Frequency and amplitude stabilized terahertz quantum cascade laser as local oscillator

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We demonstrate an experimental scheme to simultaneously stabilize the frequency and amplitude of a 3.5 THz third-order distributed feedback quantum cascade laser as a local oscillator. The frequency stabilization has been realized using a methanol absorption line, a power detector, and a proportional-integral-derivative (PID) loop. The amplitude stabilization of the incident power has been achieved using a swing-arm voice coil actuator as a fast optical attenuator, using the direct detection output of a superconducting mixer in combination with a 2nd PID loop. Improved Allan variance times of the entire receiver, as well as the heterodyne molecular spectra, are demonstrated. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4751247]

A terahertz (THz) quantum cascade laser (QCL) is the most promising solid-state source as the local oscillator (LO) for a high resolution heterodyne receiver operating at frequencies above 2 THz and, in particular, for a multi-pixel array receiver because of its high output power (typically mW).1,2 Among different types of applications, a super-THz array receiver because of its high output power (typically frequencies above 2 THz and, in particular, for a multi-pixel for a high resolution heterodyne receiver operating at fre-

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dissipation power (<1 W) because of the metal-metal waveguide structure. In detail, the laser used consists of a 10 μm thick MBE grown GaAs/AlGaAs active region with 27 periods of gratings and a total length of 1070 μm. It radiates a single mode emission line tunable from 3452.0 to 3450.8 GHz by varying the bias voltage from 13.9 V to 14.9 V. Its maximum output power is 0.8 mW at an operating temperature of ~12 K. The divergence of the main beam is about 12° in both vertical and horizontal directions. The same laser has been used for demonstrating heterodyne molecular spectroscopy with tuning capability and frequency locking.

As the mixer, we employ a superconducting NbN HEB mixer with a nanobridge of 0.2 x 2 μm² in size, operated at liquid He temperature (4.2 K) and requiring an optimal LO power of 150 nW at the detector itself. The HEB mixer is the most sensitive heterodyne detector operated at frequencies between 1.5 THz and 6 THz. The mixer performance such as the mixing conversion gain and intermediate frequency (IF) output power depends strongly on the LO power. Thus, any variation in LO power can affect the operating state and thus induce instability in the mixing performance.

Fig. 1 shows the complete setup for the amplitude and frequency stabilization experiment as well as for the heterodyne spectroscopy measurements. We start with the setup required only for the stabilization experiment. The QCL is operated in a pulse tube cryocooler at a stabilized operating temperature of 16 K. The THz radiation from the QCL is first focused with a high-density polyethylene (HDPE) lens, and then passes through the voice coil attenuator. Subsequently, the QCL signal is split into two beams by a 13 μm thick Mylar beam splitter, where the reflected signal works as a LO to pump the HEB mixer, while the transmitted beam is used for the frequency locking. The frequency locking loop consists of a gas cell (Gas cell 1) at room temperature, in which a methanol absorption line is used as the frequency reference. Furthermore, a 2nd superconducting NbN hot electron bolometer is operated only as a direct power detector, together with a PID controller and a lock-in amplifier. The technique used for the frequency locking is very similar to that reported in Refs. 12 and 14. The voice coil actuator together with a second PID feedback loop is used to realize the amplitude stabilization, where the DC current of the voltage biased HEB mixer is used as a power reference signal. If the incident LO power fluctuates, a feedback current will be generated to drive the voice coil that acts as a variable optical attenuator by interrupting partial LO beam to maintain a constant DC current of the mixer. The voice coil is superior to a rotational polarizer since it responds fast (up to 1 kHz), and has the advantage of high resolution and full dynamic range. This technique can reduce not only the instability of the LO amplitude but also other instability factors like atmospheric turbulence in the LO path and LO mechanical instability. To characterize the stability of the receiver and measure Allan variance times, a hot/cold (295/77 K) blackbody load is applied as the input signal. The IF signal from the HEB mixer is amplified by a wide-band cryogenic amplifier, followed by two room temperature amplifiers, with a 100 MHz bandwidth (1.4–1.5 GHz) bandpass filter. The IF signal is further sampled by a power meter.

For the frequency locking experiment, a bias circuit for the QCL combines three input signals, where a DC bias voltage, an AC sinusoidal modulation signal (~1 kHz), and a feedback control signal are employed to independently control the laser. By feeding the output current of the HEB power detector to a lock-in amplifier, the derivative signal of the absorption profile is obtained. Then, a feedback signal from a PID controller is used to actively lock this derivative signal, maintained at zero value. In this way, the laser frequency is stabilized to a particular methanol absorption line. And this frequency locking alone has been realized previously for a QCL in Refs. 12 and 14.

To characterize the stabilization, we monitor the frequency fluctuation of the QCL by the output of the lock-in amplifier, the amplitude fluctuation of the incident power by the DC current of the HEB mixer, and the stability of the HEB receiver by the output of the IF amplifier chain in four different operation modes, covering (1) free running; (2) only frequency stabilized; (3) only amplitude stabilized; and (4) both frequency and amplitude stabilized. Fig. 2 shows the key results by plotting the three signals within four operation modes. In the free running mode, the observed low frequency fluctuations and drift in the lock-in signal are a result of the frequency noise of the laser due to external contributions mainly from the temperature variations of the cryocooler. The contribution of the cryocooler also induces amplitude instability, reflected by the fluctuations of the HEB mixer current and of the IF output power. In the second operating mode when the frequency stabilization loop is enabled, the lock-in signal becomes well stabilized and is maintained at the set point of zero, which implies that the QCL frequency is fully stabilized. However, in this case, the fluctuations in the amplitude of the QCL increase, reflected by those in the HEB current. Also the fluctuations in the mixer IF output are increased as a result of the fluctuations.

FIG. 1. Schematic of the measurement setup for demonstrating both amplitude and frequency stabilization of a 3.5 THz QCL as local oscillator for a heterodyne receiver. It is also the setup for the Allan variance and spectroscopic measurements.
The linewidth of the QCL is estimated by transforming the variation in voltage of the lock-in signal in the time domain into the frequency domain.\textsuperscript{12} As a result, we obtain a free running linewidth of about 1.5 MHz, while the locked linewidth is around 35 kHz in the fully stabilized state. The linewidth reduction factor is the same as one reported in Ref. 12, and the linewidth value has the same order of magnitude as well (18 kHz measured previously), which is sufficiently narrow for practical use as a local oscillator. The difference in the absolute value can be due to the different operating conditions of the QCL.

We also perform an Allan variance measurement in the total power (continuum) mode to quantify the effect of the stability of the amplitude to the entire receiver. Allan variance is a well-known, powerful tool for characterizing the stability of a system.\textsuperscript{16} We measure the Allan variance $\sigma^2_A(\tau)$ of the normalized IF output power, given by $\sigma^2_A(\tau) \equiv \langle \sigma(\tau)^2 \rangle$, where $\sigma^2$ is the average squared standard deviation of each number from its mean and $\tau$ is the sampling period. The measured $\sigma^2_A(\tau)$ for the entire receiver is plotted as a function of the sampling time in Fig. 3 for three different measurement conditions. For comparison, the radiometer equation for an effective noise fluctuation bandwidth of 13.5 MHz is also plotted. The Allan time when the QCL in free running state is below 0.01 s. And the measurement shows an extremely unstable behavior, suggested by the presence of strong oscillations attributed to the low frequency temperature oscillations in the pulse tube cryocooler. In contrast, the Allan time from a both frequency and amplitude stabilized receiver is about 0.3 s for a measured 13.5 MHz bandwidth. An improvement with a factor of more than 30 is achieved by introducing the amplitude stability in addition to the frequency locking. Furthermore, the data from the HEB in the superconducting state show the stability of the entire IF amplifier chain, which gives a total power Allan time at around 2 s. The Allan times for the stabilized receiver and from the superconducting state are all shorter than reported in Ref. 9 indicating a non-optimized IF amplifier chain as the main limiting factor. The improvement can

The underlying physics is relatively straightforward. It is known that both frequency and output power of a THz QCL are a function of both DC bias and operating temperature. The emission power, in general, decreases if either the temperature increases or the DC bias decreases, which is true in the operating regime of our QCL. However, the frequency behavior can be different and is device dependent. Based on our previous measurement on the same QCL,\textsuperscript{11} we find that the frequency decreases if the temperature increases or the voltage increases. Thus, a small increase in temperature as a distortion will decrease the emission frequency as well as the amplitude. In response, the frequency locking loop through the PID will generate a negative voltage signal to compensate for the frequency decrease. However, as a result, the amplitude will further decrease. In other words, the fluctuations in the amplitude will increase as shown in Fig. 2. In contrast, for the 3rd operating mode, when the voice coil is applied to stabilize the amplitude, no effect has been seen to the frequency fluctuations since the amplitude adjustment is completely independent of the QCL operation.
be realized by carefully designing and arranging the set-up with respect to, for example, the air turbulence and the temperature stabilization of the room temperature IF amplifiers.

To further verify the performance of the stabilized receiver, we perform heterodyne molecular spectroscopic measurements. The measurement setup is also sketched in Fig. 1, where the HEB mixer and QCL parts are the same as the one described for the stability experiment, except for the input signal and IF readout (the backend). In this case, the signal source is a combination of a methanol gas cell (Gas cell 2) and a hot/cold blackbody load. The same IF amplifier chain is used, but with a 0–1.5 GHz low pass filter in between. The spectrum is recorded by a fast Fourier transform spectrometer (FFTS). In fact, two types of spectroscopic measurements are performed. One is to measure the methanol emission lines using the QCL-HEB receiver with both frequency and amplitude stabilized. The main figure in Fig. 4 plots methanol emission lines in the intermediate frequencies between 0 and 1.5 GHz, which are down converted from 3.5 THz methanol lines. Also, a modeled spectrum for the same frequency range is plotted in the main figure. It can be seen that an excellent agreement between the calculation and the data is obtained when both frequency and amplitude of the LO is stabilized (in red). The gas pressure is 1.9 mbar, using a 3 s integration time for each data trace. Each spectrum is re-measured after a 1 h interval. We find that two spectra can overlap well when both frequency and amplitude are stabilized, while there is a frequency offset of about 5 MHz between the two spectra when only amplitude is stabilized (but no frequency stabilization). The latter implies a frequency drift of the LO. It proves that the LO frequency can indeed be locked, which is crucial for the spectroscopic measurement. It is worthwhile to note that, because of the full stabilization, we can resolve fine spectral lines as narrow as 10 MHz at the low gas pressure.

In conclusion, we succeeded in demonstrating a fully stabilized 3.5 THz QCL, both in its amplitude and frequency, as a local oscillator operated in a pulse tube cryocooler for a heterodyne receiver. The frequency is locked to a methanol absorption line through the PID and the bias voltage, resulting in a linewidth as narrow as 35 kHz. The amplitude is stabilized by applying a swing-arm actuator blocking part of the LO beam for rapid feedback LO intensity control. The effectiveness of the amplitude stabilization and frequency locking is supported by the improved Allan time of the entire heterodyne receiver and also the high-resolution heterodyne spectroscopic measurements.

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