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High-Power Broadband Amplification and High-Speed Optical-Signal Processing by Quantum-Dot Semiconductor Optical Amplifiers

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1. Introduction

Quantum-dot semiconductor optical amplifiers (SOAs) have opened a new frontier in the field of semiconductor optical devices for high-capacity and flexible optical data transmission. Since we first proposed multi-wavelength and high-speed pattern-effect-free signal amplification and processing by quantum-dot SOAs based on their nonlinear optical properties [1] and our device theory [2,3], we have discovered and demonstrated diverse promising features both theoretically and experimentally [4-10]. Among them are high-saturation-power, broad-gain-bandwidth, low-power-consumption, low-noise, and pattern-effect-free amplification of single- and multi-channel signals [4-7,10], pattern-effect-free high-speed wavelength conversion by the cross-gain modulation [5-8,10], and symmetric high-speed wavelength conversion by nondegenerate four-wave mixing [9,10]. We expect these promising features of quantum-dot SOAs to provide high-performance amplifiers as well as all-optical switches in the next-generation photonic networks. This paper highlights their operation principles, promising features, and recent progress in the 1.5-μm wavelength region.

2. Device Structure and Operation Principles

Self-assembled InGaAs semiconductor quantum dots on GaAs substrates and their application to semiconductor lasers have been intensively studied since the 90s. They are nano-size semiconductor islands with a wetting layer grown via the Strasnki-Krastanow mode under highly-mismatched epitaxy.

The quantum-dot SOA has the active region including self-assembled quantum dots embedded in the middle of the light waveguide, and operates in the way that the current is injected into the active region, and the input optical signals are amplified via the stimulated emission or processed via incoherent and coherent optical nonlinearities by the quantum dots.

3. Promising features of quantum-dot SOAs

We developed an operation theory to describe the linear and nonlinear optical response of quantum-dot SOAs with arbitrary spectral and spatial distribution of quantum dots in the active region under the multi-mode light [10]. Promising features predicted based on the quantum-dot SOA theory are listed as follows:

High-power, low-power-consumption, low-noise, and broad-gain-bandwidth amplification: High saturation power originates from the small modal differential gain due to their small crystal size (volume effect) as well as due to their discrete density-of-states (quantum effect). A theoretical calculation using typical material parameters of self-assembled quantum dots shows a 3-dB saturation power of 23 dBm with the amplifier gain of 15 dB at the length of 1.2 mm. Low noise figure is realized under low power consumption because the population inversion factor approaches to one under low current injection due to both volume and quantum effects. The inhomogeneous gain broadening due to size fluctuation and the low density–of-states due to the volume effect result in the broad gain bandwidth.

High-speed amplification under gain saturation without pattern effect: In quantum-dot SOAs, gain saturation occurs by the incoherent spectral hole burning due to slow response time of gain saturation of several femtoseconds, and due to the prevention of carrier transfer among spatially localized dots. Pattern effect is negligible owing to the compensation of the spectral hole by the carriers relaxing from the excited states including the wetting layer, i.e., the upper states work as carrier reservoirs. As a result, we can expect high-bit-rate (40 to160 Gb/s) amplification under gain saturation without pattern effect. This opens way to optical regenerators and wavelength convertors.

Multiwavelength amplification and processing: Spatial isolation of dots prevents the transfer of carriers among dots, leading to negligible cross talk between different wavelength channels under gain saturation, when the channels are separated by more than the homogeneous broadening.

High-speed cross gain modulation without pattern

effect: The interaction of two different wavelength channels occurs due to incoherent and coherent spectral hole burning when both channels are within the homogeneously broadened spectral hole. This enables the high-bit-rate (40 to 160 Gb/s) cross gain modulation without pattern effect, which can be applied to various optical switching like wavelength conversion.

Symmetric wavelength conversion by four-wave mixing: Conventional SOAs with the bulk or quantum-well active region have a serious drawback in the four-wave mixing wavelength conversion that the detuning dependence of the conversion efficiency to a longer wavelength shows a strong dip. This is due to the destructive interference of the two major coherent nonlinear components named the carrier density pulsation and the coherent spectral hole burning [11]. In quantum-dot SOAs, we can expect highly efficient symmetric wavelength conversion due to the enhanced coherent spectral hole burning caused by retarded carrier relaxation, and due to the decreased carrier density pulsation in the discrete energy states.

4. Quantum-Dot Amplifiers in the 1.5-μm Range

Figure 1 shows our state-of-the-art device structure. To achieve a gain covering 1.5-μm band, we used InAs Stranski-Krastanow quantum dots on InP (100) substrate. We embedded the dot active layer in a current-confining structure. We introduced a tilted waveguide having an 8-degree off angle and a window structure to suppress lasing action up to thermal limit of the current density. The waveguide length, stripe width, number of dot layers, and density of dotss were 6.15 mm, 2.2 μm, 5, and 4 x 10^{10} cm^{-2}, respectively.

Figure 2 shows the pattern-effect-free operation and high-power property to ensure the high-quality waveform as well as a negligible error-free power penalty for a chip-out power as high as 23.1 dBm, which is far superior to the quantum-well SOA. Note the slight improvement of the power penalty. This can be attributed to the suppression of high-level noise due to intensity limiting action of ultrafast gain nonlinearity, which is 2R regeneration [3].

Acknowledgments

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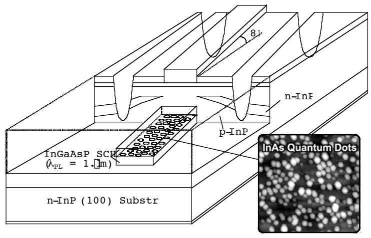

Fig. 1 Device structure

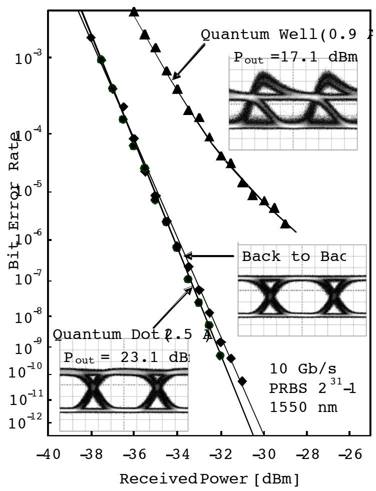

Fig. 2 Bit error rate and eye diagrams