High frequency modulation and (quasi) single-sideband emission of mid-infrared ring and ridge quantum cascade lasers

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Abstract: We investigate the high frequency modulation characteristics of mid-infrared surface-emitting ring and edge-emitting ridge quantum cascade lasers (QCLs). In particular, a detailed comparison between circular ring devices and ridge-QCLs from the same laser material, which have a linear waveguide in a “Fabry-Pérot (FP) type” cavity, reveals distinct similarities and differences. Both device types are single-mode emitting, based on either 2nd - (ring-QCL) or 1st -order (ridge-QCL) distributed feedback (DFB) gratings with an emission wavelength around 7.56 µm. Their modulation characteristics are investigated in the frequency-domain using an optical frequency-to-amplitude conversion technique based on the ro-vibrational absorptions of CH4. We observe that the amplitude of frequency tuning ∆f over intensity modulation index m as function of the modulation frequency behaves similarly for both types of devices, while the ring-QCLs typically show higher values. The frequency-to-intensity modulation (FM-IM) phase shift shows a decrease starting from ∼72° at a modulation frequency of 800 kHz to about 0° at 160 MHz. In addition, we also observe a quasi single-sideband (qSSB) regime for modulation frequencies above 100 MHz, which is identified by a vanishing -1st-order sideband for both devices. This special FM-state can be observed in DFB QCLs and is in strong contrast to the behavior of regular DFB diode lasers, which do not achieve any significant sideband suppression. By analyzing these important high frequency characteristics of ring-QCLs and comparing them to ridge DFB-QCLs, it shows the potential of intersubband devices for applications in e.g. novel spectroscopic techniques and highly-integrated and high-bitrate free-space data communication. In addition, the obtained results close an existing gap in literature for high frequency modulation characteristics of QCLs.

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1. Introduction

The absorption measurement and sensitive detection of various molecules in the mid-IR spectral range have gathered much attention in recent years. Especially gases held responsible for greenhouse-processes and global warming are of great interest. This includes e.g. carbon dioxide (CO2), nitrous oxide (N2O) or methane (CH4), which make up to 98% of the global greenhouse gas emission (IPCC 2014 [1]). They have, together with many other molecules, their fundamental absorptions in the mid-IR spectral range.

In this context, laser-based optical detection of gaseous molecules has many advantages such as: fast response time and rapid measurements in the microsecond range [2], low limits of detection (LOD) up to the parts-per-trillion range [3], the determination of isotope ratios (e.g. for CO2 [4]), the analysis of minute-amounts of probe-samples in the microliter-range [5], high gas selectivity [5] with no requirements for sample pre-treatment [5] and the realization...
of small-footprint and portable sensor-configurations [6]. For achieving this, various trace
gas sensors have recently been demonstrated. This includes dual-comb spectroscopy in the
mid-IR [2], QEPAS [7,8], multipass gas measurements [6] and various other concepts [3–5].

Besides those detection schemes, another class of sensors has recently emerged, based on
dispersion spectroscopy measurements. It combines features like baseline- and normalization-
free (immune to source-power fluctuations) characteristics with a linear output-dependency on
gas concentration and constant sensitivities. Typical examples are CLaDS [9], HPSDS [10]
or most recently 2f-wavelength modulation Fabry-Pérot photothermal interferometry (2f-WM
FP-PTI) [11], probing the changed dispersion in a FP cavity.

While all mentioned detection schemes share that they rely on high-performance mid-IR lasers,
among them the dispersion techniques are sensitive to the modulation characteristics of the
source. This includes the frequency and intensity modulation, FM and IM, respectively, and
also the modulation cut-off frequency (defined as the 3-dB cut-off) and the sideband ratio (SR).
Especially the latter is a very interesting figure of merit in singlemode emitting devices which,
for some special FM-state, can even lead to the full suppression of one sideband-order (i.e. +1st
or -1st order). This is called the single-sideband (SSB) regime. More details on this specific
state can be found in: [12,13]. References on possible spectroscopic or telecommunication
applications are [14] and [15].

A type of coherent emission source that addresses all those characteristics is the quantum
cascade lasers (QCLs) [16]. QCLs are semiconductor lasers emitting in the mid-infrared to
THz spectral region [17–23], which can e.g. be used for various applications like molecular
spectroscopy and medical diagnostics [5], food screening [24], security applications [25,26]
and optical free-space communications [27]. Focusing on the recent advancements in dispersion
spectroscopy and related techniques, the modulation capabilities of QCLs are of great interest.
Previous work has shown that, in contrast to diode lasers which show a limiting relaxation-oscillation
peak in their modulation response at relatively low frequencies (typically low GHz-range [28]),
QCLs are capable of direct high-frequency current-modulation [12,13,29–31]. This is a di-
rect consequence of their ultrafast intersubband transitions (~low picosecond range) and the
interplay with the cavity photon lifetime on the nanosecond timescale. Nowadays, optimized
low-capacitance mid-IR emitting DFB-QCLs reach modulation frequencies of up to 23.5 GHz
and 26.5 GHz, in their optical and electrical response, respectively [13]. But until now, only
linear edge-emitting ridge-waveguide devices have been analyzed in such experiments, leaving
out surface-emitting ridge- and ring-QCL geometries. The latter show significant potential
for array-integration [32,33], farfield-emission, -collimation and -direction [34–38], as well as
polarization control of the emitted radiation in ring-devices [34] and most recently presented
also in monolithic integration of ring-cavity on-chip laser-detector schemes [39,40].

By, for the first time, investigating and comparing the modulation-characteristics of current-
modulated mid-IR surface emitting ring- and edge emitting ridge-DFB QCLs from the same gain
material, this work is hence contributing to closing the existing gap in literature. As it was shown
in literature [13], changing the mode coupling mechanism by implementing a 1st-order DFB
grating to a FP-cavity leads to a completely different modulation response, by showing a strong,
unexpected, resonance-feature around the roundtrip frequency of the cavity. When comparing
such ridge DFB-QCLs with typical 2nd-order ring-DFB QCLs, which, in contrast to linear cavity
devices, support counter-propagating whispering gallery modes [41], their modulation response
needs to be investigated in detail.

The high frequency modulation properties of lasers are the product of their electrical and
optical response. While the electrical characterization is typically done using a rectification
technique ([13,29,42]), the optical response of DFB lasers can be analyzed by direct optical
sidebands measurements with an FTIR (for modulation frequencies in the GHz-range) [13],
by beating measurements on a fast detector of the modulated laser under investigation with a
reference DFB laser that is not modulated [13], or by using an optical frequency-to-amplitude conversion technique and by analyzing the obtained signal amplitude and phase with a lock-in amplifier. We chose the latter technique to directly investigate the FM-IM response of our devices. Those measurements give novel insight into the dynamical properties and the suitability of ring-QCLs for dispersion spectroscopy and other related fields of application, where fast modulation capabilities and high integration-levels, i.e. small and compact laser-sources/sensors, are highly beneficial.

![Fig. 1](https://example.com/fig1.png)

**Fig. 1.** (a) Experimental setup using the frequency-to-amplitude conversion technique (red arrows indicate the direction of electrical current, the green square highlights the bias-tee which is used for all measurements above 2 MHz). (b) Singlemode laser spectra taken in continuous-wave mode of the ring-QCL at 100 K (black line: 150 mA, red line: 180 mA). The region of the molecular absorption which is used for the frequency-to-amplitude conversion is marked in gray (1322.04 cm$^{-1}$ to 1322.2 cm$^{-1}$).

2. **Device design, experimental setup and electrical characterization**

The devices used in this work are based on a typical state-of-the-art two-phonon resonance design with an In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As active region grown on low-doped InP substrate. The active region is comprised of 35 periods, sandwiched between two 500 nm thick InGaAs spacers (Si-doped, $n = 5 \times 10^{16}$ cm$^{-3}$) and designed for lasing around $\lambda \sim 7.5 \mu$m. The top cladding consists of two subsequent InAlAs layers (1$^{st}$: 1500 nm, Si-doped: $n = 1 \times 10^{17}$ cm$^{-3}$, 2$^{nd}$: 800 nm, Si-doped: $n = 2 \times 10^{17}$ cm$^{-3}$), covered by a highly doped InGaAs contact- (350 nm, Si-doped, $n = 8 \times 10^{18}$ cm$^{-3}$) and an InGaAs capping-layer (100 nm, Si-doped, $n = 1 \times 10^{20}$ cm$^{-3}$). More details on the device design can be found in [43,44]. For achieving singlemode emission, a first-order DFB grating is implemented to the edge-emitting ridge-devices and a second-order DFB grating to the ring-QCLs for surface/substrate-emission. Typical ring- as well as ridge-devices are investigated and compared to each other in the following. They are driven in continuous-wave (CW) mode at liquid nitrogen temperatures between 80 K and 100 K at two distinct bias currents, one close to lasing-threshold and the second one at $\sim$20-25% higher drive currents, while the current modulation ranges from 800 kHz to 160 MHz (limited by the used function generator "Rigol DG4062") with modulation-amplitudes of a few milliamperes. More precisely, for frequencies ranging from 800 kHz to 2 MHz, the laser current is modulated via the current driver (Wavelength Electronics "QCL OEM300") without using a bias-tee. For such kind of measurements, the current modulation amplitude $I_{AC,0}$ is set via the analogue input of the current driver to 1 mA. For frequencies above 2 MHz, a bias-tee is used, by connecting its AC-port directly to the signal generator output (see green box in Fig. 1(a)). The measurements were
repeated with two modulation amplitudes of 50 mVpp and 500 mVpp, respectively, set directly at the signal generator. We used this measurement to analyze the impact of the modulation depth on the obtained modulation characteristics. Subsequently, the data was analyzed independently and compared, yielding identical results, which shows that there is no distinguishable impact of the modulation amplitudes in our experiments (i.e. the measurements are performed in the so called small signal regime; for more details see section 3.).

The resulting modulation characteristics of the lasers are analyzed in the presented experiments concerning their relative frequency-to-intensity (or amplitude) modulation as well as the relative phase between frequency and amplitude modulation response, both as function of modulation frequency. To measure the frequency tuning of the devices, we use a frequency-to-amplitude conversion technique, as shown e.g. in [45] using CO$_2$. A detailed theoretical description of the data analysis follows in the next chapter.

In the present experiment we use the absorption lines of CH$_4$ (instead of CO$_2$) at low pressure (30 mbar, diluted to about 1%V to result in a peak absorption of $\alpha \cdot L = 0.5$ for a 10 cm absorption cell; see also Fig. 2(a) for the corresponding spectra of CH$_4$), which are centered around 1316.8 cm$^{-1}$ and 1322.12 cm$^{-1}$, respectively. Consequently, any induced frequency modulation is converted into a directly detectable intensity modulation through those CH$_4$-absorptions (wavelength-dependent portion of the laser radiation is absorbed). To illustrate this technique Fig. 1(a) shows the used experimental setup including the frequency-to-amplitude conversion technique. More details can also be found in [10]. In addition Fig. 1(b) shows typical emission spectra for the ring-QCL at 100 K and drive currents of 150 mA (black trace) and 180 mA (red trace), respectively. Typical absorption- and dispersion-spectra of CH$_4$ are given in Fig. 2(a). The spectral region of frequency-to-amplitude conversion is marked in gray in both figures. To tune both devices under investigation to the CH$_4$ absorption lines (i.e. the marked gray area in Fig. 1(b)), while driving them at fixed drive currents, their temperatures had to be adapted accordingly: $\sim$100 K for the ring-QCL and $\sim$80 K for the ridge-QCL, respectively.

The analysis of the modulation characteristics is performed in the frequency-domain. For the investigated modulation frequencies between 800 kHz and 160 MHz, the detector signal is directly fed into a lock-in amplifier which analyzes the amplitude and phase of the signal at the modulation frequency. Since the lock-in amplifier’s bandwidth is limited to 250 kHz, the detector signal is down-mixed using a reference signal at a frequency which is 100 kHz lower than the modulation frequency of the laser itself (see Fig. 1(a) and [10]). After low-pass filtering, the resulting down-converted signal is analyzed at the difference frequency of 100 kHz. The output
Fig. 3. (a) Amplitude of frequency tuning $\Delta f$ over intensity modulation index $m$ as function of modulation frequency (800 kHz to 160 MHz) for the ring and ridge laser at different laser driving conditions. Ring laser ($J_{th} = 110$ mA): 148 mA and 185 mA, ridge laser ($J_{th} = 231$ mA): 245 mA and 297 mA. (b) FM-IM phase shift within the modulation range (800 kHz to 160 MHz) of the two QCLs (ring and ridge) for the same different laser driving conditions as shown in (a).

of the lock-in amplifier is continuously recorded, while the center frequency of the modulated laser is slowly scanned across the molecular resonance (1 Hz, averaging of 19 scans), resulting in spectral traces as shown in Fig. 2(b) and (c) (red line).

3. Frequency domain analysis

The theoretical model for fitting the spectral data recorded through the Lock-in amplifier was adopted from the one described by Hangauer et al. [12]. It is based on the calculation of the complex laser spectrum under modulation-conditions, which is composed of a set of discrete, equally spaced lines (given by the modulation frequency), located around the laser center frequency. Neglecting scaling factors, the spectrum is analytically calculated from the intensity modulation index $m = \frac{I_{AC,0}}{I_{DC}-I_{thr}}$ ($I_{AC,0}$ is the amplitude of the modulation current $I_{AC}$, $I_{DC}$ stands for the DC bias current and $I_{thr}$ represents the threshold current of the respective laser), which is much smaller than 1 in the so-called small signal regime ($I_{AC,0} \ll I_{DC} - I_{thr}$), the frequency modulation index $\beta = \frac{\Delta f}{f_{mod}}$ ($\Delta f = I_{AC,0} \cdot \gamma$, instantaneous frequency tuning amplitude with the current tuning coefficient $\gamma$) and the frequency- to intensity-modulation (FM-IM) phase shift $\phi_{FM-IM}$ [46]. Next, each line is multiplied with the complex transfer function $T(f_{center} + n \cdot f_{mod})$ given by the Faddeeva function (cp. Fig. 2(a)). It models the response, i.e. attenuation and phase change, of the gas and corresponds to the transmission spectrum of the gas sample including anomalous dispersion. The resulting signal is then detected by a square-law detector which allows extracting the frequency component at the modulation frequency $f_{mod}$. Each spectral line is multiplied by the complex conjugate of its neighbor and all products are summed up. This procedure is repeated for each center frequency, leading to an amplitude- and phase-spectrum, corresponding to the measured spectra.

The model was fitted to each complex spectrum adjusting the local variables ($\phi_{IM}$ (phase of IM), $\bar{v}_0$ (laser center frequency), $\gamma$, $\phi_{FM-IM}$ and $S_1$ (scaling factor)). To remove the small uncertainty in the scaling of the wavelength axis, the well-known spacing between the two absorption lines centered around 1322.12 cm$^{-1}$ is used, to include the stepsize of the wavenumber axis as fitting parameter and consequently to adapt, i.e. slightly stretch/compress, the wavelength axis.
4. Results and data analysis

The frequency tuning amplitude of both devices is analyzed first. For removing scaling effects with the modulation current $I_{AC}$, Fig. 3(a) shows the frequency tuning amplitude $\Delta f$ normalized to the current modulation index $m$, as function of the modulation frequency between 800 kHz and 160 MHz. The IM index normalized FM behavior is consistently slightly larger in the ring-devices, while the overall trend is similar in both types of devices and also in good agreement with literature [12]. The larger frequency tuning originates partly from the higher drive current above threshold ($J - J_{th}$) of the ring-devices which was, together with the temperature, needed to tune the wavelength of the rings to the absorption line of $CH_4$. The contribution from geometrical differences between both devices (e.g. different waveguide-width, longer ring resonator etc.) which might especially impact the FM behavior through the refractive-index tuning in this high frequency tuning regime and which impacts the whispering gallery modes in the ring cavity differently than the DFB-modes in the ridge device, have to be analyzed in more detail in future work.

Figure 3(b) completes the data by showing the corresponding FM-IM phase shift in the same modulation frequency range. We observe the expected decay in this curve for both types of devices, due to the operation of the devices in the electronic tuning regime with its spectral blue-shift and its FM-IM phase of zero. This also corresponds well with recent findings from literature [12] and can be understood in more detail by the transition from a temperature driven and therefore red-shifting regime (low modulation frequencies in the kHz-range, FM-IM phase of 180°) to a regime driven by the blue-shifting charge carrier density mechanism (high modulation frequencies, FM-IM phase 0°) [12].

Finally, Fig. 4 shows the so-called sideband-ratio (SR) of the devices, i.e. the ratio between the amplitudes of the two first-order frequency components of the modulated lasers. In good agreement with the findings in [13] and [12], both, ring- and ridge-QCL, can operate in the quasi single-sideband (qSSB) modulation regime. The single-sideband (SR) regime is characterized by a vanishing sideband of one order (positive or negative side), while the other one (negative or positive side, respectively) can still be observed. A precursor of this is the qSSB regime, where the SR reaches small values, typically below 0.1, or even side-mode suppression ratios of...
above 15 dB for one of the two first-order sideband modes. For our devices this qSSB regime is achieved for high modulation frequencies above ~100 MHz together with low laser driving currents (\(1^{st}\) order sideband). Following the observed trend, we expect that the SR is further decreasing for even higher modulation frequencies above 160 MHz up to the GHz range, that are currently not possible with our setup. Such predictions for the GHz-modulation behavior include the analysis of a possible SSB resonance around the cavity roundtrip frequency of the DFB-QCLs (between 35 GHz and 40 GHz for our ring devices), comparable to resonances obtained in ridge-DFB QCLs [13], and are the topic of future investigations.

In addition to its dependency on the device properties (e.g. cavity geometry like ring- vs ridge-device), the drive conditions of the devices play an important role for the operation in the (q)SSB regime. This includes the DC driving current of the lasers, since the IM-index \(m\) depends on the DC optical output power of the devices [12]. In good agreement with literature, Fig. 4 shows lower SRs when driving the QCLs at lower driving currents [12]. We observe this behavior for both, ring- and ridge-DFB devices.

Such a SSB/qSSB regime is an interesting and unique feature, since it allows the selective tuning, including switching off and on, of a specific spectral (laser) emission feature. Classical diode lasers do not show such a behavior [12], which is e.g. beneficial for high-speed laser spectroscopy [14] or telecommunication links [15].

In conclusion we investigated the high frequency modulation capabilities of typical singlemode surface-emitting ring-QCLs in the range of 800 kHz to 160 MHz. In comparison to ridge-QCLs from the same gain material, a frequency-domain analysis shows similar behavior with slightly higher values for \(\Delta f/m\) and the FM-IM phase shift in the ring-devices. At the same time the qSSB regime can be achieved with the surface-emitting ring- and the edge-emitting ridge-QCLs. This makes them, together with their use in array-integration, their low divergence farfield emission, their excellent collimation and direction capabilities and polarization control of their optical emission, very good candidates for spectroscopic measurements and high-bitrate free-space data communication using highly integrated systems.

Further work will include a device-analysis for even higher modulation frequencies up to the GHz-range. To allow experiments at such high modulation frequencies, first of all a faster function generator is needed. In addition, typical state-of-the-art experiments also use specially designed RF-waveguides such as 50-Ω impedance matched coplanar waveguides or microstrip lines to reduce the parasitic capacitance to the low picofarad-range, as e.g. shown in [13,29]. To obtain a further reduction in the parasitic inductance, which is e.g. introduced by using bond-wires (even when only a few millimeter long), such RF-cavities are typically combined with special multi-contact RF-probes.

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