Phase-locked 2.7-THz quantum cascade laser with a microwave reference

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We demonstrate phase-locking of a 2.7-THz metal-metal waveguide quantum cascade laser (QCL) to an external microwave signal. The reference is the 15th harmonic, generated by a semiconductor superlattice nonlinear device, of a signal at 182 GHz, which itself is generated by a multiplier-chain (×12) from a microwave synthesizer at ~15 GHz. Both laser and reference radiations are coupled into a bolometer mixer, resulting in a beat signal, which is fed into a phase-lock loop. Spectral analysis of the beat signal confirms that the QCL is phase locked. This result opens the possibility to extend heterodyne interferometers into the far-infrared range.

Terahertz quantum cascade lasers (QCLs)[1] are promising sources for various applications such as high-resolution heterodyne spectroscopy, sensing, and imaging. In particular, QCLs hold great promise for local-oscillator (LO) applications because of their demonstrated [2-3] performances: a broad frequency coverage of 1.2 - 5 THz, high output power (≥1 mW), and compactness. Recently, their suitability as LOs has been demonstrated in hot electron bolometer (HEB) receivers with free-running QCLs, calibrated with a broadband blackbody radiation. To proceed with the applications of THz QCLs as LOs in a heterodyne spectrometer, stabilization of the frequency or phase is required to either eliminate the frequency jitter or to reduce the phase noise. For a heterodyne interferometer either on the Earth[4] or in space' phase locking of multiple LOs to a common reference at low frequency is essential.

Phase locking a laser to a reference means to control the phase of the laser radiation field precisely. This serves not only to stabilize the frequency but also to transfer the line profile of the reference to the laser. In the case of frequency-locking, the laser's average frequency is fixed, but its linewidth remains equal to the laser's intrinsic linewidth. Until now, only two experiments[5,6] to stabilize a THz QCL have been published. One is the frequency locking of a 3.1 THz QCL to a far-infrared (FIR) gas laser[5], the other is the phase-locking of the beat signal of a two lateral modes of a THz QCL to a microwave reference[6]. These experiments have suggested the feasibility of phase-locking, but have not led to a practical scheme for a LO. For a practical solution the phase needs to be locked to an external reference that can be generated conveniently and should preferably be far below the LO frequency. Therefore, an important challenge is the demonstration of phase-locking of a single-mode THz QCL to a microwave reference signal (MRS), which is the scheme commonly used in existing solid-state LOs. The MRS should be multiplied to a THz frequency in the vicinity of the laser frequency in order to obtain a beat note or an intermediate frequency (IF). As demonstrated in the measurements of FIR gas laser frequency, the harmonics of MRS at 3.8 THz and at 4.3 THz can be generated by Josephson junction harmonic mixers, resulting in a beat between the laser and the up-converted frequencies. Another commonly used harmonic generator is a Schottky diode. Recently phase-locking has also been demonstrated in a THz photomixer source operated at 0.3 THz to an optical frequency comb of a femtosecond laser. In contrast to THz QCLs, such a source has so far not demonstrated sufficient output power at frequencies above 1 THz.

In this letter, we report the phase-locking of a 2.7-THz QCL to a harmonic generated from a MRS by a semiconductor superlattice (SL) nonlinear device in combination with a multiplier chain. In addition to its immediate application in LOs, this work also demonstrates that the frequency of a photonic source (QCL) can be controlled precisely with an electronic source. This is a unique feature of THz QCLs which is not available to other lasers (gas lasers or solid-state lasers at higher frequencies).

To realize a THz reference from a MRS we apply two stages of frequency multiplication; first with a multiplier chain consisting of a Schottky-doubler and -tripler (×2×3), a power amplifier, and a varactor-doubler (×2), and then with a harmonic generator based on a superlattice (SL) nonlinear device[7], operated at room temperature, whose higher order harmonics are at THz frequencies.

To obtain the beat signal between the QCL and the THz reference, we use a lens-antenna coupled superconducting NbN HEB mixer[8]. It requires low LO power (< 300 nW). This turns out to be crucial for our phase-locking experiment because the QCL has a divergent far-field beam with strong interference patterns[9], resulting in a limited amount of usable power coupled into the mixer.

Fig. 1 shows a schematic diagram of the complete setup. The reference starts with a microwave synthesizer (Agilent 83640B) operated at 15.196 GHz followed by the multiplier chain that brings up the frequency to 182.352 GHz with a power level of 20-30 mW. The latter is used to pump the SL device

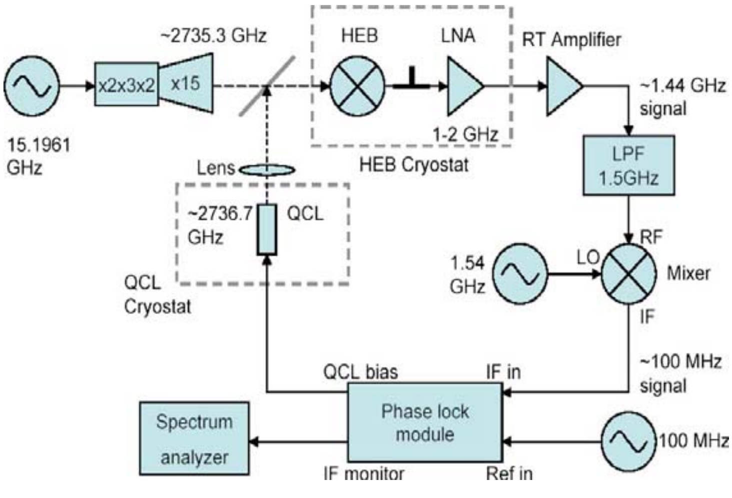

Fig. 1 Schematic diagram of the experimental setup to phase lock a THz QCL at 2.7 THz to a microwave reference.

to generate the 15th harmonic at 2.73528 THz, which is in the vicinity of the QCL's frequency, with a power level of 1-2 pW. The QCL is biased by a DC current, supplied by a phase-lock module (XL Microwave 800A-801, typically for Gunn and YIG oscillators). The reference signal and output of the QCL are combined in the HEB mixer via a beam-splitter. The beat signal is amplified by an IF chain[8] consisting of an isolator, a cryogenic low noise amplifier, and room temperature amplifiers.

We first monitor the beat signal of the free-running QCL by a spectrum analyzer which is connected directly to the output of the IF chain. From the spectrum we obtain the frequency of the QCL to be 2.73673 THz. With this technique we can determine the frequency with a very high precision. By varying the current bias of the QCL, as shown in the inset of Fig. 2, the lasing frequency shifts monotonically and increases by 1.6 GHz from 30 to 46 mA (corresponding to 10.8 to 11.4 V), with the rate of 98 MHz/mA. This blue shift is most likely due to the frequency pulling of a Stark-shifted gain spectrum. The tuning mechanism which has a time constant of ~ps is much faster than the thermal tuning (>1 ms) that results in a red shift[5]. The faster tuning allows the use of a feedback control with a broad bandwidth (~1 MHz). In essence, the QCL behaves as a voltage controlled oscillator for the bias range of interest, which is required for phase-locking[5,6].

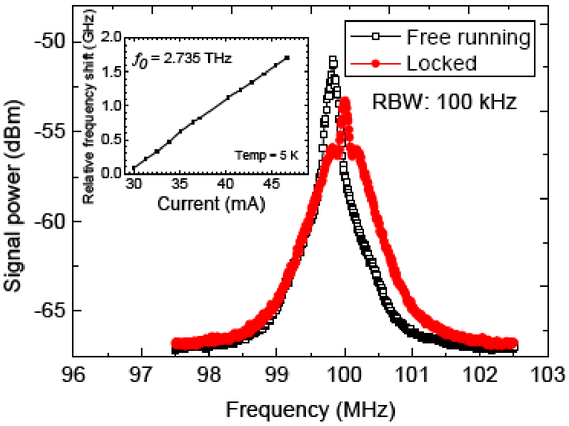

FIG. 2. (Color online). A typical power spectrum of the beat signal of the THz QCL that is phase locked to a microwave reference recorded by the spectrum analyser with a low resolution bandwidth (RBW) of 100 KHz. For comparison, a spectrum of the free-running QCL is also shown. The inset shows a relative frequency shift of the free- running QCL versus the biasing current at 5 K. The starting frequency is 2.735 THz.

To further demonstrate phase-locking, we monitor the power spectra of the beat by systematically reducing both RBWs and spans of the spectrum analyzer. Fig. 3 shows a selected set of power spectra of the beat for RBWs from 3 KHz down to 1 Hz. As indicated, the 3dB-linewidth appears to decrease as the RBW is reduced. The linewidth of the beat can be as narrow as 1 Hz, limited by the minimum RBW of the instrument, while the S/N increases from 15 dB for a RBW of 3 kHz to 50 dB for 1 Hz. These spectra are reproducible and stable for an indefinitely long

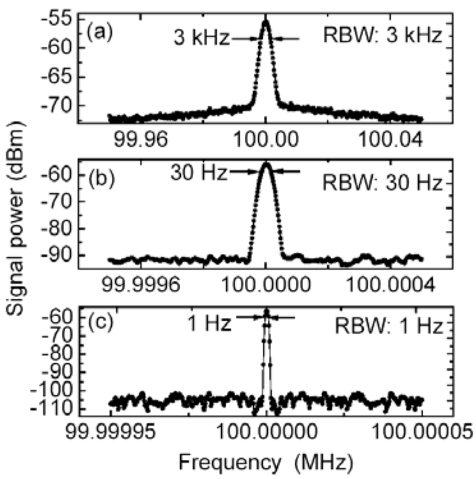

FIG. 3 Power spectra of the beat signal of the THz QCL that is phase locked to a microwave reference recorded by the spectrum analyser with different resolution bandwidths (RBW) and spans, but a fixed video bandwidth (VBW) of 300 Hz. A 3-dB linewidth of the beat signal is also indicated. To avoid confusion, we note that this linewidth is not the actual linewidth of the QCL (see text)

time. Since the spectra of the beat only reflect the relative phase noise spectral density between the laser and the reference, the extremely narrow linewidth of the beat implies that the line profile and stability of the reference are now transferred to the QCL[6]. Thus, the THz QCL is phase locked. To quantify the phase-locking performance, we estimate how much power is in phase with the reference.. Based on the peak power of -47 dBm within 1 MHz and -56 dBm within 1 Hz RBW we find about 13 % of the QCL power to be concentrated in the narrow band of the reference. This low value is the result of a reduced effective regulation bandwidth of PLL system due to the non-optimal experimental condition and complexity (as shown by figure 1), including long cables of several meters, the way of cabling, and non-optimized damping setting (loop filter) in the regulation loop. All these can cause additional delay and thus reduce the bandwidth to be considerably smaller than 1 MHz.

In summary, we have demonstrated true phase-locking of a 2.7-THz QCL to a high-order harmonic from a microwave synthesizer generated by a superlattice harmonic generator. By extending harmonics of the superlattice device to the high end of THz range (3-6 THz), our phase-locking scheme can be potentially used in many applications of THz QCLs as local oscillators, in particular, for a space heterodyne interferometer[5]. Additionally, the phase-locked QCLs, with at least an accuracy of 1 part in 10^{12}, determined by an electronic source, have potentials for other applications such as THz frequency standard, metrology, and precision molecular spectroscopy.

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