Overview of Techniques for THz QCL phase-locking
Khudchenko, A.; Pavelev, D.~G.; Vaks, V.~L.; Baryshev, A.~M.

Published in:
European Physical Journal Web of Conferences

DOI:
10.1051/epjconf/201819504003

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2018

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Khudchenko, A., Pavelev, D. G., Vaks, V. L., & Baryshev, A. M. (2018). Overview of Techniques for THz QCL phase-locking. In European Physical Journal Web of Conferences (Vol. 195). (European Physical Journal Web of Conferences). EPJ Web of Conferences. https://doi.org/10.1051/epjconf/201819504003

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Overview of Techniques for THz QCL phase-locking

A. Khudchenko1,2, D.G.Pavelev3, V.I. Vaks4, A.M. Baryshev1,5

1Kapteyn Astronomical Institute/NOVA, University of Groningen, Groningen, Netherlands, a.khudchenko@sro.nl
2Kotel’nikov Institute of Radio Engineering and Electronics RAS, Moscow, Russia
3Lobachevsky State University, Nizhny Novgorod, Russia
4Institute for Physics of Microstructures RAS, Nizhny Novgorod, Russia
5Astro Space Center, Lebedev Physical Institute of Russian Academy of Science, Moscow, Russia

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.

In 2010 Barbiere 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 nω 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).

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
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/AlAs 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 its 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 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 powers corresponding. All the experiments in [17], [18], [19] and [20] can be reflected by very simple scheme shown in fig. 3.

![Simplified block-diagram of QCL phase-locking](image)

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 mW 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].

References

[1] R. Köhler, A. Tredicucci, et al. // Terahertz semiconductor heterostructure laser // Nature 417, 156–159, 2002.
[2] A. W. M. Lee, Q. Qin, et al. // “Real-time terahertz imaging over a standoff distance (>25 meters) // Appl. Phys. Lett., 89, 141125, 2006.
[3] H.-W. Hübner, S. G. Pavlov, et. al. // High-resolution gas phase spectroscopy with a distributed feedback terahertz quantum cascade laser // Appl. Phys. Lett. 89, 061115 2006.
[4] H. Richter, M. Weinold, et al. // 4.7-THz Local Oscillator for the GREAT Heterodyne Spectrometer on SOFIA // IEEE Trans. on TST 5, 539–535, 2015.
[5] [https://www.sron.nl/misstions-astrophysics/quato](https://www.sron.nl/misstions-astrophysics/quato)
[6] http://millimetron.ru/index.php/en/
[7] [http://www.locus_satellite.com/](http://www.locus_satellite.com/)
[8] J. Fortney et al. https://arxiv.org/abs/1803.07730
[9] A. L. Betz, R.T. Boreiko, et al. // Frequency and phase lock control of a 3 THz quantum cascade laser // Opt. Lett. 30, 1837-1839, 2005
[10] A. Baryshev, J. N. Hovenier, A. J. L. Adam, I. Kaalynas, J. R. Gao, T. O. Klaassen, B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno // Phase locking and spectral linewidth of a two-mode terahertz quantum cascade laser // Appl. Phys. Lett. 89, 031115, 2006.
[11] D. Rabanus, U. U. Graf, M. Philipp, O. Ricken, J. Stutzki, B. Vowinkel, M. C. Wiedner, C. Walther, M. Fischer, and J. Faist // Phase locking of a 1.5 Terahertz quantum cascade laser and use as a local oscillator in a heterodyne HEB receiver // Opt. Express 17, 1159–1168, 2009.
[12] P. Khosropanah, A. Baryshev, W. Zhang, W. Jellema, J. N. Hovenier, J. R. Gao, T. M. Klipwijk, D. G. Pavlev, B. S. Williams, S. Kumar, Q. Hu, J. L. Reno, B. Klein, and J. L. Hesler // Phase locking of a 2.7 THz quantum cascade laser to a microwave reference // Opt. Lett. 34, 2958–2960, 2009.
[13] D. G. Pavlev, Yu. I. Koschurinov, V. M. Ustinov, A. E. Zhukov, F. Lewen, C. Endres, A. M. Baryshev, P. Khosropanah, W. Zhang, K. F. Renk, B. I. Stahl, A. Semenov, and H.-W. Huebers // conf. proc., ISSTT, 319, 2008.
[14] L. Consolino, A. Taschin, P. Bartolini, S. Bartalini, P. Cancio, A. Tredicucci, H. E. Beere, A. D. Ritchie, R. Torre, M. S. Vitiello, and P. De Natale // Phase-locking to a free-space terahertz comb for metrological-grade terahertz lasers // Nat. Commun. 3, 1040.
[15] S. Barbieri, P. Gellie, G. Santarelli, L. Ding, W. Maineut, C. Sirtori, R. Colombelli, H. Beere, and D. Ritchie // Phase-locking of a 2.7 THz quantum cascade laser to a mode-locked erbium-doped fibre laser // Nat. Photonics 4, 636–640, 2010.
[16] M. Ravaro, C. Manquest, C. Sirtori, G. Barbieri, G. Santarelli, K. Blary, J. F. Lampin, S. P. Khanna, and E. H. Linfield // Phase-locking of a 2.5 THz quantum cascade laser to a frequency comb using a GaAs photomixer //, Opt. Lett., vol. 36, pp. 3969–3971, 2011.
[17] D. J. Hayton, A. Khudchenko, D. G. Pavlev, J. N. Hovenier, A. Baryshev, J. R. Gao, T. Y. Kao, Q. Hu, J. L. Reno, and V. Vaks // Phase-locking of a 3.4-THz Quantum Cascade Laser using a harmonic super-lattice mixer // Appl. Phys. Lett. 103, 051115.
[18] A. Khudchenko, D. J. Hayton, D. G. Pavlev, A. Baryshev, J. R. Gao, T. Y. Kao, Q. Hu, J. L. Reno, V. Vaks // Phase locking a 4.7 THz Quantum Cascade Laser using a Super-lattice Diode as Harmonic Mixer // conf. proc., IRRMW-THz, 2014.
[19] A. Danilov, N. Erickson, A. Light, and J. Waldman, // Phase locking of 2.324 and 2.959 terahertz quantum cascade lasers using a Schottky diode harmonic mixer // Opt. Lett., vol. 40, pp. 5090–5092, 2015.
[20] B.T. Bulcha, J.L. Hesler, A. Valavanis, V. Drakinskiy, J. Stake, R. Dong, J.X. Zhu, P. Dean, L.H. Li, A.G. Davies, E.H. Linfield, N.S. Barke. // Phase locking a 4.7 THz Quantum Cascade Laser to a frequency comb using a GaAs photomixer //, IEEE Trans. on TST 5, 539–535, 2015.