Dynamic characteristics of 20-layer stacked QD-SOA with strain compensation technique by ultrafast signals using optical frequency comb

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Received 28 July 2016, revised 22 September 2016, accepted 23 September 2016
Published online 12 October 2016

Keywords optical frequency combs, quantum dots, semiconductor optical amplifiers

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In this article, we evaluated the static and dynamic characteristics of 20-layer stacked quantum dot semiconductor optical amplifiers (QD-SOAs) grown on an InP(311)B substrate with a strain compensation technique using an optical frequency comb. The gain peak wavelength of the fabricated QD-SOA was 1520 nm, and a maximum gain of approximately 15.8 dB was obtained when the injection current was 350 mA. By using optical bit rate multiplier modules, an optical pulse, which was generated by the use of the optical frequency comb, was multiplexed. We observed the dynamic behavior of the QD-SOA with the pulse trains. The minimum interval between pulses was 4.2 ps, and we measured using an optical sampling oscilloscope. It was found the QD-SOA could respond to ultrafast pulses that were equivalent to the signals of 220 Gb s⁻¹ class speed without any large pattern distortions. In addition, we could obtain a rather clear optical pulse waveform. We also estimated the gain recovery time of the QD-SOA to be 6.0 ps by using a pump probe-like method. One of the reasons that the fabricated QD-SOA could respond to ultrafast signals was its ultrashort gain recovery time.

1 Introduction

In recent years, communication traffic has increased exponentially because of the spread of smart devices [1] such as smartphones and tablet PCs. Thus, the development of an ultrafast and high-capacity advanced photonic network is needed. In addition, the increase of communication traffic in access networks and datacenters is higher than in other networks. Compact and high functional photonic integrated circuits (PICs) with high stability of temperature, such as heterogeneous [2–8] or monolithic integrated [9–12] devices, are desired in the networks. In particular, a semiconductor optical amplifier (SOA) is a key device that functions as a gain medium and nonlinear element in PICs.

On the other hand, quantum dots (QDs) are very promising materials for high-performance photonic devices because of their delta-function-like density of states. Many researchers have noted that QD-based optical devices such as laser diodes (LDs), SOAs, and nonlinear optical devices exhibit high performance. These characteristics include high temperature stability, ultrafast response, low threshold current, and low chirp [13–18]. However, it is difficult to grow properly shaped QD structures in the 1.55-μm band on an InP(001) substrate. Instead, quantum dash (QDash) structures tend to be used [19–23].

In our previous work, we demonstrated highly stacked QD structures with more than 100 layers by utilizing the strain compensation technique. We also showed their application in LDs and SOAs on InP(311)B substrates [24, 25]. So far, for the QD-SOA, we indicated a high gain of more than 25 dB for a device length of 2 mm and a clear eye-pattern waveform of a nonreturn-to-zero signal of 50 Gb s⁻¹ [26]. However, we have not investigated pulse responses of higher than 50 GHz for highly stacked QD-SOAs grown.
on an InP(311)B substrate using the strain compensation technique. In addition, there is almost no reports about the dynamic characteristics of QD-SOA with InP(311)B substrates although some papers have reported on a wavelength conversion of more than 160 Gb s\(^{-1}\) utilizing cross-gain modulation or four-wave mixing in columnar-shaped QD-SOAs with InP(001) substrates [28, 29].

In this article, we measured the static and dynamic characteristics of 20-layer stacked QD-SOAs grown on an InP(311)B substrate with a strain compensation technique by ultrastep signals using an optical frequency comb. First, we evaluated the fundamental gain characteristics of fabricated QD-SOAs. Then, we observed the dynamic behavior of a QD-SOA with the multiplexed pulse trains whose minimum pulse interval was 4.2 ps by using an optical sampling oscilloscope (OSO). We also estimated the gain recovery time of the QD-SOA by utilizing the picosecond pulse of the optical frequency comb.

2 Device structure We fabricated a QD-SOA with a simple ridge structure by utilizing the strain compensation technique. Figure 1 shows a schematic diagram of the fabricated QD-SOA. The fabrication procedures are as follows. A 150-nm-thick lattice matched n-InAlAs cladding layer, 20 pairs of an In\(_{0.49}\)Ga\(_{0.26}\)Al\(_{0.25}\)As spacer and InAs QD layer, 2-μm-thick p-InAlAs cladding layer, and a 50-nm-thick p\(^{+}\)-InGaAs contact layer were grown on an InP(311)B substrate by molecular beam epitaxy. The thickness of a pair of InAs QD and InGaAlAs spacer layer was 20 nm. In this epitaxial growth process, 20-layer stacked QD layers could be fabricated by the strain compensation technique. The strain compensation technique is the method that balances the strain energy between QDs and the matrix. The strain compensation technique has been reported in the almost same epitaxial growth conditions were approximately 2.5 nm, 35 nm, and 8.5–9.0 × 10\(^{10}\) cm\(^{-2}\), respectively. The optical confinement factor of this active region was estimated about 0.13 by using the film matching method and volume ratio of QDs in InGaAlAs layers, in which the refractive indices of them were calculated by the modified effective oscillator method. The width of the ridge waveguide was 2.7 μm, and its height was approximately 1.8 μm. Finally, a QD-SOA module was assembled using the SOA chip, which was mounted on a metal stem with the p-side facing downward and coupled by lenses to single-mode optical fibers.

3 Measurements and discussion The gain spectra under a current of 300 mA for the polarization of the TE and TM modes are shown in Fig. 2. The power of a continuous wave (CW) input light was −30 dBm. From this figure, the wavelength of the gain peak was 1520 nm, which was a slightly shorter wavelength than the center wavelength of the C-band. In addition, fiber-to-fiber gains of 3 dB and above 10 dB were obtained with bandwidths of 24 nm and over 35 nm, respectively. Here, we defined the fiber-to-fiber gain as a modal gain including a fiber coupling loss of approximately 10 dB (5 dB/facet) at both facets. A relatively large coupling loss was caused by the mismatch of mode field patterns between the waveguide facet of the fabricated QD-SOA device and the optical fiber. The narrow 3 dB bandwidth indicates only a minor size deviation of the QDs in each layer owing to the use of an InP(311)B substrate and strain compensation technique. The gain bandwidth could be broadened by using higher injected currents and utilizing excited states.

Then, a CW input light with a power \(P_{cw}\) of −30 dBm and a wavelength \(\lambda_{cw}\) of 1525 nm, which was almost at a gain peak, was injected into the QD-SOA. The dependence of gain on the injected current or current density is shown in another dry-etching. Then, a p-contact electrode was formed on the planarized surface by using an electron beam evaporation system. After the InP(311)B substrate was thinned, an n-contact electrode was also formed. The sample was cleaved to a device length of 2 mm, and both facets were coated with TiO\(_2\) and SiO\(_2\) films for anti-reflection coating. The typical average height, diameter, and sheet density of InAs QDs in the almost same epitaxial growth conditions were approximately 2.5 nm, 35 nm, and 8.5–9.0 × 10\(^{10}\) cm\(^{-2}\), respectively. The optical confinement factor of this active region was estimated about 0.13 by using the film matching method and volume ratio of QDs in InGaAlAs layers, in which the refractive indices of them were calculated by the modified effective oscillator method. The width of the ridge waveguide was 2.7 μm, and its height was approximately 1.8 μm. Finally, a QD-SOA module was assembled using the SOA chip, which was mounted on a metal stem with the p-side facing downward and coupled by lenses to single-mode optical fibers.

![Figure 1](image1.png) Schematic diagram of fabricated QD-SOA.

![Figure 2](image2.png) Gain spectra under a current of 300 mA for polarization of TE and TM modes.
Current density of approximately 5.5 kA cm⁻² is so high as to 300 mA, which was corresponding to the injection current was not estimated to be approximately 10 dB. In addition, there are smaller losses at the low-current region. This indicated a weaker interaction between the CW light in the TM mode and carriers in QDs compared with the TE mode. As already reported in some papers [30], the PDG should be able to be suppressed if the thicknesses of InGaAlAs intermediate layers are designed to be decreased, and the wave functions of electrons and holes in each QD are coupled to each other vertically by that design.

The fiber-to-fiber gain characteristic as a function of the output light power at 300 mA is shown in Fig. 4. The wavelengths of the input was approximately 1525 nm. From this result, the 3 dB saturation output powers were estimated to be −5 and −10 dBm in the TE and TM modes, respectively. One of the reasons for this relatively low saturation output power is that the injection current was not so high as to 300 mA, which was corresponding to the current density of approximately 5.5 kA cm⁻². Because a current can be highly injected into the QD-SOA module if the device or module design is optimized, the 3 dB saturation output power should be increased than these relatively low values of −5 and −10 dBm.

Next, we evaluated the dynamic characteristics of the QD-SOA by using picosecond pulses of an optical frequency comb. The experimental setup of ultrafast optical signals is shown in Fig. 5. Picosecond optical pulses with a 10 GHz repetition rate were obtained by the optical frequency comb generator. The optical frequency comb generator was composed of a high-accuracy Mach–Zehnder LiNbO₃ (LN) modulator, RF amplifiers, and electrical control circuits. Then, an optical frequency comb could be generated by modulating an injected CW light, whose wavelength was 1525 nm, and adjusting the biases and powers of 10 GHz RF signals. The signals were generated by an RF synthesizer into each arm of the LN modulator [31, 32]. However, the generated pulse width was 6.8 ps, which was not enough for 16-time optical time division multiplexing (OTDM). Therefore, an EDFA, 1-km-long single-mode fiber (SMF), and 1459-m-long dispersion decreased fiber (DDF) were utilized in order to compress the pulse width by a nonlinear effect [33]. However, as the compressed pulses contained vibrations similar to a Sinc function, we used an optical bandpass filter whose bandwidth was approximately 3.5 nm. To remove the vibrations, the transmission center wavelength was slightly red-shifted from the wavelength of input light. The spectrum of the optical frequency comb at the point after the optical bandpass filter is indicated in Fig. 6. Then, by using optical bit-rate multiplier (OBRM) modules, optical pulse trains could be obtained by multiplexing up to 16 times. We evaluated the optical pulse response of the fabricated QD-SOA by using an OSO with a 500 GHz bandwidth and an optical spectrum analyzer (OSA).

In Fig. 7(a) and (b), pulse trains going into and emerging from the QD-SOA that were multiplexed 16 times and whose minimum interval was 4.2 ps are shown. In this experiment, the injection current into the QD-SOA was 300 mA. As seen in Fig. 7(a), the pulse interval was not completely uniform, and there were slightly wide intervals between every four pulses. The reason was because the condition of OBRM modules we used was a little bad; therefore, the intervals could not be accurately and uniformly adjusted. However, the shortest interval of 4.2 ps was equivalent to the signals of substantially 220 Gb s⁻¹ class speed. In addition, the average peak power of the input pulses was approximately 1 mW. This input power is the operational condition of the gain saturation region in the fabricated QD-SOA. As shown in Fig. 7(b), rather clear output pulses were obtained, and the gain was estimated to be approximately 4.6 dB. Furthermore, the output waveform from the QD-SOA showed almost no distortion, although the peak level deviation of the output pulses was slightly increased over that of the input pulses. The deviations of the input and output were 1.5 and 1.75 dB, respectively. Although the reason for the 0.25 dB increase in deviation is a result of a pattern effect, supposedly the QD...
structure is one reason why the increase in deviation was not too high.

Then, we evaluated the gain recovery time (i.e., the effective carrier recovery time). The experimental setup for evaluating the gain recovery time is shown in Fig. 8 [34]. We utilized the picosecond optical pulses mentioned above, whose repetition rate was 10 GHz, and formed two serial duplicated pulses by using a 3 dB coupler and optical delay line, which was inserted in one of the two passes, as shown in Fig. 9. We measured the relative peak intensities of the second pulse to the first one by changing the interval of the two pulses, as shown in Fig. 9. In Fig. 10, the relative peak intensity as a function of pulse interval time is indicated. In this case, we injected a current of 300 mA into the QD-SOA. We adjusted the peak power of the two serial pulses to be approximately 1 mW. From this result, the 100% gain recovery time in the QD-SOA was estimated to be approximately 6.0 ps.

It is supposed that the carrier reservoir effect is the reason that the QD-SOA had such an ultrafast gain recovery time. As reported in some papers [28, 35], the upper energy state of carriers in QDs functions as carrier reservoirs because the carriers are three-dimensionally confined in QDs. On the other hand, in this experimental result, we did not observe the slow gain recovery component that was reported in other papers. One of the causes may be the accumulation of carriers in the upper energy state. If there are enough carriers in the upper energy state, there may be a possibility that the slow gain recovery component cannot be seen since the decreased carriers by an input pulse are compensated instantaneously even if it is operated in the deep gain saturation region. This may be a result of the highly stacked QD structure. Therefore, the fabricated QD-SOA could respond to ultrafast signals whose interval was 4.2 ps, as indicated above. And, when injection current or current density is increased, effective carrier transition time from upper energy state to ground state should be decreased, then it causes the gain recovery time to be faster to some extent [36, 37]. Hence, in that case, the QD-SOA is expected to be able to respond such ultrafast signals more clearly.

![Figure 5](image1.png)

**Figure 5** Experimental setup of ultrafast optical signals. PC, polarization controller; ATT, attenuator; SMF, single-mode fiber; DDF, dispersion decreased fiber; OBRM, optical bit-rate multiplier; VOA, variable optical attenuator; OSO, optical sampling oscilloscope; OSA, optical spectrum analyzer.

![Figure 6](image2.png)

**Figure 6** Spectrum of optical frequency comb at the point after the optical bandpass filter.

![Figure 7](image3.png)

**Figure 7** Pulse trains multiplexed 16 times (a) going into and (b) emerging from the QD-SOA, observed by an OSO.
Conclusions

In this article, we evaluated the static and dynamic characteristics of 20-layer stacked QD-SOAs grown on an InP(311)B substrate with the strain compensation technique by ultrafast signals using an optical frequency comb. The gain peak wavelength of the fabricated QD-SOA was 1520 nm. A maximum gain of approximately 15.8 dB was obtained with an injection current of 350 mA. By using OBRM modules, an optical pulse that was generated by the use of the optical frequency comb was multiplexed. We evaluated the dynamic behavior of the QD-SOA with pulse trains. The minimum pulse interval was 4.2 ps, measured by OSO. It was found that the QD-SOA could respond to ultrafast pulses, which were equivalent to the signals of 220 Gb s\(^{-1}\) class speed, without any large pattern distortions, and we could obtain a rather clear optical-pulse waveform. In addition, we estimated the gain recovery time of the QD-SOA to be 6.0 ps by using the pump probe-like method. One of the reasons that the fabricated QD-SOA could respond the ultrafast signals was because of the ultrashort gain recovery time.

Acknowledgements

This work was partly supported by the Japanese Government funding for “R&D to Expand Radio Frequency Resources” by the Ministry of Internal Affairs and Communications.

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