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Phase locking of 2.324 and 2.959 terahertz quantum cascade lasers using a Schottky diode harmonic mixer

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The 23rd and 31st harmonics of a microwave signal generated in a novel THz balanced Schottky diode mixer were used as a frequency stable reference source to phase lock solid-nitrogen-cooled 2.324 and 2.959 THz quantum cascade lasers. Hertz-level frequency stability was achieved, which was maintained for several hours. © 2015 Optical Society of America

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Steady improvement in the performance of THz quantum cascade lasers (QCLs) over the last decade [1] has generated considerable interest in their use as compact sources and local oscillators (LOs) for both coherent (e.g., radar) and incoherent (e.g., high-resolution astronomical spectra) THz heterodyne detection systems [2,3]. One of the remaining obstacles is the development of a compact QCL frequency stabilization technique. Several frequency- and phase-locking methods have been applied to improve temporal coherency of THz QCLs since 2005, when Betz published the first paper on QCL frequency stabilization [4]. In most cases, their added complexity compromises the value of employing the QCL source. A summary of those methods can be found in [5].

It is widely understood that the high harmonic of an ultrastable microwave source is an ideal frequency reference source for THz QCL frequency or phase locking since microwave synthesizers are compact and readily available. However, the signal-to-noise ratio (SNR) of a beat signal decreases rapidly with increasing harmonic number, and conventional THz Schottky diode (SD)-based devices, whether open resonator (e.g., corner-cube mounted) or planar waveguide mounted, cannot produce a sufficiently strong intermediate frequency (IF) signal for laser frequency or phase locking at frequencies above, roughly, 1.5 THz [6].

A breakthrough came in 2012 when a 2.324 THz QCL was frequency locked to the 21st harmonic of a microwave signal [5] using a novel room temperature 1.5 THz waveguide-mounted SD mixer [7,8], based on a THz monolithic microwave-integrated circuit (MMIC) chip, which was fabricated at Jet Propulsion Laboratory (JPL) [9].

Less than a year later, an alternative practical approach was reported by Hayton *et al.* [10]. The authors phase locked a 3.4 THz distributed feedback (DFB) laser to the 18th harmonic of a 190.7 GHz reference source employing a room temperature GaAs/AlAs superlattice diode. The obstacle to THz QCL frequency stabilization using microwave sources has therefore been overcome with both the THz SD MMIC chip and the superlattice diode.

Motivated by the high-frequency performance of the 1.5 THz SD and with available MMIC chips designed and fabricated for 2 and 3 THz, a THz fundamental waveguide mixer block containing a 2.0–2.5 THz SD balanced mixer chip was assembled. In the work described here, the mixer was used to phase lock QCLs at 2.324 and 2.959 THz to the 23rd and 31st harmonics of microwave frequencies.

The THz QCLs were both grown and fabricated at the University of Massachusetts Lowell Photonics Center. The bound-to-continuum, semi-insulating surface plasmon waveguide structure was used in both QCLs. They have a 3 mm cavity length and a 250 μm waveguide ridge width. A description of 2.324 THz laser was reported in [5]. It produces 1.6 mW of power from a single facet at 52 K while the 2.959 THz QCL generates 220 μW at the same temperature. Solid nitrogen (SN_2), which was achieved by pumping on liquid nitrogen until it solidified, was used as a cryogen of the QCL dewar to maintain the lasers at an operational temperature of about 52 K [11].

The THz balanced mixer used in the phase-locking experiment was modified for use as a harmonic mixer by adding a separate W-band waveguide (WR10) port for injecting a frequency stable microwave reference signal into the internal IF microstrip line, leaving the coaxial IF port free for coupling out the 3 GHz IF beat signal between a harmonic of the microwave and laser signals. In this work the mixer was biased with 1 mA of current.

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A simplified block diagram of the complete phase-locking scheme of both lasers is shown in Fig. 1. Two off-axis parabolic mirrors focused 2.324 or 2.959 THz QCL radiation into the LO port of the balanced mixer. QCL power delivered into the mixer was estimated using a SD video signal. 400 nW and 72 nW were obtained for the two QCLs, respectively. For the first laser, a 33.725 GHz signal from a microwave synthesizer was tripled and delivered to the mixer IF port through WR10 waveguide and the 3 GHz IF signal was coupled out through the coaxial IF port. With the second laser, the 3 GHz signal was generated after beating the 2.959 THz signal with the 31st harmonic of a tripled 31.78 GHz source. In both cases, about 5 mW of LO power was delivered into the mixer. After amplification and filtering, 3 GHz was downconverted to 240 MHz using a second low-frequency mixer. This signal was displayed on a spectrum analyzer to observe laser frequency stability. Then, the signal was directed to a digital phase-lock loop (PLL), where it was mixed with the 240 MHz signal from the third microwave source to generate a time-varying DC error signal. After suitable amplification, to complete the negative feedback loop, the correction signal was coupled into a QCL bias circuit. An integrator monitor allowed observing the voltage of the PLL integrator, which is responsible for long-term frequency stability of the system.

The phase-lock electronics use a digital phase-frequency detector followed by a 50 MHz bandwidth op-amp. The QCL bias supply is converted to nearly pure resistive source impedance using a 20 Ω resistor in series with a voltage source power supply, and this provides a convenient summing point. The error signal is coupled into this summing point with a resistor chosen for optimum loop gain. In addition the loop has much larger gain at frequencies below 10 Hz to produce an error large enough to hold the QCL in lock against long-term drifts and to pull the laser into lock as long as the offset falls within the system IF band.

The frequency fluctuations of the free-running lasers were about 1 MHz [see Fig. 5(a), in [5]], which is related to QCL temperature and current instabilities. The results of the phase-locking experiment are presented in Figs. 2(a) and 2(b), where spectra of 240 MHz beat signals, corresponding to 2.324 and 2.959 THz QCLs, are plotted. The data were obtained with a resolution bandwidth (RBW) of 1 kHz. The lasers were phase locked for several hours. The holding time was only restricted by the amount of SN_2 in the QCL cooling system.

To estimate a degree of phase locking, the total amount of IF power in a spectrum was calculated by integration over the whole frequency span and compared to the power around the central peak of the 240 MHz IF signal. 97% of the 2.324 THz QCL radiation power was locked by the PLL within ±20 Hz of the central peak. This broadening can mainly be attributed

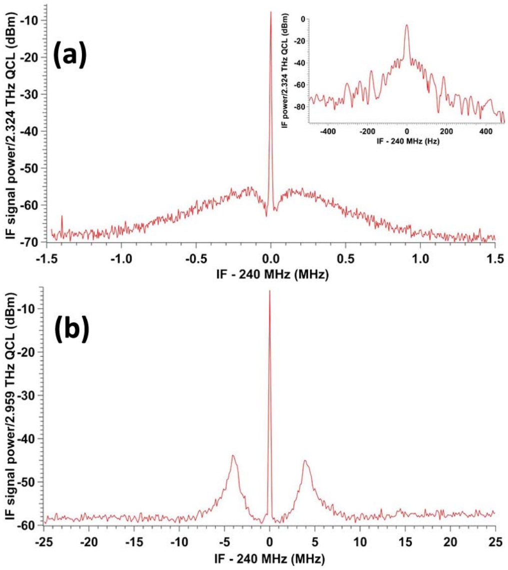

Fig. 2. Frequency spectra of the 240 MHz beat note produced by (a) 2.324 THz QCL (the inset shows a similar spectrum but with a 1 kHz span and 10 Hz RBW) and (b) 2.959 THz QCL and recorded from the spectrum analyzer (RBW of 1 kHz) under phase-locked conditions.

to noises from the balanced mixer and the synthesizer. Any phase variation in the synthesizer is increased by 10 log N^2 during multiplication of the microwave signal and added to the phase of the IF signal limiting the quality of the lock. The phase noises of the 3 × 23 rd and 3 × 31 st harmonics of microwave frequencies are increased by approximately 36 and 39 dB, correspondingly. As a result, the phase noise at 1 Hz offset after multiplication is capable even by itself without the mixer noise of broadening the central peak, producing a phase noise power comparable to that of the carrier. In general, it is a challenge to separate noise contributions from the mixer and the microwave source.

To estimate a harmonic mixing ability of the diode, SNRs of 3 GHz beat notes, produced by various high harmonics of the microwave source and both QCLs, were recorded. The results are shown in Tables 1 and 2 for 2.324 and 2.959 THz QCLs, respectively.

Beat signals generated by the 28th and 29th harmonics and the 2.959 THz QCL were not found. Such a balanced mixer

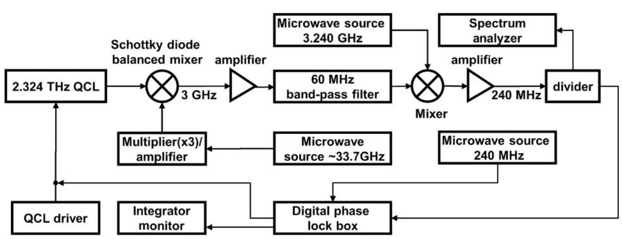

Fig. 1. Experimental setup.

Table 1. SNR of a Beat Signal between the *N*th Harmonic of a Microwave Source and the 2.324 THz QCL (RBW = 300 KHz)

Harmonic	20	21	22	23	24	25
SNR (dB)	30	20	32	33	24	25

Table 2. SNR of a Beat Signal between the *N*th Harmonic of a Microwave Source and the 2.959 THz QCL (RBW = 300 KHz)

Harmonic	25	26	27	30	31	32
SNR (dB)	13	32	35	30	30	20

should work only on odd harmonics of the LO, but much of the symmetry is lost at these high frequencies, and both even and odd harmonics produced similar results.

The fact that the same THz mixer was successfully used to phase lock QCLs 600 GHz apart indicates that these type mixers are wideband. To further evaluate the high-frequency limits of this device, the harmonic mixer was used to downconvert free-running optically pumped laser (OPL) lines at 2.52, 3.10, and 4.25 THz with measured conversion losses of 83 dB, 93 dB, and 106 dB, respectively. For example, the 37th microwave harmonic mixing with the 4.25 THz OPL line produced a 22 dB SNR beat signal at 3 GHz IF, at a spectrum analyzer RBW of 30 kHz. These preliminary unpublished results demonstrate that this mixer can still be used for harmonic mixing at frequencies above 4 THz.

In this work, THz QCLs in the 2–3 THz range were phase locked using a novel THz balanced SD mixer to internally generate a THz-frequency-stable reference signal that simultaneously downconverted a QCL frequency to the microwave regime for electronic processing and QCL frequency control. With little modification this method should lead to a compact phase-locked QCL-based THz source, which can be used as a LO for a hot electron bolometer-based heterodyne detection system for airborne and spaceborne THz observations. The technique is also extendable to higher-frequency QCLs. With further improvements in power and spatial mode quality it should be possible to use THz QCLs as LOs for these SD mixers.

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