An Ultrawide-Band (120 nm) Semiconductor Optical Amplifier Having an Extremely-High Penalty-Free Output Power of 23 dBm Realized with Quantum-Dot Active Layers

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Abstract: A semiconductor optical amplifier having a gain of > 20 dB, noise figure of < 7 dB, and 3-dB saturation output power of > 19 dBm, over the record widest bandwidth of 120 nm among all kinds of optical amplifiers, and also having a penalty-free output power of 23 dBm, the record highest among all the semiconductor optical amplifiers, was realized by using quantum dots.

OCIS codes: (250.5980) semiconductor optical amplifiers; (140.4480) optical amplifiers; (140.5960) semiconductor lasers

1. Introduction

Not only the progress in the dense WDM systems, but the recent trend of the WDM systems, where the cost of components is cut down by increasing the channel spacing, has accelerated the development of various optical amplifiers covering transmission-bands outside the EDFA-bands. Fiber Raman amplifiers (FRAs) [1], Pr-doped [2] and Tm-doped [3] fiber amplifiers, Telluride-based EDFAs [4], and semiconductor optical amplifiers (SOAs) [5-8] are representative of those amplifiers. In order to fill the gap of the wavelength bands not covered by rare-earth-doped fiber amplifiers, FRAs and/or SOAs, having a large degree of freedom in wavelength choice, are required. To provide a reasonable gain, however, FRAs require high pump powers and long optical fibers on the order of kilometers, which makes their current practicality in low-cost systems questionable. Also, as for SOAs, the degradation of signal quality coming from both ASE noise addition (large noise figure (NF)) and signal distortion in the gain-saturated regime (pattern effect), is a critical problem, which is the main reason that SOAs have been kept away from practical commercial applications. In SOAs, the input fiber-coupling loss, as well as the degree of population inversion and the ratio of the internal loss to the gain, has been the main origin of the large NF. At present, it is not difficult to reduce this coupling loss down to ~ 1 dB [9]. As for signal distortion, output power has to be, typically, at least 4 dB below the 3-dB saturation output power (P_{sat}) to be immune from pattern effect, which severely limits the usable output power. Gain clamping [8,10,11] is effective in increasing the usable output power, and recently a very simple scheme utilizing only one VCSEL chip has been proposed [12]. Our approach to this problem is replacing the active material with quantum dots (QDs), which can make usable output power close to P_{sat} [13-18]. With this approach, we have successfully demonstrated the record highest penalty-free output power of 20 dBm [9]. Taking into account the requirement of cost effectiveness, covering as wide range of transmission bands as possible with the simplest and minimum number of optical amplifiers is of great importance. QDs are also effective in drastically increasing the bandwidth of SOAs, i.e. the wavelength range where the values of gain, NF, and P_{sat} satisfy the requirements. In our previous report, however, this property was not eminent due to both of the insufficient heat dissipation from the SOA chip and the limitation in the injection current by lasing threshold [9]. By relaxing these problems, we have successfully realized a single-chip optical amplifier having the record-widest bandwidth among all kinds of optical amplifiers, and also having a penalty-free output power of 23 dBm, 3-dB improvement compared to the record in our previous report.

2. Operation Principle

The characteristic property of QDs, contributing to distortion-free amplification in the gain-saturated regime (which increases the usable output power), is an ultrafast gain response (~ a few ps) [9,13-18]. As illustrated in Fig. 1 (a), an incident signal triggers stimulated emission, by which only electrons in the QDs that are resonant to the signal are extracted, and accordingly, the gain is saturated (hole burning). Supply of the electrons remaining in the other QDs and the surrounding material, which is special to QDs, helps realize an ultrafast gain recovery. Unlike QW and bulk SOAs, this gain response is fast enough to follow the intensity change of 10 - 40 Gb/s signal and to suppress the gain fluctuation (Fig. 1 (a)) [9,13-18]. Another property of QDs, also contributing to an increase in the usable output power, is the increase in P_{sat} (Fig. 1 (b)) by raising the Fermi level at the maximum of current density (limited by the thermal effect) [9]. This is achieved by concentrating the injected carriers into nano-sized QDs, which have a smaller total volume of active material [19]. By combining the two properties described above, we can achieve a drastic improvement in penalty-free output power. The rise in Fermi level also leads to improvement in the peak values of NF and P_{sat}, as well as broad bandwidths for certain values of gain, NF, and P_{sat} [20].

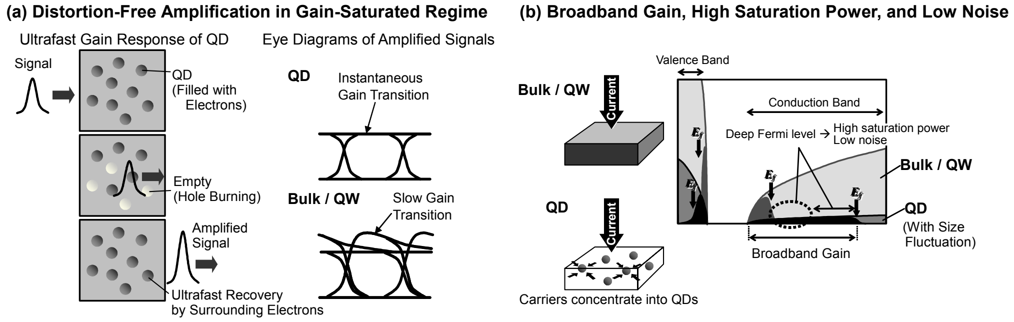

Fig. 1. Schematic illustration of principles of (a) distortion-free amplification in the gain-saturated regime, and (b) broadband gain, high saturation power, and low noise

3. Device Structure

To achieve a gain covering 1.5-μm band, we used InAs Stranski-Krastanow QDs on InP (100) substrate, suitable for increasing the QD size due to a smaller lattice mismatch, and for increasing the current density by embedding in a current-confining structure (Fig. 2). We introduced a tilted waveguide having an 8-degree off angle and window structure to suppress lasing action up to thermal limit of the current density. The waveguide length, stripe width, number of QD layers, and density of QDs were 6.15 mm, 2.2 μm, 5, and 4 × 10^{10} cm^{-2}, respectively.

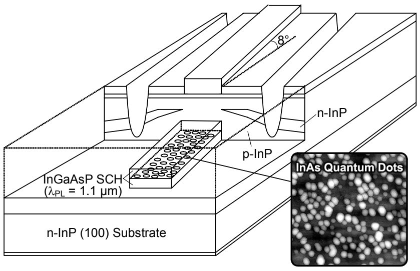

Fig. 2 Structure of a quantum-dot SOA.

4. Bandwidths of Gain, Noise Figure, and 3-dB Saturation Output Power

With the distinctive properties of QDs (Fig. 1 (b)) combined with the structure in Fig. 2, we have successfully achieved a gain of > 20 dB, NF of < 7 dB, and P_{sat} of > 19 dBm, over the record widest bandwidth of 120 nm (hatched areas in Figs. 3 (a) - (c)), which has been unachievable with bulk or QW SOAs. It should also be noted that, this bandwidth is the widest among *all kinds of* optical amplifiers (Fig. 5 (a)).

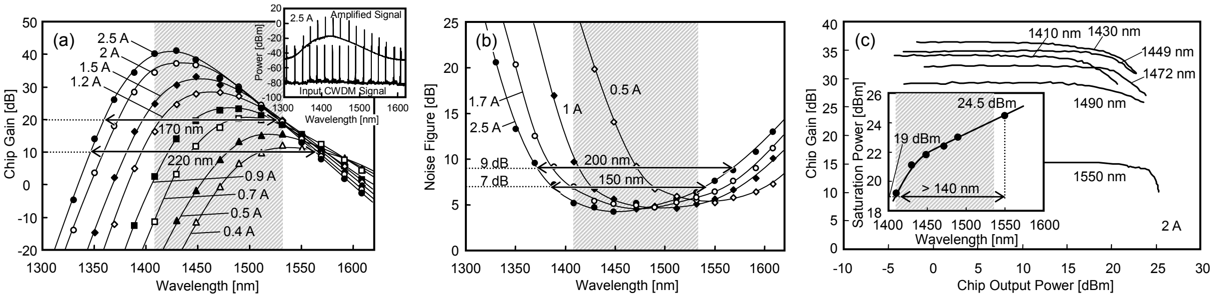

Fig. 3 Bandwidths of (a) gain, (b) NF, and (c) 3-dB saturation output power. The hatched areas are the wavelength range where gain of > 20 dB, NF of < 7 dB, and 3-dB saturation output power of > 19 dBm can be achieved at the same time.

5. Waveform Quality in Gain-Saturated Regime and Penalty-Free Maximum Output Power

Due to another property of QDs explained in Fig. 1 (a), we also succeeded in suppressing waveform distortion in the gain-saturated regime and in effectively increasing the usable output power (Fig. 4 (a)). For comparison, results obtained with a 1.2-mm-long 6-layer 0.8%-compressive InGaAsP QW SOA having P_{sat} of 17 dBm, and a 1.6-μm stripe width is shown in Fig. 4 (b). The waveform for output power as high as 22.8 dBm (Fig 4 (a)) is quite similar to the input and the corresponding Q-factor change shown in the lower part is negligible although measured in the gain-saturated regime. In contrast, the degradation of Q factor in a QW SOA is significant in the gain-saturated regime (Fig. 4 (b)). The slight increase in Q factor, i.e. regeneration around the beginning of the gain-saturated regime for the QD SOA can be attributed to the “1”-level-noise suppression by the intensity limiting action of ultrafast gain nonlinearity. Due to this ultrafast gain nonlinearity, the QD SOA shows quite a small pattern effect even in the deep gain-saturated regime (25.7 dBm output power).

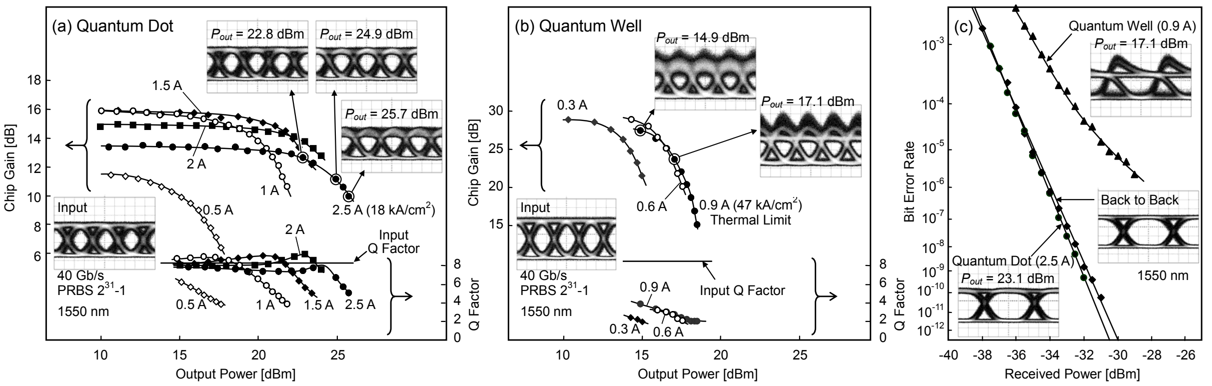

Fig. 4 Gain saturation characteristics and waveform quality of amplified signal as a function of average output power for (a) quantum-dot, and (b) quantum-well SOA. (c) Bit error rate and eye diagrams tested at 10 Gb/s.

The high-quality waveform of QD SOAs ensures a negligible error-free power penalty for an output power as high as 23.1 dBm (Fig. 4 (c)), which is 3-dB improvement compared to our previous result [9], and far superior (+ 8 dB) to the best results obtained by the conventional SOAs (Fig. 5 (b)). It should also be noted that, this high penalty-free output power can be obtained without sacrificing energy conversion efficiency, P_{out} / I.

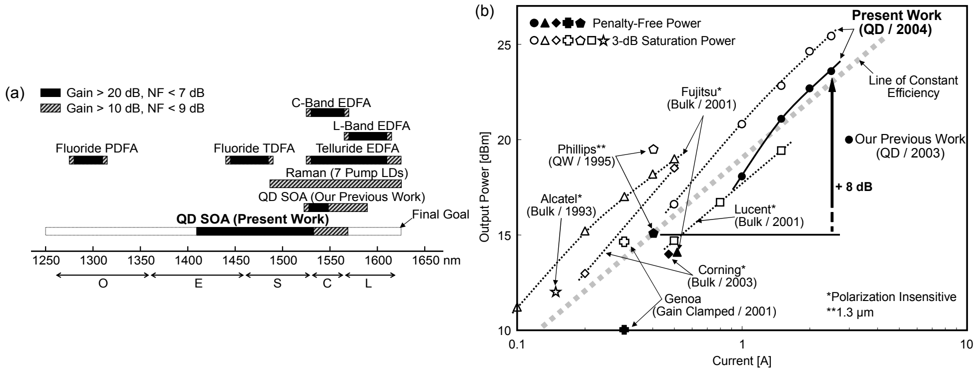

Fig. 5 (a) Comparison of bandwidth. Black (hatched) bars are bandwidths satisfying both gain of > 20 dB (10 dB) and NF of < 7 dB (9 dB). (b) Comparison of penalty-free output power.

6. Summary

In summary, we have shown QDs to be very effective both in increasing the bandwidth and in increasing the penalty-free output power, enabling to realize a single-chip optical amplifier having the record widest bandwidth of 120 nm among all kinds of optical amplifiers, and a penalty-free output power of 23 dBm, the record highest among all the SOAs.

Acknowledgment

The authors would like to acknowledge T. Yamamoto, and E. Ishikawa for their support and discussions. This work belongs to Photonic Network Project which OITDA contracted with NEDO.

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[19] Although this decreases the gain per length, it can be compensated by increasing the device length.
[20] Noise figure decreases with an increase in the carrier occupation probability of the states.