Quantum cascade lasers for high-resolution spectroscopy

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Abstract. Despite the growing interest that quantum cascade lasers (QCLs) are gaining, they still present a few unclear aspects of their fundamental properties, such as spectral purity, that need to be deeply investigated when aiming to make these innovative laser sources suitable for high-resolution spectroscopy and metrology. This paper is a review of our efforts towards QCL-based high-resolution spectroscopy and of our experimental investigation of QCLs’ frequency noise, aimed to discover the ultimate performances attainable by QCLs and to develop the experimental techniques required to achieve them. Our results, confirmed by several independent measurements, show that QCLs have a very small intrinsic linewidth buried under a large frequency-noise background. The development of appropriate frequency stabilization techniques will make QCLs well suited for high-resolution spectroscopy and metrology in the mid and far IR.

Subject terms: quantum cascade lasers; high-resolution infrared molecular spectroscopy; frequency noise.

1 Introduction

In recent years our research has been intensively devoted to the study of the main physical characteristics of quantum cascade lasers (QCLs), in view of their application as compact and stable sources for high-sensitivity and high-resolution spectroscopy in the mid IR. Indeed, thanks to their compactness, good stability, narrow emission linewidth, and high emission power, QCLs have proven among the most suitable sources for infrared spectroscopy, with output powers as high as hundreds of milliwatts and intrinsic linewidths as narrow as a few hundred hertz. Their compact design, moreover, makes QCLs very appealing not only for high-sensitivity spectroscopy, but also for a huge variety of industrial and commercial applications.

In Sec. 2 we review our activities in referencing a mid-IR QCL to an absolute frequency standard through an optical link with a near-IR optical-frequency comb synthesizer (OFCS) and our efforts in developing simple and reliable techniques for stabilization and narrowing of the QCL emission spectrum. A successful measurement of the QCL absolute frequency, in fact, would let us combine, in the same mid-IR spectroscopic experiment, both high sensitivity and precision. In Sec. 3 we present some independent and complementary measurements of QCLs’ frequency noise and linewidth, which shed light on their intrinsic noise features and confirm their status among the narrowest solid-state laser sources.

2 Development of High-Resolution Spectroscopy with QCLs

Our absolute frequency measurements of CO2 transitions in the 4.3- to 4.4-μm wavelength range have been performed via both Doppler-limited and sub-Doppler spectroscopic experiments. In the sub-Doppler configuration, an important stability improvement was made by locking the QCL frequency to the first derivative of the Lamb-dip feature, utilizing a conventional wavelength-modulation technique. With the laser operated both locked and free-running, the optical link to the OFCS allowed a direct analysis of the efficiency of the locking loop and the long-term frequency stability of the laser emission spectrum.

In our efforts to make use of optical links between visible–near-IR optical frequency combs and mid-IR light sources, we have used single-mode distributed-feedback (DFB) QCLs emitting in the 4.3- to 4.4-μm wavelength range and operating at cryogenic temperatures. The lasers have a quite low threshold current (about 100 mA at 86 K) and a frequency tunability with current of 400 MHz/mA. Housed in a liquid-N2-cooled cryostat, the QCLs are powered by an ultralow-noise, homemade current driver.

In Fig. 1, a schematic of the experimental setup for the sub-Doppler (saturated-absorption spectroscopy) configuration is shown. A more detailed description is given in Ref. 1. For the sake of clarity and brevity, we omit discussion of the simpler Doppler-limited configuration (see Ref. 2).

The core of the setup is the up-conversion process in a periodically poled LiNbO3 (PPLN) crystal, where the QCL frequency is summed with that of a Nd:YAG laser phase-locked to the comb, thus setting the optical link with the OFCS. For this reason, after the spectroscopic interaction with the CO2 gas in the cell, a fraction of the mid-IR beam is sent to the second stage of the experimental setup, where the sum-frequency generation (SFG) and the optical link with the OFCS take place. This stage is exactly the same for both Doppler-limited and sub-Doppler configurations.

The OFCS used in this experiment is a mode-locked femtosecond Ti:sapphire laser operating in the 500- to 1100-nm range. The obtained near-IR SFG radiation is superimposed...
on the beam of a diode laser (DL), working at a close wavelength and phase-locked to the Nd:YAG laser with a direct digital synthesis (DDS) technique. An avalanche photodiode detects the rf beat note. The signal is processed by a spectrum analyzer, and its frequency is measured by a counter. The resulting beat-note spectrum reproduces exactly the line shape of the QCL emission spectrum. By counting the beat-note frequency \( f_{\text{beat}} \) it is possible to obtain the absolute value of the QCL frequency by

\[
\nu_{\text{QCL}} = \nu_{\text{DL}} - \nu_{\text{YAG}} + f_{\text{beat}}.
\]

where \( \nu_{\text{YAG}} \) and \( \nu_{\text{DL}} \) are the Nd:YAG and DL frequencies, respectively. These two frequencies are known with the OFCS precision and have linewidths of a few kilohertz, which are negligible compared to the QCL linewidth (over millisecond timescales). The beat-note frequency is counted by a commercial frequency counter.

In the saturation spectroscopy setup the optical isolation, achieved by using two crossed wire-grid polarizers (P1 and P2) and a tunable half-wave plate (T-\( \lambda/2 \)), allows the pump and probe beams to be perfectly superimposed while avoiding undesired optical feedback to the laser. Figure 2 shows a recording of the saturated (01\(^{-}1\)−01\(^{+}0\)) P(30) CO\(_2\) transition. The best fit to the experimental data, obtained using a convolution between two Gaussian functions, accounts for both the Doppler and the Lamb-dip profiles. The Lamb-dip half width at half maximum (HWHM) resulting from the fit is about 5 MHz. Since both the transit-time and pressure broadening contribute to the Lamb-dip width for less than 200 kHz, we ascribe the measured value to the QCL frequency jitter (over millisecond timescales).

Thanks to the sub-Doppler technique, we were able not only to obtain a narrow reference (the Lamb dip), but also to use its first derivative to actively stabilize the laser to the line center frequency by closing a feedback loop on the QCL current. The effects on the frequency-noise power spectral density (PSD) are shown in Fig. 3(a): a suppression of the noise PSD by up to 20 dB arises, but only within a small bandwidth (\( \approx \)500 Hz). Nonetheless, a sensible reduction of the slow frequency fluctuations is achieved, as confirmed by the improved precision of the spectroscopic measurements [Fig. 3(b)].

Furthermore, laser frequency stabilization enables long-term frequency measurements, consisting in consecutive 1-s gate-time counts of the beat-note frequency [inset of Fig. 3(b)]. Each data set yields a mean frequency value \( f_{\text{beat}} \) with the associated uncertainty (calculated as the standard deviation of the mean). The 3.5-kHz average value of these uncertainties can be taken as a reasonable estimate for the ultimate precision (5 parts in \( 10^{11} \)) achievable in the absence of systematics.

The acquisition is affected by slow drifts and oscillations, which can be mainly ascribed to the presence of residual optical interference fringes that shift the locking point by adding a variable background to the derivative signal. Such unwanted effects are barely visible in the typical time scale of a single acquisition, but are much more evident when comparing several separate data sets. Figure 4 presents a comparison of the overall precision of the absolute frequency measurements between the case of Doppler-limited spectroscopy with the QCL in free-running configuration [Fig. 4(a)] and the case of sub-Doppler spectroscopy with the frequency-stabilized QCL [Fig. 4(b)].

In the former case, the free-running laser frequency is slowly tuned across the 13CO\(_2\) (00\(^{0}0\)−00\(^{0}0\)) P(30) Doppler-broadened molecular line by controlling the driving current with a step-shaped signal. The absorption signal and the beat-note frequency are simultaneously acquired at a rate of 2 Hz, thereby reconstructing the molecular profile on an absolute frequency scale. A Voigt fit allows us to determine the corresponding line-center frequency, whose average value is \( \nu_c = 67678.415 \) GHz, with an uncertainty of 2 MHz. The result is consistent with the value provided by

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**Fig. 1** Standard pump-probe saturation spectroscopy with electronic feedback to the laser. The QCL is housed in a continuous-flow cryostat, and its temperature stabilized around 80 K. After collimation, the beam is split in two parts for the pump-probe saturation spectroscopy. The SFG process in the 4-cm-long PPLN crystal produces near-IR radiation at approximately 850 nm, which is compared with that of a comb-referenced diode laser. The beat note is detected and its frequency is measured. The cell is 12 cm long and has AR-coated CaF\(_2\) windows. P1 and P2 are wire-grid polarizers, T-\( \lambda/2 \) is a tunable half-wave plate, and BS is a beamsplitter.

**Fig. 2** Saturation spectrum of the (01\(^{-}1\)−01\(^{+}0\)) P(30) CO\(_2\) transition in direct-absorption (inset) and first-derivative detection, with a gas pressure in the cell of 20 mTorr (which leads to a relative absorption of about 10%). The pump intensity interacting with the gas sample is about a factor of 2 higher than the saturation level. The first-derivative signal was obtained by a lock-in amplifier with a 1-ms integration time constant. Its best fit is also shown.

**Fig. 3** (a) Noise PSD of the QCL frequency (inset) and (b) first-derivative signal of the (01\(^{-}1\)−01\(^{+}0\)) P(30) CO\(_2\) transition.

**Fig. 4** Comparison of the overall precision of the absolute frequency measurements between the case of Doppler-limited spectroscopy with the QCL in free-running configuration and the case of sub-Doppler spectroscopy with the frequency-stabilized QCL.
the HITRAN database5 ($\nu = 67678.413$ GHz, with an error in the 3- to 30-MHz interval).

In the latter case, when the laser is frequency-stabilized, the precision of the absolute frequency measurement is improved by several orders of magnitude. Figure 4(b) displays the mean frequency values $f_{\text{beat}}$ and the associated uncertainties (standard deviation of the mean) of the recorded data sets over a period of 2 weeks. Although the statistical error associated to a single mean value is only a few kilohertz, the overall uncertainty of the measured absolute frequency of the transition is worse, due to the poor repeatability of the measurements. This is clearly visible in the spread of the points, and ultimately limits the final uncertainty on the absolute frequency measurement to approximately 75 kHz. Nevertheless, compared to the Doppler-limited case, the improvement is evident, with the overall uncertainty about 2 orders of magnitude smaller than that of the HITRAN value (3 to 30 MHz).

The results so far presented are only a step towards stabilizing the QCL emission frequency to metrological-grade levels. A more efficient and robust stabilization of the device requires the upgrade to a more stable locking signal, unaffected by the systematics (background fluctuations) that limit the repeatability of the measurements, and to a better locking loop with a wider bandwidth.

To this aim, together with the development of current drivers with better noise performance and wider modulation bandwidths, we have adopted a new approach to the frequency-locking signal by devising a double-balanced polarization-spectroscopy (PS) apparatus (see Ref. 6 for details on the experimental setup). The key concept is the production of a zero-background, symmetric dispersive

**Fig. 3** (a) Frequency-noise power spectral density of the laser radiation, recorded in both free-running and locked configuration. The comparison shows the locking bandwidth ($\approx 500$ Hz), as expected with a 1-ms lock-in time constant, (b) Comparison, in free-running and locked configurations, of the spreads of the beat-note frequency values as measured by the counter. The inset shows a 20-min-long acquisition of the beat-note frequency, with the laser locked.

**Fig. 4** (a) Absolute frequency measurement of the $^{13}$CO$_2$ (00$_3^0$–00$_0^0$) P(30) Doppler-broadened transition with a gas pressure $P = 250$ mTorr in the cell. The nonuniform distribution of the points is due to a slow temperature drift of the QCL during the acquisition. The red line represents the Voigt fit to data. (b) Measured beat-note frequencies acquired over a two-week period with the Lamb-dip-locked QCL. Each point, with its associated error bar (standard deviation of the mean), corresponds to the mean value of absolute frequency measurements taken over a long time interval [as that shown in the inset of Fig. 3(b)]. The mean value and standard deviation of these points are also shown (red line and gray area, respectively). (Color online only.)
The (0111–0110) P(30) CO2 transition is acquired with the double-balanced polarization technique (a) and with the sub-Doppler first-derivative lock-in technique (b). The experimental conditions are the same except for the acquisition times: 40 ms for the trace in (b), and 1.5 ms for the trace in (a). In the latter case the signal is sharper and its bandwidth larger, thanks to the absence of any dither. In (c) the two traces are overlapped, on the same vertical and horizontal scales, for a direct comparison. (Color online only.)

The absence of any dither offers a direct benefit from the point of view of spectral purity and allows full use of the available modulation bandwidth for the locking loop. Moreover, it simplifies the electronics involved in the locking loop (the lock-in amplifier is no longer required). Also, double-balanced polarization spectroscopy provides a significant enhancement of the signal-to-noise (S/N) ratio, increasing the loop gain.

The improvements made in sensitivity and bandwidth of the signal are notable. Figure 5 shows the comparison between the locking signal obtained by the lock-in first derivative of the Lamb dip (red curve) and the double-balanced polarization signal (blue curve) on the same molecular line: By measuring the sharpness of the two central slopes, the resultant improvement in sensitivity due to the polarization setup (almost one order of magnitude) is readily apparent.

As shown in Fig. 5(a), the signal is perfectly symmetric and exhibits negligible background. We intend to use this signal for our next frequency-locking loop, and we expect significant improvements in all the critical parameters: bandwidth, gain, sensitivity, and stability.

3 Frequency Noise in QCLs

The measurements presented in the Sec. 2 suggest that QCLs have considerable potential for high-resolution spectroscopy. Other complementary results, such as the achievement of sub-kilohertz linewidths in frequency-stabilized QCLs7, 8 and small α-factors measured by self-mixing or heterodyne techniques,9–11 further support this guess.

The optical link to the OFCS, described in the previous section, also provided a way to directly characterize the emission spectrum of the QCL, shedding light on the contribution of the frequency noise to the emission line shape, over different time scales. This aspect is dealt with in Sec. 3.1 and introduces a more comprehensive and accurate analysis of the frequency-noise PSD of the QCL, described in Sec. 3.2. This complementary approach is more complete than the first one, in that it can provide quantitative information not only on the laser linewidth, but also on its physical causes (Sec. 3.3).

3.1 Preliminary Considerations on the Laser Linewidth

The spectral analysis of the beat note fbeat, performed by a real-time fast-Fourier-transform (FFT) spectrum analyzer, allows for a preliminary characterization of the QCL emission linewidth and stability, over different time scales. Figure 6 shows a frame of the laser frequency noise recorded by direct acquisition of the FFT spectrum of the beat note: This method allows us to understand the statistical distribution of the noise itself over time.

The use of the OFCS and the locking loop marks an important improvement over the existing literature.12, 13 Thanks to frequency stabilization of our device, in fact, acquisitions of the beat note over longer time intervals are possible. In particular, this allows a comparison (Fig. 6) between a fast shot (70 μs long) of the emission spectrum and its long-averaged (over 70 ms) profile, both taken with the laser locked: The linewidth of the 70-μs shot appears very narrow, yet over longer time scales the unsuppressed fast jitter of the frequency determines a Gaussian broadening of the line shape, even under frequency-locking conditions. Nevertheless, the regular shape of this Gaussian envelope as well as its long-term stability (ensured by locking) allows one to count the frequency, leading to the results presented in the previous section.

Particular emphasis has to be given to the 70-μs-long shot of the emission spectrum: It indeed reveals the existence of a very narrow fast linewidth of the QCL that, once achieved experimentally over longer time intervals, would make this kind of light sources suitable for high-precision experiments. This observation has been confirmed by our recent
3.2 Measurement of the Frequency-Noise Power Spectral Density of a QCL

In the following, we provide a brief overview of our latest results regarding a frequency characterization of QCLs. In particular, we present a complete characterization of the frequency-noise PSD of a mid-IR QCL from 10 Hz up to 100 MHz, which allowed the first measurement of its intrinsic linewidth. The frequency-noise PSD provides, for each frequency, the amount of noise contributing to the spectral width of the laser emission. Thus, its determination gives the most direct way to characterize the spectral purity, since it allows one to derive the laser emission spectrum over any accessible time scale. It also allows one to calculate the linewidth reduction achievable by a frequency-locking loop, once its bandwidth is known. Finally, it enables tracing of spurious noise sources that can be eliminated in order to measure only the intrinsic laser noise. In this sense the measurement of the frequency-noise PSD is more meaningful than the direct observation of the emission spectrum (see previous section), since it contains a lot of additional information that can help in understanding the physics governing laser action.

The experimental setup for a wideband, low-noise measurement of the frequency-noise PSD is conceptually quite simple but technically very challenging, and this is why the few previous papers reporting on a similar characterization covered a very small spectral region (below 1 MHz). Indeed, a really comprehensive frequency-noise characterization must cover the widest possible range of frequencies, and thus requires a detection chain that is both very fast and sensitive. Though these requirements can be easily fulfilled in the visible and near-IR portions of the electromagnetic spectrum, they prove still very challenging in the mid IR. Combining fast detection with low-noise FFT acquisition, we were able to reconstruct the frequency noise of a free-running QCL within a 7-decade spectral window (from 10 Hz to 100 MHz) and with an 11-decade dynamic range. The concept of the experiment is the following: Amplitude measurements are performed to retrieve information in the frequency domain. To this purpose, conversion of laser frequency fluctuations into detectable amplitude variations had to be implemented. The main requirement for the converter is that it must introduce negligible noise while providing a gain factor suitable for a good detection. It is also expected to show an almost flat response over the whole frequency range of measurement. The ideal choice, in this case, falls on what can be considered a virtually noiseless discriminator: the side of a Doppler-broadened molecular transition. The spectrum of the signal transmitted by such a discriminator, when the laser frequency \( \nu_0 \) is stabilized at the center of the region of linear response, reproduces the spectrum of the laser frequency fluctuations, “amplified” by the slope of the absorption profile. However, a precise knowledge of the transfer function is required, in order to correctly understand the spectrum up to frequencies where the response is not linear. A rigorous treatment shows a cut-off at about 50 MHz, so that in the chosen range of 100 MHz this effect is taken into account for correctly reconstructing the “real” profile of the frequency-noise PSD (see Ref. 14 for further details).

Since the typical QCL tuning coefficients are very large (several hundred megahertz per milliampere), a significant experimental effort has been addressed also to the development of an ultralow-noise current driver, approaching the shot-noise level and significantly surpassing the performance of the best commercially available current drivers. This activity has been of fundamental importance: By using commercial current drivers, we would have never been able to observe the intrinsic laser noise, which would have been buried under the current-noise contribution.

To properly evaluate the contribution of the driving current to the laser frequency noise, we performed an accurate measurement of the current-noise PSD. First, the noise spectrum of the voltage drop over a sample resistor connected to the current driver was recorded. This, however, is not sufficient; the QCL response function versus the current, over the
QCL frequency noise PSD. In Fig. 8(a) two frequency-noise PSD curves are shown. The orange curve corresponds to the homemade current driver, while the gray curve corresponds to the commercial current driver. On the other hand, the black curve shows the QCL intrinsic linewidth, which is the intrinsic to the QCL device. The red curve shows the frequency-noise PSD, which is the result of the integration of the noise contribution arising from the current noise and the frequency noise. The noise floors show that the current noise alone does not explain the whole observed laser frequency noise. The presence of some additional frequency noise source must be assumed.

Entire Fourier frequency range has to be studied too. We now describe the calibration procedure followed for directly comparing current noise and frequency noise. The method relies on the fact that, for small current modulations, the amplitudes of the current and the induced frequency modulations are proportional, as shown in Fig. 7(a). By sine-modulating the driver current during both the current-noise and frequency-noise measurements, the resulting spectra show narrow peaks arising from the noise floor. The noise floors can be vertically aligned by overlapping the edges of these peaks, as shown in Fig. 7(b) for a small portion of the spectrum. This calibration allows us to quantitatively compare the two noises, and hence evaluate the driver current-noise contribution to the QCL frequency noise.

By sticking together adjacent sets of traces like that shown in Fig. 7(b) we have obtained a complete characterization of the current noise, correctly compared with the measured QCL frequency noise PSD. In Fig. 8(a) two frequency-noise PSD spectra, with the QCL powered by two different current drivers, are shown. Although the noise contributions of the two drivers are different, it is worth noting that below 10 kHz the two frequency-noise PSD spectra overlap perfectly. This is clear evidence of the presence of some other frequency-noise source, not directly correlated with current noise. At higher frequencies, on the contrary, the spectrum corresponding to the commercial current driver (gray curve) shows a larger noise, which is clearly related to the driver current noise (black curve). On the other hand, the noise contribution arising from the homemade current driver (red curve) always stays well below the measured frequency-noise PSD (orange curve), thus ensuring that the measured quantity is intrinsic to the QCL device.

This is a very important point, not only for the high-frequency region of the spectrum, which allowed a direct measurement of the QCL intrinsic linewidth, but also for the low-frequency region. Indeed, the 1/f and 1/f² trends observable below and above 100 kHz can provide important information on the nature of the charge and heat transport phenomena that govern the complex QCL heterostructure.

As already stated, the flattening to a white-noise level, occurring above 30 MHz, allows the first direct measurement of the QCL intrinsic linewidth. The latter falls in the range of a few hundred hertz and depends on the ratio between the operating current and the threshold current. As we have explained elsewhere, this result is the first experimental confirmation of a very recent theory, developed by Yamanishi et al., that rewrites the Schawlow-Townes formula, tailoring it to the peculiar band configuration of QCLs, and predicts an intrinsic linewidth much narrower than for conventional bipolar lasers. The importance of this result is that it sets a very low limit for the ultimate linewidth achievable with QCLs, confirming them among the intrinsically narrowest solid-state laser sources. Their peculiarity, indeed, lies in the presence of a very efficient nonradiative relaxation channel for the upper state, which explains the overcoming of the linewidth limit set by the radiative lifetime.

### 3.3 Integration of the Frequency-Noise PSD and Comparison with Direct Observation

From the measured frequency-noise PSD it is possible to recover, with an appropriate mathematical transformation, the emission spectrum of the laser over any time scale. Following the general approach proposed in Ref. 15, and denoting by \( S(f_n) \) the frequency-noise PSD, the laser power spectrum \( W_{\gamma}(\Delta \nu) \) is expressed by

\[
W_{\gamma}(\Delta \nu) \propto \int_{0}^{\infty} \cos(2\pi \Delta \nu \tau) \times \exp\left\{-2 \int_{1/T}^{\infty} S(f_n) \left[ \frac{\sin(\pi f_n \tau)}{f_n} \right]^2 df_n \right\} d\tau,
\]

where \( T \) is the integration time, \( \Delta \nu \) is the linewidth, and \( \gamma \) is the gain wavelength.
where $\nu_0$ is the central frequency of the laser and $\Delta \nu = \nu - \nu_0$.

The lower bound of the inner integral is set by the time interval $T$ chosen for the measurement of the laser power spectrum. We can apply this procedure to both the orange and gray curves of Fig. 8(a), in order to check if a lower-frequency-noise PSD leads to a narrower power spectrum. The comparison is shown in Fig. 8(b), where for both integrals the same time scale of 70 ms has been set by choosing the same integration bounds.

Some interesting conclusions can be drawn from this comparison. First, the resulting profiles of the emission spectra are well approximated by Gaussian curves. A flat-frequency-noise PSD, on the contrary, would have generated an emission spectrum with a Lorentzian profile. Secondly, the seemingly small difference between the two spectra, occurring between 10 kHz and 1 MHz, translates into a significant difference between the resulting linewidths: about 6 MHz for the QCL driven by the homemade supply versus about 9 MHz for the QCL driven by the commercial supply. This is a further confirmation of the importance of low-noise current supplies.

A final verification of the consistency of these measurements comes from the comparison between the spectra recovered by the frequency-noise PSD and the ones directly measured by the beat-note experiments described in the previous section of this work (see Fig. 6). On similar time scales, as expected, the widths of the two Gaussian profiles are comparable (see Fig. 9).

Once again, it is worth remembering that the observation of the beat note over a certain time $T$ is equivalent to calculating the inner integral of Eq. (2) with the lower bound 1/T. In this sense, measurement of the frequency-noise PSD is much more complete than measurement of the beat-note spectrum, the latter being derivable from the first, with an appropriate calculation. Therefore, the ultimate limit for the QCL intrinsic linewidth, which can only be argued in a measurement like the one presented in Fig. 6 (the beat-note spectrum on the shorter time scale of the spectrum analyzer), can be rigorously calculated from the frequency-noise PSD. In the limit of “instantaneous” observation, only the white component of the PSD is present, and this corresponds to an intrinsic linewidth of a few hundred hertz. By studying the linewidth dependence on the observation time scale, it is possible to estimate the bandwidth of a frequency-locking loop necessary to achieve a given frequency stability.

4 Conclusions

In the year that celebrates the fiftieth anniversary of the invention of the laser, we have made a step forward in the understanding of one of the most recently born, the quantum cascade laser. A deeper knowledge of QCLs is necessary for a thorough exploitation of their peculiar features in high-resolution spectroscopy, whenever very high detection sensitivity combined with a high discrimination degree and an absolute frequency scale is required. In the last few years, we have focused our attention on mid-IR-emitting QCLs, which are also much better known than far-IR-emitting ones. From the results reported here, it clearly emerges that mid-IR QCLs can become key sources even for the most demanding spectroscopic applications. Molecules are the most natural target for such sources, given their IR absorption range, and...

Therefore, new physical achievements should be triggered by QCLs, given their unique properties, discussed in this work.

QCLs, given their unique properties, discussed in this work. Therefore, new physical achievements should be triggered by QCLs, and the next step should be unveiling the intrinsic properties of far-IR-emitting (terahertz) QCLs, which could prove crucial for manipulating and interrogating molecules using their rotational transitions.

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References


Borri et al.: Quantum cascade lasers for high-resolution spectroscopy

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the frontier field of cooling and interrogation of very low-temperature molecular samples will probably make use of QCLs, given their unique properties, discussed in this work. Therefore, new physical achievements should be triggered by QCLs, and the next step should be unveiling the intrinsic properties of far-IR-emitting (terahertz) QCLs, which could prove crucial for manipulating and interrogating molecules using their rotational transitions.
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