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Monolithically Integrated Quantum Dot Optical Modulator with Semiconductor Optical Amplifier for T-Band Optical Communication

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Abstract

A monolithically integrated quantum dot (QD) optical gain modulator (OGM) with a QD semiconductor optical amplifier (SOA) was successfully developed with T-band QD optical gain material for Gbps-order high-speed optical data generation. Insertion loss due to coupling between the device and optical fiber was effectively compensated for with the SOA section. It was also confirmed that the monolithic QD-OGM/SOA device helped achieve > 4.8 Gbps optical data generation with clear eye opening. These results suggest that the developed monolithic QD-OGM/SOA device will be advantageous in ultra-broadband optical frequency systems that utilize the T-band that for short- and middle-range optical communications.

1. Introduction

High-capacity and high-speed photonic networking and device technologies are essential for constructing advanced short- and middle-range communication systems. Additionally, high-capacity wireless connections have been widely developed and standardized in recent years. Moreover, radio-over-fiber (RoF) systems and short-reach interconnections and/or data center networks require large numbers of channels for their many port-to-port connections [1]. Solutions that satisfy these requirements involve two technical processes to increase the operational optical frequency range: the use of alternative wavebands and the use of ultra-broadband photonic devices and materials. As an alternative waveband application, we recently proposed the use of the Thousand (T) and O bands (T band: 1000–1260 nm; O band: 1260–1360 nm) because large optical-frequency resources (>70 THz) are easily employed in these wavebands [2 - 4]. Self-assembled quantum dot (QD) structures are one of the most promising candidates for realizing high-performance broadband optical gain media in the T+O band [2]. It is also expected that QD optical gain materials will enable high-temperature device stability and pattern-effect-free amplification of the data signals.

On the other hand, a Gbps-order high-speed optical modulator is a critical photonic device for optical data and high-frequency optical signal generation and distribution. In particular, inexpensive and compact Gbps-order high-speed optical modulators are expected to be used in RoF systems and as an interconnection between short- and middle-range communications. Recently, devices such as QD optical modulators have been intensively investigated with the objective of achieving compact optical modulators. We therefore focused on the development of a QD optical modulator and QD semiconductor optical amplifier (SOA) by using ultra-broadband QD optical gain media in the T+O band [4]. In this paper, we report first the successful development of a monolithically integrated QD optical gain modulator (OGM) with a QD-SOA device for T-band Gbps-order high-speed optical signal generation.

2. Development of monolithic QD-OGM/SOA device

An ultra-broadband optical gain medium for the T+O band can be effectively obtained by using a QD growth technique on a large-diameter GaAs wafer. We previously developed a high-growth-rate epitaxial technique to obtain high-quality and high-density QDs. Figure 1 shows cross-sectional images of a developed QD ridge-type waveguide of the monolithic QD-OGM/SOA device.

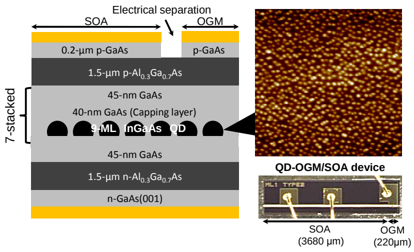

Fig. 1 Cross-sectional schematic of crystal structure of monolithic QD-OGM/SOA device. Right picture shows 1 µm^2 AFM image of QD and top view of developed QD-OGM/SOA device.

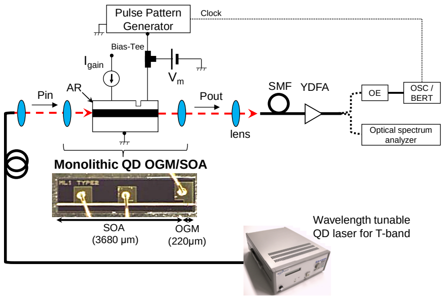

Fig. 2 Opto/electrical setup for characterizing developed device, and demonstration of high-speed optical data generation with monolithic QD-OGM/SOA device.

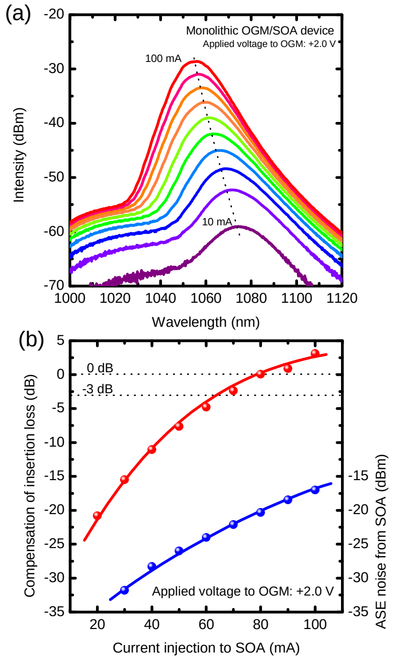

Fig. 3 (a) ASE spectra from SOA section of monolithic QD-OGM/SOA device for various DC currents (10~100 mA) applied to SOA section. (b) Insertion loss compensation characteristics of QD-SOA section of fixed T-band wavelength of 1060 nm, and ASE noise from SOA.

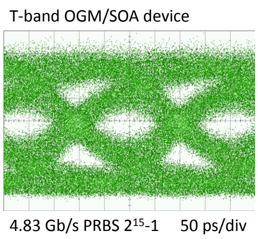

Fig. 4 Clear eye opening for 4.82 Gbps data generation using monolithic QD-OGM/SOA device in T band. Carrier wavelength is fixed at 1060 nm.

$In_{0.4}Ga_{0.6}As$ QDs (9.0 monolayers) were grown within a GaAs matrix by molecular beam epitaxy. Seven highly stacked QD layers can be formed to obtain a broadband optical gain in the T-band. An electrical separation region for a dual-sectional waveguide was fabricated by using an etching sequence in an area a few micrometers wide.

Figure 2 shows the optical setup for characterization of the QD-OGM/SOA device. A DC current was injected into the SOA section. An RF bias voltage and offset DC bias voltage were applied to the OGM section. An electrical pulse pattern generator was also applied to evaluate the data generation. 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.

Figure 3(a) shows the amplitude spontaneous emission (ASE) spectra from the developed QD-OGM/SOA device during an SOA current injection. The spectrum clearly reveals that the peak wavelength of the ASE occurs in the T band. Thus, it is anticipated that the developed monolithic QD-OGM/SOA device can be applied in T-band optical communications. The SOA section is expected to be used for insertion-loss compensation. Insertion loss is a significant problem when using a high-index waveguide device in a photonic network. We anticipate that the QD-SOA section will be important in insertion-loss compensation. Figure 3(b) shows the dependence of insertion-loss compensation on the SOA current. The input power P_{in} was fixed at approximately -10 dBm. When the SOA current was approximately >80 mA, the insertion loss could be compensated (Insertion loss: 0 dB) for with the SOA section. This result clearly reveals that the SOA section can effectively compensate for insertion loss in a QD device.

We expect that high-speed optical gain modulation of QD devices will be key technique in realizing a novel external modulator that utilizes many wavelength channels. We estimated the usability of the QD-OGM/SOA device for high-speed optical data generation. Figure 4 shows an eye diagram of Gbps-order amplitude shift-keying signal generation obtained by using the monolithic QD-OGM/SOA device. A pseudorandom binary sequence (PRBS) electrical signal (V_{pp}: 2.0 V; data length: 2^{15}-1) was applied to the QD-OGM section with a DC offset bias voltage. Additionally, an electrical low-pass filter was used at the back of the photodetector. We successfully confirmed clear eye opening for > 4.8 Gbps data generation by using the developed QD-EOM/SOA device in the T band.

4. Conclusions

By using the high-quality T-band QD optical gain, a monolithically integrated QD-OGM with a QD-SOA was successfully developed for Gbps-order high-speed optical data generation. It was demonstrated that the monolithic QD-OGM/SOA device helped achieve over 4.8 Gbps optical data generation with a clear eye opening in the T-band. Additionally, it was clearly observed that the insertion loss based on the optical fiber coupling could be compensated for effectively by using the SOA section. These results suggest that operating the developed monolithic QD-OGM/SOA device in the T band will be advantageous as the large number of wavelength channels in the T band can then be utilized for simple high-speed short- and middle-range optical communications.

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