

Invited Paper

Repetition frequency locking of a terahertz quantum cascade laser emitting at 4.2 THz

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Abstract: The electrically-pumped terahertz quantum cascade laser (QCL) is characterized by high power emission, compact, broad frequency coverage, and so on, which shows abilities for frequency comb operations. Although free-running QCLs can work as frequency combs by designing the laser structure with small group velocity dispersions and/or inserting mirrors to compensate laser intrinsic dispersions, the ideal comb operation can only be obtained by firmly locking the repetition frequency and carrier frequency of a laser. In this work, we have reported a repetition frequency locking of a terahertz QCL emitting around 4.2 THz. When the 6-mm-long laser is operated in continuous wave mode without any locking techniques, the repetition frequency is measured to be ~6.15 GHz with a linewidth of hundred kilohertz. Once a phase lock loop (PLL) is applied to dynamically control the drive current of the QCL, we have demonstrated a successful repetition frequency locking of the laser with a signal to noise ratio of 80 dB. This technique can be employed for the frequency comb and dual-comb operations of terahertz QCLs for high-resolution applications.

Keywords: Terahertz, Quantum cascade laser, Frequency comb, Phase-lock

1. Introduction

The terahertz wave [1-3], roughly defined in the frequency range between 0.1 and 10 THz, has attracted most interests over past decades due to its unique features such as covering multiple “fingerprints” (characteristic absorption lines) of different molecules, penetration through body tissue without ionization, ultra-fast transmission speed for communications and so on. Development of terahertz technology is strongly dependent on high performance radiation sources, for example, uni-travelling-carrier photodiodes (UTC-PDs) [4], Schottky barrier diodes (SBDs) [5], photoconductive antennas [6], vacuum tubes [7], quantum cascade lasers (QCLs) [8-9], and so on. Among them, the terahertz QCL that is based on the electron inter-subband transitions between

laser states in the multiple-quantum-well active region is one of the most efficient terahertz radiation sources in the frequency range between 1 and 5 THz [10-11]. Furthermore, due to the broad frequency coverage [12], high power output [13], narrow far-field divergence [14-15], the electrically-pumped terahertz QCL is the ideal device for generating terahertz frequency combs.

Characterized by evenly spaced frequency lines and ultra-short optical pulse generation, optical frequency combs [16-17] are of great significance for various applications, including precision spectroscopy, metrology, imaging, communications [18-21], etc. Although the first frequency comb was proposed in infrared wavelengths, attentions on terahertz combs have been rising over the following years due to the increasing demand in practical applications [22-24]. It has been proved that QCLs are suitable for generating stable terahertz frequency combs, but additional phase lock technique, in principle, is required for ultrahigh resolution applications. The terahertz QCL can be fully stabilized by locking both repetition frequency and carrier frequency, and here focus are mainly on the former, i.e. inter-mode beat note (IBN) frequency. In this work, we experimentally demonstrate a phase lock loop (PLL) to lock the repetition frequency of a 4.2 THz QCL. By beating the QCL with the referenced RF signal and then comparing it with an ultra-stable signal in MHz-level, the phase difference can be obtained and converted into feedback current to the QCL chip. Finally, the locking is accomplished in a dynamical process and eventually a shrinking linewidth below 1 Hz and impressive signal noise ratio (SNR) up to 80 dB are achieved in our experiment.

This article is organized as follows. In the second section, we describe the design and basic performance of the terahertz QCL used in this study. In the third section, the experimental setup for phase-locking the repetition frequency of the terahertz QCL is demonstrated in detail. And then we present the experimental results after the PLL is applied to the laser comb.

2. Design and characteristics of the QCL

The terahertz QCL used in this work employs a hybrid active region structure. The calculated band structure with potential distribution and wavefunctions is shown in Fig. 1 (a). The hybrid structure is featured by the bond-to-continuum transitions for generating terahertz photons (red arrow) and longitudinal optical phonon scattering (blue arrow) for efficiently depopulating the lower laser state.

After the growth of the QCL wafer using the molecular beam epitaxy (MBE) technique based on GaAs/AlGaAs material system, the wafer is fabricated into a single plasmon waveguide structure employing traditional laser fabrication technologies. In the single plasmon waveguide, the terahertz field is confined between the upper metal electrode and the lower GaAs contact layer with a field leakage into the semi-insulating GaAs substrate. Figure 1(b) shows the calculated

electrical field distribution of the fundamental transverse mode of the single plasmon waveguide at 4.2 THz. It can be clearly seen that large amount of electric field goes into the substrate.

To improve the laser temperature performance, the substrate is thinned down to $\sim 200 \mu\text{m}$. The fabricated laser ridges are cleaved into 6 mm long and then mounted onto a copper heat sink for electrical and optical measurements. It is worth mentioning that the laser ridge width of $150 \mu\text{m}$ is intentionally chosen to obtain small group velocity dispersion for frequency comb operation [25].

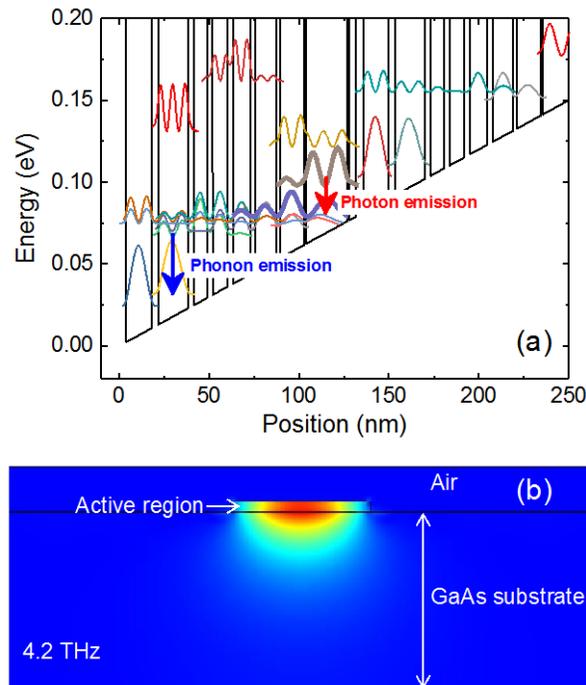


Fig. 1 Structure of active region and waveguide of QCL. (a) Sketch of conduction band structure, where the red arrow represents photon emission from bond state to continuum state and blue arrow represents phonon emission for fast carrier depletion. (b) Calculated electric field distribution of the laser with a single plasmon waveguide. The calculation was performed at a frequency of 4.2 THz.

Figure 2(a) shows the measured light-current-voltage ($L-I-V$) characteristics of the 6-mm-long and $150\text{-}\mu\text{m}$ -wide laser. The laser is operated in continuous wave mode and the temperature is stabilized at 20 K. It can be seen that the laser can output 2.5 mW power in continuous wave mode at 20 K with an ultralow threshold current (density) of 0.6 A (67 A/cm^2) and a broad current dynamic range (up to 1.3 A).

The emission spectral characteristic of the laser is measured using a Fourier transform infrared (FTIR) spectrometer equipped with a room temperature pyroelectric detector. The light emitted from the terahertz QCL is coupled into the FTIR chamber using two parabolic mirrors. To reduce the water absorption as much as possible, the beam path is purged by nitrogen gas. A typical emission spectrum of the laser electrically-pumped at 1100 mA at 20 K is shown in Fig. 2(b) measured with a spectral resolution of 0.1 cm^{-1} . From Fig. 2(b), we can see that the laser is emitting

at 4.2 THz with a spectral bandwidth of 200 GHz.

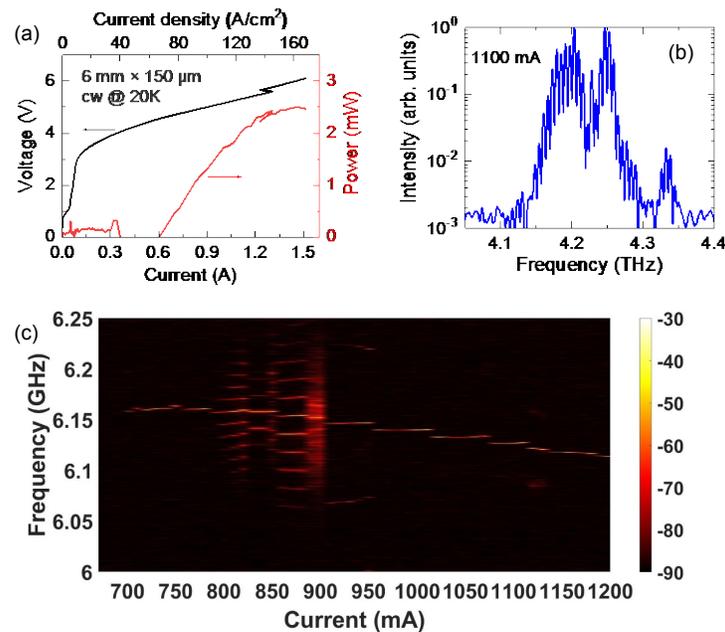


Fig. 2 Performance of the terahertz QCL. (a) Light-current-voltage characteristic of the 6-mm-long and 150- μ m-wide laser in continuous wave mode measured at 20 K. (b) Normalized emission spectrum of the laser measured at 1100 mA at 20 K. (c) Inter-mode beat note mapping of the laser measured in the current range from 680 to 1200 mA.

The spectrum shown in Fig. 2(b) cannot evidence the laser frequency comb operation since the spectral resolution is limited by the FTIR spectrometer. To investigate the frequency stability of the laser, normally the electrical inter-modal beat note (IBN) measurement can be utilized [26-27]. The IBN measurement is to measure the beating between the optical modes, which can be implemented electrically using the laser itself as a detector. The IBN frequency depends on the laser cavity, which is equal to the cavity round trip frequency or laser repetition frequency. This signal is normally in the microwave frequency range and can be easily registered using a spectrum analyzer with an extremely high resolution (1 Hz). Therefore, the linewidth of the IBN signal in the microwave frequency range is a sign of the frequency stability of the optical modes in the terahertz regime. Figure 3(c) plots the IBN mapping of the terahertz QCL with a current span from 670 to 1200 mA. It can be observed that stable single frequency signal appears at some drive currents, for example, between 950 and 1125 mA. The single narrow IBN signal is a proof that the terahertz modes are relatively stable and the frequency comb operation is achieved.

However, as we have already mentioned, although the frequency comb operation is obtained, the terahertz modes are still moving and they are not firmly locked. To make the frequency lines more stable, external locking techniques should be applied, i.e., the carrier and/or IBN frequencies should be firmly locked. In the following, we will demonstrate how to lock the IBN frequency of the terahertz QCL emitting at 4.2 THz employing a PLL.

3. PLL of the terahertz laser comb

A frequency comb can be fully described by two frequencies, one is the carrier frequency and the other is the repetition frequency. Once the two frequencies are known, each frequency line of the frequency comb is well defined. Therefore, the frequency stabilization of a frequency comb is, in principle, to stabilize the carrier and/or repetition frequencies. The PLL is an efficient method to firmly lock the repetition frequency of a laser comb. What a PLL does is to send the feedback current to the QCL and make the generated IBN frequency (that is strongly dependent on the laser drive current) identical to the frequency of the local oscillator (LO). Figure 3 schematically plots the experimental setup for the PLL of the terahertz QCL comb. We use the laser to self-detect the laser IBN signal which is sent to a broadband bias-tee and then monitored by a spectrum analyzer. The PLL is then implemented to lock this IBN frequency (repetition frequency) of the laser comb. The PLL is normally operated with a narrow bandwidth. However, the IBN signal generated by the 6-mm-long laser is around 6 GHz which is far beyond the bandwidth of the PLL. Therefore, the PLL cannot directly work with the 6 GHz signal. In view of this, a mixer is used to down-convert the IBN signal to a low frequency around 13 MHz which is then filtered and amplified before it is sent to the PLL. The PLL module only reads signal with a frequency ranging from 10 to 300 MHz and a power value greater than -30 dBm. It compares phase of the mixed signal and the LO offered by an ultra-stable signal generator, and then feeds back the difference to QCL in the form of current. In this way, the IBN fluctuations are suppressed, namely the realization of repetition frequency locking. The dynamic response of mixed signal can be observed on spectrum analyzer 2.

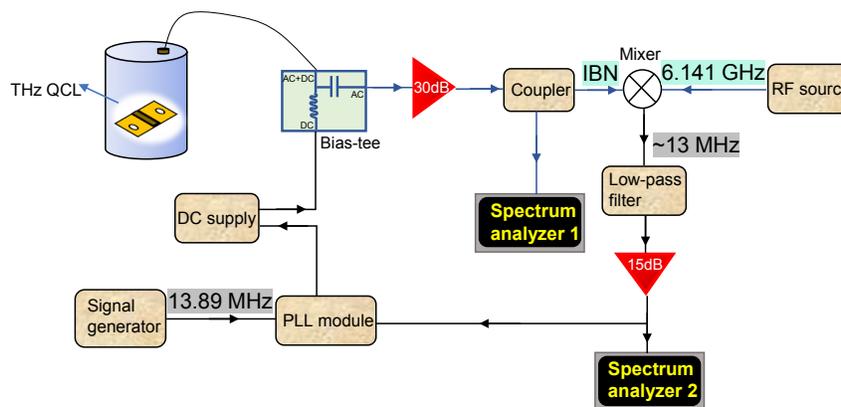


Fig. 3 Schematic plot of the PLL experimental setup.

In order to clearly show the locking effect, we first plot the IBN spectrum of the laser without any external locking as shown in Fig. 4(a). It can be seen that in free running mode, the unlocked IBN shows a linewidth of 394 kHz when a resolution bandwidth (RBW) of 10 kHz is used.

Although the IBN is not fully locked, the signal is single line and the frequency comb operation is obtained in free running. For comparison, the locked results are shown in Figs. 4(b) and 4(c). When the PLL is activated, we can see that the IBN can be firmly locked and the linewidth reduction is significant. Figures 4(b) and 4(c) show the spectra of down-converted IBN at 13.89 MHz measured with a RBW of 50 Hz and 1 Hz, respectively. Note that the measured 3-dB linewidth of the spectra shown in Figs. 4(b) and 4(c) are 50 Hz and 1 Hz, respectively, which are identical to the RBW parameters used for the measurements. Limited by the instrument, we are not able to measure the IBN signal using even higher spectral resolutions. One thing that can be verified is that after the PLL is applied, the IBN linewidth can be reduced down to <1 Hz. Besides the linewidth reduction, we can also observe a significant improvement of the signal-to-noise ratio (SNR). Without the PLL, the IBN signal shows a SNR of 50 dB as shown in Fig. 4(a). While, the PLL can result in an improved SNR up to 80 dB measured using an RBW of 1 Hz as shown in Fig. 4(c). It is worth mentioning that the SNR of QCL can be improved over 80 dB under the effect of PLL, and it is unprecedented in other way of phase lock. Both the linewidth and SNR comparison indicate that the PLL works successfully with the terahertz QCL comb emitting at 4.2 THz. In [Supplementary video](#), we show the locked IBN spectrum registered on the spectrum analyzer.

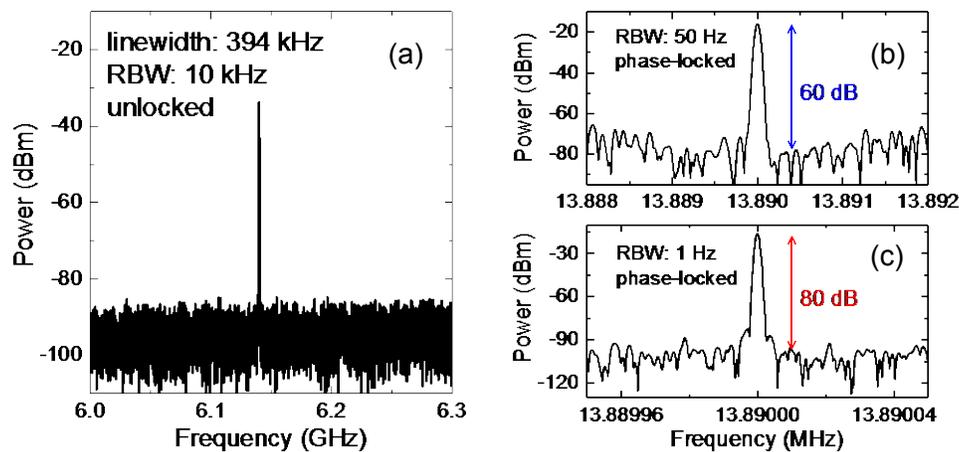


Fig. 4 IBN spectra of the free-running terahertz QCL comb (a), PLL-locked QCL measured with an RBW of 50 Hz (b) and 1 Hz (c).

The PLL technique is currently used for the single laser comb to fully lock the IBN frequency or the repetition frequency. The results shown in Fig. 4 prove that the PLL is a robust method for the phase locking of terahertz QCL combs. Furthermore, in the future this PLL should be also implemented for generating stable terahertz dual-comb laser sources [28-31]. There should be two options to apply the PLL to a terahertz QCL dual-comb system. One is that the two IBN signals generated from the two laser combs can be locked separately using two PLLs. In this situation, although each laser is locked, the relative phase relationship between the two lasers is still not fixed. Alternatively, we can lock the dual-comb line to fix the relative phase relationship between the two combs. In this method, the strongest line of the dual-comb spectrum can be chosen, filtered out,

and amplified for the PLL. The advantage of the technique is that without locking the carrier frequencies of the two laser combs, the dual-comb lines can be firmly locked. The latter can be used for some practical spectroscopic applications.

4. Conclusion

In summary, we have demonstrated a method utilizing PLL to lock the repetition frequency of a terahertz QCL emitting at 4.2 THz. Compared with the case of the laser in free-running mode, we have observed a significant linewidth reduction of the IBN signal by applying the PLL technique. Furthermore, the SNR of the locked IBN is improved to 80 dB when it is measured with an RBW of 1 Hz. The locked QCL comb is more suitable for high resolution spectroscopic applications. The PLL technique also shows potentials for phase-locking of the dual-comb laser sources.

Acknowledgements

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