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Tunable Laser with Emission-Wavelength-Controlled InAs Quantum dots for 1.1-µm Waveband Swept-Source Optical Coherence Tomography Applications

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Abstract

An optical gain chip with emission-wavelength-controlled InAs quantum dots (QDs) was developed for 1.1-µm-waveband swept-source optical coherence tomography (SS-OCT) applications. Optical gain spectra of the gain chip were characterized by the Hakki-Paoli method. Then, the tunable lasing of the gain chip with a grating-coupled external cavity was verified. In addition, the tunable external cavity laser was introduced into an SS-OCT system, and was evaluated as a light source for SS-OCT by measurements of its point spread function.

1. Introduction

Optical coherence tomography (OCT) [1], which is a non-invasive profile biological/medical imaging technology, is an attractive application of broadband near-infrared (NIR) light sources. The wavelength of the light probe within the NIR waveband is suitable for OCT because of its large penetration depth in biological samples [2]. In particular, a 1.0–1.1-µm wavelength band provides an optimal balance between absorption and scattering in biological tissues. In addition, a Si-based photodetector can be used for this wavelength band, contributing to an affordable OCT system. Swept-source (SS)-OCT, which uses a tunable laser as a light probe, has been intensively developed because of its longer coherence length, which results in a larger imaging depth. However, a broadband tunable laser is still required, especially for the 1.0–1.1-µm wavelength band, because the broader bandwidth contributes to a higher axial resolution in OCT imaging.

Therefore, an optical gain chip was developed in this study using self-assembled InAs quantum dots (QDs) [3]. The InAs-QDs possess an inherent size distribution and exhibit NIR broadband emission. In addition, the growth conditions can alter the emission center wavelength of QDs spanning 1–1.3 µm. In this work, we optimized the growth conditions of InAs-QDs for realizing a tunable laser in the 1.0–1.1-µm wavelength band, and fabricated and characterized a QD-based optical gain chip. Furthermore, a tunable laser based on the QD-based gain chip was developed and introduced into an SS-OCT system.

2. Experiment

An edge-emitting chip including InAs-QDs was fabricated on a wafer grown using molecular beam epitaxy. As shown in Fig. 1(a), four stacked layers of InAs-QDs were embedded in a 240-nm-thick GaAs waveguide layer, which was sandwiched between 1.5-µm-thick p-/n-$Al_{0.35}Ga_{0.65}As$ cladding layers for optical and electronic confinement. To control the emission wavelength of the InAs QDs, the substrate temperature during the growth and capping processes for each QD layer was set at a slightly higher temperature than that for conventional InAs QDs emitting at a 1.2–1.3-µm wavelength.

A straight ridge-type waveguide (ST-RWG) with a 5-µm width and 1.4-µm height was fabricated using photolithography and dry-etching techniques. After deposition and area-selective wet etching of a thin SiO_2 insulation film on the RWG, contact electrodes were formed on both sides of the wafer. The wafer consequently was cleaved to form an edge-emitting chip of 2 × 2 mm^2, as shown in Fig 1(b).

The chip was characterized under the temperature controlled with a thermoelectric cooler (TEC) at 25 °C. Above the threshold current of approximately 65 mA, the gain chip exhibited edge-emitting Fabry–Perot (F–P) lasing, which can be detected with a Si-based image sensor, as shown in Fig. 1(c). Gain spectra of the fabricated chip were measured by the Hakki–Paoli (H–P) method [4] under various injection currents. The injection current was set below the threshold current of the F–P lasing in the RWG.

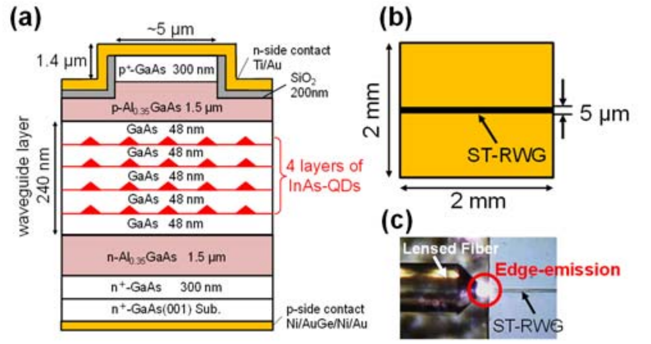

Fig. 1 (a) Schematic profile of a fabricated QD-based gain chip. (b) Illustration of the RWG fabricated on the chip with as-cleaved edges. (c) Photograph of an edge of the RWG coupled to a lensed fiber.

The QD-based gain chip was introduced into a grating-coupled external cavity (EC), and the tunable lasing was evaluated. Then, the QD-based EC tunable laser was introduced into an SS-OCT system, which we set up as shown in Fig. 2. The point spread function (PSF) was measured through interference signals between a reference mirror and a sample mirror set at an optical path difference of 300 µm.

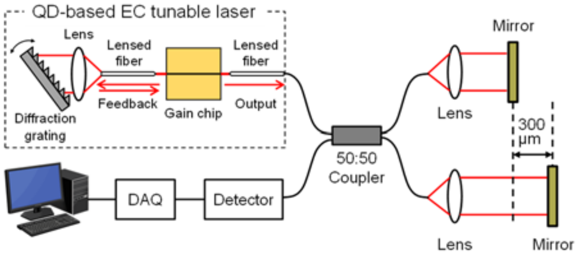

Fig. 2 Schematic of the SS-OCT system with the QD-based EC tunable laser.

3. Results and Discussion

Figure 3 presents gain spectra obtained by the H–P method. The gain peak wavelength exhibited at approximately 1145 nm indicated the successful emission wavelength control of QDs for the 1.1-µm waveband. The gain bandwidth was increased with the increase in the injection current (*I*) up to approximately 70 nm with *I* = 64 mA.

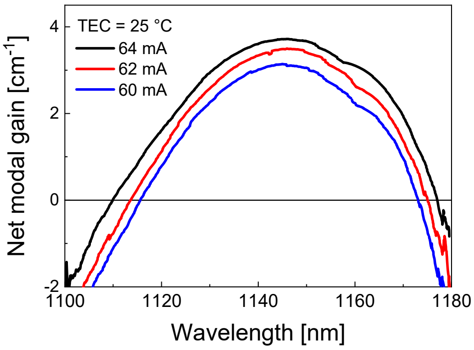

Fig. 3 Gain spectra under various injection currents obtained from the gain chip by the H–P method.

Then, the EC tunable lasing was verified. Figure 4 presents lasing spectra obtained with rotating the diffraction grating to vary the optical feedback wavelength to the gain chip under *I* = 64 mA. Although the tunable range was lower than the gain spectrum estimated by the H–P method, the continuous lasing was obtained in the 1.1-µm waveband. Consequently, the QD-based tunable laser was introduced into the SS-OCT system, and the PSF was obtained at *I* = 64 mA, as shown in Fig. 5. The peak position of the PSF corresponds to the optical path difference, and it demonstrates that the QD-based tunable laser is applicable to the SS-OCT light source.

The axial resolution of the OCT image was estimated at approximately 30 µm from the linewidth of the PSF, even when using only the lasing under the threshold current of F–P lasing. The tunable width can be extended with further injection currents as the internal F–P lasing is suppressed; thus, the axial resolution, which is inversely proportion to the tunable width, can be further improved.

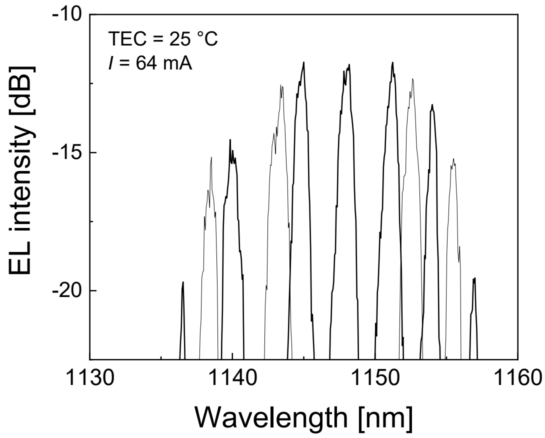

Fig. 4 Tunable lasing spectra obtained from the QD gain chip.

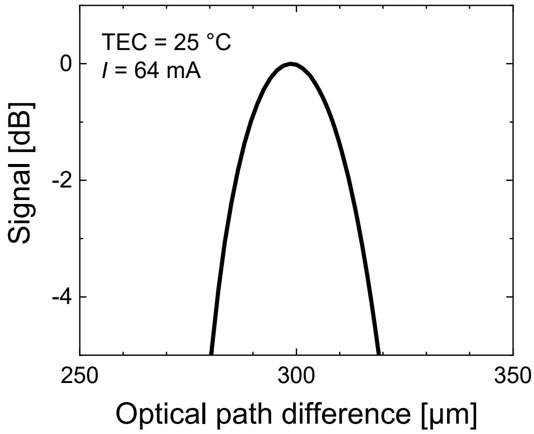

Fig. 5 PSF obtained from the SS-OCT with the tunable laser.

4. Conclusions

A gain chip including emission-wavelength-controlled InAs-QDs was characterized and introduced into an SS-OCT system as a tunable laser source. An increase in the gain width with the injection current was confirmed, and the tunable lasing was obtained using a grating-coupled EC. This tunable lasing was introduced into the SS-OCT system, and a reasonable PSF was obtained. These results demonstrate the feasibility of the gain chip based on emission-wavelength-controlled InAs-QDs for 1.1-µm waveband SS-OCT applications.

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References

[1] Brezinski, M. E., *Optical coherence tomography: principles and applications*, Academic Press, (2006).
[2] M. S. Patterson, et al., Lasers in Medical Science **6** (1991) 379.
[3] L. Goldstein, et al., Appl. Phys. Lett. **47**, 1099 (1985).
[4] B. W. Hakki and T. L. Paoli, J. Appl. Phys. **46**, 1299 (1975).