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Optical Coherence Tomography Imaging by Using a Superluminescent Diode Based on InAs/GaAs Quantum Dots

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Abstract

We developed a superluminescence diode (SLD) based on InAs quantum dots (QDs) grown on GaAs substrate and applied it to imaging of optical coherence tomography (OCT). By stacking InAs QDs with controlled emission center wavelengths, a SLD chip was obtained to exhibit a Gaussian-like-shape spectrum centered at 1.2 μm with 80-nm-bandwidth. Furthermore, an optical module including the QD-SLD was fabricated and introduced in an optical-fiber-based OCT system. OCT images with 7-μm-resolution were acquired by using the QD-SLD.

1. Introduction

Optical coherence tomography (OCT) is a non-invasive cross-sectional imaging technology for biological tissues [1]. OCT operates by a low-coherence interferometry with a broadband near-infrared (NIR) light source. The performances of OCT, such as the axial resolution and the measurement depth, depend on the light source. The resolution of OCT is determined by the coherence length, which is inversely proportional to the bandwidth of the light source. Also, light with wavelength in NIR region which have better permeability to the tissue is necessary for enough measurement depth. Thus, the light source having a broad spectral bandwidth in NIR region is required to achieve high axial resolution and longer penetration depth in OCT images. In addition, some attention should be paid to the spectral shape of the light source so that clear OCT images are possible. A spectrum containing large dips will have side-lobes in the Fourier-transformed power spectrum (coherence function), which leads to noise in the OCT images[2].

We have developed a superluminescent diode (SLD) based on self-assembled InAs quantum dots (QDs) to meet the requirements[3]. The InAs-QDs possess certain size distribution and emit a broadband spectrum due to the quantum size effect. In addition, the emission wavelength of the QDs is approximately 1.2-1.3 μm, which is suitable for obtaining large penetration depth in bio-samples. In this work, we fabricated a InAs-QD-based SLD (QD-SLD) with an optimized (Gaussian-like) spectrum shape and introduced the QD-SLD into OCT system to evaluate the QD-SLD as a light source of OCT.

2. Experiment

InAs-QDs were grown by molecular beam epitaxy on a GaAs (100) substrate. In a sample, four QD layers with different emission wavelengths controlled by thicknesses of capping layers for the QDs were included. Although the growth procedures were almost same with the previous reported sample [3], growth parameters such as capping layer thickness were optimized in order to obtain a broadband spectrum with Gaussian-like shape. A QD-SLD chip was fabricated by forming a straight ridge-waveguide and electrodes on the grown sample. After electroluminescence (EL) from the QD-SLD chip was measured at room temperature, the QD-SLD chip was mounted on a chip-carrier and installed in an optical module coupled to a single mode fiber (SMF).

A spectral domain (SD)-OCT with QD-SLD was set up as shown in Fig. 1. SD-OCT is a method for obtaining a depth profile of a sample by Fourier-transformed (FT) interference signals [4]. Using the OCT setup, an OCT image

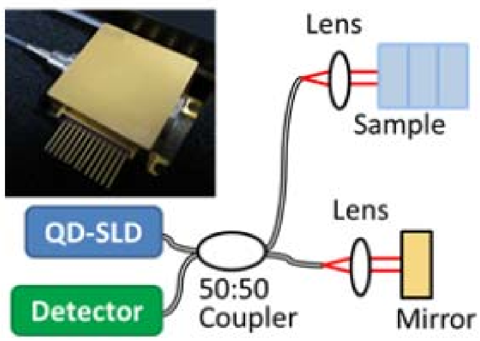

Fig. 1 Schematic image of SD-OCT setup including QD-SLD.

was acquired. As a test sample, stacked three cover glasses were prepared. A thickness and refraction index of each cover glass is 120-170 μm and approximately 1.5, respectively.

3. Results and Discussions

Figure 2 shows the EL spectra obtained from the QD-SLD with different injection currents (26.7-400 A/cm^2). The bandwidth of the emission spectrum gradually increased and the peak wavelength shifted up to 1.19 μm with increase in the injection current. The bandwidth was achieved 85 nm with an injection current of 400 A/cm^2. Also, the EL spectrum became Gaussian-like shape with the injection current. This is resulted from increases in emissions caused by electron-hole recombination between exited states (ES) in the QDs in addition to the emission from ground states (GS).

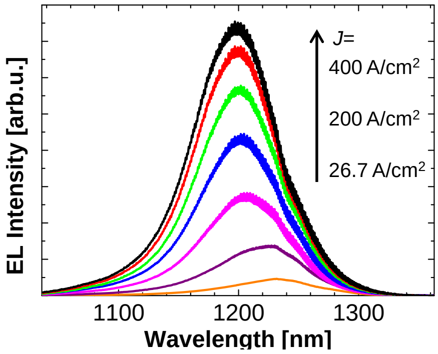

Fig. 2 EL spectra of QD-SLD

Figure 3 shows the spectrum obtained from the QD-SLD module. Although the bandwidth was decreased by coupling loss to SMF, the QD-SLD module shows broadband Gaussian-like emission with 68-nm-bandwidth. Inset in Fig. 3 shows the FT spectrum obtained from the emission spectrum of the QD-SLD. The axial resolution of the OCT images can be estimated from the half-width at half-maximum (HWHM) of the peak of the FT spectrum as 7.5 μm. In the FT spectrum, no apparent side lobes beside the main peak was confirmed. This results from the Gaussian-like spectral shape, which prevents ghost noise and improves OCT image quality.

Figure 4 shows results of OCT imaging obtained from the test sample. Figure 4(a) shows typical depth profile obtained from FT interference signal. Six peaks in the profile indicate reflections from surfaces or interfaces in the sample. By collecting the depth profile with sample scanning in a lateral direction, an OCT image was produced as shown in Fig. 4(b). White lines in the image represent the reflective surfaces or interfaces in the sample; surfaces of the stacking three glasses are distinguished. The distance between the surfaces of each glass is approximately 230 μm, which is consistent with the thickness of the cover glass multiplied by its refraction index. Also, the full-width at half-maximum (FWHM) of each white line is approximately 7 μm, which corresponds with the axial resolution calculated from the FT spectrum of the emission spectrum. These results demonstrate the effectiveness of the developed QD-SLD for OCT imaging.

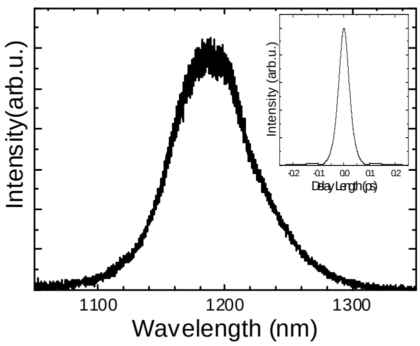

Fig. 3 Spectrum of the modularized QD-SLD

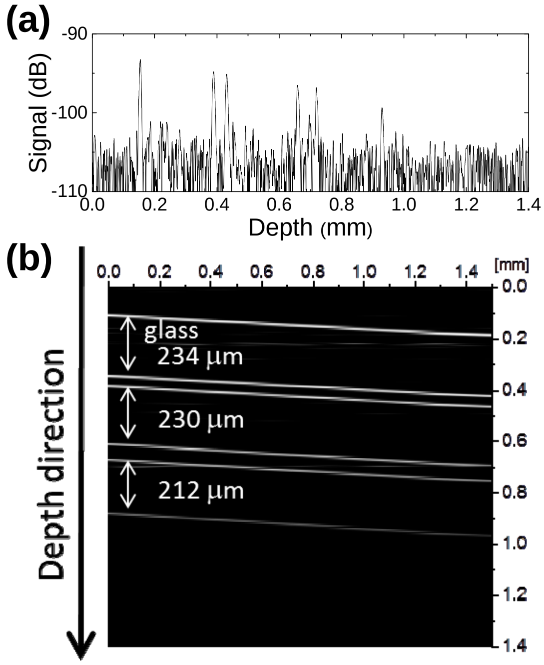

Fig. 4 (a) Depth profile obtained from an interference signal. (b) OCT image formed with depth profiles in a lateral direction.

4. Conclusions

We fabricated SLD based on self-assembled InAs QDs and succeeded in obtaining OCT images with the QD-SLD. The QD-SLD module, which exhibits a Gaussian-like spectral shape with the 68-nm-bandwidth, achieved noiseless OCT images with 7-μm-resolution. These results indicate the potential of the QD-SLD as an OCT light source.

Acknowledgements

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