Phase-locking of a 3.1THz quantum cascade laser to terahertz reference generated by a frequency comb

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Abstract— **We are developing a low noise heterodyne receiver at 3THz band for applications of atmospheric and astronomical research and for application of wireless communications. We have developed a phase-locking system of a terahertz quantum cascade laser (THz-QCL) by using a hot electron bolometer mixer. The THz-QCL was locked to terahertz reference generated by an optical frequency comb and a photo mixer. The beat signal with IF frequency of 230MHz was compared with a microwave reference, and the error signal was applied to a loop filter with feedback to the bias current of the THz-QCL. The line width of the phase-locked beat signal of narrower than 1Hz which is limited by the resolution bandwidth of a spectrum analyzer was achieved.**

I. INTRODUCTION

We are developing a HEBM (Hot Electron Bolometer Mixer) using a THz-QCL (quantum Cascade Laser) as a local oscillator for atmospheric or astronomical observations. For these applications, it's important to reduce the line width and the phase noise of the THz local oscillator and to give it the absolute frequency. Although the FWHM of free running THz-QCL is around 20kHz within the short-period (several milliseconds) [1], [2], it's around 10MHz in the longer integration time due to the instability of the temperature and the bias [2].

Several reports have been published for phase-locking of the THz-QCL. They are phase-locking of THz-QCL by using a harmonic mixer [3], [4], [5], that of 1.5THz QCL to solid state oscillator and frequency multiplier chains [6], that of 2.7THz QCL to the 15tn harmonic generated by a semiconductor superlattice nonlinear devices [7], that using a free-space THz-comb and HEBM [8], that using a PCA (Photo Conductive Antenna) and a frequency comb [9], and that using a EO sampling by ZnTe crystal and a frequency comb [10]. Frequency-locking of 2.55 THz-QCL to absorption line of methanol gas was also reported [11].

We have developed a phase-locking system of a THz-QCL using a HEBM to detect a beat signal between a THz-QCL and a THz reference. THz reference signal was generated by photomixing two optical modes of a frequency comb.

II. PHASE-LOCKING SYSTEM OF A THz-QCL

Figure 1 shows a system block diagram of a phase-locking system of a THz-QCL. A beat signal detected by a HEBM with IF frequency of 230MHz was compared with a microwave reference, and the error signal was applied to a loop filter with feedback to the bias current of the THz-QCL.

THz-CW signal was generated by photomixing two optical modes of a frequency comb. Figure 2 shows a system block diagram of the THz-CW source. The CW-THz source is composed of a Mach-Zehnder-modulator (MZM)-based flat comb generator (MZ-FCG), a nonlinear (NL) fiber, band pass filters, and a photo mixer [12]. Figure 3 shows a detailed system block diagram and photographs of a phase-locking system of the THz-QCL.

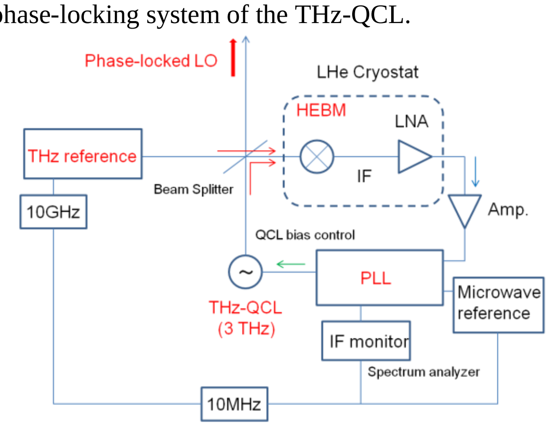


Fig. 1. A System block diagram of a phase-locking system.

As for the THz-QCL, metal-metal type waveguide type THz-QCL was fabricated in our clean room. The size of waveguide structure is 40μm in width and 1.5 mm in length. Figure 4 shows a measured voltage and laser power characteristics as a function of current. The operation current and voltage is around 133mA and 11.4V, respectively. Therefore, the electric power consumption is about 1.5W. The laser output power is about 100μW at a heat sink temperature of 15K in CW mode. Figure 5 shows a measured spectrum using a Fourier transform spectrometer. The longitudinal mode oscillating frequencies for the main modes are 3.07 THz and 3.09 THz. Frequency tuning sensitivities by the bias current is ~30MHz/mA.

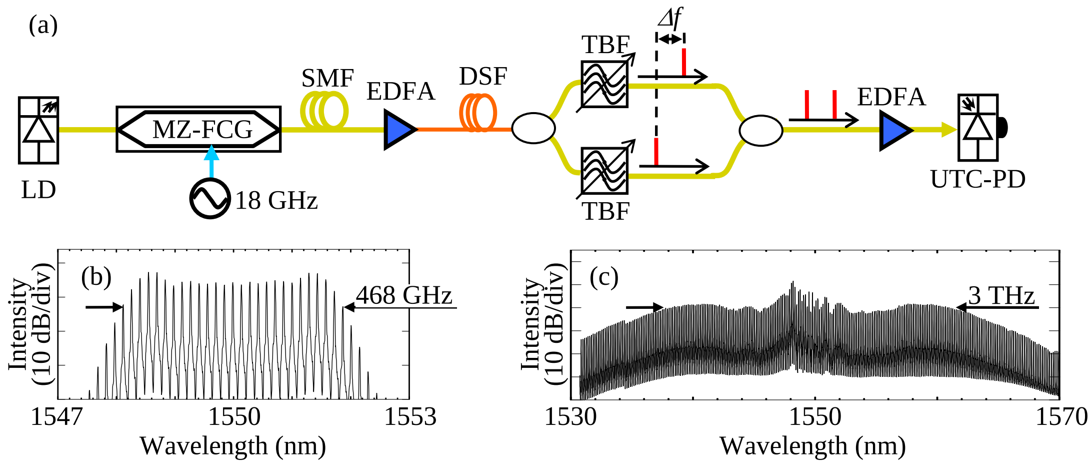


Fig. 2. (a) System block diagram of a CW-THz source composed of a modulator-based comb source. Broadband optical combs were generated by a combination of a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG) and a dispersion-shifted fiber (DSF). Optical two-mode signals were extracted from the comb by using a pair of tunable bandpass filters (TBFs), and CW-THz signals were generated by a unitraveling carrier photodiode (UTC-PD). LD: laser diode, SMF: single-mode fiber, EDFA: erbium-doped fiber amplifier. Spectra of comb signals (a) generated by the MZ-FCG and (c) broadened by the DSF.

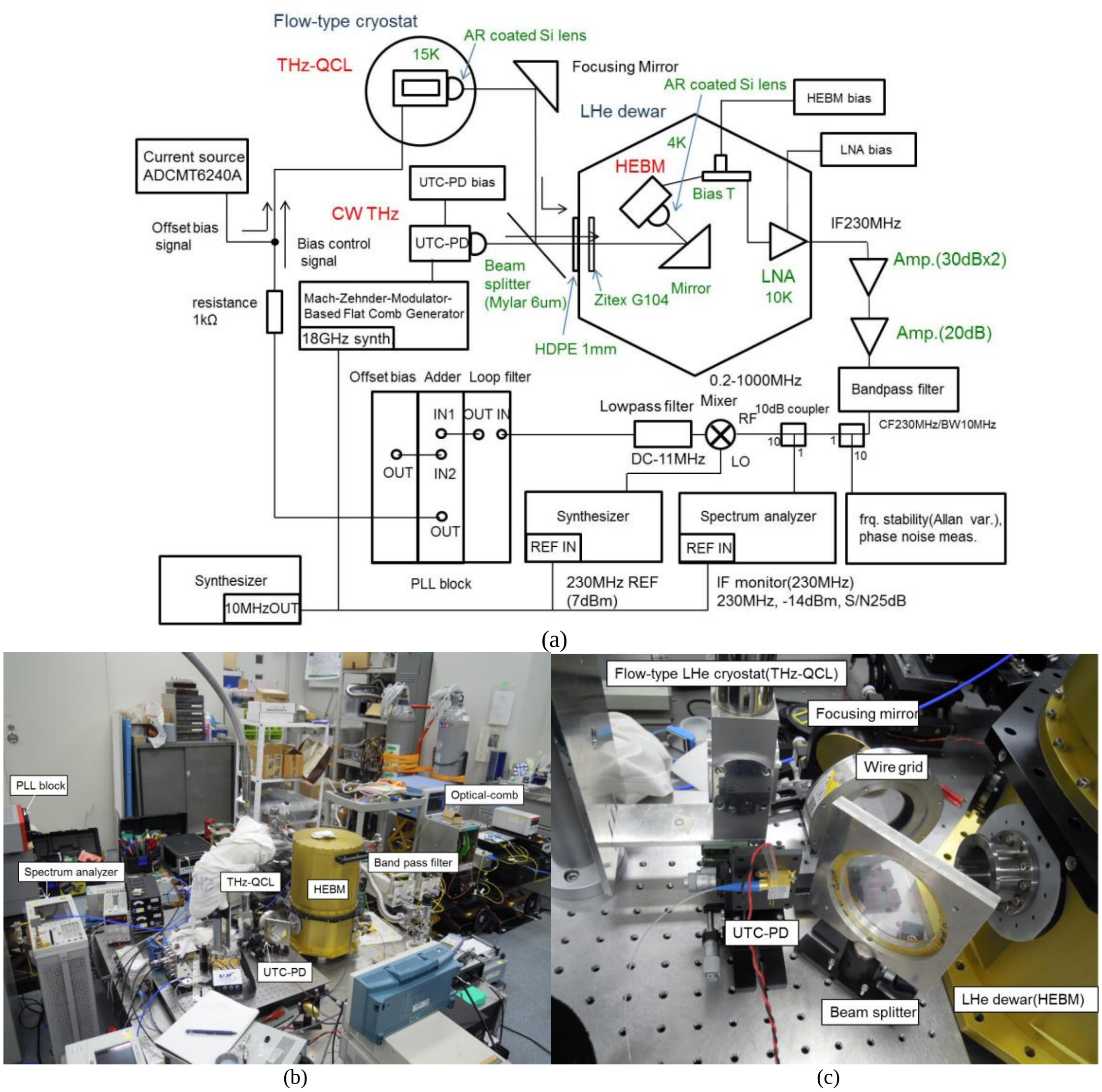


Fig. 3. A detailed system block diagram (a) and photographs (b), (c) of a phase-locking system of the THz-QCL.

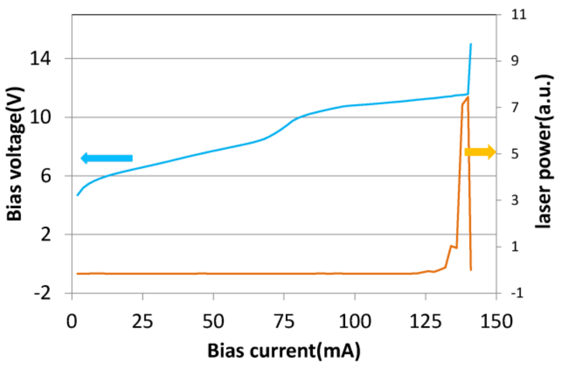


Fig. 4. Measured current vs voltage (I-V) curve (blue line) and current vs laser power characteristics (red line) at heat sink temperature of 15K. The maximum laser power is ~100μW in CW mode.

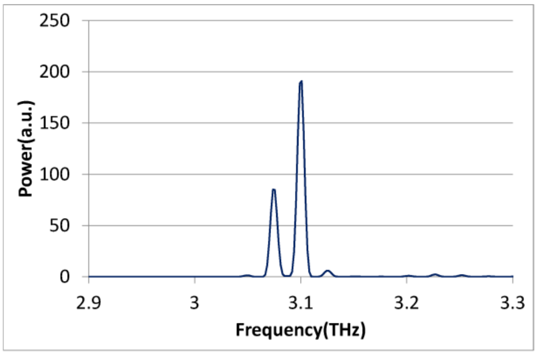
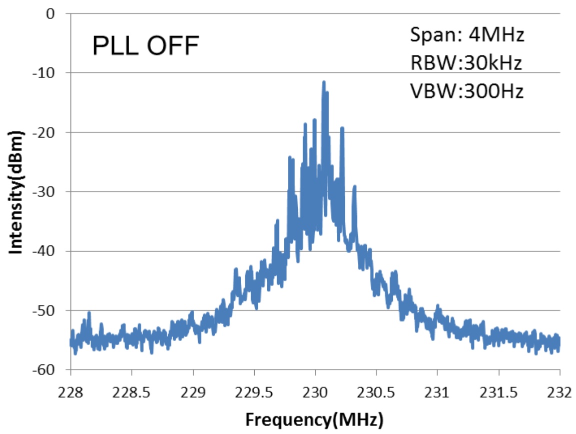


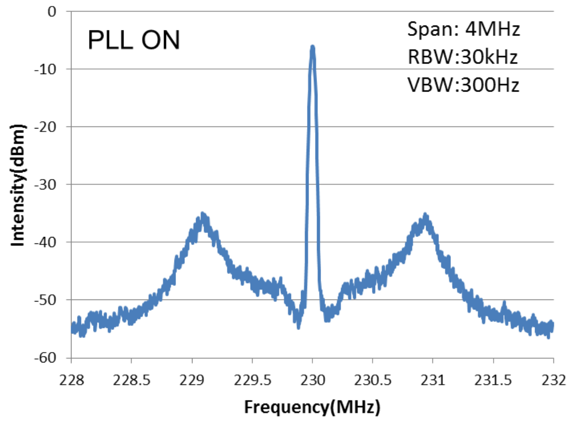
Fig. 5. Measured frequency spectrum of the THz-QCL operated in CW mode by using a FTIR. The longitudinal mode oscillating frequencies for the main modes are 3.07 THz and 3.09 THz.

III. RESULTS

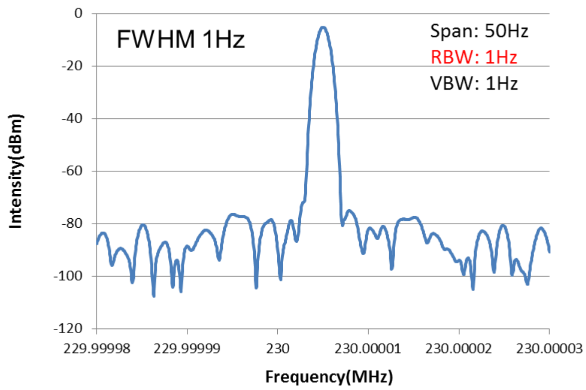
Figure 6 (a) and (b) show measured beat signals for PLL OFF and PLL ON (span: 4MHz, RBW: 30kHz, VBW: 300Hz). The signal to noise ratio for phase locked signal is more than 40dB. Figure 6(c) shows the phase locked beat signal with resolution band width of 1Hz. The FWHM (Full Width Half Maximum) is better than the limit of the resolution of the spectrum analyzer of 1Hz.



(a)



(b)



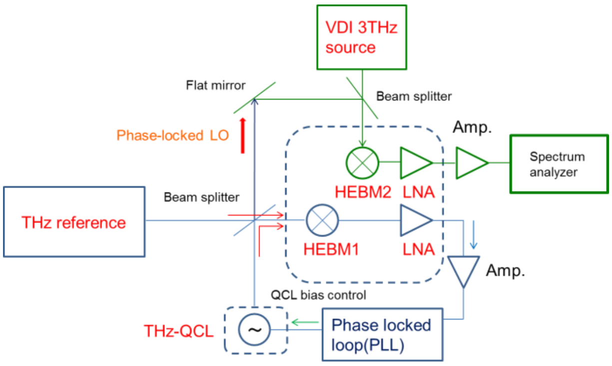
(c)

Fig. 6. Measured beat signals for PLL OFF (a) and PLL ON (span: 4MHz, RBW: 30kHz, VBW: 300Hz) (b). The SN ratio for phase locked signal is more than 40dB. Figure 6(c) shows the phase locked beat signal with resolution band width of 1Hz. The FWHM is better than the limit of the resolution of the spectrum analyzer of 1Hz.

As the next step, we actually used the phase-locked THz-QCL as a local oscillator for a heterodyne receiver. Another HEBM was installed in the same LHe dewar and a portion of the THz-QCL radiation was coupled in to the HEBM. We prepared a VDI 3THz CW source as a test signal and confirmed that the heterodyne receiver with the phase-locked THz-QCL worked properly. We will further investigate the performance of the phase-locked THz-QCL in terms of residual phase noise and frequency stability. Figure 7 shows a system block diagram and a photograph.

IV. SUMMARY

We have developed a phase-locking system of a THz-QCL by using a HEBM as a detector and a THz-CW generated by photomixing two optical modes of a frequency comb. The FWHM of the phase locked beat signal is better than 1Hz which is the limit of the resolution band width of the spectrometer. The performance of the heterodyne receiver using the HEBM and the phase-locked THz QCL was preliminary evaluated. For future application, low power consumption, reduction in size and weight etc. are important issues.



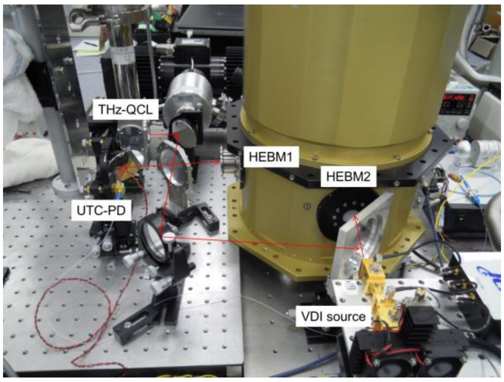


Fig. 7. The phase-locked THz signal is used as a local oscillator for another HEBM installed in the same LHe dewar. The beat signal using a VDI 3THz CW source was measured with FWHM of less than 1Hz same as the phase-locked LO source.

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