Performance Evaluation of Phase-Locking for THz-QCL

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Abstract— **We are developing a low noise superconducting heterodyne receiver based on a hot electron bolometer mixer (HEBM) and a THz Quantum Cascade Laser (THz-QCL) as a local oscillator at 3THz for atmospheric and astronomical observations. The best value of the uncorrected receiver noise temperature of 1,200 K (DSB) which corresponds to 8 times quantum limit was achieved. We demonstrated phase-locking of a 3 THz-QCL using the HEBM and evaluated its performance.**

I. Introduction

We are developing a low noise heterodyne receiver system at 3 THz based on a hot electron bolometer mixer (HEBM) and THz quantum cascade laser (THz-QCL) as a local oscillator for atmospheric and astronomical observations. For these applications, it's important to reduce the line width and the phase noise of a THz-QCL. A simple solution for the narrowing is a phase-locking to a stable reference. There are many works on the phase-locking and a frequency locking of a THz-QCL [1]-[11]. We successfully demonstrated a phase-locking of the 3 THz-QCL to a THz reference using the HEBM [12].

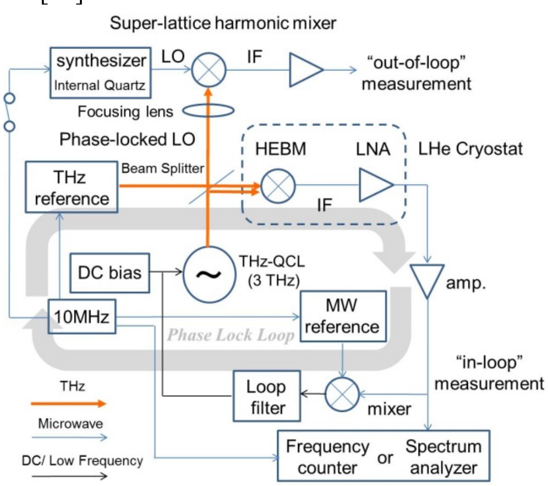

Fig.1. A system block diagram of a phase-locking of a THz-QCL.

II. Development and Measurement

The NbN HEBM device with a log-spiral antenna and the double metal waveguide type 3 THz-QCL were fabricated in our clean room facility. We have developed a low noise superconducting heterodyne receiver with the best value of the receiver noise temperature of 1,200 K (DSB) using a vacuum optics and a 4.5 µm-thick Mylar beam splitter, which corresponds to 8 times quantum limit, and successfully phase-locked the 3 THz-QCL to a THz reference. Fig. 1 shows the system block diagram of the phase-locking and performance evaluation. At first we used a 3 THz amplifier/multiplier chain (AMC) source as the THz reference. The beat signal between the 3 THz-QCL and the 3 THz reference is derived from the HEBM and used for the phase-locking the THz-QCL. In addition, we succeeded in phase-locking of the THz-QCL in both cases of using a 3 THz-CW source generated by photo-mixing two modes of an optical comb [13] and a broadband THz-comb generated by Cherenkov radiation as the THz references. We have also demonstrated phase-locking of the THz-QCL by using a super-lattice harmonic mixer.

III. Performance Evaluation

Fig. 2 shows an "in-loop" beat signal between 3 THz-QCL and 3 THz reference in cases of PLL OFF/ON. When the phase-lock loop is closed, the linewidth of the THz-QCL is drastically narrowed. Due to a resolution bandwidth of a spectrum analyzer, the linewidth is limited to 1 Hz in Fig. 2. For more precise evaluation we did frequency measurements of the beat signal by a high-resolution frequency counter. Longer than 1 hour measurement showed fractional frequency instability of 2×10^{-16} at an averaging time of 100 seconds (Fig. 3). Note that this is not an actual frequency instability of the phase-locked 3 THz QCL but that of phase-lock loop system. The obtained value is much lower than typical frequency stabilities of a hydrogen maser and a rubidium clock, indicating that our PLL circuit worked properly and the THz-QCL was tightly phase-locked to the THz reference.

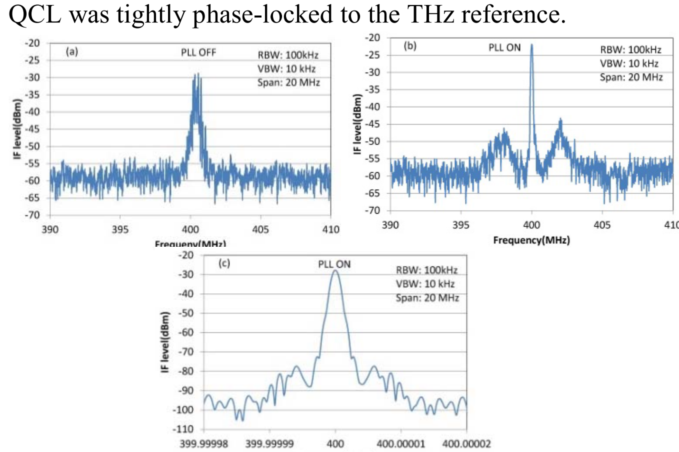

Fig.2. An "in-loop" beat signal between the THz-QCL and the AMC 3 THz source for PLL OFF (a) and ON (b), (c). The line width of the phase-locked signal is better than 1 Hz that is the limit of the resolution bandwidth of the spectrum analyser as shown in the bottom graph (c).

Also, we confirmed that a frequency tuning of the phase-locked THz-QCL was possible by tuning the THz reference or the microwave reference. So far, it can be tuned over +/-90 MHz with keeping PLL condition. Further optimizations would expand the tuning range.

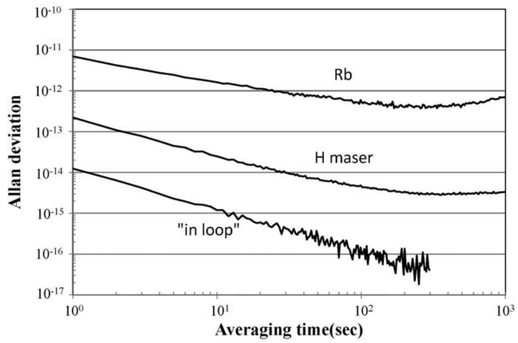

Fig.3 Frequency instability of the “in-loop” signal of the phase-locked 3 THz-QCL. The obtained value is much lower than typical frequency stabilities of a hydrogen maser and a rubidium clock, indicating that our PLL circuit worked properly and the THz-QCL was tightly phase-locked to the THz reference.

In order to evaluate actual frequency instability of the phase-locked THz-QCL, we measured "out-of-loop" signal using a super-lattice harmonic mixer (Fig. 1). The “out-of-loop” beat signal is shown in Fig. 4. Fig. 5 shows measured fractional frequency instability of 5×10^{-15} at an averaging time of 100 seconds. We have also measured fractional frequency instability of 7×10^{-12} at an averaging time of 100 seconds when a reference for a local oscillator of the super-lattice harmonic mixer is switched to an internal quartz reference.

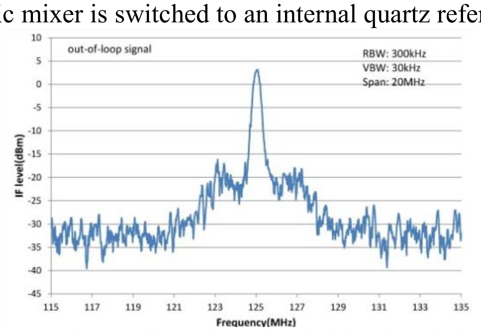

Fig.4. A measured “out-of-loop” beat signal of the phase-locked THz-QCL using a super-lattice harmonic mixer.

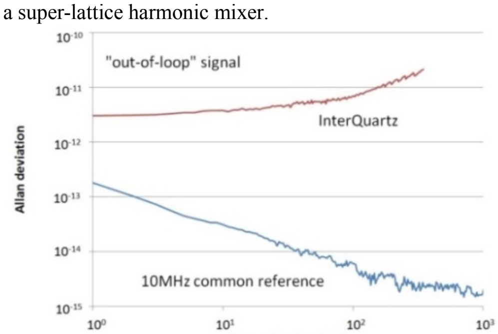

Fig.5. Frequency instability of the “out-of-loop” signal of the phase-locked THz-QCL and the internal quartz of the synthesizer.

IV. CONCLUSIONS

We demonstrated phase-locking of 3 THz-QCL using a HEBM and evaluated its performance. By evaluating “in-loop” signal of the phase-locked 3 THz-QCL, we confirmed high performance of our PLL system. We have also evaluated actual frequency instability of the phase-locked THz-QCL by measuring the "out-of-loop" signal.

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