Quantum-Dot-Based Photonic Devices

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Adopting nanometer-sized semiconductor particles, called quantum dots, in the active regions of photonic devices provides the characteristics specific to 3-dimensional quantum effects. This will greatly improve the performance of photonic devices in many respects. We are developing quantum-dot lasers and quantum-dot optical amplifiers through joint research conducted with the University of Tokyo. This paper introduces our development of technology for these devices, along with some recent results. For quantum-dot lasers, we have realized temperature-insensitive direct modulation at a modulation rate of 10 Gb/s in the 1.3-μm wavelength range. We have also fabricated high-performance, quantum-dot optical amplifiers with a wide bandwidth of over 100 nm, high gain of 20 dB, and high optical output power of over +20 dBm. Fujitsu established a venture company called QD Laser, Inc., through a joint capital investment with Mitsui Venture Capital Corporation to commercialize these high-performance quantum-dot-based photonic devices.

1. Introduction

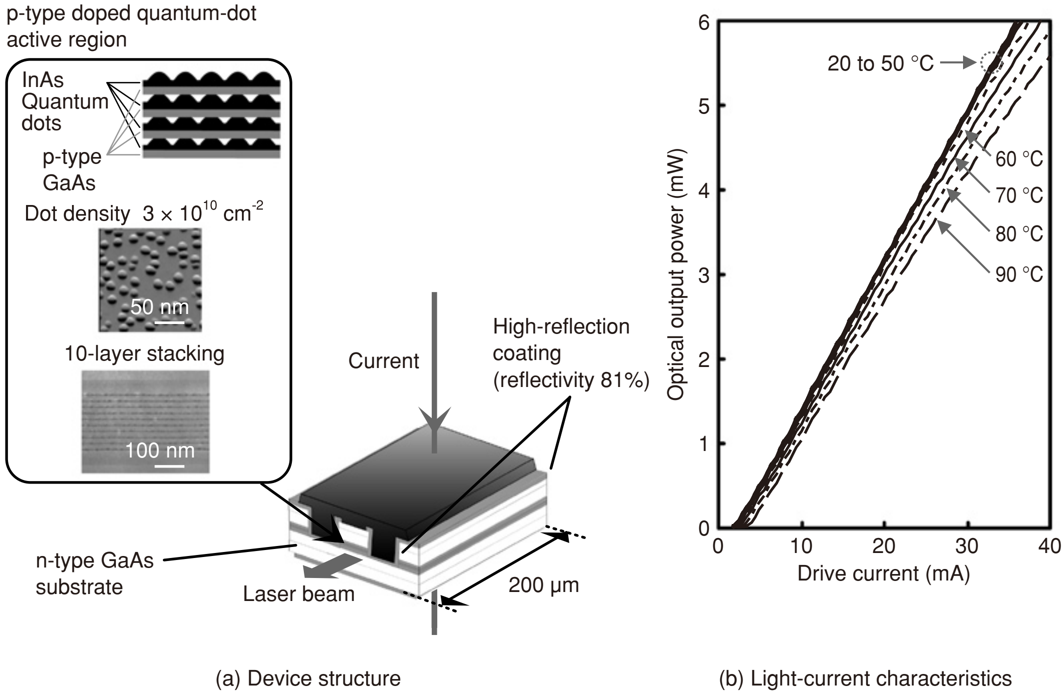
Quantum dots are nanometer-sized semiconductor particles. As the diameter of one quantum dot is about several ten nanometers, equivalent to the total length of several tens to several hundreds of atoms, a quantum dot has quantum effects in all directions in 3-dimensional space, which shows unique properties. Therefore, by using the many quantum dots formed on a semiconductor substrate in the active regions of such photonic devices as semiconductor lasers and semiconductor optical amplifiers (SOAs) for optical communication, unique characteristics not obtained in conventional devices can be provided. For example, semiconductor lasers using quantum dots can have temperature-insensitive characteristics, while optical amplifiers using quantum dots can have high optical output power and wide-band characteristics. The authors initiated research and development in this field during the early 1990s, and have since sustained the lead in this field.[1)-4)] Our recently developed devices based on technologies accumulated over a relatively long time have characteristics specific to quantum dots.

This paper introduces our current development of technology for quantum-dot lasers and quantum-dot optical amplifiers, along with some recent results, through joint research being conducted with the University of Tokyo.

2. Quantum-dot lasers

Adopting nanometer-sized, 3-dimensional structures such as quantum dots in the active regions of semiconductor lasers reduces the current required for laser oscillation and reduces the dependence on temperature. These effects come from that an electron in a quantum dot can only occupy a specific energy level due to the quantum effect. Improving the performance of semiconductor lasers in this way was first proposed in 1980s.[5] To make nanometer-sized structures, the self-assembling method of naturally assembling quantum dots during crystal growth under specific conditions was developed in the early 1990s. This self-assembling method has since been used as a mainstream method in fabricating nanostructures for the active regions of semiconductor lasers. The characteristics of quantum-dot lasers have been improved in line with advances made in such crystal growth technologies as the size and density control technologies of naturally assembled quantum dots. In the 21st century, then, the theoretically predicted unique characteristics of quantum-dot lasers have been realized. The authors have advanced the research on quantum-dot lasers based on quantum-dot crystal technologies that have been researched since the early 1990s. The authors recently developed the world's first semiconductor lasers which provide temperature-insensitive direct modulation at a modulation rate of 10 Gb/s, the highest modulation rate for direct-modulation lasers in practical use, in the 1.3-µm wavelength range. The temperature-insensitive characteristics, which could not be realized in conventional lasers, are the effects of quantum dots.

Figure 1 (a) schematically shows the structure of the developed 1.3-µm wavelength quantum-dot laser.[4] Unlike in conventional lasers for optical communication already used in practical applications, GaAs is used as a substrate in this laser. The active region is made of InAs quantum dots with an area density of 3×10^{10} cm^{-2}. The authors designed the structure to realize 10 Gb/s high-speed modulation and low operating current by using an analysis model which took the effects specific to quantum-dot lasers into account. As a result, the laser was made of ten quantum-dot layers, with a cavity length of 200 µm and both facets of the laser high-reflection coated with the reflectivity of 81%. The other important point is to



(a) Device structure (b) Light-current characteristics

Figure 1
Quantum-dot laser.

provide holes beforehand in the quantum dot by doping p-type impurities near the quantum dot. This reduces the temperature dependence. **Figure 1 (b)** shows the light-current characteristics when the temperature changes from 20°C to 90°C. In conventional lasers, the characteristics change in response to a rise in temperature. Conversely, constant light-current characteristics are obtained in quantum-dot lasers regardless of temperature change. When the temperature exceeds 60°C, the threshold current gradually rises and optical output power decreases. However, even at 90°C, the variations in optical output power remain within a narrow range. **Figure 2** shows the temperature dependence of extinction ratio and modulation waveforms under 10 Gb/s modulation of this laser. In this experiment, the driving conditions of the laser were constant regardless of temperature. We confirmed that the extinction ratio was maintained and good modulation waveforms were obtained under 10 Gb/s modulation in the temperature range of 20°C to 90°C without adjusting the driving conditions. To use conventional lasers without temperature control, the driving conditions must always be adjusted according to temperature. As shown in

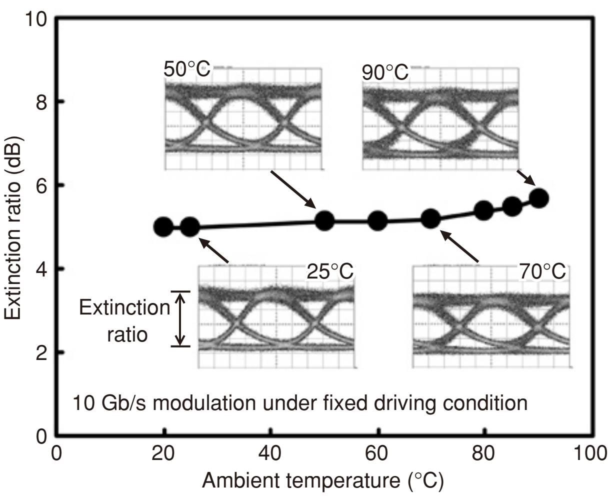


Figure 2
10 Gb/s modulation characteristics of quantum-dot laser.

Figure 2, however, quantum-dot lasers could be simply used without adjusting the driving conditions. We then conducted a data transmission experiment using multiple mode fibers (MMF) primarily utilized in a local area network (LAN). In this experiment, we combined this laser with a receiver that contained an electric dispersion compensator (EDC). We confirmed that error-free transmisson could be achieved over 300-meter-long MMF at a modulation rate of 10 Gb/s.[6)]

We will establish these device technologies for product commercialization, and also develop the technologies for single-mode oscillation and for 1.55 μm-wavelength lasers.

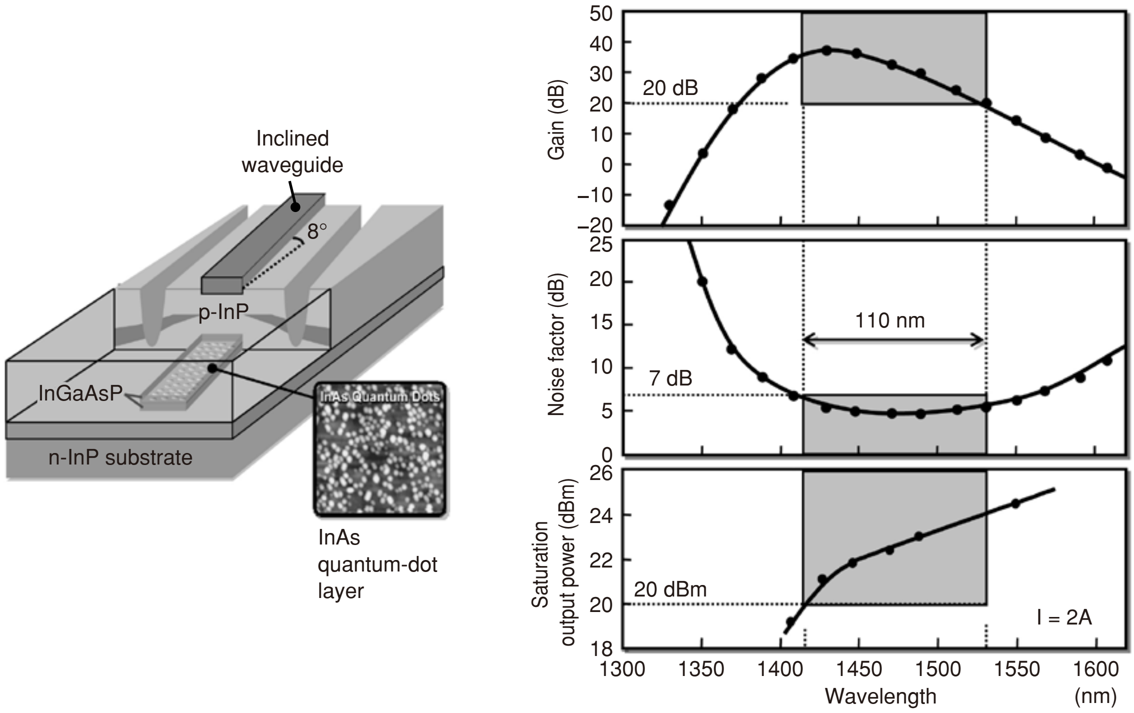
3. Quantum-dot optical amplifiers

To correctly receive optical signals on the receiving side, an optical communication system needs optical amplifiers to amplify directly the optical signals that are attenuated due to transmission loss in the optical fibers. Present optical communication systems, particularly trunk-line optical communication systems, primarily use erbium-doped fiber amplifiers (EDFA). EDFA is characterized by a small coupling loss and no polarization dependent loss (PDL). However, we must consider several problems to be resolved in next-generation optical communication networks having an extended transmission band, higher optical packet routing capacity, and faster speed. In other words, the amplification band is restricted to the C/L-band, the response speed is slow (submilliseconds), and device downsizing difficult. SOAs are characterized by a wide gain band, flexible design of wavelength-range, high-speed response (nanoseconds), small device size, and easy integration. Since EDFA lacks these superior characteristics, SOAs are expected to be used as optical amplifiers for next-generation optical communication networks.

In particular, quantum-dot-based SOAs are generally superior to bulk and quantum-well

SOAs, in terms of band, output power, noise, operation speed, and power consumption characteristics. These superior characteristics of quantum-dot-based SOAs are attributed to an effective increase in carrier density and wider carrier energy distribution. These are due to the quantum-dot quantum effect and nano-size effect. The authors proposed such characterized quantum-dot SOA first in the world, and then produced and demonstrated prototypes.[3),7)] **Figure 3 (a)** shows the structure of the quantum-dot SOA; **Figure 3 (b)** shows its amplification characteristics. As shown in this figure, an InGaAsP optical waveguide is formed on the InP substrate with InAs quantum dots formed in the active region in the optical waveguide. The InAs quantum dots are distributed at a density of 2 to 8 × 10^{10} cm^{-2}. The dimensions of the InAs quantum dot are 20 to 40 nm in width and 1 to 10 nm in height. A nonreflecting film is formed on the both end facets with the optical waveguide inclined by 8 degrees from the end facet to suppress laser oscillation. A current confining structure is formed to efficiently supply current to the active region, based on the optical device design and manufacturing technologies developed by Fujitsu Laboratories for many years. As shown in the amplification characteristics in Figure 3 (b), a gain of 20 dB, saturation output power of 20 dBm or more, and noise factor of 7 dB or less were demonstrated in a wide band of over 100 nm, which is least three times as wide as the EDFA wavelength band. We also demonstrated that 10-Gb/s modulation signals can be amplified up to an output power of 23.1 dBm without distortion. Unlike our quantum-dot devices, devices made of conventional materials cannot provide such characteristics.

The polarization direction of the input signal beam always changes depending on such



(a) Structure

(b) Amplification characteristics

Figure 3
Quantum-dot optical amplifier.

transmission-path environment conditions as temperature and distortion. Accordingly, the characteristics of an amplifier for practical use must be free from polarization dependency. The conventional quantum-dots formed by the self-assembling method have a flat structure and include 2-axis compressive strain. These quantum-dots respond to transverse electric (TE) polarization (transversal waves), but do not respond at all to transverse magnetic (TM) polarization (longitudinal waves). The authors successfully developed a unique quantum-dot structure that provides amplification characteristics having no polarization dependency. **Figure 4 (a)** shows this unique structure.[8] Here, 10 to 25 conventional quantum-dots are stacked vertically with a gap of 1 nm to form this isotropic structure. Moreover, strain opposite to the one of the quantum dot is added to the semiconductor material that covers the quantum dot to minimize the strain of the quantum dot. **Figure 4 (b)** shows the polarization dependence of the gain spectrum (amplified spontaneous emission [ASE]) of the prototype produced using the quantum dots with this unique structure. The height of the quantum dot is 11 nm in the graph on the left side of this figure, while the height is 22 nm in the graph on the right side. The quantum-dot device on the left side has larger gain in TE polarization, but the quantum-dot device on the right side has larger gain in TM polarization. This suggests that a polarization-independent structure will be obtained between these quantum-dot structures.

We are now attempting to develop and demonstrate polarization-independent, wide-band, high-output, and low-noise quantum-dot devices by optimizing the device structure.

4. Conclusion

This paper introduced the technologies

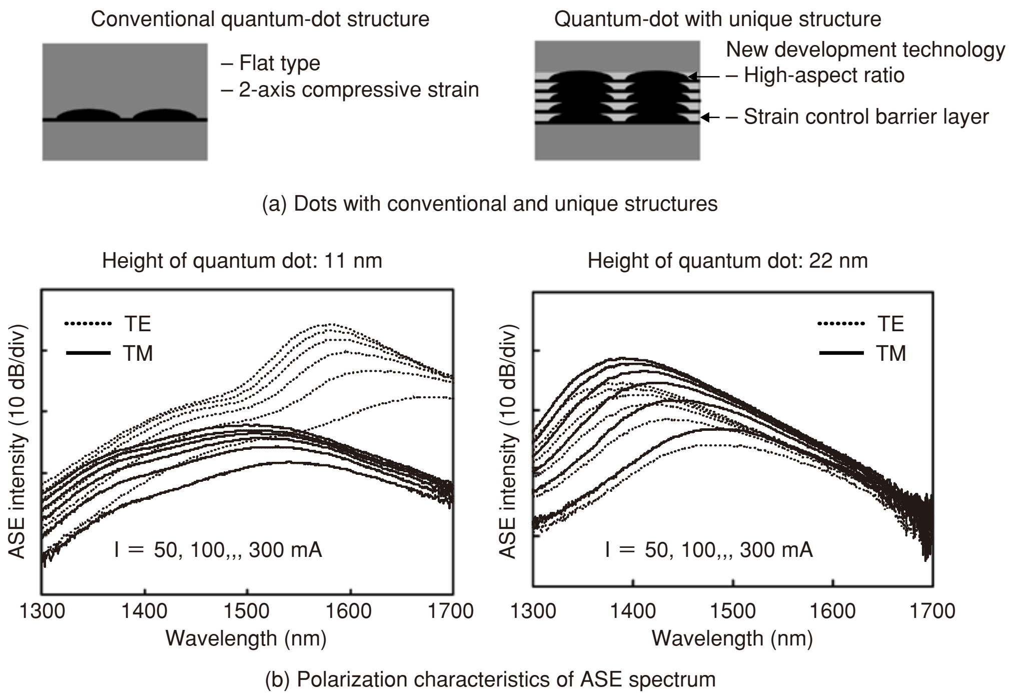


Figure 4
Technologies for polarization independence.

being developed by the authors for quantum-dot lasers and quantum-dot optical amplifiers. In April 2006, Fujitsu established a venture company called QD Laser, Inc., through a joint capital investment with Mitsui Venture Capital Corporation in order to commercialize these high-performance quantum-dot-based photonic devices having superior characteristics as described above. We will continue this development through joint research being conducted with the University of Tokyo and Fujitsu Laboratories, in order to release quantum-dot photonic devices in the optical communications market as soon as possible.

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References

1) K. Mukai et al.: Self-Formed $In_{0.5}Ga_{0.5}As$ Quantum Dots on GaAs Substrates Emitting at 1.3 µm. *Jpn. J. Appl. Phys.,* **33**, p.L1710-L1712 (1994).

2) K. Mukai et al.: 1.3-µm CW Lasing of InGaAs-GaAs Quantum Dots at Room Temperature with a Threshold Current of 8 mA. *IEEE Photon. Technol. Lett.,* **11**, p.1205-1207 (1999).

3) T. Akiyama et al.: An Ultrawide-Band Semiconductor Optical Amplifier Having an Extremely High Penalty-Free Output Power of 23 dBm Achieved with Quantum Dots. *IEEE Photon. Technol. Lett.*, **17**, p.1614-1616 (2005).

4) M. Ishida et al.: Low-driving-current temperature-stable 10 Gbit/s operation of p-doped 1.3 µm quantum-dot lasers between 20 and 90°C. *Electron. Lett.*, **43**, p.219-221 (2007).

5) Y. Arakawa et al.: Multidimensional qunatum well laser and temperature dependence of its threshold current. *Appl. Phys. Lett.*, **40**, p.939-941 (1982).

6) T. Yamabana et al.: Temperature independent transmission for 10 Gbps 300 m-MMF using low driving-current quantum dot laser. Optical Fiber Communication Conference (OFC2006), OFL3, March 2006.

7) M. Sugawara et al.: Theory of Optical Signal Amplification and Processing by Quantum-Dot Semiconductor Optical Amplifiers. *Phys. Rev. B*, **69**, 235332 (2004).

8) N. Yasuoka et al.: First Demonstration of TM Dominant Gain in Quantum Dot Semiconductor Optical Amplifiers. The 19th Annual Meeting of the IEEE Lasers & Electro-Optics Society (LEOS) post deadline paper, 29 October – 2 November 2006.

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