ThP5
16:00 – 17:30

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

Masahiro Uemukai, Shunsuke Nozu and Toshiaki Suhara
Department of Electronic 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

*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 from the monolithic curved-DBR laser.

## 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. Squeezed light can be generated by constant-current driving of semiconductor lasers over wide frequency range to suppress the pump noise [1-6]. 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. Squeezed light generation by multimode GaAs TJS lasers [6] and injection-locked lasers [4] at low temperature has been demonstrated. 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 high quantum efficiency and a very high side-mode suppression ratio (SMSR) to avoid mode partition noise. In a previous work, we demonstrated high-efficiency single-mode lasing with high spectrum purity of an InGaAs quantum-well (QW) DBR laser with a surface curved grating [7]. In this work, we present design and fabrication of a high-efficiency InGaAs QW curved-DBR laser, and demonstrate squeezed light generation by constant-current driving of the monolithic laser at room temperature.

## 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 GRIN-SCH waveguide [8], 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 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 $\alpha \sim 3\ \mathrm{cm}^{-1}$ [9]. As a result of optimization to obtain high reflectivity and sharp wavelength selectivity, the coupling coefficient $\kappa$ was determined as $130\ \mathrm{cm}^{-1}$. Using these values and a DBR length of 250 μm, the reflectivity of the DBR grating and wavelength bandwidth were calculated as 97% and 1.5 nm, respectively.

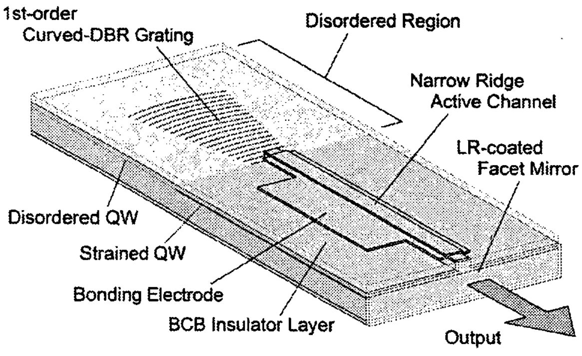

Fig. 1 Schematic of the high-efficiency DBR laser with curved grating.

The squeezing of semiconductor laser light can be analyzed by solving the rate equations including the Langevin noise sources [1,2]. Using the parameters experimentally measured or estimated for the DBR laser, the intensity noise characteristics for constant-current driving

0-7803-8627-2/04/$20.00©2004 IEEE

were calculated for various facet reflectivities. The result shows that the intensity noise can be reduced to ~4 dB below the SQL for a 100 mW output and 7% facet reflectivity.

## Device Fabrication

The QW in the DBR grating region was selectively disordered by rapid thermal annealing with thick and thin $SiO_2$ caps [9]. 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 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.

## Experimental Results

The laser performance was measured under CW operation. The dependence of the output power and the external differential quantum efficiency $\eta_d$ 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. $\eta_d$ as high as 0.71 up to 90 mA injection and the SMSR as high as 52 dB were achieved.

The intensity noise of the laser was measured by constant-current driving with a series inductor. Balanced detection technique was employed to measure the intensity noise relative to the SQL [3,5]. A half-wave plate and polarization beam splitter were used to divide the optical power equally between two Si PIN photodiodes. The sum and difference of the two photodiode output signals, corresponding to the intensity noise of the laser under test and the SQL reference level, respectively, are shown alternately in Fig. 3. The result shows that the laser noise level is about 0.5 dB below the SQL. Compensation for the detection efficiency of the measurement system (57%) gives a result that the laser intensity noise level is 0.8 dB below the SQL. This is the first demonstration of the squeezed light generation by the monolithic semiconductor laser at room temperature.

## References

[1] Y. Yamamoto, S. Machida and O. Nilsson, *Phys. Rev. A*, **34**, pp. 4025-4042, 1986.

[2] Y. Yamamoto and S. Machida, *Phys. Rev. A*, **35**, pp. 5114-5130, 1987.

[3] S. Machida, Y. Yamamoto and Y. Itaya, *Phys. Rev. Lett.*, **58**, pp. 1000-1003, 1987.

[4] H. Wang, M. J. Freeman and D. G. Steel, *Phys, Rev. Lett.*, **71**, pp. 3951-3954, 1993.

[5] M. J. Freeman, H. Wang, D. Steel, R. Craig and D. Scifres, *Opt. Lett.*, **18**, pp.2141-2143, 1993.

[6] S. Lathi, K. Tanaka, T. Morita, S. Inoue, H. Kan and Y. Yamamoto, *IEEE J. Quantum Electron.*, **35**, pp. 387-394, 1999.

[7] M. Uemukai, K. Kitano, N. Shimada and T. Suhara, *Microoptics Conf.*, M2, pp. 398-401, 2003.

[8] N. Eriksson, M. Hagberg and A. Larsson, *IEEE J. Quantum Electron.*, **32**, pp. 1038-1047, 1996.

[9] N. Shimada, Y. Fukumoto, M. Uemukai, T. Suhara, H. Nishihara and A. Larsson, *IEEE J. Select. Topics Quantum Electron.*, **7**, pp. 350-354, 2001.

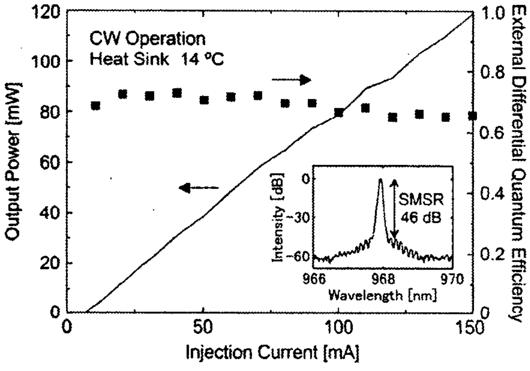

Fig. 2 Dependence of the output power and the external differential quantum efficiency on the injection current. The inset shows the lasing spectrum at 80 mA injection.

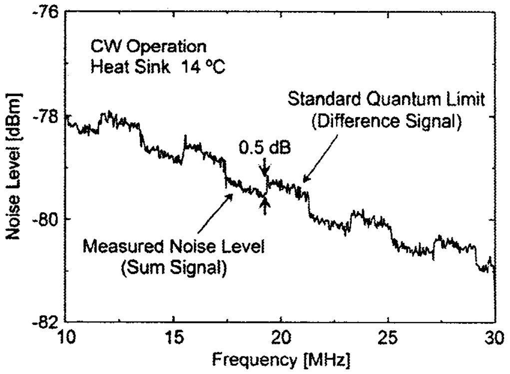

Fig. 3 Noise spectrum relative to standard quantum limit measured using balanced detectors at 80 mA injection.