Direct Radio Frequency Modulation of Quantum Cascade Lasers for mid-IR Applications

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Abstract: We present a QCL-based integrated laser module operating in the mid-IR range with direct modulation of RF signals up to 1.2 GHz and a miniaturized, fully functional electronic module for spectroscopic signal retrieval.

The laser sources operating in the mid-IR range have become attractive in many applications and fields of science, such as free-space optical communications [1,2] and laser spectroscopy for trace gas detection of many dangerous and toxic gas compounds [3,4]. However, most laser applications require amplitude or frequency modulation to achieve the desired form of optically transmitted information or to utilize physical phenomena to investigate the interaction of light with matter. Herein, we present a direct, current-injected high frequency-modulated Quantum Cascade Laser (QCL) module operating in the mid-infrared (mid-IR) range at 8.29 µm. Since the wavelength of the QCL laser corresponds to the absorption lines of hydrogen sulfide (H_2S), the designed laser module was applied into practice for the detection of these gas molecules, using a custom-designed, compact, dedicated electronic measurement module that replaces the entire laboratory measurement apparatus needed for the Chirped Lasers Dispersion Spectroscopy (CLaDS) technique [5].

The direct QCL frequency modulation was realized by utilizing a bias tee module. An RF bias tee circuit was specially designed, fabricated and integrated directly into the PCB of the radio frequency (RF) modulation circuit (Fig. 1a), providing 50 Ω impedance matching and a much higher current carrying capacity for the choke (up to 1 A), which blocks the RF signal returning to the DC circuit powering the laser. The effectiveness of RF signal attenuation to the DC circuit feeding the laser was measured in the frequency range of up to 3 GHz (Fig. 1b) and averaged RF power attenuation of 35 dBm (comparable to commercially available bias tee circuits). In addition, in order to obtain actual temperature readings of the laser structure and to better stabilize it thermally, two additional miniature spring-loaded connectors were introduced. This feature enabled a direct temperature reading from a miniature NTC sensor at the QCL laser structure. However, this required redesigning the entire module and using precision 3D SLA printing from liquid photopolymer resins since the NTC sensor contact fields on the QCL laser structure were 400 µm wide. The gap between them was only 200 µm (Fig. 2b). Meanwhile, QCL laser structures require excellent thermal contact with the substrate. Manufacturers do not recommend using thermally conductive pastes (possible damage through evaporation and deposition of volatile compounds on the laser structure).

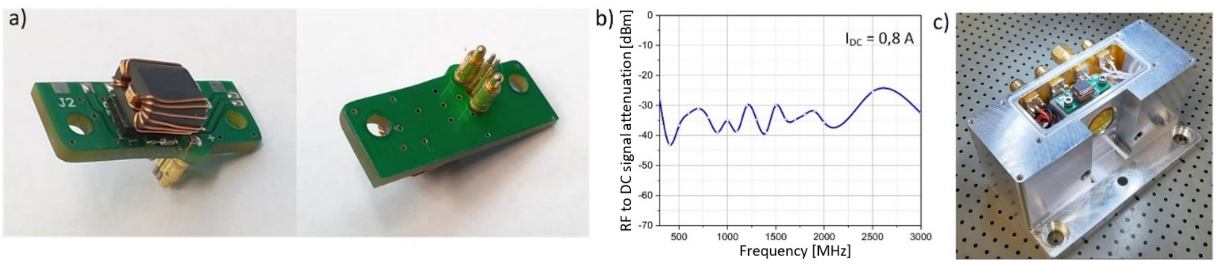

Fig. 1. Designed electronic PCB with a direct RF modulation circuit and integrated QCL laser module.

Excellent thermal contact to the structure was provided by polishing the surface of the copper block, obtaining a mirror-quality surface and an indium foil spacer (Fig. 2c). The complete thermoelectrically cooled QCL laser module (Fig. 2a) was housed in a designed and machined (CNC) aluminium housing, from which mid-IR radiation is emitted through a glued-in zinc selenide (ZnSe) window. A ZnSe lens placed in front of the window in a translation mount was used to properly collimate the QCL laser beam. In the next step, the optical output power characteristics of the QCL laser were determined as a function of the DC current value for two different temperatures of the laser structure, as presented in Fig. 3a. The obtained results are well matched with the bare QCL characteristic provided by the manufacturer (Thorlabs), which indicates a proper configuration of the developed module.

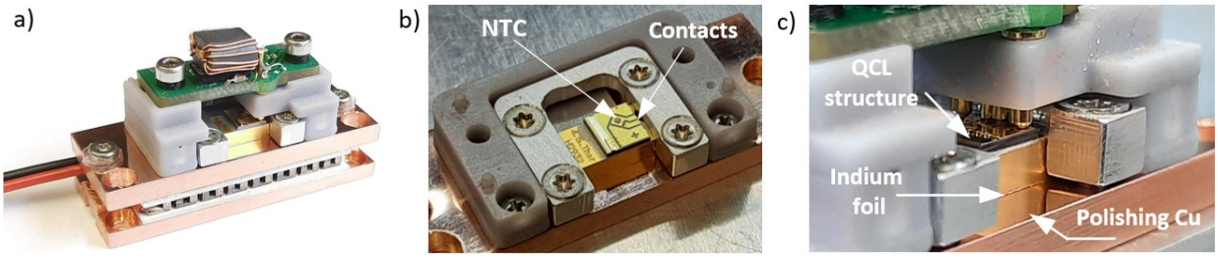

Fig. 2. Fabricated QCL laser module with direct RF modulation and thermoelectric cooling.

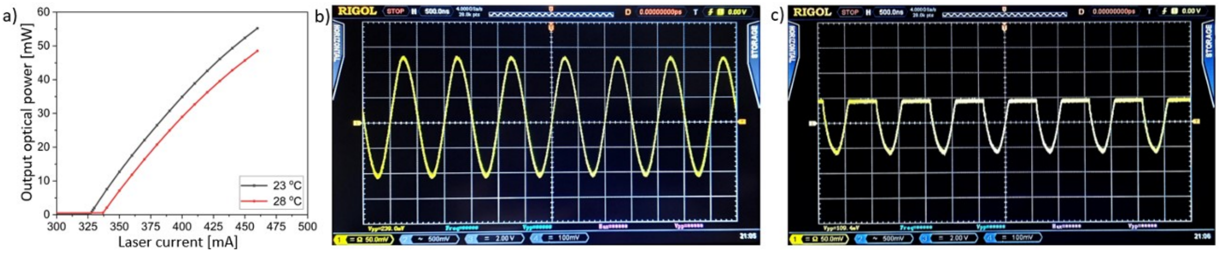

Fig. 3. Laser optical power vs. current characteristics of the QCL laser and the effect of direct modulation of the laser in the time domain.

Next, the properties of direct modulation of the laser with an RF signal were checked. First, the ratio of direct RF modulation of the laser was determined. Knowing the threshold current of the laser (Fig. 3a) and recording with a mid-IR detector (Vigo System) the time signals of the direct modulation of the laser above the threshold current (Fig. 3b) and for the value of the threshold current when the peak-to-peak modulation signal is "cut in half" (Fig. 3c), the ratios of RF signal to laser current value were determined for 10 MHz and 100 MHz frequencies and RF signal strengths of 0 dBm (0.63 Vpp), 3 dBm (0.89 Vpp) and 10 dBm (2 Vpp), respectively. Regardless of the RF signal parameters, very similar values of the ratio were obtained, with an average value of 38.7 ± 0.3 mA/V. Thus, for a given RF signal power, it is easy to determine whether the maximum value of the RF modulation signal does not exceed the maximum operating current of the QCL laser, which in this case was 630 mA. Next, the frequency modulation efficiency of the QCL laser module was checked by recording the mid-IR detector signal with an RF spectrum analyzer (Rohde&Schwarz), with the RF modulation signal turned on (Fig. 4a) and the additional modulation of the laser's DC current with a test sine wave low-frequency signal called "chirp" (Fig. 4b).

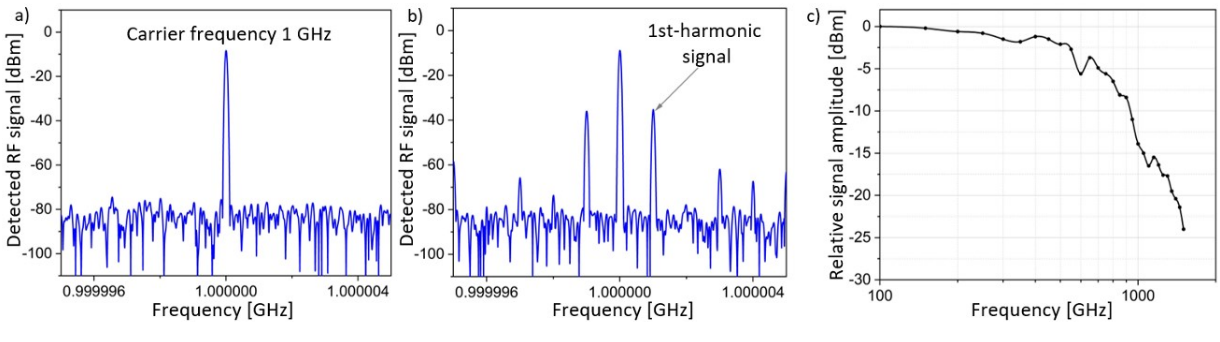

Fig. 4. Spectra of the RF signal with direct modulation of the laser f=1 GHz, additional modulation by the "chirp" signal, and the measured amplitude response of the optical path.

When the mid-IR wavelength of the laser beam interacts with gas molecules along beam propagation length, the 2nd-harmonic "chirp" signal after FM demodulation will appear, and its amplitude is proportional to the concentration of the gas being detected.In addition, the amplitude RF signal transfer characteristics were measured (Fig. 4c), which clearly indicates the frequency bandwidth limitation of the mid-IR detector itself. In the wavelength range used, it is not possible to optically determine the frequency response of the RF signal of the QCL laser structure itself, due to the limitation of the frequency response of the commercially available apparatus (mid-IR photodetectors). If it is needed to make measurements for RF signals above 1 GHz, amplifying the detector signal with RF amplifier modules is necessary. The results of the design and experimental work carried out, and in particular, the measurements of RF spectra with direct frequency modulation of the QCL laser together with additional modulation of the "chirp" signal, confirm the effectiveness of the performance of the developed electronic module for direct wavelength modulation of the QCL laser. QCL's direct frequency modulation module has been proven in in the mid-IR laser spectroscopy. For this purpose, a compact electronic signal processing module for laser spectroscopy was designed and constructed, which includes an IQ demodulator and a microprocessor-based driver module. The electronic IQ demodulator module has a frequency range spanning from 300 MHz to 9 GHz. However, this range was also reduced due to the limited bandwidth of the mid-IR detector. Two simultaneous THS1206 analog-to-digital converters with a maximum signal sampling rate of 6 Msps were used to convert the IQ quadrature signals into digital form. With this arrangement, each IQ signal is sampled twice at the exact moment. It allowed the IQ signals to be quickly averaged on "in-fly," that is, at the moment between reading the data in the transducers and writing to the data array in memory. The benefit of this solution is that it improves the signal-to-noise ratio (SNR) by an additional 6 dB. The management unit of the acquisition module is an STM32F407 microprocessor with an

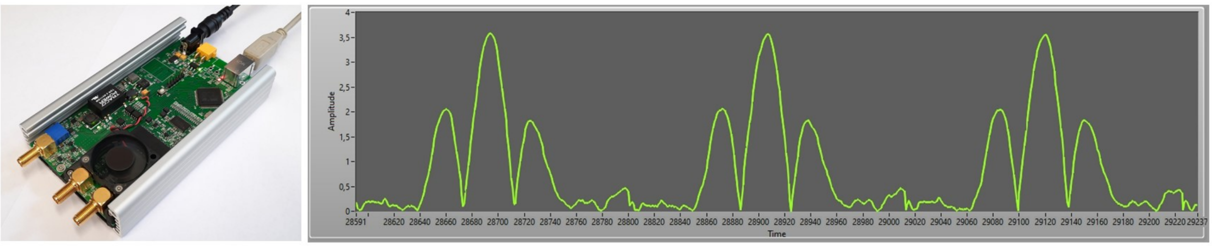

Fig. 5. Compact electronic module for CLaDS-based spectroscopic signal retrieval and obtained gas concentration signal during a sweep across absorption line (real-part signal at 2^{nd}-harmonic of modulated sine wave).

operating frequency of 168 MHz, whose task is to digitally operate the ADCs, acquire and preprocess the data, communicate with the application and transfer the data via a USB interface. In addition, the designed electronic module provides digital generation of a slow-variable sinusoidal signal (so-called chirp) of adjustable amplitude and microprocessor-controlled frequency, as well as a ramp signal (triangular waveform), for sweeping the laser frequency through the absorption line of the gas to be detected, and synchronization of the modulating sinusoidal signal with the acquisition of FM-demodulated IQ signals. Figure 5 shows a practical implementation of an electronic module for spectroscopic signal analysis based on the CLaDS technique and amplitude of the frequency-demodulated signal at the 2^{nd}-harmonic peak, which indicates a concentration of detected gas molecules during the sweep through the absorption line.

Acknowledgements

The National Centre for Research and Development (NCBR) for funding Grant No. WPC2/HiSensTech/2021.

References

[1] K. Zou, et al. "High-capacity free-space optical communications using wavelength-and mode-division-multiplexing in the mid-infrared region." Nature Communications **13**.1, 7662 (2022).
[2] A. Soibel, et al. "Midinfrared interband cascade laser for free space optical communication." IEEE Photon.Technol.Lett. **22**.2,121-123 (2009).
[3] Hu, Mengyuan, and Wei Ren. "Wavelength-modulation dispersion spectroscopy of NO with heterodyne phase-sensitive detection." Optics Letters **47**.11, 2899-2902 (2022).
[4] G. Dudzik, et al. "Mid-IR parts-per-billion level nitric oxide detection using solid-state laser intracavity photothermal sensor (SLIPS)." Sensors and Actuators B: Chemical **380**, 133413 (2023).
[5] M. Nikodem, et al."Chirped laser dispersion spectroscopy for remote open-path trace-gas sensing." Sensors 12.12, 16466-16481 (2012).