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Monolithically Integrated Quantum Dot Electro-Optic Modulator with Semiconductor Optical Amplifier for Short-Reach Optical Communications

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Abstract

A monolithically integrated quantum dot (QD) electro-optic modulator (EOM) with a QD semiconductor optical amplifier (SOA) was successfully developed with a broadband QD optical gain material for Gbps-order high-speed optical data transmission. An optical gain change as high as approximately 6–7 dB can be obtained with a low EOM voltage of 2.0 V. An insertion loss was also compensated through the SOA section. Additionally, it was confirmed that the QD-EOM/SOA device helped achieve 6.0-Gb/s error-free optical data transmission over a 2.0-km photonic crystal fiber. These results suggest that the developed QD-EOM/SOA will become attractive for short-reach communications.

1. Introduction

Short-reach interconnection and/or data center networks strongly require a high data transmission capacity and a large number of channels for the many port-to-port connections [1]. Solutions for satisfying these requirements involve the use of alternative wavebands to increase the usable optical frequency range. We recently proposed the use of the T and O bands (thousand band: 1000–1260 nm, O band: 1260–1360 nm) as the alternative wavebands because large optical frequency resources (>10 THz) compared with the C band (1530–1565 nm, 4.4 THz) are easily employed in this waveband [2–4]. Additionally, photonic devices are also expected to have a small footprint and low power consumption in short-reach data transmission. Therefore, we focused on the use of self-assembled quantum dots (QDs) as a three-dimensional confined structure for the development of high-functional photonic devices, because the QD structure is suitable for realizing broadband optical gain media in the T+O band [2, 4]. Furthermore, the QD optical gain material is expected to have many important characteristics, such as a low threshold current and high temperature stability of the optical gain device, and the absence of pattern effects for high-speed data amplification. In this context, we have developed QD photonic devices such as a narrow-linewidth wavelength-tunable QD laser, broadband QD comb laser and short-pulse laser, QD semiconductor optical amplifier (SOA), and photodetector for optical communications [4].

An optical modulator is a critical photonic device for optical data signal generation. In particular, Gbps-order, high-speed optical modulators that are inexpensive and compact are expected to be used in short-reach interconnections. Techniques such as electro-absorption (EA) modulation are employed to achieve compact devices and high-data-rate optical signal generation. Optical data generation at up to 2.5-Gb/s by an external modulator using the EA effect of QDs was previously reported [5]. We expect that complicated short-reach networks will become smart by using the broadband optical frequency resource of the QD optical gain in the T+O band. Therefore, we focus on develsoping a QD electro-optic modulator (EOM) device using the optical gain change. In this paper, we report the successful development of a monolithically integrated QD-EOM with a QD-SOA in the O-band and demonstrate Gb/s-order high-speed optical transmission.

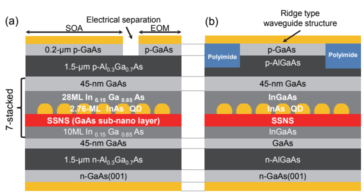

Fig. 1 (a) Side and (b) front schematic images of crystal structure of developed QD-EOM/SOA device.

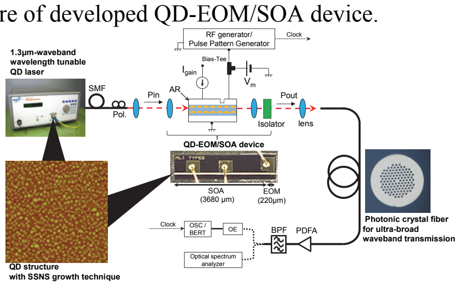

Fig. 2 Opto/electrical setup for characterizing the developed QD-EOM/SOA device, and demonstration of high-speed optical data transmission with the QD-EOM/SOA.

2. Development and characterization of QD-EOM/SOA

An ultrabroadband optical gain medium for the T+O-band can be effectively obtained using a QD growth technique on a large-diameter GaAs wafer. We previously proposed a sandwiched sub-nano separator (SSNS) technique as an effective growth method to obtain high-quality high-density QDs [4]. Figure 1 shows cross-sectional images of a developed QD ridge-type waveguide in the QD-EOM/SOA device. InAs QDs (2.76 monolayers) were grown within an InGaAs quantum well structure using the SSNS growth technique by molecular beam epitaxy. A QD density as high as 8.2×10^{10} cm^{-2} was obtained, and seven highly stacked QD layers can be formed to obtain a broadband optical gain. An electrical separation region for a dual-sectional waveguide was fabricated using an etching sequence in an area a few micrometers wide. The SOA and EOM section lengths were 3680 and 220 μm, respectively.

Figure 2 shows the optical setup for characterization of the QD-EOM/SOA device. A DC current was injected into the SOA section. An RF bias voltage and an offset DC bias voltage were applied to the EOM section. An electrical pulse pattern generator was also applied to evaluate the data transmission. Previously, we successfully developed a wavelength-tunable QD laser in which the QD light source was used as the optical carrier generator in the O-band [4]. The input (P_{in}) and output (P_{out}) optical powers were coupled between a single-mode (SM) optical fiber and the QD device by a collimator lens setup. We also used a 2.0-km holey fiber as a photonic crystal fiber (PCF) to demonstrate optical data transmission, because the ultrabroadband transmission window can be obtained using an endlessly SM characteristic of the PCF [3].

The SOA section is expected to be used for insertion loss compensation. Figure 3(a) shows the dependence of a compensated insertion loss on the SOA current. The input power P_{in} was fixed at approximately -10 dBm for each wavelength. When the SOA current was approximately >50 mA, the insertion loss could be compensated using the SOA section in a broadband 1.3-μm wavelength range. This result clearly shows that the SOA section compensates for the insertion loss of the QD device effectively.

We expect that high-speed optical gain modulation of the QD device will become a key technique for realizing a novel external modulator for the use of many wavelength channels. Figure 3(b) shows the typical dependence of the optical gain change on the bias voltage applied to the EOM section when the SOA current is fixed at 50 mA. We divide the optical gain change into three regions, as shown in Fig.

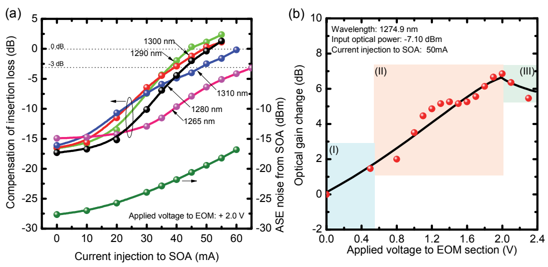

Fig. 3 (a) Insertion loss compensation characteristics of the QD-SOA section in broad wavelength range (1265-1310 nm), and ASE noise from SOA. (b) Typical dependence of optical gain change on DC bias voltage applied to EOM section.

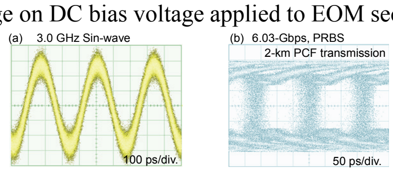

Fig. 4 (a) 3.0-GHz sin-wave form and (b) clear eye opening for 6.0-Gb/s data transmission over 2.0-km-long PCF using QD-EOM/SOA device. Error-free (BER < 10^{-9}) operation was confirmed for 6.0-Gb/s and 2.0-km-long data transmission.

3(b). The optical gain increased with increasing bias voltage up to +2.0 V [region II in Fig. 3(b)] and then saturated or decreased slightly with further increases in the voltage (region III). Additionally, the optical absorption of the EOM section is considered to be decreased in region I, because the photovoltaic effect was observed in the *I–V* characteristics. From Fig. 3(b), we obtained a large optical gain change of approximately 6–7 dB using the QD-EOM device with a low bias voltage of +2.0 V. These results demonstrated that the optical intensity change of the carrier is clearly controlled by controlling the EOM bias voltage.

3. QD-EOM/SOA device for optical data transmission

We estimated the usability of the QD-EOM/SOA device for high-speed optical data transmission. Figure 4 shows a 3.0-GHz sin-wave form and clear eye opening for a 6.03-Gb/s amplitude shift-keying signal after 2.0-km PCF transmission. A pseudorandom binary sequence (PRBS) electrical signal (V_{pp}: 2.0 V, data length: 2^7-1) was applied to the QD-EOM section with a DC offset bias voltage. Additionally, a limiting amplifier was used at the back of the photodetector. We successfully confirmed error-free [bit error rate (BER) < 10^{-9}] 6.0-Gb/s data transmission over a 2.0-km PCF using the developed QD-EOM/SOA device.

4. Conclusions

Using the high-quality broadband QD optical gain, a monolithically integrated QD-EOM with a QD-SOA was successfully developed for Gbps-order high-speed optical data transmission in the 1.3-μm waveband. It was observed that the insertion loss can be compensated through the SOA, and an optical gain change as high as approximately 6–7 dB can be obtained with a low voltage of 2.0 V. It was also confirmed that the QD-EOM/SOA device helped achieve 6.0-Gbps error-free optical data transmission over a 2.0-km-long PCF. These results suggest that the developed monolithic QD-EOM/SOA device will become attractive for increasing the number of wavelength channels for simple high-speed short-reach communications.

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