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1.3-µm-Waveband Quantum-Dot External-Cavity Laser for Near-Infrared Microscopic Bio-Medical Imaging

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1. Introduction

Improved "Quality of life: QoL" is an essential goal while designing better bio-medical imaging and sensing systems. Photonic devices and their applications have been extensively studied world-wide, with considerable attention being paid to the development of non-invasive bio-medical imaging systems. Near-infrared (NIR) light in the wavelength range between 1.0 and 1.3 µm is expected to become a useful wavelength band because it is known to be easily transmitted through water and skin that comprises the human-body.

To develop an attractive non-invasive and microscopic bio-medical imaging system, a bright and stable light source operating in the 1.0- to 1.3-µm waveband is a key component. Recently, we have focused on the use of self-assembling quantum dots (QDs) to obtain media with excellent optical gain, while operating in the ultra-wideband wavelength range of 1.0 to 1.3 µm [1]. QD light sources, fabricated on large-diameter GaAs wafers, have attracted considerable attention as a low-cost light source offering low power consumption and high performance. Previously, we proposed a sandwiched sub-nano separator (SSNS) growth technique as an easy means for obtaining high-quality and high-density QD structures embedded in a quantum well (QW) structure operating in the 1.0- to 1.3-waveband [1]. In this paper, we describe the fabrication of a new QD external-cavity laser (QD-ECL) to newly develop a bright and stable illumination light source operating in the 1.3-µm waveband for future bio-medical imaging systems. We also construct an NIR microscopic bio-imaging system using the developed 1.3-µm waveband QD-ECL to evaluate the usability of the QD light source for the bio-imaging application. Using the developed microscopic bio-imaging system with the QD-ECL, we successfully observed an ultra-fine and high-contrast microscopic bio-image of a leaf.

2. Development of 1.3-µm waveband InAs/InGaAs quantum-dot external-cavity laser

A multi-stacked high-density InAs/InGaAs QD material was used to obtain broadband optical gain media in the 1.3-µm waveband. An InAs QD on an InGaAs QW structure was fabricated on a low-cost, large-diameter n-type (001) GaAs substrate using solid-source molecular beam epitaxy. Figure 1 shows a typical surface image of the InAs/InGaAs QD structure fabricated using the SSNS growth technique, as observed through the use of an atomic force microscope, where a 3.0-monolayer (ML) GaAs thin film as a SSNS structure was sandwiched between the 2.76-ML InAs QD layer and the 10-ML $In_{0.15}Ga_{0.75}As$ QW as the ground layer. As shown in Fig. 1, ultra-high QD densities over 8×10^{10} /cm^2 can be successfully obtained using this technique. We developed a ridge-type waveguide QD optical gain device using a seven-stacked InAs/InGaAs QD structure using the SSNS technique [1]. Additionally, an anti-reflection (AR, reflectance: < 0.3 %) dielectric coated QD optical gain chip is placed at an edge of the external cavity system as shown in Fig. 2. A cleaved facet of the QD optical gain chip and a half-mirror (reflectance: 60%) form the external cavity structure. As an optical mode selection technique for the QD-ECL, dual optical filters such as a narrow optical band-pass filter and an etalon filter were used to select the emission wavelength [2]. The threshold current of the developed QD-ECL was as low as approximately 60 mA. Fig. 3 shows a wavelength tunable characteristic of the fabricated QD-ECL. It is clear that the ultra-broadband tuning range, between 1.265 and 1.321 µm (56 nm), was achieved using the InAs/InGaAs QD optical gain chip fabricated using the SSNS technique[3]. In Fig. 3, output power from the QD-ECL was finely controlled to −3.0 dBm with an optical attenuator included in the light source module. As a result, we conclude that the useful 1.3-µm waveband QD-ECL, which is finely tunable in wavelength and power, was successfully developed.

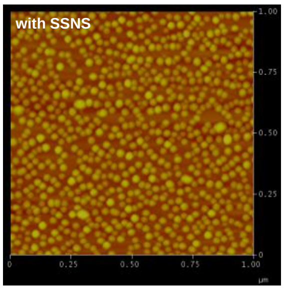

Fig. 1 AFM image of high-density InAs/InGaAs QD structure using SSNS growth technique.

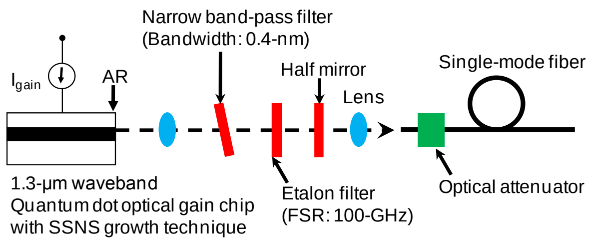

Fig. 2 Optical set-up for the 1.3-µm waveband QD-ECL.

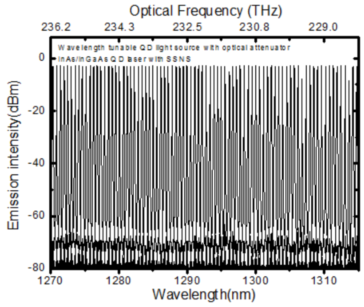

Fig. 3 Wavelength tunable characteristics of the developed QD-ECL.

3. Demonstration of microscopic NIR bio-imaging using QD-ECL

Using the QD-ECL, we constructed an NIR microscopic imaging system, as shown in Fig. 4 for better bio-medical imaging. We then observed the NIR bio-images of a leaf to evaluate the constructed bio-imaging system using the QD-ECL. In this system, a bench-top QD-ECL module, shown in Fig. 1, was used for NIR bright illumination. A 1.3-μm wavelength light from the QD-ECL is transmitted to a collimation lens using an optical fiber. The collimated light beam, approximately 2.0 mm in diameter, is passed through the space. An objective lens (×10) for NIR light is used to obtain the microscopic bio-image. We used a NIR camera (STEC-320, SEKI Technotron Co.) fabricated by an un-cooled InGaAs focal plane array device (320 × 256 pixels). The bio-material to be observed is set between the collimator lens and the objective lens, that is, the 1.3-μm light beam from the QD-ECL penetrates through the object. Figure 5(a) and (b) show two images of the leaf using two different wavelengths of 1320 nm and 1030 nm. For the 1030-nm wavelength emission, an InGaAs/GaAs QW DFB laser diode is used in this experiment. The 1320-nm wavelength is, of course, emitted from the wavelength tunable QD-ECL. The output power in both wavelengths is fixed at ~60 μW for obtaining the bio-images. From the observation results in Fig. 5(a), it is clear that a better ultra-fine and high-contrast microscopic bio-image of the veins in the leaf is successfully observed at the 1320 nm wavelength laser using the developed QD-ECL, as compared with the observation image shown in Fig. 3, obtained with the 1030-nm wavelength laser. It is considered that a finer observation of bio-images under the 1320-nm laser transmission is made possible by a reduction in the light scattering efficiency with the use of the longer-wavelength NIR light beam, as compared with the use of the 1030-nm light, as well as by a moderate absorption of light by water in the leaf at the 1320-nm wavelength.

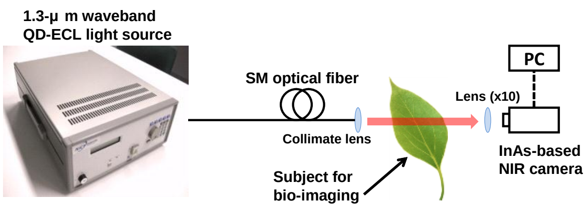

Fig. 4 NIR microscopic bio-imaging system with a newly developed bright and stable 1.3-μm waveband QD-ECL.

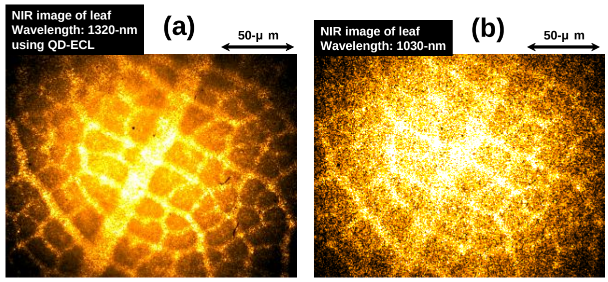

Fig. 5 NIR images of leaf at the wavelength of (a) 1320 nm and (b) 1030 nm. The 1320-nm wavelength light illumination is obtained using the QD-ECL

4. Conclusions

A 1.3-μm waveband InAs/InGaAs QD-ECL fabricated using the SSNS growth technique was newly developed as a stable and bright illuminator for use in the NIR bio-medical imaging application. An ultra-wideband wavelength tuning range between 1.265 and 1.321 μm (56 nm) was achieved using the QD-ECL. The NIR microscopic bio-imaging system was constructed with the QD-ECL to evaluate usability of the QD light source for better bio-medical imaging and sensing. As a result, an ultra-fine and high-contrast bio-image of a leaf was successfully obtained using the QD light source operating at a wavelength of 1320 nm, when compared with the image taken using an illumination source of 1030 nm wavelength. From these results, we conclude that the developed 1.3-μm waveband QD-ECL will become a great candidate as a viable and useful illuminator for more advanced NIR microscopic bio-medical imaging systems.

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