was 3.7 dBm and 6.9 dBm, respectively. The insets show the eye-patterns of the 160-Gbit/s XGM signals before (upper) and after (bottom) the blue-shift. The recovery time was dramatically improved by the effect of the blue-shift. We believe that this can be attributed mostly to the much stronger blue-chirp available in the QD-SOA used. The remaining slow trailing edge of the converted signal could be properly suppressed because the filter is largely shifted to maximize the blue chirp frequency shift and minimize the slow trailing red-shifted edge component.

4.2. Wavelength tunable operation in full C-band at 160-Gbit/s

To investigate the wavelength tunability of the AOWC, we demonstrated the full C-band operation using 160-Gbit/s signals. Figure 4(a) shows the BER characteristics of the 40-Gbit/s back-to-back (BtoB), 160-Gbit/s input data (original), and converted signals. The wavelength of the input data and CW probe (converted) signals was 1545 nm and 1560 nm, respectively. The center wavelength of the BPF at the output of the QD-SOA was blue-shifted by 5.0 nm to speed up the gain recovery time. The injected power into the QD-SOA of the pump and probe signals was 3.7 dBm and 6.9 dBm, respectively. In all the 40-Gbit/s tributaries, the power penalties at the error-free (BER = 10^-9) between the original and converted signals were less than 1.6 dB. Figure 4(b) shows the error-free received powers of the original and converted signals over the entire C-band. In this work, to avoid the large signal spectral overlapping between the input and converted signals, the input wavelength was set to 1545 nm or 1565 nm, according to the converted wavelength. In Fig. 4(b), the average power penalties of less than 2.0 dB could be obtained in the wavelength range between 1540 nm and 1565 nm. On the other hand, the power penalty at the wavelength of 1535 nm was more than 4.0 dB. We believe that this larger penalty was not only due to the QD-SOA performance at shorter wavelengths but also due to the demultiplexing performance of the employed EAM-based DEMUX at 1535 nm.
Figure 5 shows the 160-Gbit/s eye-patterns of the converted signals in the tunable range. All the eye-patterns had clear eye-openings. To the best of our knowledge, this is the first demonstration of full C-band tunable operation of an AOWC operating at 160-Gbit/s. The obtained tunable range is wider than the previous demonstration using a PPLN at the same bit rate [5]. In order to realize widely tunable operation of XGM-based AOWC, high gain available for the XGM, which covers the operating wavelength range, has to be required. The QD-SOA we used had much broader gain bandwidth compared with those of common SOAs, as shown in Fig. 1(a). The gain characteristics were enough to induce the XGM effect in the full C-band, and resulted in achieving the broadband tunable operation with low power penalties at 160-Gbit/s. In addition, the measured wavelength range was limited primarily by equipment such as the DEMUX and EDFA, and not by the AOWC. Based on the QD-SOA performance alone, an AOWC with a wider wavelength range should be possible.

4.3. Ultrahigh-speed operation at 320-Gbit/s

Fig. 6. 320-Gbit/s signal spectra at the outputs of the QD-SOA (red, dotted line) and the AOWC (blue, solid line) and the shape and position of the BPF (green, dashed line).
For 320-Gbit/s operation of the AOWC, we measured the conversion performance of the AOWC. Figure 6 shows the 320-Gbit/s signal spectra at the outputs of the QD-SOA (red, dotted line) and the AOWC (blue, solid line). At around 1530 nm, the signal component with a 320-GHz tone was clearly observed in the signal spectra at the QD-SOA output. This was induced by the FWM process between the 320-Gbit/s input and converted signals. This means that the QD-SOA we used has a high FWM conversion efficiency. Indeed, we successfully demonstrated error-free 320-Gbit/s wavelength conversion by means of FWM using the QD-SOA [19]. The spectrum represented by the dashed line (green) is the shape of the employed BPF for the blue-shift filtering in this experiment. The center wavelength of the BPF at the output of the QD-SOA was blue-shifted by 5.0 nm. In the 320-Gbit/s experiment, the wavelength of the input data and CW probe signals was 1545 nm and 1559 nm, respectively. The power of the input data and probe signals injected into the QD-SOA was 6.7 dBm and 6.9 dBm, respectively. The measured power of the converted signal at the output of the AOWC was −6.36 dBm. The calculated conversion efficiency, which is defined as the power ratio between the input data and converted signals, was −13.06 dB. The obtained value was much larger than that of the previous 320-Gbit/s AOWC using the common SOA [13] because a special filter with high insertion loss at the tail of the AOWC was not additionally required in the previous experiment. A simpler scheme was achieved owing to the unique gain dynamics and strong blue chirp of the QD-SOA. As shown in Fig. 6, the spectral shape of the converted signal had clearly changed due to the blue-shift filtering and the periodical filter property of the delayed-interferometer in the AOWC. On the other hand, the 320-GHz tone, which corresponded to the bit rate of the input signal, was clearly observed.

![Figure 6](image_url)

**Fig. 6.** Shows the 320-Gbit/s signal spectra at the outputs of the QD-SOA (red, dotted line) and the AOWC (blue, solid line). At around 1530 nm, the signal component with a 320-GHz tone was clearly observed in the signal spectra at the QD-SOA output. 

To evaluate the conversion performance, we measured the BER characteristics of the demultiplexed 40-Gbit/s input data (original) and converted signals, as shown in Fig. 7 (a). For all the eight 40-Gbit/s tributaries, no error floors were observed. The average power penalty for BER = 10^-9 between the original and converted signals was approximately 4.2 dB, which were much smaller than that of the 320-Gbit/s AOWC using the common SOA [13]. Figures 7(b) and 7(c) show the 320-Gbit/s pulse train and demultiplexed 40-Gbit/s eye-patterns of the original and converted signals, respectively. It should be noted that the pulse widths of the demultiplexed original and converted signals were broadened and appeared to
the same, compared to the original and converted trains before demultiplexing in Fig. 7(b). This was because of pulse broadening, not by the dispersion of the HNLF in the NOLM, but by the spectral slicing of the BPF located at the tail of the NOLM. Therefore, no performance degradation was observed due to the intersymbol interference of the neighboring channels. The obtained eye-patterns of the converted signals showed clear eye openings, which was consistent with the BER results.

5. Summary

We successfully demonstrated error-free 320-Gbit/s all-optical wavelength conversion using a QD-SOA. To the best of our knowledge, this is the highest bit-rate operation of AOWC using a QD-SOA. We also demonstrated full (1535–1565 nm) C-band tunable operation at 160-Gbit/s. The obtained results indicated that QD-SOAs have higher potential to dramatically improve the conversion performances of AOWCs than common SOAs.

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