Characterization of an optically generated 3THz continuous wave using a phase-locked QCL and a HEB mixer

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***Abstract*—We characterized a 3THz continuous wave generated by photomixing two optical modes of a broadband optical frequency comb. This optically generated THz wave and the output beam of a 3THz quantum cascade laser phase-locked to a THz reference were coupled onto a hot electron bolometer mixer operated at 4K and the beat signal was precisely evaluated. This direct comparison at 3THz reveals that the optically generated 3THz wave has fractional frequency instability of 4×10^{-15} at 100sec averaging time and the power spectral density of -10 dBc/Hz at 1Hz Fourier frequency.**

I. Introduction

Recent research activities at Terahertz (THz) frequency band demand an accurate and stable THz frequency standard. A low-phase noise THz signal is required for a high-speed digital coherent wireless communication and an accurate THz signal is used as a THz reference for a high-resolution THz spectroscopy or for frequency stabilization of THz quantum cascade laser. In order to supply an accurate and stable THz continuous wave for several THz applications we have developed simple THz synthesizer. Our THz synthesizer system is based on photomixing of two optical modes of a broadband optical frequency comb. Two optical modes of the optical comb having a THz-level gap are selectively extracted using the stimulated Brillouin scattering (SBS) technique. By coupling the two extracted optical modes into a uni-travelling carrier photodiode (UTC-PD), an accurate and stable THz continuous wave is generated by photomixing (Figure 1). Changing the frequency of widely-tunable laser stimulating Brillouin scattering, the extracted optical mode can be selectable, consequently, the frequency of the optically generated THz wave can be tuned. Even though the potential tuning frequency ranges from 100MHz to 10THz, we confirmed the actual generation of continuous waves at 100GHz, 700GHz and 3THz. The output power is limited by UTC-PD and it decreases inversely proportional to the fourth power of the frequency. The output power of 3THz wave is estimated to be 100nW. In evaluations of 100GHz and 700GHz waves, a harmonic mixer is available. By heterodyne mixing with the harmonics of the microwave signal, we confirmed that the optically generated THz wave had the same quality as the microwave synthesizer, which was used for a stabilization of repetition frequency of the optical frequency comb. It indicates that mode-extractions by SBS and photomixing by UTC-PD do not give additional phase noises.

Recently, a harmonic mixer with superlattices has become available for frequencies of a few THz, however, relatively high input power (about a few hundred μW) is required to obtain a beat signal with high SN ratio. For precise evaluation of the 3THz wave with an output power of about 100nW, we used a hot electron bolometer (HEB) mixer as a THz heterodyne mixer and phase-locked THz quantum cascade laser (THz-QCL) as a stable local oscillator (LO) for the HEB mixer.

II. Evaluations of Optically Generated 3THz Wave

The THz-QCL device adopted in this experiment was fabricated in the Photonic Device Lab of NICT. The metal-metal waveguide type THz-QCL with the size of waveguide structure of 40μm width and 1.5 mm length realizes laser output power of ~1mW in CW-mode at a heat sink temperature of 15K. The operation current and the voltage are around 133mA and 11.4V, respectively. The oscillating frequency for the main mode of the Fabry-Perot type THz-QCL is 3.09 THz and it can be fine-tuned by adjusting the bias current. The output beam for the 3.1THz-QCL was coupled into a superlattice harmonic mixer and a beat signal between the 3.1THz-QCL and the 256th harmonics of 12GHz microwave signal was derived from the intermediate frequency (IF) port of the mixer. The error signal for the phase-locking was obtained by comparing the beat signal with the microwave reference, and it was fed back to a bias current for the THz-QCL. In this way, the 3.1THz-QCL was phase-locked to the harmonics of the microwave signal.

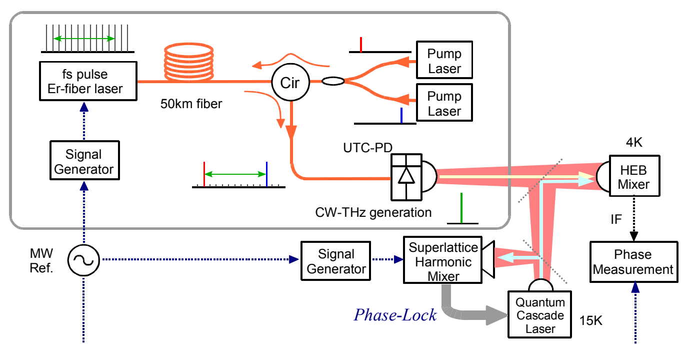

Fig.1: Experimental setup for CW-THz generation and quality evaluation using a phase-locked QCL and a HEB mixer.

A portion of the output beam from the phase-locked 3.1 THz-QCL and the optically generated 3.1THz wave were collinearly superimposed onto a HEB mixer at liquid-helium temperature (4K). This HEB device was also fabricated at NICT. The size of the superconducting bridge is 0.2~0.4μm length and 2~4μm width. The thickness of the superconducting film is around 3nm. Our HEBM device has a planar log-spiral antenna on a Si substrate and it is installed into a quasi-optical mount with high resistivity (10kΩ-cm) Si lens that anti-reflective (AR) coated by Parylene C. The double side band (DSB) receiver noise temperature used in this experiment was ~1900 K at 3.1THz. This liquid-helium temperature (4K) cooled superconducting device works as a THz heterodyne mixer making it possible to generate beat signals of coupled THz radiations. By precisely evaluating the beat signal derived from the IF port of the HEB mixer, the optically generated 3.1THz wave was fully characterized against the phase-locked 3.1THz QCL.

Frequency stability was evaluated by means of the Allan deviation. As shown in Figure 2, the fractional frequency instability at an averaging time of 1second is $<2 \times 10^{-13}$ and it goes down to 4×10^{-15} at 100 sec, which corresponds to a center frequency fluctuation within 12 mHz.

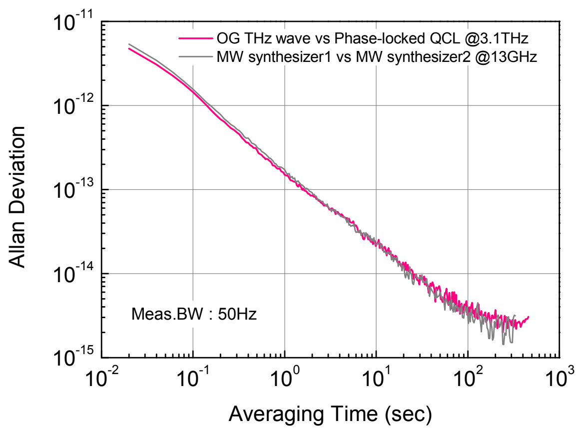

Figure 2: The fractional frequency instability of the optically generated 3.1THz wave against 3.1THz phase-locked quantum cascade laser. It is the same as that of the microwave synthesizer.

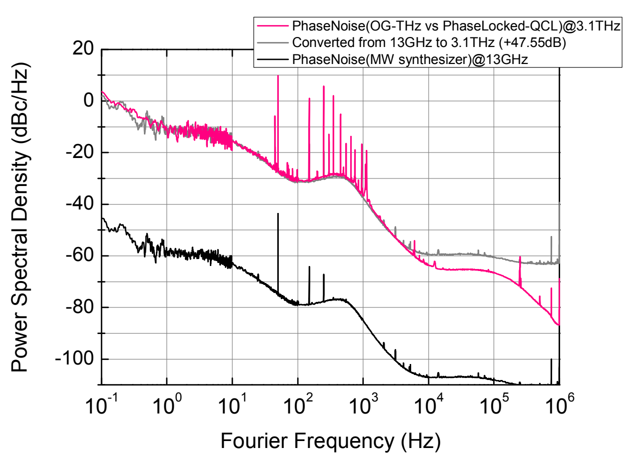

Figure 3: The power spectral density of the optically generated 3.1 THz wave. It is in accordance with a calculated value by multiplying the phase noise at 13 GHz of the microwave synthesizer by a factor of $(3.1\text{THz} / 13\text{GHz})^2$.

The power spectral densities of the optically generated 3.1THz wave are -10 dBc/Hz at 1Hz Fourier frequency and -65 dBc/Hz at 10 kHz. This phase noise level is in accordance with that as converted to 3.1THz assuming that the phase noise at 13 GHz of the microwave synthesizer dominates, as shown in Figure 3. From the obtained results of frequency stability and phase noise, it can be said that the quality of the 3THz wave generated from our THz synthesizer is dominated by the microwave source used for the stabilization of the optical comb. The processes of mode-extractions by SBS and photomixing by UTC-PD do not give any noises at 3THz as well at other lower frequencies.

III. SUMMARY

We evaluated an optically generated 3THz continuous wave from our THz synthesizer with using a phase-locked THz-QCL as a stable reference and a HEB mixer as a sensitive heterodyne detector. The results reveal that the generated 3THz wave has the same quality as the microwave source which is used as the reference, as well as 100GHz and 700GHz waves. Simultaneously, it is also confirmed that the quality of the phase-locked THz-QCL is dominated by the microwave reference for a superlattice harmonic mixer, indicating that the phase-locking loop works properly and neither the HEB mixer nor the harmonic mixer give any phase noises.