Terahertz Sideband-Tuned Quantum Cascade Laser Radiation

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***Abstract*— A compact, tunable, narrowband terahertz source was demonstrated by mixing a single longitudinal mode 2.408 THz, free running quantum cascade laser with a 2-20 GHz microwave sweeper in a conventional corner-cube-mounted Schottky diode. The sideband spectra were characterized with a Fourier transform spectrometer, and the radiation was tuned through several D_2O rotational transitions to estimate the longer term (t ≥ several sec) bandwidth of the source. A spectral resolution of 2 MHz in CW regime was observed.**

I. Introduction And Background

TERAHERTZ (THz) quantum cascade laser (TQCL) development is progressing rapidly, with demonstrations of higher power, improved efficiency, and longer wavelength operation. Unlike mid-IR distributed feedback QCLs, which can be tuned several cm^{-1} by, e.g., ramping the device bias voltage, a single longitudinal mode, fabry-perot-cavity TQCL provides only about 0.1 cm^{-1} tuning range. To obtain a spectral bandwidth useful for spectroscopy we have mixed the TQCL radiation with a 2-20 GHz synthesized sweeper in a corner-cube-mounted Schottky diode and used primarily the upper sideband to measure several rotational transitions in low pressure D_2O vapor. The spectroscopic results, in turn, enabled us to estimate the spectral content and center frequency of the TQCL source, when operating in either a pulsed or continuous wave (CW) mode.

II. Results

The THz quantum cascade laser (2.408 THz) was grown by the Photonics Center (University of Massachusetts Lowell), processed by Spire Corporation, and fully characterized by Submillimeter-Wave Technology Laboratory (University of Massachusetts Lowell). The SB radiation was generated by mixing the TQCL and microwave signals supplied by a 2-20 GHz synthesized sweeper in the SD. When the TQCL emitted single longitudinal mode radiation (about 240 μW of power), the measured SB power was approximately 150 nW, giving the power conversion efficiency of the SB generation system to be approximately 6×10^{-4}. A diagram of the sideband (SB) generation setup is shown in Fig. 1. The spectra of the SB radiation with the TQCL operating in a single longitudinal mode were measured using the FTIR spectrometer at 0.11 cm^{-1} resolution. The TQCL was operating CW and pulsed mode at a 12.95% duty cycle (3.5 ms pulse length, 37 Hz) using a DC power supply with a few mA current noise. Fig. 2 shows composite spectra of the sideband radiation in the pulsed and CW modes.

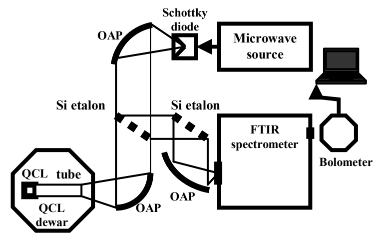

Fig. 1. Setup used for sideband generation experiment.

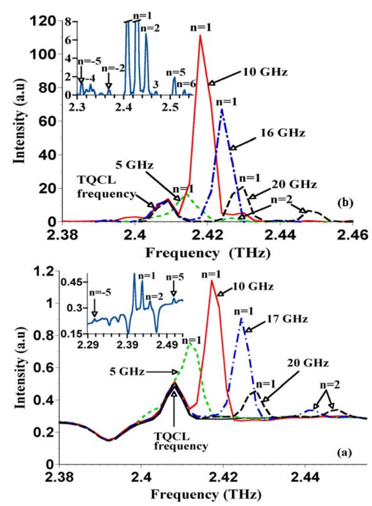

Fig. 2. Spectra of the sidebands produced by applying different microwave frequencies in CW (a) and pulsed (b) regimes with a 2.408 THz QCL. Insets are the sideband spectra corresponding to 20 GHz RF signal, which allow observing higher order sidebands.

To conduct the D_2O gas spectroscopy experiment, the spectrometer was replaced with a 37-cm-long gas cell. D_2O spectra when the TQCL was operating CW and pulsed regime (the shape of the pulse with a 300 μs rise time can be seen in the inset of the Fig.7) were measured at a gas pressure of 500 mTorr as the microwave source was swept from 2 to 20 GHz. Figure 3 displays the D_2O spectra. Four of the strongest lines were identified[1] as transitions at the first harmonic, upper sideband for a CW mode and a pulsed mode. These transitions in the CW mode were shifted up about 250 MHz in microwave frequency, compared to the corresponding pulse mode data, as a result of the red shift of the TQCL with

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increasing temperature. The 2420782 MHz line was chosen as a reference line and the TQCL wavelengths of 2407750 MHz (CW mode) and 2408000 MHz (pulsed mode) were calculated with MHz accuracy.

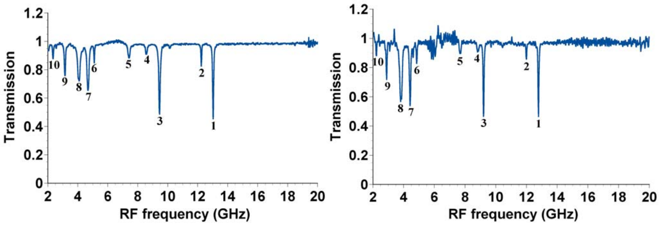
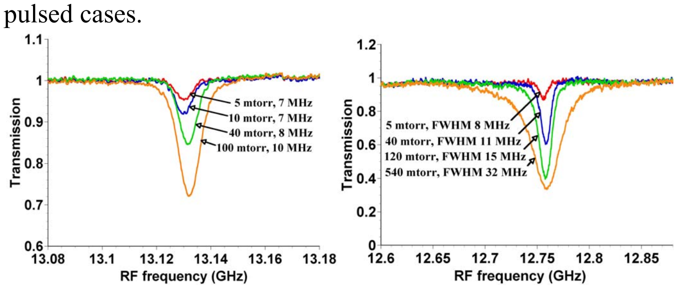


Fig. 3. Spectra of D_2O at 500 mTorr in CW (a) mode and pulsed (b) mode produced by sweeping the microwave frequency from 2 to 20 GHz.

The D_2O spectra of the reference line (J=10, K_a=4, K_b=7 to J=10, K_a=5, K_b=6) were measured for gas pressures from 3 torr down to several millitorr. The synthesizer was swept over about 400 MHz. The measured linewidth of the line continued to narrow down to approximately the theoretical Doppler linewidth of 6.7 MHz. A value of 7 MHz was measured in the CW mode and 8 MHz in the pulsed mode where a frequency chirp might be anticipated. Deconvolution of the measured line gave the laser linewidth, of about 2 MHz (CW mode) and 4.4 MHz (pulsed mode) for the case of the lowest pressures, where the time to sweep across the width of the line was about a few seconds. Figures 4a and 4b are plots of the relative transmitted intensity through the gas cell for the CW and pulsed cases.



(a) (b)

Fig. 4. Spectra of 2420782 MHz line of D_2O in CW (a) mode and pulsed (b) mode at different pressures of D_2O.

Similar spectral linewidths were obtained by conventional heterodyne methods. The free-running QCL was mixed with a CO_2 pumped far-infrared gas laser lasing on the 2409.293 GHz line of CH_2DOH in CW mode. Mixing was done by using a corner-cube-mounted Schottky diode. The TQCL frequency is about 1 GHz lower than the frequency of the gas laser. The IF signal was sent through an IF amplifier with a gain of 30 dB. Typical intermediate frequency (IF) signals obtained using a spectrum analyzer are shown in Fig. 5, where the TQCL was driven in the CW mode with a DC power supply. The measured beat frequency as a function of TQCL current and voltage is shown in the inset of Fig. 5. The results give a tunability of about 6.5 GHz/A, and 1.5 GHz/V. Using a 6 V battery instead of a DC power supply decreased the TQCL linewidth from a few MHz to a linewidth narrower than 200 kHz (bandwidth resolution (BW) of 10 kHz, sweep time (ST) of 10 s, span (SP) of 1 MHz) (see inset of Fig. 6). The 12 MHz side lobes in the spectra are due to the presence of another transverse mode of the gas laser. Reducing the sweep rate to 18 kHz/ms (BW=10 kHz, ST=50 ms, SP=900 kHz) gives the TQCL linewidth of 10 kHz. The 40 kHz sidelobes are artifacts of a CO_2 laser power supply (Fig. 6). A 300 ms sweep over 100 kHz frequency range of the IF signal with BW of 1 kHz reveals the short-term TQCL linewidth of about 1 kHz, as shown in the second inset of Fig. 6.

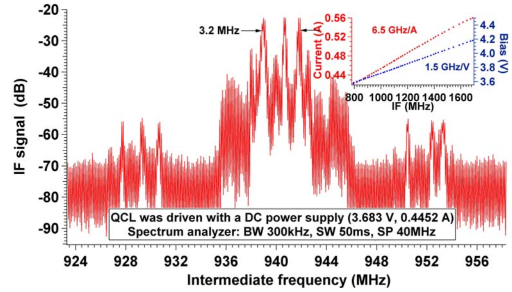


Fig. 5. Beat signal between the QCL driven with a DC power supply and the FIR gas laser. Inset, current and voltage tuning of the QCL.

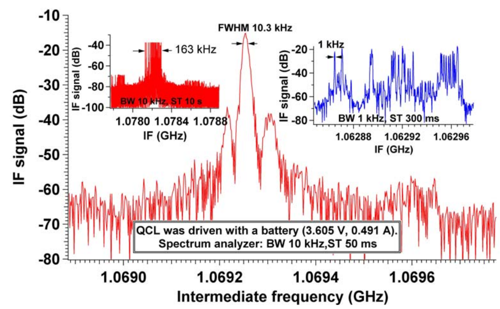


Fig. 6. Beat signal between the QCL driven in the CW mode with a battery and the FIR gas laser. Left inset, long-term (10 s) IF signal. Right inset, IF signal with a high 1 kHz resolution.

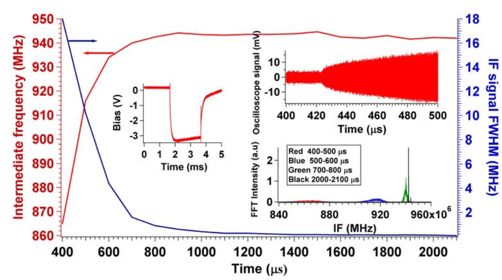


Fig. 7. Intermediate frequency and the linewidth of IF signal change during the QCL driving pulse. Insets: QCL driving pulse; the first 100 μs part of the oscilloscope signal; the spectra obtained by computing the FFT of the oscilloscope signal.

The results of mixing the TQCL operating in the pulsed mode (37 Hz, 2 ms) with a CW FIR gas laser is shown in Fig. 7. The IF signals were recorded as oscilloscope traces from the Infiniium MSO8104A oscilloscope. The traces were divided into 100 μs sections to sample IF signals properly. As an example of the trace, the first 100 μs part is shown in the inset of Fig. 7. The fast Fourier transformation (FFT) was computed of each section of the trace (see inset of the Fig.7). The linewidths and the center frequencies of the obtained spectra are plotted in Fig. 7 as a function of time measured after the leading edge of the pulse.

REFERENCE

[1] http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html