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Overview of Techniques for THz QCL phase-locking

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Since the first demonstration of a THz Quantum Cascade Laser (QCL) in 2002 [1] it was rapidly improved towards practical applications, for example THz imaging [2] and molecular spectroscopy [3] with high resolution.

At the moment, QCL is one of the most attractive continuous wave (CW) sources in the frequency range of 3-6 THz for heterodyne spectroscopy. In the terahertz astronomy QCLs are used as LO sources in heterodyne receivers for projects SOFIA [4] and GUSTO [5] and are considered for space observatories such as Millimetron [6], LOCUS [7] and OST [8]. Frequency stability of LO is absolutely crucial for a heterodyne instrument because it influences the quality of scientific data delivered by the receiver. The most reliable option to stabilize the LO frequency is phase-locking. Phase-locking of a THz QCL has been demonstrated by various groups using various methods. Here we make an overview of these techniques.

The first frequency stabilization was demonstrated by Betz *et al.* in 2005 [9] by frequency-locking (and partial phase-locking) of 3 THz 1 mW QCL to a far-infrared (FIR) gas laser using GaAs Schottky mixer. A while later, in 2006 Baryshev *et al.* [10] showed phase-locking of two-mode QCL, using an inter-mode beat signal generated on hot-electron bolometer mixer (HEB). Both these experiments were important demonstration of QCL stabilization, though they were difficulties for practical applications.

Afterwards, in 2009 Rabanus *et al.* [11] and Khosropanach *et al.* [12] showed independently stable phase-locking for single-tone QCL, in [11] it was used 1.5 THz 0.3 mW laser and in [12] – 2.7 THz 0.38mW one. The key moment is that both groups used HEB mixer to generate the beat signal for phase locking loop (PLL) system. The reference RF signal in [11] was generated by a high power multiplying chain able to pump an HEB mixer, while in [12] was used a frequency comb generated by superlattice diode mixer [13] pumped by 182 GHz microwave source. A little later, in 2010 Consolino *et al.* [14] realized similar approach for phase-locking of 2.5 THz 1 mW QCL, using HEB mixer, though the reference RF reference was a COMB signal generated by the Cherenkov effect in a lithium niobate waveguide effected by Ti:sapphire femtosecond laser. These three phase-locking approaches [11][12][14] can be combined in one group show schematically on fig.1, utilizing HEB mixer, which is known to be the most sensitive mixer from 1.5 to 6 THz. Nether the less, presence of HEB an in the locking scheme means arranging a separate 4K cryostat. It is not an

issue for lab experiments, but it makes serious complications for on-board application of a locking system.

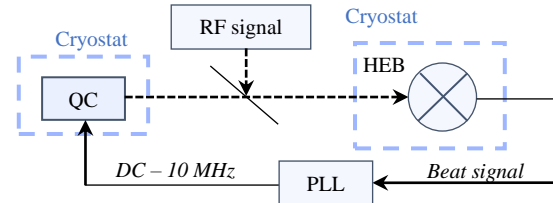


Fig. 1. Simplified block-diagram of QCL phase-locking described in papers [11], [12] and [14]. In all the cases the HEB mixer is used to provide a beat signal between the QCL and a reference signal. The RF signals in all the approaches are generated in different way.

In 2010 Barbieri *et al.* [15] demonstrated another approach of QCL phase-locking. In this experiment, a mode-locked femtosecond laser and a QCL radiation (2.7 THz, power of 25 mW) were applied to electro-optic detection system. This photo-mixing system generated a mixing product between a QCL frequency and the n_{th} harmonic of repetition rate of femtosecond laser of 90 MHz. The photocurrent beat signal frequency was 30 MHz. The electro-optic detection system is based on ZnTe crystal modulating amplitude of femtosecond pulses with the QCL frequency and on high speed (bandwidth of 300 MHz) silicon photodiodes. Similar technique was used a year later in 2011 by Ravaro *et al.* [16] to phase-lock 10mW QCL radiating at 2.5 THz (see fig. 2).

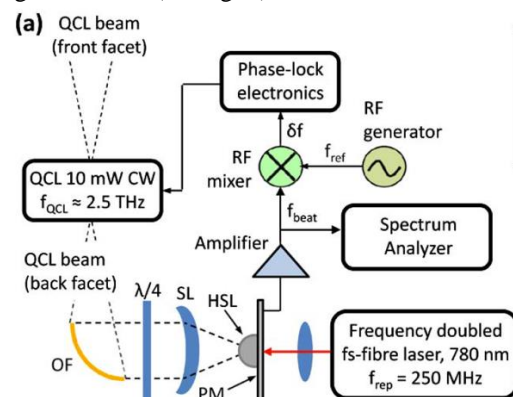


Fig. 2. Block-diagram of QCL phase-locking taken from [16]. THz field from the QCL is mixed with the photocarrier THz comb induced in the PM by the fs pulse train generated in fiber laser with repetition rate of 250 MHz.

The main new element relative to [15] is a GaAs photomixer. A big advantage of scheme in [15] and [16] is that only a room-temperature-operated elements are used. A fiber laser technology and the semiconductor

photomixer are much more light and compact than superconducting bolometer mixers.

Another way of QCL phase-locking has been described in 2013 by Hayton *et al.* [17]. The authors phase locked a 3.4 THz 1 mW distributed feedback (DFB) laser to the 18th harmonic of a 190.7 GHz reference source using a room temperature GaAs/AIAs superlattice diode. Next year Khudchenko *et al.* [18] employed the same technique for 4.7 THz 0.25 mW QCL. The key element of this scheme (see fig. 3) is the harmonic mixer receiving QCL signal and mixing it with n_{th} harmonic of a reference microwave signal of about 10 mW power at frequency around 200 GHz. The product is used by PLL system to control phase and frequency of QCL. All the elements of the locking loop are working at room temperature. A very similar approach, but using Schottky harmonic mixer instead of super-lattice one, was been published in 2015 by Danylov *et al.* [19] and Bulcha *et al.* [20]. In [20] it was phase locked a 2.5 THz laser, and in [19] – 2.3 THz and 2.9 THz lasers of power correspondingly. All the experiments in [17], [18], [19] and [20] can be reflected by very simple scheme shown in fig. 3.

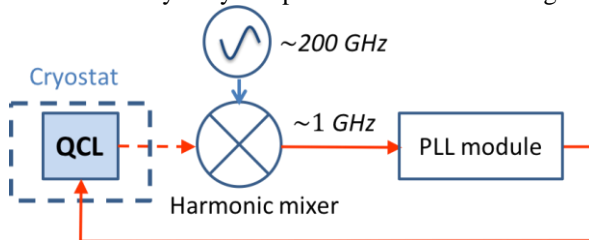


Fig. 3. Simplified block-diagram of QCL phase-locking shown in [17], [18], [19] and [20].

The latest conceptually unique method of QCL phase locking was presented in 2017 by Freeman *et al.* [21]. The 2 THz 1.7 mW QCL was locked not by an active feed-back system but by injection locking method. Employing infrared frequency combs and InGaAs photomixers a reference signal of 100 nW was generated at frequency very close to the QCL frequency. This signal was injected into the QCL and synchronized its radiation.

To summarize, the most promising are four techniques: [15]/[16]; [17]/[18]; [19]/[20] and [21].

However, only in [18] it was shown phase locking at 4.7 THz, all the other QCLs are below 3 THz. Though, one of the most interesting applications for QCL is a role of LO in on-board heterodyne receiver at 4.7 THz to observe atomic oxygen line [4-8].

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