Broadband Wavelength Conversion with S/C/L-band Flexible Operation Using Cross-Gain-Modulation in a Single Quantum Dot SOA

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Abstract: We experimentally demonstrated operating original and converted wavelengths flexible wavelength conversion using cross-gain-modulation in a single quantum dot semiconductor optical amplifier with covering the entire S-, C-, and L-bands.

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

1. Introduction

In future photonic networks, all-optical wavelength converter (AOWC) is one of the key devices to utilize effective wavelength resources in wavelength-division-multiplexing (WDM) systems [1]. An important function of AOWC is to operate flexibly in wider wavelength range. In other words, broadband AOWC, which hops flexibly an arbitrary wavelength in a wider range, will be required without the restriction of the operating wavelength range of the original and converted signals. In particular, as S-, C-, and L-bands are practical transmission bands for metro/core networks, broadband AOWC with covering these bands will play an important role in future networks.

A number of broadband AOWCs using various kinds of integratable nonlinear elements such as silicon waveguides [2] and chalcogenide glass chips [3] have been reported so far. However, these operation principles were based on four-wave mixing (FWM). Thus, the original and converted wavelengths were not fully flexible, because the operating wavelength range was restricted by the residual dispersion of the nonlinear elements, and a conversion wavelength pair of the original and pump wavelengths determined the converted wavelength. Although we demonstrated the 300-nm wavelength conversion using cascaded semiconductor optical amplifier-based AOWCs, different cascaded schemes had to be required according to the original and the converted wavelengths [4, 5].

Quantum-dot semiconductor optical amplifiers (QD-SOAs) have many advantages, including higher gain, higher output saturation power, and faster gain recovery time, compared to common bulk and quantum well SOAs [6]. So far, all-optical signal regenerations [6, 7] and high bit-rate wavelength conversions [8, 9] using QD-SOAs have been already reported. On the other hand, wide gain bandwidth is also attractive function of QD-SOAs, and it is well known that QD-SOAs have widest gain bandwidth among all kinds of optical amplifiers [6]. However, no practical applications to all-optical signal processing utilizing fully wide gain bandwidth has been reported so far.

This paper presents a broadband wavelength conversion using cross-gain-modulation (XGM) in a single QD-SOA. In this scheme, the original and converted signal wavelengths were flexibly selected due to the wide gain bandwidth of the QD-SOA. This converter achieved broadband operation with covering the entire S-, C-, and L-bands with high conversion performance.

2. Experimental setup

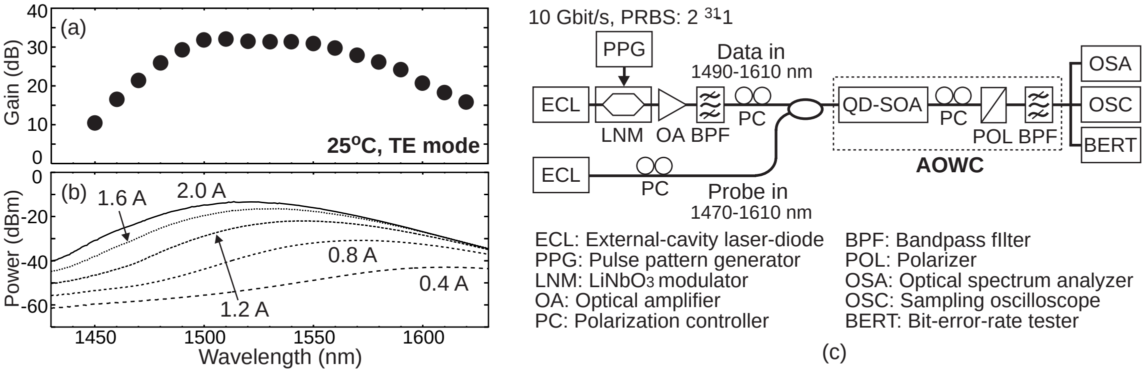


Fig. 1. (a) Gain characteristics of the employed QD-SOA. (b) ASE spectra for various forward currents. (c) Experimental setup.

To achieve broadband operation of AOWC, a QD-SOA with a wide gain bandwidth was used. The QD-SOA (QD Laser, Inc.) was optimized for broadband operation and a 5-mm-long device with Stranski-Krastanow (SK) QDs. The gain was transverse electric (TE) mode dominated. Figure 1(a) shows the gain characteristics of the QD-SOA in the wavelength range between 1450 nm and 1620 nm, while Figure 1(b) shows the amplified spontaneous emission (ASE) spectra for various forward currents. As the forward current became increased, the gain peak wavelength was 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 bandwidth with over 20 dB gain was about 150 nm. The 3 dB saturation output power at 1550 nm was about 10 dBm. The QD-SOA was employed in the following experiments.

The experimental setup for broadband wavelength conversion using a single QD-SOA is shown in Fig. 1(c). The 10-Gbit/s non-return-to-zero (NRZ) transmitter consisted of an external-cavity laser-diode (ECL) and a 1.55-μm $LiNbO_3$ modulator (LNM) for a data modulation of 2^{31}-1 pseudo-random bit sequence (PRBS) generated by a pulse pattern generator (PPG). The operating wavelength was tuned from 1490 nm to 1610 nm. The offset bias of the LNM was adjusted to obtain the highest signal quality at each input signal wavelength. However, it should be noted that it was impossible for the LNM to generate NRZ signal with high quality at a shorter wavelength than 1490 nm. After passing through the LNM, the injected data signal power into the QD-SOA was adjusted by the gain of an optical amplifier (OA) followed by a tunable bandpass filter (BPF) to remove amplified spontaneous emission noise. As the OA, an S-band thulium-doped optical amplifier (TDFA), or a C/L-bands erbium-doped optical amplifier (EDFA) was selected, according to the input data signal wavelength. The continuous-wave (CW) probe was generated from an ECL with the operating wavelength range between 1470 nm and 1610 nm. The data and probe signals were combined by a 3 dB coupler, and injected into the QD-SOA. In order to achieve the highest conversion performances at each operating wavelength, the injected powers of the data and probe signals into the QD-SOA were optimized in the power range between 0 dBm and 10 dBm. The operating temperature and forward current of the QD-SOA were set to 25 ºC and 2.0 A, respectively. The state of polarization (SOP) of the input data signal was set to obtain the highest gain by adjusting a polarization controller (PC) at the input of the coupler. The AOWC consisted of the QD-SOA, a PC, a polarizer (POL), and a BPF. In this scheme, to obtain simultaneously the lowest space level and the highest eye opening of the converted signal, we adjusted the SOPs of the probe at the input of the QD-SOA and the converted signal at the input of the POL. The operation principle of the AOWC was based on XGM. Thus, all the data logics of the converted signal were inverted. After passing through the BPF, the converted signal was detected by an optical spectrum analyzer (OSA), a sampling oscilloscope (OSC) with the bandwidth of 40 GHz, or a bit-error-rate tester (BERT) to evaluate the signal quality.

3. Experimental results

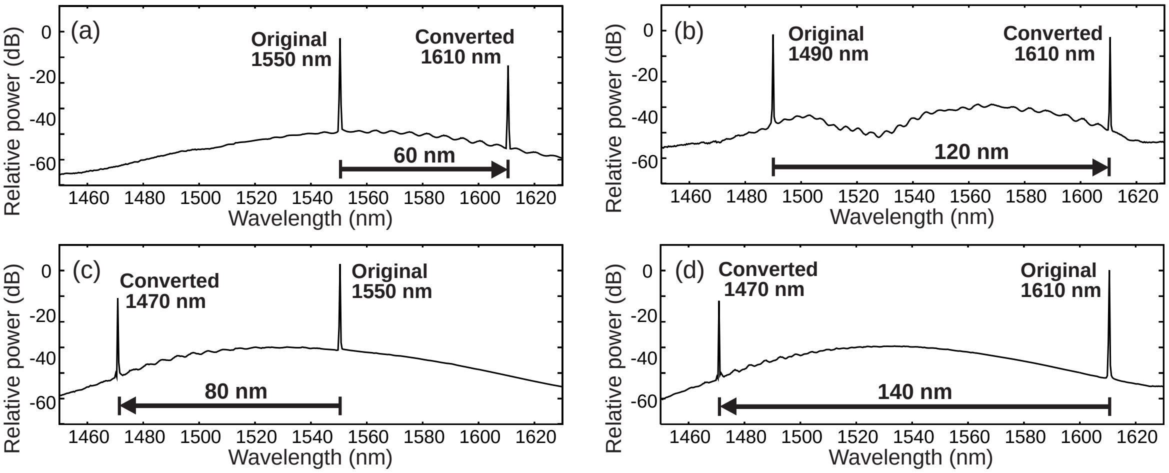
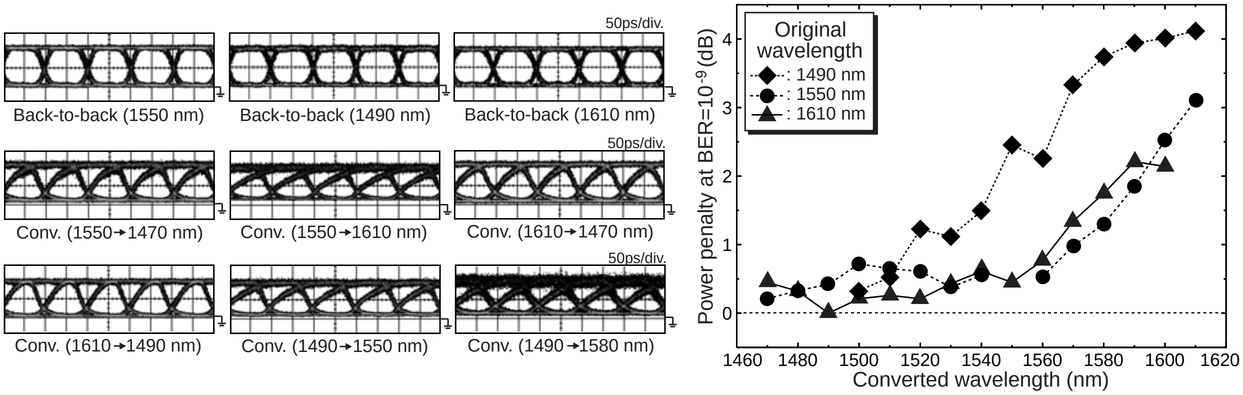


Fig. 2. Examples of signal spectra at the output of AOWC without BPF. (a) Down-conversion from 1550 to 1610 nm, (b) Up-conversions from 1550 to 1470 nm, (c) Down-conversion from 1490 to 1610 nm, and (d) Up-conversion from 1610 to 1470 nm.

To examine the conversion performance of the AOWC, we measured the signal spectra at the output of the AOWC without the output BPF. Figure 3 shows the signal spectra for various conversion cases. Due to the wide gain bandwidth of the QD-SOA, the high output optical signal-to-noise ratios (OSNRs) of the converted signals were clearly observed in all the cases. In particular, it was found that the large wavelength hopping to a much shorter wavelength was achieved with the high OSNR as shown in Fig. 3(d). In conventional AOWC with common SOAs, it was very difficult to perform up-conversion (long to short wavelength) with large hopping range beyond the entire S-, C-, and

L-bands, because the OSNR of the converted signal at much shorter wavelength side was drastically degraded due to the high absorption loss of the SOA [4]. On the other hand, the AOWC using the QD-SOA achieved a large wavelength hopping to a much shorter wavelength.



(a) (b)

Fig. 3. (a) Examples of output eye-patterns of the BtoB and converted signals for various conversion cases. (b) Power penalties of the AOWC to the BtoB signal at each original signal wavelength for various conversion cases.

Figure 3(a) shows the examples of the output eye-patterns of the back-to-back (BtoB) and converted signals for various conversion cases. Although the converted signals included slow trailing edge due to the finite gain recovery time of the QD-SOA, clear eye openings were successfully observed in all the cases. On the other hand, we found that the trailing time became slow and output OSNR was degraded, as the converted (probe) wavelength became longer. We think that it was due to the wavelength dependence on the gain recovery time of the employed QD-SOA in the wide operating wavelength range.

To evaluate the conversion performances of the AOWC in the entire S-, C-, and L-bands, the bit-error-rate (BER) characteristics were measured. Figure 3(b) shows the power penalties of the AOWC to the BtoB signals at each original signal wavelength at the BER=10^{-9} for various conversion cases. In all the operating wavelength range, the low power penalties were successfully obtained. On the other hand, the power penalties tended to become increased regardless of the original signal wavelength, as the converted signal wavelength became longer. This was due to waveform distortion induced by the slower trailing time as mentioned before. However, the obtained power penalties were less than 4.2 dB in all the operating wavelength range. This means that this AOWC will be useful for broadband operation with covering the entire S-, C-, and L-bands. The measured wavelength range was primarily limited by the employed equipments such as ECL, BPF and OA, not by the AOWC. With better measurement setup, more precise characteristics would be obtained in a wider wavelength range.

5. Conclusions

We have presented an operating original and converted wavelengths flexible, all-optical wavelength conversion using cross-gain-modulation in a single QD-SOA. The converter operated in the entire S-, C-, and L-bands with the power penalties of less than 4.2 dB.

6. References

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