Phase locking of a 2.7 THz quantum cascade laser to a microwave reference

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Received July 6, 2009; revised August 25, 2009; accepted August 26, 2009; posted August 31, 2009 (Doc. ID 113522); published September 24, 2009

We demonstrate the 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 ($\times 12$) from a microwave synthesizer at $\sim$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. The 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. © 2009 Optical Society of America

OCIS codes: 250.5590, 300.6310, 300.6495, 350.1270, 040.2235.

Terahertz quantum cascade lasers (QCLs) [1] are promising sources for various applications such as high-resolution heterodyne spectroscopy, sensing, and imaging. Recently, their suitability as local oscillators (LOs) has been demonstrated [2,3] in hot electron bolometer (HEB) receivers with free-running QCLs. To proceed with the applications of terahertz QCLs as LOs in a heterodyne spectrometer, the 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 [5], the phase locking of multiple LOs to a common reference at low frequency is essential.

Phase locking [6] 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. Several experiments to stabilize a terahertz QCL have been published. They are the frequency locking of a 3.1 THz QCL to a far-infrared (FIR) gas laser [7], the phase locking of the beat signal of two lateral modes of a terahertz QCL to a microwave reference [8], and the phase locking of a 1.5 THz QCL to a multiplier chain LO source [9]. Since the multiplier chain source has been demonstrated only up to about 2 THz, for a practical solution for the use of a QCL as LO beyond this frequency, the phase needs to be locked to an external reference that can be generated conveniently and should preferably be far below the QCL frequency. Therefore, an important challenge is the demonstration of the phase locking of a single-mode terahertz 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 terahertz frequency in the vicinity of the laser frequency 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 [10] and at 4.3 THz [11] can be generated by Josephson junction harmonic mixers, resulting in a beat between the laser and the upconverted frequencies. Another commonly used harmonic generator is a Schottky diode [12].

In this Letter, we report the phase locking of a 2.7 THz QCL to a harmonic generated from an MRS by a semiconductor superlattice (SL) nonlinear device in combination with a multiplier chain. We demonstrate a practical phase-locking scheme that is extendable to a much higher frequency and quantify the phase-locked power.

The QCL used is based on the double-resonant-phonon depopulation design [13]. The Fabry–Pérot cavity of the QCL is a double-sided metal waveguide, which is 19 μm wide and 800 μm long. The QCL is operated with a current of 53 mA and a voltage of 12 V and is cooled in a liquid-helium cryostat. The maximum output power is 0.38 mW in cw mode. The emission spectrum measured by a Fourier-transform spectrometer shows a single-mode line at 2.735 THz.

To realize a terahertz stability reference from a MRS, we apply two stages of frequency multiplication: first with a multiplier chain consisting of a

0146-9592/09/192958-3/$15.00

Schottky doubler and tripler (×2×3), a power amplifier, and a varactor doubler (×2) and then with a harmonic generator based on a molecular-beam-epitaxy-grown SL nonlinear device [14] with an area of the mesa of 2–3 μm^2. It is operated at room temperature and can produce higher-order harmonics up to at least 3 THz. It is mounted on a block consisting of a diagonal horn to couple out the terahertz radiation and a waveguide for pumping.

Figure 1 shows a schematic of the complete setup. To obtain the beat signal between the QCL and the terahertz reference, we use a lens–antenna coupled superconducting NbN HEB mixer that requires an LO power of less than 300 nW [15]. 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 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). The reference signal and the output of the QCL are combined in the HEB mixer via a beam splitter. The beat signal is amplified by an IF amplifier chain [15].

We first monitor the beat signal of the free-running QCL by a spectrum analyzer (alternatively by a fast-Fourier-transform spectrometer), 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. 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 10.8–11.4 V), with the rate of 98 MHz/mA. This blueshift is most likely due to the frequency pulling of a Stark-shifted gain spectrum [16]. The tuning mechanism, which has a time constant of approximately picoseconds, is much faster than the thermal tuning (>1 ms) that results in a redshift [7]. 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 the phase locking [7–9].

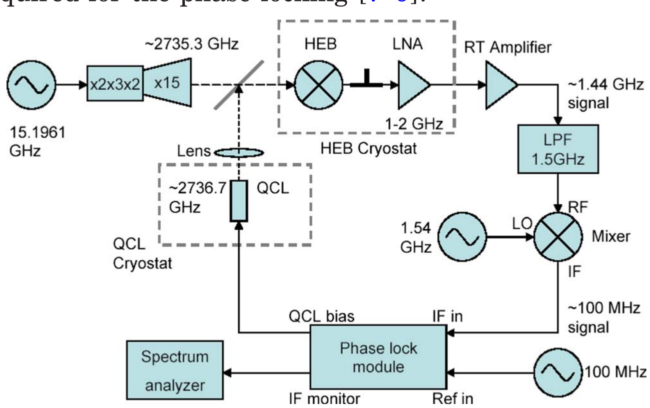

Fig. 1. (Color online) Schematic of the experimental setup to phase lock a terahertz QCL at 2.7 THz to a microwave reference. Not shown is that all the spectrum analyzers and the signal generators are phase locked to a common 10 MHz reference.

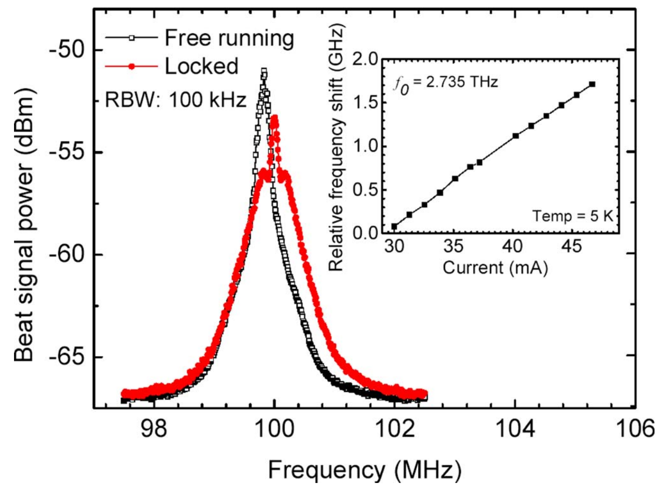

Fig. 2. (Color online) Typical power spectrum of the beat signal of the phase-locked terahertz QCL, recorded by the spectrum analyzer with a low RBW of 100 KHz. For comparison, a spectrum of the free-running QCL is also shown. The inset shows a relative frequency shift of the free-running QCL versus the biasing current at 5 K. The starting frequency is 2.735 THz.

To close the phase-lock loop (PLL), the beat signal—as shown in Fig. 1—is fed into a low-pass filter and then downconverted to about 100 MHz by a microwave mixer that has a microwave source at 1.54 GHz as an LO. This is technically necessary, since our phase-lock module is designed for the phase comparison with a synthesized reference signal at 100 MHz. The phase error signal is fed back into the DC bias to the QCL. The PLL gain bandwidth is 1 MHz. All the instruments (the spectrum analyzer and the signal generators) are phase locked to a common 10 MHz reference.

Figure 2 shows a power spectrum of the beat under the phase-locking condition, recorded using a low resolution bandwidth (RBW) of 100 KHz. For comparison, a free-running spectrum is also plotted in the same figure. It is clear that using the PLL the beat signal is characterized by an additional stable peak in the center.

We monitor the power spectra of the beat by systematically reducing both the RBWs and the spans of the spectrum analyzer. Figure 3 shows a selected set of power spectra of the beat for the RBWs from 3 KHz down to 1 Hz. As indicated, the 3 dB 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 signal-to-noise ratio 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 time. Since the spectra of the beat only reflect the *relative* phase noise spectral density between the QCL and the reference, the extremely narrow linewidth of the beat implies that the line profile and the stability of the reference are now transferred to the QCL [6,17]. Thus, the terahertz QCL is phase locked. To quantify the phase-locking performance, we estimate how much power is in phase with the reference using the same method as in [18]. Based on the peak power of −47 dBm within 1 MHz and −56 dBm within 1 Hz

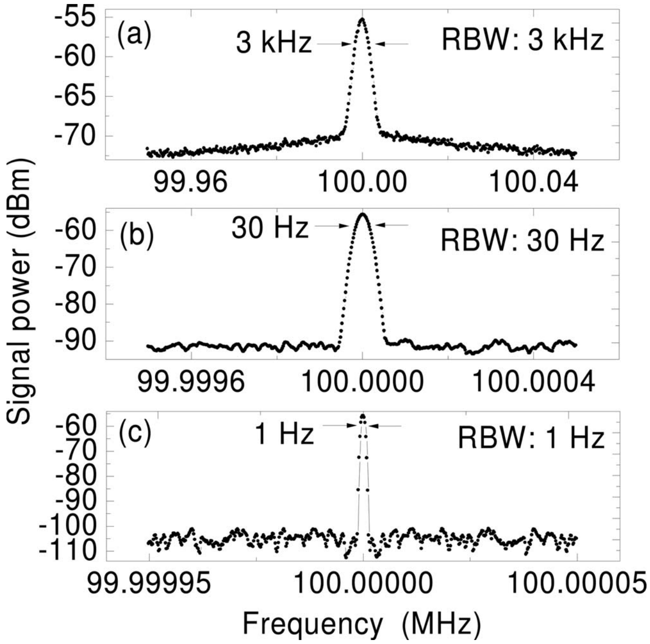

Fig. 3. Power spectra of the beat signal of the phase-locked terahertz QCL recorded by the spectrum analyzer with different RBWs and spans, but with a fixed video bandwidth of 300 Hz. A 3 dB linewidth of the beat signal is also indicated.

RBW, we find that about 13% of the QCL power is concentrated in the narrow band of the reference. This low value is the result of a reduced effective regulation bandwidth of the PLL system owing to the nonoptimal experimental condition, including long cables of several meters, the way of cabling, and the nonoptimized damping setting (loop filter) in the regulation loop. All of 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 SL harmonic generator. By increasing the regulation bandwidth of the PLL system and extending harmonics of the SL device to the high end of the terahertz range (3–6 THz), our phase-locking scheme can be potentially used in many applications of terahertz QCLs as LOs, in particular, for a space heterodyne interferometer [5].

The authors acknowledge NASA-Jet Propulsion Laboratory (JPL) for the use of a *W*-band power amplifier chain. The work at Delft University of Technology and SRON is partially supported by the AMSTAR+ of RadioNet under FP7. The work at MIT is supported by the U.S. Air Force Office of Scientific Research (AFOSR), NASA, and the National Science Foundation (NSF). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy (DOE) under contract DE-AC04-94AL85000.

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