High-Efficiency Distributed Bragg Reflector Laser with Curved Grating for Squeezed Light Generation

Masahiro Uemukai and Toshiaki Suhara
Department of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University
2-1, Yamada-Oka, Suita, Osaka 565-0871, Japan
Tel: +81-6-6879-7770, Fax: +81-6-6879-7793
Email address: uemukai@eei.eng.osaka-u.ac.jp

Abstract: A high-efficiency InGaAs quantum-well curved-DBR laser was designed and fabricated using selective-area quantum-well disordering technique. Ultra low noise characteristic below the standard quantum limit was achieved by wideband constant-current driving.

1. Introduction

Amplitude-squeezed light is characterized by photon number fluctuations below the standard quantum limit (SQL). This ultra low noise light has potential applications to precision measurements and quantum information processing. The major origin of the intensity noise in the output of a semiconductor laser with high quantum efficiency is the noise of the pump current. When a laser is driven by a source of high impedance, the fluctuation of the driving current is reduced (wideband constant-current driving). This means that the shot noise in the injection current is suppressed, and squeezed light is generated by converting the sub-shot-noise electron flow into the photon flow with a quantum efficiency close to unity [1-6]. Squeezed light generation by multimode GaAs transverse-junction-stripe (TJS) lasers [6] and injection-locked lasers [4] at low temperature has been demonstrated. Single-mode lasers operating at room temperature are more advantageous in many applications. External cavity lasers were also used at room temperature to generate single-mode squeezed light [5].

Important requirements for achieving single-mode squeezed light generation are a high quantum efficiency to reduce excess noise and a very high side-mode suppression ratio (SMSR) to avoid mode partition noise. We demonstrated high-efficiency single-mode lasing with high spectrum purity of an InGaAs quantum-well (QW) distributed Bragg reflector (DBR) laser with a surface curved grating [7] and squeezed light generation by constant-current driving of the monolithic laser at room temperature [8]. We present design and fabrication of the high-efficiency DBR laser, and describe squeezed light generation characteristics.

2. Device Description and Design

The laser is constructed with a narrow active channel and a surface curved DBR grating using an InGaAs/AlGaAs strained-layer single QW graded-index separate-confinement-heterostructure (GRIN-SCH) waveguide [9], as shown in Fig. 1. The narrow ridge structure ensures lateral single-mode operation, and the first-order curved DBR grating provides high reflectivity for the diverging guided wave from the end of the active channel. The QW is selectively disordered in the DBR region to accomplish low absorption loss. Low-reflection (LR) coating on the front facet enhances the external quantum efficiency and improves catastrophic optical damage (COD) threshold.

The curved DBR grating for a wavelength of 970 nm was designed. By using selective-area QW disordering, the absorption loss in the DBR grating region can be significantly reduced to $\alpha \sim 3$ cm^{-1} [10]. As a result of optimization to obtain high reflectivity and sharp wavelength selectivity, the coupling coefficient κ was determined as 124 cm^{-1}. Using these values and a DBR length of 250 μm, the reflectivity of the DBR grating and wavelength bandwidth were calculated as 97% and 1.4 nm, respectively.

The intensity noise and squeezing of semiconductor laser light can be analyzed by solving the rate equations including the Langevin noise sources [1, 3]. We derived simplified analytical expressions for the noise power spectrum [11]. The values of the parameters in the expression were determined by preliminary experiment for the DBR laser with an active channel length of 800 μm, front facet and DBR reflectivities of 5% and 90%, threshold current of 16.4 mA, external differential quantum efficiency of 0.68 and quantum efficiency of 0.57 at an injection current of 100 mA. Assuming the pump noise was suppressed, intensity noise power spectra were calculated for internal loss of 3 cm^{-1}, internal quantum efficiency of 0.8, transparency carrier density of 1.36×10^{19} cm^{-3}, differential gain of 7.8×10^{-9} cm^{3}/s, carrier lifetime of 4.2 ns, photon lifetime of 4.3 ps and spontaneous emission factor of 1.0×10^{-5}. The result shows that the amplitude

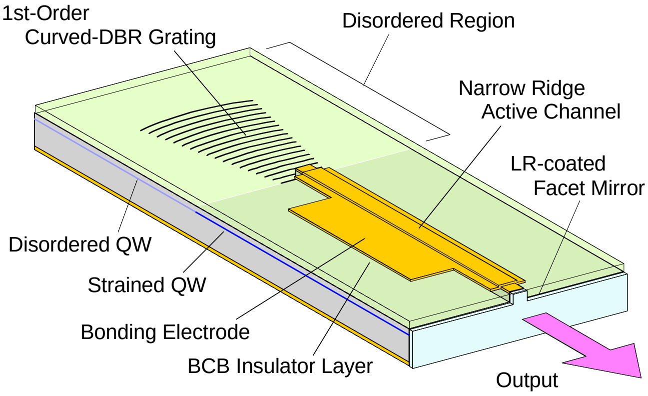

Fig. 1 Schematic of high-efficiency DBR laser with curved grating.

1-4244-1174-2/07/$25.00 ©2007 IEEE

squeezed light is generated and the intensity noise can be reduced to ~4 dB below the SQL for a 100 mW output.

3. Device Fabrication

The QW in the DBR grating region was selectively disordered by rapid thermal annealing with thick and thin SiO_2 caps [10]. After the fabrication of a p-electrode, the ridge structure was formed by reactive ion etching (RIE) using the electrode as a mask. The first-order curved DBR grating was fabricated by electron beam writing and two-step RIE. A bonding electrode was then formed on a benzocyclobutene (BCB) insulator layer and an n-electrode was evaporated on the backside. A facet mirror was formed by cleaving, and an Al_2O_3 LR layer was evaporated on the cleaved facet to obtain ~7% reflectivity. The laser was soldered on a Cu heat sink.

4. Experimental Results

The laser performance was first measured under conventional constant-current driving. The dependence of the output power and the external differential quantum efficiency η_d on the injection current is shown in Fig. 2. The threshold current was 7 mA and the maximum output power of 120 mW was obtained. η_d as high as 0.71 up to 90 mA injection and the SMSR as high as 52 dB were achieved. A high quantum efficiency of 0.63 was obtained at an injection current of 80 mA.

The laser was driven by a current source with a series inductor (1.5 mH) for constant-current driving required for the pump noise suppression over a wide RF range. Balanced detection technique [2, 5] was employed to measure the intensity noise relative to the SQL. A half-wave plate and a polarization beam splitter were used to divide the optical power equally between two Si PIN photodiodes, as shown in Fig. 3. The sum and difference of the two photodiode outputs, corresponding to the intensity noise of the laser under test and the SQL reference level, respectively, were displayed alternately on an RF spectrum analyzer using a RF hybrid and a RF switch. The total quantum efficiency of the measurement system, including all optical losses and the quantum efficiency of the photodiodes, was estimated as $\eta_{det} = 0.57$. Figure 4 shows that the measured noise level S_{mes} at an injection current of 80 mA for a frequency range between 10 and 30 MHz is about 0.5 dB below the SQL level. Compensation for the detection efficiency by using $S_{mes} = \eta_{det} S + (1-\eta_{det})$ gives a result that the actual noise level S is 0.8 dB below the SQL level. The reason for low noise characteristic is the high quantum efficiency, the low threshold and the high SMSR. The reason for discrepancy between the calculated and experimental results of the intensity noise has not been clarified. Future work includes clarification of the reason for the discrepancy and better reduction of the noise level.

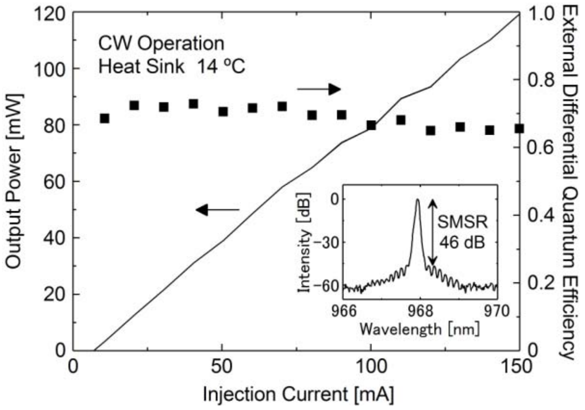

Fig. 2 Dependence of output power and external differential quantum efficiency on injection current. Inset shows lasing spectrum at 80 mA injection.

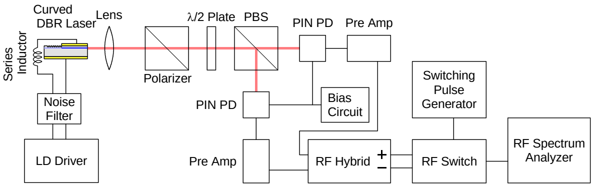

Fig. 3 Experimental setup for noise measurement using balanced detectors.

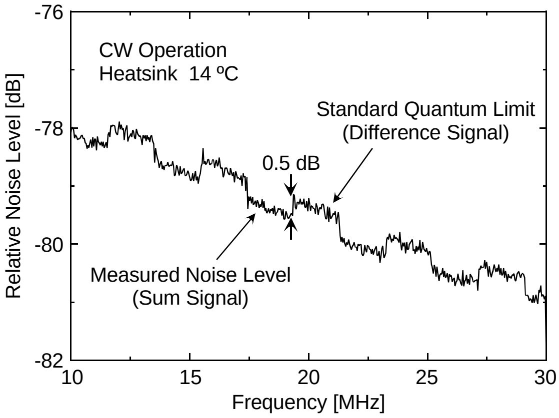

Fig. 4 Noise spectrum relative to standard quantum limit measured using balanced detectors at 80 mA injection.

References

[1] Y. Yamamoto, S. Machida and O. Nilsson, Phys. Rev. A, **34**, 4025 (1986).
[2] S. Machida, Y. Yamamoto and Y. Itaya, Phys. Rev. Lett., **58**, 1000 (1987).
[3] Y. Yamamoto and S. Machida, Phys. Rev. A, **35**, 5114 (1987).
[4] H. Wang, M. J. Freeman and D. G. Steel, Phys, Rev. Lett., **71**, 3951 (1993).
[5] M. J. Freeman, H. Wang, D. G. Steel, R. Craig and D. Scifres, Opt. Lett., **18**, 2141 (1993).
[6] S. Lathi, K. Tanaka, T. Morita, S. Inoue, H. Kan and Y. Yamamoto, IEEE J. Quantum Electron., **35**, 387 (1999).
[7] M. Uemukai, K. Kitano, N. Shimada and T. Suhara, Jpn. J. Appl. Phys., **43**, 5918 (2004).
[8] M. Uemukai, S. Nozu and T. Suhara, IEEE J. Select. Topics Quantum Electron., **11**, 1143 (2005).
[9] N. Eriksson, M. Hagberg and A. Larsson, IEEE J. Quantum Electron., **32**, 1038 (1996).
[10] N. Shimada, Y. Fukumoto, M. Uemukai, T. Suhara, H. Nishihara and A. Larsson, IEEE J. Select. Topics Quantum Electron., **7**, 350 (2001).
[11] T. Suhara, Proc. Eur. Conf. Integrated Optics, Thp1, 73 (2003).