Development of THz Quantum Cascade Laser as a Local Oscillator for Heterodyne Receivers

Y. Irimajiri[1*], S. Shiba[1, 2], N. Sekine[1], I. Hosako[1], T. Koyama[1, 3], T. Yamakura[4], H. Maezawa[3], and S. Yamamoto[2]

1 National Institute of Information and Communications Technology, Koganei, Tokyo, Japan*
2 Dept. of Physics, The University of Tokyo, Bunkyo-ku, Tokyo, Japan
3 Solar-Terrestrial Environment Laboratory, Nagoya University, Chikusa-ku, Nagoya, Japan
4 University of Tsukuba, Department of Physics, Tsukuba, Ibaragi Japan
* Contact: irimaji@nict.go.jp, phone +81-42-327 6089

***Abstract*— We are developing THz-QCL (quantum cascade laser) as a local oscillator for heterodyne receivers. THz-QCLs are made of GaAs/$Al_{0.15}Ga_{0.85}As$ using resonant LO phonon scattering depopulation scheme, and processed in a metal-metal waveguide using gold-gold thermo compression wafer bonding technique. CW mode operation of the THz-QCL has been achieved up to a heat-sink temperature of 74 K at the lasing frequency of 3.1 THz using a device with the size of 40 μm wide and 1.5 mm long fabricated by dry-etching method. The peak output power was measured to be about 34 μW at a heat-sink temperature of 15 K. We have also detected the QCL output with an HEB (Hot Electron Bolometer) mixer as a change in the I-V characteristic of the HEB mixer. The HEB mixers using an NbTiN ultra thin film as the superconducting material are coupled with the THz radiation by a quasi-optics twin slot antenna. The receiver noise temperature was measured to be 5600K in DSB.**

I. INTRODUCTION

THz-QCLs (Quantum cascade lasers) are compact, high output power and high frequency purity coherent CW sources and are promising THz radiation sources as a local oscillator for heterodyne receivers. THz-QCLs have potential for various applications such as security, foods inspection, medical, non-destructive inspection, imaging, and spectroscopic observation in astronomy or atmospheric science from a balloon-borne [1] or a space-borne [2], [3] system in THz region (0.1 – 10 THz).

In the frequency range from millimeter wave up to ~2 THz, combination of a solid state oscillator and frequency multiplier chains can be used as a local oscillator for heterodyne receivers. However, this method can no longer provide enough power for operation of HEB mixers above that frequency. THz-QCLs are promising solution for this problem, because it has good spectral purity and enough output power (order of mW) to drive HEB mixers. For this purpose, THz-QCLs have to be operated in the continuous wave (CW) mode under the relatively high-temperature operation by liquid nitrogen or Peltier cooling. Stabilization of the frequency and the line width for THz-QCLs of the order of $\Delta f/f \sim 10^{-7} \sim 10^{-8}$ is required for spectrum measurements. With these in mind, we are developing THz-QCLs for heterodyne receivers. So far we have succeeded in developing THz-QCL that can be operated in the CW mode at 3.1 THz up to heat-sink temperature of 74 K, and evaluating a performance of HEB mixer combined with the THz-QCL.

II. DESIGN AND FABRICATION OF THz-QCL

In this study, metal-metal type waveguide structure was selected because this type of THz-QCLs has low threshold current (i.e. low power consumption). The output power is expected to be an order of 10 mW, which is lower than that of SISP (semi-insulation surface plasmon) type. However, the output power of the metal-metal type THz-QCLs should practically be enough for driving the HEB mixer because the required power for the HEB mixer is an order of 100 nW [4]. In practical use, the necessary power is about 10 μW in minimum there are various losses due to imperfect optical alignments and the beam splitter coupling efficiency of 10 % or less.

The design of the QC structure is referred to the GaAs/$Al_{0.15}Ga_{0.85}As$ resonant LO phonon scattering scheme, which achieved the CW operation up to 117 K at 3.0 THz [5], [6]. The thickness of each layers are **4.9**/7.9/**2.5**/6.6/**4.1**/15.6/**3.3**/9 (nm) (bold fonts represent $Al_{0.15}Ga_{0.85}As$). The THz-QCL are fabricated in Photonic Device Lab. of NICT. First, we grow 178 periods of the QC structure about 10 μm thick on a semi insulating GaAs substrate by Molecular Beam Epitaxy (MBE), and confirm that the error is less than 1 % from the design by X-ray diffraction measurement. For the metal-metal waveguide structure, we deposit a 350 nm thick gold film both on this epi-wafer and the n-GaAs substrate, and bond them by using the gold-gold thermo compression wafer bonding method. After removing the substrate of the epi-wafer side, we fabricate a Fabry-Perot resonator whose size is 40 μm in width and 1.5 mm in length by using a dry etching process. Finally we wrap the n-GaAs substrate down to about 180 μm thickness to improve thermal conduction. Figure 1 shows a SEM image of the device, where the side surface is etched almost vertically. The fabricated THz-QCL is mounted on a chip carrier using Au-Sn eutectic alloy, and is wire-bonded with φ18 μm gold wire.

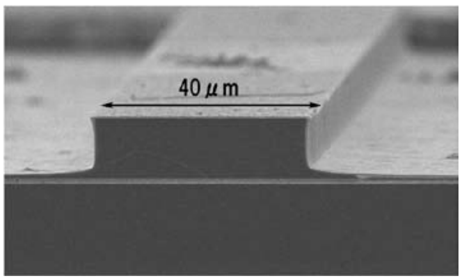

Fig.1. SEM image of the fabricated THz-QCL device.

III. MEASUREMENT RESULTS

A. IVL characteristics

Figure 2 shows a measurement setup of IVL characteristics of the THz-QCL. The device is cooled in a flow-type liquid helium dewar, where the temperature is controlled by a heater. The output power of the THz-QCL is detected by a liquid-helium-cooled Ge bolometer or a Pyro electric detector. The THz-QCL is operated in CW mode and the output power is modulated by an optical chopper and is measured with a lock-in detection. Prior to the measurements, the optical alignment is tuned as much as possible with the aid of the He-Ne laser. Figure 3 shows the IV (current-voltage), IL (current-laser power), and differential resistance characteristics of the THz-QCL measured under various heat-sink temperatures. This device has achieved the maximum output power of about 34 μW at a heat-sink temperature of 15 K. Both the threshold current density (147 A/cm^2) and output power are relatively low in comparison with the results given in the earlier studies [5, 6], which may come from insufficient optimization of doping density in our case and so on. It should be noted that the laser oscillation threshold seems fairly higher than differential resistance jump. Hence there is a possibility that a low-level output power which is undetectable with the present detection system may come out even below the oscillation threshold down to the differential resistance jump position. The consuming power of this device is about 1 W. The IL curve exhibits hysteresis; it differs between increasing and decreasing bias current. The laser output was measured up to the heat-sink temperature of 74 K, and the characteristic temperature T_0 is derived to be 14 K. The temperature of the THz-QCL device should be higher than the heat-sink temperature due to the high thermal resistance at the metal bonding surface.

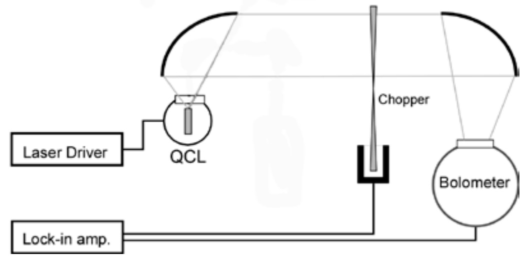

Fig. 2. Measurement setup of IVL characteristics of the THz-QCL.

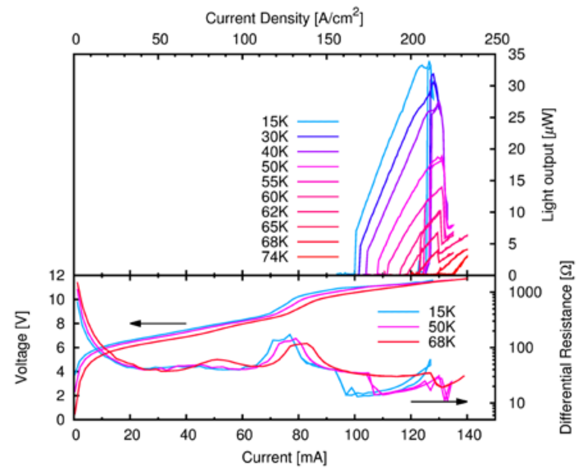

Fig. 3. Measured IVL characteristics of the THz-QCL.

B. Spectra characteristics

We measured the THz-QCL spectrum using a Fourier transform spectrometer. Figure 4 shows examples of the measured spectra. The longitudinal mode oscillating frequencies for the main modes are 3.07 THz and 3.09 THz, which are close to the designed frequency. The frequency difference of 25 GHz is corresponds to Fabry-Perot mode for the resonance length of 1.5 mm and the refraction index of 4. The oscillating frequency can be changed by varying the operating temperature or the bias current. Although the frequency resolution of FTIR is about 3 GHz, we can actually see the change by determining the center frequency of the spectrum carefully through the Gaussian fit (Figure 5). Tuning sensitivities by the heat-sink temperature and the bias current are roughly estimated to be 90 MHz/K and 30 MHz/mA, respectively, although the dependences on the heat-sink temperature and the bias current are not linear. This frequency variation is caused by change of refractive index or cavity length by temperature difference [7], [8]. We also see the mode hopping during the temperature and bias tuning.

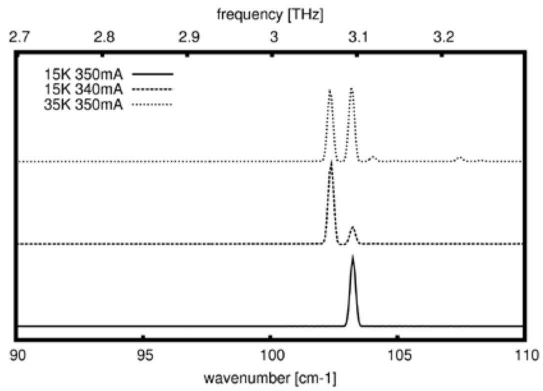

Fig. 4. Measured spectrum of the THz-QCL at different heat-sink temperature and bias current.

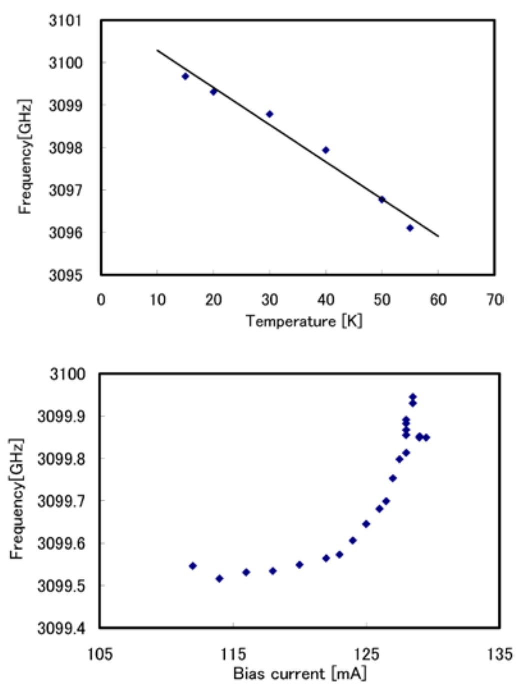

Fig. 5. Oscillation frequency dependence of the THz-QCL within a Fabry-Perot mode at 3.09 THz on the operation temperature (upper) and the bias current (bottom).

C. *Combination of the THz-QCL with the HEB mixer*

The output power of the THz-QCL is fed into the HEB mixer, where the HEB mixer and the THz-QCL are mounted on the different dewar and cooled by liquid helium. The HEB mixer was cooed to 4 K and the operating temperature of THz-QCL was around 25 K by its own heat in the CW mode operation.

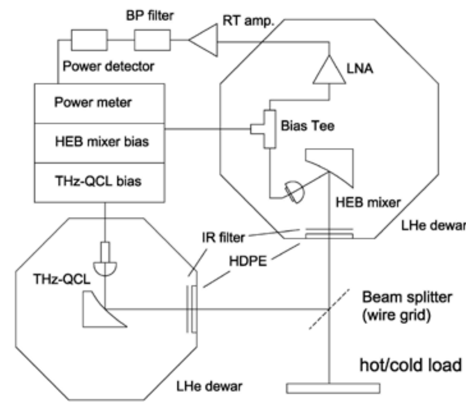

Fig. 6. Measurement setup of combination of the THz-QCL with the HEB mixer.

Each dewar has a window of high density polyethylene with 1 mm thickness and an infrared filter of Zitex G104. The transmission of these films is estimated to be about 90 % on the basis of the FTIR measurement. To focus the THz-QCL beam, an anti-reflection coated hyper hemispherical Si lens made of high resistivity silicon (10 kΩ/cm) is attached [9]. The measurement setup is shown in Figure 6.

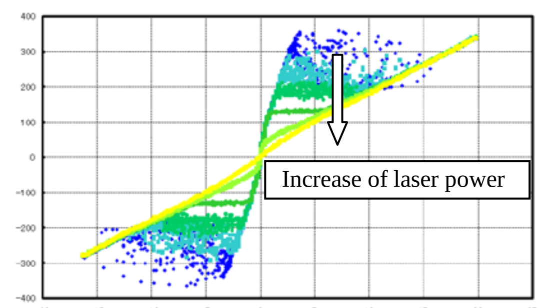

Fig. 7. IV characteristics of the HEB mixer with different laser input. The critical current decreases with increasing the laser input power.

The HEB mixer employed utilizes the superconducting NbTiN film with thickness of about 10 nm deposited on the Si substrate. The HEB device is fabricated in the University of Tokyo [10]. The size of the micro bridge structure is 2 μm in width and 0.3 μm in length. For the coupling with the THz radiation, a quasi-optical twin-slot antenna pattern is used. The laser output is vertically polarized and we used a wire grid as a beam splitter to couple the THz-QCL output to the HEB mixer, where the coupling efficiency is controlled by its tilt angle. As shown in Figure 7, the critical current of the HEB mixer decreased with increasing input laser power, which indicates that the laser power was detected by the HEB mixer. The receiver noise temperature was measured by using Y-factor method. The Y-factor of about 0.15 dB is obtained, which corresponds to the receiver noise temperature of 5600 K (DSB) considering Callen & Welton's law [11]. This value is not so good in comparison with the other reports [12]-[14], because the HEB mixer and the antenna pattern are not designed for the THz-QCL frequency (3.1 THz) but for the 2.5 THz band. Furthermore we need to optimize the optics between the THz-QCL and the HEB mixer. When these effects are corrected, the receiver noise temperature becomes 2100 K. Because only the optical loss is considered in this correction, this performance can be achieved if higher LO power is available and the optical path is evacuated.

Furthermore our result is obtained with the NbTiN HEB mixer. So far, the NbN superconducting film is always used for the HEB mixer in the frequency region higher than 1.5 THz. Our result demonstrates for the first time that the HEB mixer using the NbTiN superconducting film can achieve the comparable performance in such a high frequency region.

V. SUMMARY

We have developed THz-QCL which can be operated at 3.1 THz in the continuous wave mode up to a heat-sink temperature of 74 K. The receiver noise temperature in DSB was demonstrated to be 5600 K by using the THz-QCL as a local oscillator combined with the HEB mixer. Phase-locking of the THz-QCL and further improvements such as higher power and higher operation temperature for the THz-QCL are necessary.

REFERENCES

[1] Irimajiri, T. Manabe, S. Ochiai, H. Masuko, T. Yamagami, Y. Saito, N. Izutsu, T. Kawasaki, M. Namiki, I. Murata, **"**BSMILES—A Balloon-Borne Superconducting Submillimeter-Wave Limb-Emission Sounder for Stratospheric Measurements**,"** Geosci. Remote Sensing Lett., vol.3, no.1, pp.88-92, 2006.

[2] S. Ochiai, S. Tsujimaru, Y. Irimajiri, T. Manabe, and I. Murata, "Stratospheric ozone and ClO measurements using balloon-borne submillimeter limb sounder," IEEE Trans. Geosci. Remote Sensing, vol. 43, no. 6, pp.1258-1265, 2005.

[3] K. Kikuchi, T. Nishibori, S. Ochiai, H. Ozeki, Y. Irimajiri, Y. Kasai, M. Koike, T. Manabe, K. Mizukoshi, Y. Murayama, T. Nagahama, M. Sano, S. Sato, M. Seta, C. Takahashi, M. Takayanagi, H. Masuko, J. Inatani, M. Suzuki, and M. Shiotani, "Overview and Early Results of the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES)," J. Geophys. Res., 115, D23306, doi: 10.1029/2010JD014379, 2010.

[4] L. Jiang, S. Shiba, T. Shiino, K. Shimbo, N. Sakai, T. Yamakura, Y. Irimajiri, P G Ananthasubramanian, H. Maezawa, and S. Yamamoto, "Development of 1.5 THz waveguide NbTiN superconducting hot electron bolometer mixers," Supercond. Sci. Technol., 23 2010.

[5] S. Kumar, B. S. Williams, S. Kohen, Q. Hu, and J. L. Reno, "Continuous-wave operation of terahertz quantum-cascade lasers above liquid-nitrogen temperature," Appl. Phys. Lett., vol.84, no.14, pp.2494-2496, 2004.

[6] B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Operation of terahertz quantum-cascade lasers at 164K in pulsed mode and at 117K in continuous-wave mode," Opt. Express, vol.13, no.9, pp.3331-3339, May 2005.

[7] A. L. Betz, R. T. Boreiko, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Frequency and phase-lock control of a 3 THz quantum cascade laser," Opt. Lett., vol.30, no.14, pp.1837-1839, 2005.

[8] D. Rabanus, U. U. Graf, M. Philipp, O. Ricken, J. Stutzki, B. Vowinkel, M. C. Wiecner, C. Walther, M. Fischer, and J. Faist, "Phase locking of a 1.5 Terahertz quantum cascade laser and use as a local oscillator in a heterodyne HEB receiver," Opt. Express, vol.17, no.3, pp.1159-1168, 2009.

[9] A. W. M. Lee, Q. Qin, S. Kumar, B. S. Williams, Q. Hi, and J. L. Reno, "High-power and high-temperature THz quantum-cascade lasers based on lens-coupled metal-metal waveguides," Opt. Lett., vol.32, no.19, pp.2840-2842, 2007.

[10] T. Yamakura, "Development of THz band quasi-optical hot-electron bolometer mixer employing superconducting NbTiN microbridge," dissertation, University of Tsukuba, 2010.

[11] A. R. Kerr, "Suggestions for Revised Definitions of Noise Quantities, Including Quantum Effects," IEEE Trans. Microw. Theory Tech., vol.47, no.3, pp.325–329, 1999.

[12] J. R. Gao, J. N. Hovenier, Z. Q. Yang, J. J. A. Baselmans, A. Baryshev, M. Hajenius, T. M. Klapwijk, A. J. L. Adam, T. O. Klaassen, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Terahertz heterodyne receiver based on a quantum cascade laser and superconducting bolometer," Appl. Phys. Lett., 86, 244104, 2005.

[13] P. Khosropanah, W. Zhang, J. N. Hovenier, J. R. Gao, T. M. Klapwijk, M. I. Amanti, G. Scalari, and J. Faist, "3.4 THz heterodyne receiver using a hot electron bolometer and a distributed feedback quantum cascade laser," J. of Appl. Phys., 104, 113106, 2008.

[14] J. R. Gao, M. Hajenius, Z. Q. Yang, J. J. Baselmans, P. Khosropanah, R. Barends, and T. M. Klapwijk, "Terahertz Superconducting Hot Electron Bolometr Heterodyne Receivers," IEEE Trans. On Appl. Superconductivity, vol.17, no.2, 2007.