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Characterization of wavelength tunable quantum dot external cavity laser (QD-ECL) for 1.3-μm waveband narrow line-width coherent light source

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1. Introduction

The expansion of wavelength division multiplexing (WDM) channels increases usable wavelength bands and optical frequency resources. Therefore, we have recently focused on thousand-band (T-band) and O-band (1.00–1.26 μm and 1.26–1.36 μm, respectively) for optical communications because optical frequency resources greater than 10 THz can be employed at these wavebands [1, 2]. It has been anticipated that these wavelength bands will be used for metro/access photonic networks and as optical interconnects in datacenters [3]. To increase the frequency utilization efficiency for data transmission, coherent communication technology has also been intensively investigated worldwide. One of the essential components for realizing a coherent communication system is a narrow line-width wavelength tunable coherent light source. It is well known that a narrow spectrum line-width of less than a few hundred kHz is required to achieve a quadrature amplitude modulation (QAM) format [4]. In the near future, it is believed that coherent communication technology will be applied to the T- and O-bands of photonic transport systems to achieve optical communications with ultra-high bit-rates and capacities.

A self-assembled quantum dot (QD) laser diode fabricated on a large-diameter GaAs wafer has attracted considerable attention as a T-band or O-band light source as it offers low cost, low power consumption, and high performance. Therefore, we have considered a QD structure to be one of the most promising candidates among optical gain media for lengthening the operating wavelengths of light sources. Additionally, we have proposed a novel sandwiched sub-nano separator (SSNS) growth technique for obtaining high-quality and high-density QD optical gain media operating in the T- and O-bands [2].

Based on these considerations, it is easy to project that a narrow line-width wavelength tunable QD laser will become an essential component for constructing WDM and coherent communication systems operating in the T- and O-bands. Therefore, in this study, we developed and characterized a narrow line-width wavelength tunable InAs/InGaAs QD external cavity laser (QD-ECL) using the SSNS growth technique for O-band operation.

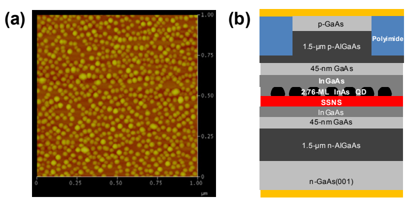

Figure 1 (a) AFM image of InAs/InGaAs QD structure fabricated using SSNS growth technique. (b) Cross-sectional image of ridge-type QD laser diode structure.

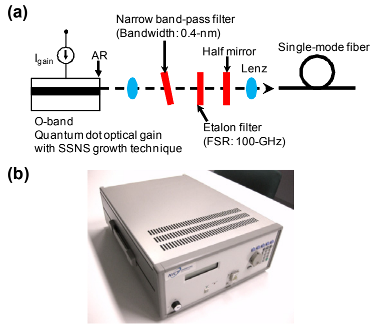

Figure 2 (a) Optical setup for wavelength tunable InAs/InGaAs QD-ECL using optical mode selection technique. (b) Compact bench-top coherent light source of developed narrow line-width wavelength tunable QD-ECL.

2. Fabrication of wavelength tunable QD-ECL using SSNS growth technique

Self-assembled InAs QD structures were grown on (001)-oriented n-type GaAs substrates using solid-source molecular-beam epitaxy (MBE). Recently, we proposed a novel InAs/InGaAs QD structure using an SSNS growth technique [2]. According to this technique, a sandwiched GaAs thin film was used to modify the surface conditions of the quantum well (QW) under the QD structure. Fig. 1(a) shows an atomic force microscope (AFM) surface image of the 2.76-ML InAs QD fabricated on a 10-ML $In_{0.15}Ga_{0.85}As$ QW using the SSNS growth technique. A 3-ML (0.85-nm) GaAs thin film was used as the SSNS structure. We confirmed that the SSNS technique would largely suppress the giant dot structures, achieving an ultra-high QD density of approximately $8.0 \times 10^{10}/cm^2$.

To develop a 1.3-μm waveband QD optical gain chip, a multi-stacked InAs/InGaAs QD as an active-region was formed on the GaAs substrate. Fig. 1(b) is a cross-sectional image of the fabricated optical gain chip consisting of the 7-stacked InAs/InGaAs QD structure fabricated using the SSNS growth technique. Additionally, carrier-doped

1.5-μm AlGaAs cladding layers were grown at 540 °C. A ridge-type waveguide structure was fabricated with an electrode width of 3.4 μm and a waveguide length of 1950 μm. Fig. 2(a) shows the setup of the fabricated QD-ECL. The temperature of the QD gain chip was fixed at 300 K using a thermo-electric controller (TEC). One of the cleaved facets of the QD optical gain chip had an anti-reflection (AR) coat for the 1.3-μm waveband. An external cavity was constructed with a cleaved facet of the QD optical gain chip and a half-mirror (reflectance: 60%), where the total cavity length was as small as approximately 40 mm. We also used a narrow band-pass filter (bandwidth: <0.4 nm) and an etalon filter (free spectrum range: 100 GHz) to select a single optical mode for the lasing. As seen in Fig. 2(b), a compact bench-top coherent light source module was successfully developed for the wavelength tunable QD-ECL.

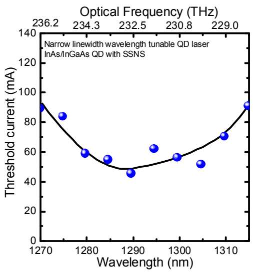

Figure 3 Dependence of threshold current on lasing wavelength of wavelength tunable InAs/InGaAs QD-ECL.

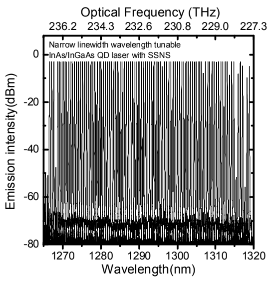

Figure 4 Ultra-broadband tuning-range of wavelength tunable InAs/InGaAs QD-ECL.

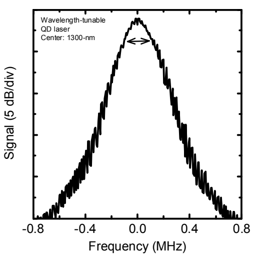

Figure 5 Estimation result for narrow line-width and stable operation of wavelength tunable InAs/InGaAs QD-ECL.

3. Characterization of narrow line-width wavelength tunable QD-ECL

Fig. 3 shows the dependence of the threshold current on the lasing wavelength. The threshold current of the wavelength tunable QD-ECL was as low as approximately 60 mA at a wavelength of around 1.30 μm. However, the threshold current slightly increased in wavelength regions of <1.275 μm and >1.315 μm. The QD optical gain in these wavelength regions is considered to be slightly lower than that at the 1.3-μm wavelength. Fig. 4 shows the wavelength tunable characteristics of the fabricated InAs/InGaAs QD-ECL. In this experiment, the current injection for operating the QD optical gain was fixed at 100 mA. Additionally, the output power was attenuated to -3 dBm. It was found that an ultra-broadband tuning range (>55 nm) between 1.265 μm and 1.320 μm was successfully achieved using the multi-stacked InAs/InGaAs QD optical gain with the SSNS growth technique. Based on the threshold current characteristics shown in Fig. 3, it can be said that this wide wavelength tuning range may correspond to the electrical ground-state of the InAs/InGaAs QD with an SSNS. As an estimation result for the wavelength tunability, it is considered that ultra-broadband optical frequency resources over 10 THz could be employed for O-band WDM communication using this wavelength tunable QD-ECL. We also estimated the optical spectrum line-width of the developed wavelength tunable QD-ECL. Fig. 5 shows the measurement result for the spectrum line-width of the wavelength tunable QD-ECL using a delayed self-heterodyne method when the lasing wavelength peak was fixed at 1.300 μm. In Fig. 5, the modulation frequency was shifted to the center of 0 Hz, and a half value of the frequency was used as the x-axis. It is clearly seen that a narrow line-width at 210 kHz was successfully obtained from the wavelength tunable InAs/InGaAs QD-ECL. It is expected that this narrow line-width of the fabricated QD coherent light source will become a useful device for coherent communications in the O-band.

4. Conclusion

We demonstrated and characterized a narrow line-width InAs/InGaAs QD-ECL with an ultra-broadband wavelength tuning range in the O-band. A high-quality QD optical gain medium for the O-band was obtained using a novel growth method for an SSNS. A wide wavelength tunability of 1.265–1.320 μm and a narrow line-width of 210 kHz were successfully achieved using an external cavity system constructed with an optical mode selection technique.

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