Jerez, B., et al. Large-signal modulation in distributed feedback quantum cascade lasers for coherent multiharmonic signal generation, In: *Optical and Quantum Electronics, 50(351), Sept. 2018, 8 pp.*

DOI: https://doi.org/10.1007/s11082-018-1619-5

Large-signal modulation in distributed feedback quantum cascade lasers for coherent multiharmonic signal generation

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Received: 10 May 2018 / Accepted: 4 September 2018

Abstract

In this Letter, an experimental analysis for coherent multiharmonic signal generation in quantum cascade lasers is presented. The underlying principle relies on the direct modulation of the laser with a large sinusoidal wave to drive the laser above and below threshold. This generates a multiharmonic optical signal in the frequency domain as the device is forced to respond in a nonlinear fashion. The impact of the modulation parameters is assessed in the resultant optical spectrum of a continuous-wave distributed feedback quantum cascade laser. Despite not creating pulses due to the ultrafast dynamics of the laser, the results reveal that a comb structure with uniform line spacing and high phase correlation between teeth can be straightforwardly generated.

Keywords Distributed feedback quantum cascade lasers · Large-signal modulation · Multiharmonic generation · Optical frequency comb · Radiofrequency photonics

1 Introduction

Quantum cascade lasers (QCLs) are unipolar devices with potential to be engineered with emission wavelengths across the whole Mid-Infrared (MIR) and THz ranges by means of an adequate design (Bartalini et al. 2014). Since their inception in 1994 (Faist et al. 1994), these devices have experienced a significant development, reaching levels of performance covering continuous-wave (CW) operation at high temperatures (Wittmann et al. 2009), multi-watt output power levels (Lu et al. 2011) and low electrical consumption (Bismuto et al. 2015), with additional broadband spectral tuning capabilities (Riedi et al. 2013). Nevertheless, one of the most actively pursued features in these devices is the potential for optical frequency comb (OFC) generation within the active region (Faist et al. 2016), offering much promise for the implementation of chip-sized multimode sources which are particularly attractive for outside-the-lab applications in the field of molecular spectroscopy (Villares et al. 2015).

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The possibility of exploiting a coherent source based on a series of discrete, equally-spaced frequencies is of particular interest in the MIR region (Schliesser et al. 2012), where the potential of the available sources has often been hindered due to the need for bulky, delicate setups-as in solid-state mode-locked lasers (Sorokin et al. 2007) or optical parametric oscillators (Leindecker et al. 2012), the use of nonlinear processes with limited efficiency—difference frequency generation (Cruz et al. 2015), or an excessively large mode spacing for practical applications—microresonators (Griffith et al. 2015). Still, the inherent features of MIR QCLs in terms of gain recovery time make the stable creation of pulses—and hence, combs in the frequency domain—particularly unfavourable and restricted to complex, specially engineered devices based on the mode-locking technique to overcome these limitations (Wang et al. 2009; Wójcik et al. 2013). This picture changed drastically in 2012, when Hugi et al. (2012) proved the generation of OFCs in Fabry-Pérot QCLs through a natural Four-Wave Mixing process in broadband gain, low dispersion waveguides. This approach offered a well-defined comb structure in the frequency domain despite not creating pulses in the active region of the laser, and also proved to be perfectly valid for applications such as dual-comb spectroscopy (Villares et al. 2014). Detailed theoretical studies followed these early demonstrations (Burghoff et al. 2015; Khurgin et al. 2014; Villares and Faist 2015) as well as significant effort to optimize comb operation in these devices (Hillbrand et al. 2018; Lu et al. 2015, 2017; Villares et al. 2016). These works yielded impressive results in terms of bandwidth efficiency and output power, relying on tailored designs aimed at optimizing the intrinsic comb operation developed into the laser, demonstrating OFCs with repetition frequencies in the range of tens of GHz with tuning capabilities within the MHz range. Additionally, new harmonic comb states have also been reported with THz repetition rates due to the suppression of adjacent cavity modes (Kazakov et al. 2017).

Here, an alternative and flexible procedure for coherent multiharmonic signal generation (i.e., comb generation) using Distributed Feedback (DFB) QCLs is proposed. The approach is based on the direct modulation of the laser by means of a large radiofrequency (RF) signal which takes the device above and below threshold to create phase-locked sidebands, and therefore, a comb-like spectrum whose line spacing can be promptly changed by adjusting the frequency of the modulating signal. An experimental analysis of the parameters which determine the comb structure is performed in a CW DFB-QCL and their impact on the resultant optical spectrum is assessed. Finally, the coherence of the multiharmonic signal and the equidistance between lines is also evaluated by careful examination of the RF beatnotes resolved by a spectrum analyser.

2 Experimental results and discussion

The schematic of the experimental setup is shown in Fig. 1. The free-running DFB-QCL under test is biased by means of a DC current and an RF modulating signal which are combined through a bias-tee. The RF component of the input signal is amplified to ensure that the laser is turned off and on within the same period of the signal. The output beam is split so the signal is simultaneously monitored with a Fourier-transform infrared (FTIR) spectrometer and an electrical spectrum analyser after heterodyning on a photovoltaic detector. The QCL is a 3.2 mm long, 10 μm wide standard ridge-type, face-emitting DFB laser (Brandstetter et al. 2014; Liu et al. 2006; Mujagić et al. 2008) that exhibits a single-mode regime across the whole range of operation. In this case, prior to driving the laser with

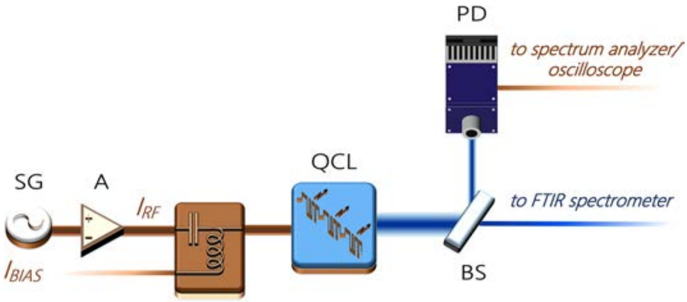

Fig. 1 Schematic of the experiment. *SG* signal generator, *A* amplifier, *QCL* quantum cascade laser, *BS* beam splitter, *PD* photodetector

external modulation, the QCL is cooled down to 80 K to guarantee its operation in CW regime.

Unlike interband lasers, the large-signal modulation in QCLs does not usually give rise to pulsed Gain-Switching (GS) operation regimes which take advantage of the excitation of the first spike of the relaxation oscillations typical of second order laser-type systems. In the case of QCLs, these oscillations are overdamped due to carrier dynamics (Paiella et al. 1999), making traditional pulse generation schemes challenging. Nevertheless, this on/off modulation may induce the laser device to respond in a nonlinear fashion leading to the broadening of the spectrum caused by the unveiling of sidebands which are equally spaced by a value defined by the modulation frequency of the QCL. Figure 2 illustrates this effect on the single-mode DFB laser (threshold current ≈ 230 mA). Figure 2a depicts the time trace recorded after photodetection by means of a fast oscilloscope revealing the distortion of the temporal signal—which in this case resembles that of a regime of strong amplitude modulation (Burghoff et al. 2015)—while Fig. 2b shows the envelope of the optical spectrum exhibiting a redistribution of optical power across all the arisen lines in the spectrum (the sidebands are not visible due to the resolution of the spectrometer but can be resolved after photodetection, as discussed later).

This expansion showed to be controllable through the set of parameters which determine the applied modulation conditions, namely the bias current of the laser, the modulation power and the modulation frequency (or repetition frequency, since it determines

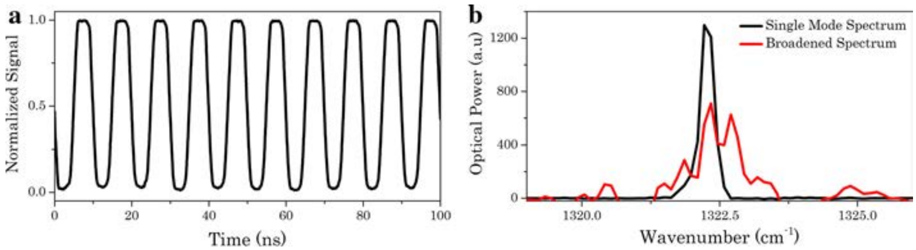

Fig. 2 Illustration of the effect of large-signal modulation at 100 MHz on the DFB-QCL. In this example, the parameters I_{BIAS}/I_{TH} (bias current over threshold current) and I_{RF}/I_{BIAS} (amplitude of the modulation current over bias current) were set at 1.2 and 0.2, respectively. **a** Time-domain photodetector signal. **b** Broadened optical spectrum recorded with a FTIR spectrometer with 0.2 cm^{-1} resolution

the spacing of the lines, as mentioned earlier). Figure 3 depicts this effect in different scenarios, where it is visible the way the power spreads across the lines and therefore, the significant change of the envelope of the resultant spectrum. In general, there is reasonable agreement with the typical behavior of diode laser under regimes of large-signal modulation (Vasil'ev et al. 2001). Particularly, Fig. 3a illustrates the effect of modifying the bias current of the laser for a fixed external modulating signal. The results are normalized to the threshold current of the laser. On the other hand, Fig. 3b details the evolution from a single-mode-like spectrum when the modulation power with respect to the bias current is too low to an enlarged, widened spectrum as the power gradually increases. Again, this behavior is consistent with the large-signal modulation regime, where a larger modulation depth translates into a wider comb-like optical spectrum. In Fig. 3c, a comparison between three different modulation frequencies is also shown, revealing the influence of this parameter on the optical spectrum. In agreement with the trend in this type of modulation regimes, a higher modulation frequency results in

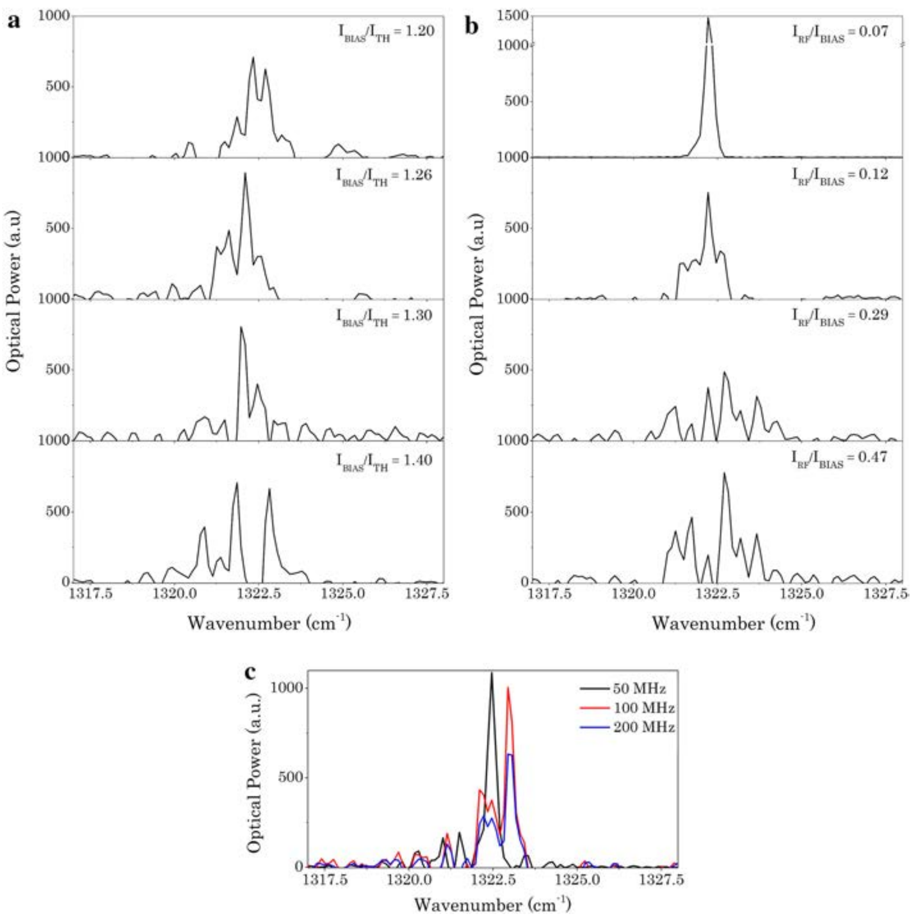

Fig. 3 Evaluation of the expansion of the DFB-QCL spectrum as a function of different parameters. **a** Bias current analysis at 100 MHz repetition frequency and $I_{RF}/I_{BIAS}=0.2$. **b** Modulation power analysis at 100 MHz and $I_{BIAS}/I_{TH}=1.2$. **c** Modulation frequency analysis at $I_{RF}/I_{BIAS}=0.4$ and $I_{BIAS}/I_{TH}=1.1$

optical spectra with wider spans and more complex structures when the modulation frequency increases within the modulation bandwidth of the laser device. A further comparison with upper frequencies was not performed due to the limited bandwidth of the detector − 180 MHz). It is important to note that no analysis of the frequency response or optimization of the comb operation of the device was performed as the purpose of this analysis is to illustrate the impact of this set of parameters on the final multiharmonic signal, which can be conveniently selected in order to generate a suitable signal for the application of interest.

In order to better understand the structure of the resultant spectra, especially when the resolution of the spectrometer is insufficient, an analysis of the electrical signal after downconversion from the optical to the RF domain needs to be carried out. To that end, a photovoltaic detector (PVI-4TE-8, Vigo Systems, S.A.) and a spectrum analyser were employed. Figure 4 illustrates the outcome of this analysis, showing numerous beatnotes, equally-spaced at the multiples of the modulation frequency of the laser which are clearly visible even beyond the roll-off frequency of the photodetector. They originate from the recombination of all the teeth (previously not resolved because of the resolution of the spectrometer). Figure 4a shows the resultant spectrum in the case of the repetition frequency of study (100 MHz) for a specific pair of parameters I_{RF}/I_{BIAS} and I_{BIAS}/I_{TH}. Further experiments with different values of these ratios and modulation frequencies were also realized leading to changes in either the amplitude of the beatnotes or the noise floor. However, no fluctuations of the lines were observed in the frequency domain, and the beatnotes remained rigidly at multiples of the repetition frequency. Despite the limited bandwidth of the detector, this technique clearly shows that the generation of equally-spaced sidebands neighboring the excited mode of the cavity is feasible.

Finally, the linewidth of the beatnotes was also assessed and compared with that of the original signal from the employed RF generator (see Fig. 4b). For the same repetition frequency (100 MHz), a 3-dB linewidth in the sub-hertz region was obtained (this value is limited by the resolution of the instrument − 1 Hz). This very narrow beatnote

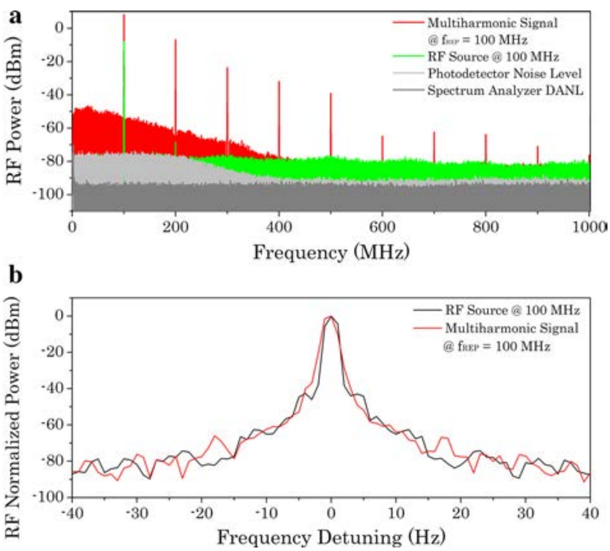

Fig. 4 **a** Evaluation of RF spectra after photodetection of the modulated optical signal. In this case, the QCL at $I_{RF}/I_{BIAS} = 0.2$ and $I_{BIAS}/I_{TH} = 1.2$ is modulated at 100 MHz. For comparison purposes, the displayed average noise level (DANL) of the instrument, the noise level of the photodetector and the spectrum of the modulating signal provided by the RF generator used in the experiment are also included in the plots. Resolution bandwidth: 5.1 kHz. **b** Comparison of the RF signal and the multiharmonic signal beatnote at the same modulation frequency (100 MHz). Resolution bandwidth: 1 Hz

was also observed for different operating conditions and multiples of the modulation frequency (higher order beatnotes), which is an indicator of high phase correlation between the teeth of the multiharmonic optical signal (Prior et al. 2015).

3 Conclusions

In summary, the presented work has explored a new approach for comb generation in QCLs. The large-signal modulation of the QCL above and below threshold is demonstrated as a viable method to create a well-defined series of evenly-spaced lines. The effect of the external modulation on the spectrum of a DFB laser has been studied, showing that an expansion of the initial spectrum occurs while preserving a stable phase relationship between the comb teeth, as the multiharmonic beatnotes reveal. The line spacing can be readily tuned by changing the modulation frequency and the high-speed capabilities of QCLs might extend the potential modulation bandwidth up to tens of GHz (Hinkov et al. 2016). The simplicity of use, tunability capabilities and versatility of these multimode signals make them well-suited to fill the existing gap within QCL-based OFCs for high spectral resolution spectroscopy. Field applications such as multiheterodyne detection of chemical compounds with narrow absorption features in the MIR region may benefit from this approach without the need for interleaving spectra while maintaining the compact nature of QCL sources.

Acknowledgements B.J., P.M.-M., C.D. and P.A. would like to thank the Spanish Ministry of Economy, Industry and Competitiveness for supporting the project under the TEC2017-86271-R Grant. R.S. and G.S. acknowledge the support by the Austrian Science Fund (FWF) Project #49 (Next-Lite). The work by B.J. has been performed in the frame of an FPU Program, #FPU014/06338 and a Mobility Aids for Short Stays and Temporal Transfers Program, #EST16/00172, both granted by the Spanish Ministry of Education, Culture and Sports.

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