Electrically driven frequency blue-chirped emission in Fabry–Perot cavity quantum cascade laser at room temperature

Cite as: Appl. Phys. Lett. 118, 021108 (2021); https://doi.org/10.1063/5.0033030
Submitted: 14 October 2020 . Accepted: 27 December 2020 . Published Online: 12 January 2021

S. Chin, V. Mitev, E. Giraud, R. Maulini, S. Blaser, and D. L. Boiko
Electrically driven frequency blue-chirped emission in Fabry–Perot cavity quantum cascade laser at room temperature

ABSTRACT

We present a method to produce a fast frequency swept laser emission from a monolithic mid-infrared laser. A commercially available Fabry–Pérot cavity quantum cascade laser (QCL) operating at a wavelength of 8.15 µm was electrically driven by a current pulse with a 10 µs duration and a slow front rising time of ~2 µs. Due to the switching of the lasing emission from the vertical to the diagonal transition in the QCL and a strong quantum-confined Stark effect energy shift of the diagonal transition, the frequency of the emitted light was blue-shifting as the injection current continues to raise above the threshold. The temporal evolution of the laser spectrum was measured by a high-resolution step-scan Fourier transform infrared spectrometer. The blue-chirped emission was strongly influenced by the heatsink temperature due to the high thermal sensitivity of the threshold current and slope efficiency. By optimizing carefully the QCL operating temperature and the amplitude of the current pulse, we demonstrate a high-speed self-sweeping laser emission under room temperature operation conditions, reaching the spectral tuning range of ~25 cm⁻¹ within 1.8 µs.

Over the last decade, significant progress was made in the development of wavelength-swept laser sources in the mid-infrared (mid-IR) spectral range due to their various applications. A particularly promising application relies on spectroscopy of strong and distinct rovibrational molecular absorption features in the mid-IR region giving unique fingerprints for detection of small concentration gas species even in complex mixtures. For instance, mid-IR spectroscopy sensing systems have been implemented worldwide for disease diagnosis by breath analysis or for detection of hazard chemical threats in air.

To date, various mid-IR laser-based techniques have been proposed for spectroscopy applications, but all of them suffer from a trade-off between the covered spectral range and the spectral resolution. Among them, optical parametric oscillator (OPO), difference-frequency generation (DFG), and optical frequency comb (OFC) techniques can provide a wide wavelength range with high detection sensitivity. However, due to operational complexity and high cost, these approaches are practically limited to academic research applications. The fiber-based supercontinuum light sources are capable of providing multiple octave-spanning spectra in the mid-IR fingerprint-rich range. Yet, their power spectral density still requires improvement and the complexity of the detection schemes for resolving the spectra is the main obstacle preventing their widespread deployment. Dual-comb spectroscopy systems greatly simplify the detection apparatus but require complex schemes for the frequency stabilization of the two combs. Tunable external-cavity quantum cascade lasers (QCLs) provide a wide spectral range and power but spectral scanning is implemented mechanically. Therefore, they are relatively slow and expensive, which prevents their routine application.

Nowadays, pulsed distributed feedback (DFB) QCLs provide the most practical spectroscopic technique for atmospheric gas monitoring or gas analysis sensors. The pulsed current driving leads to the transient self-heating process in the active region of the DFB QCL. This is the key mechanism for spectral tuning. However, rapid tuning and spectral measurements on the 0.1–1 µs timescale are possible over the limited spectral band of ~2 cm⁻¹ because of the moderate wavelength thermal sensitivity of ~0.1 cm⁻¹/K. For tuning over a wider spectral band, the laser operating temperature must be changed. For instance, a tuning over the 10 cm⁻¹ spectral band would require a
In this work, we propose a wide-range frequency-swept mid-IR laser source, using a commercially available FP QCL. The principle of frequency tuning relies on the high sensitivity, in general, of a diagonal inter-subband transition to the quantum confined Stark effect (QCSE). However, instead of engineering a specific QCL structure operating on the diagonal transition, which may only provide a broadband emission (e.g., of $\sim 20–30$ cm$^{-1}$ FWHM in Ref. 15), or QCL incorporating an independently biased refractive index modulation layer, which enabled an electrically controlled tuning over 0.15 cm$^{-1}$, or other alternative approaches for rapid electrical tuning of QCLs and ICLs that can be found in a review, we use the mechanism of lasing wavelength switching and locking from the main broadband vertical transition in the active region QWs to the narrowband diagonal transition from the injector to the low laser level. By carefully tuning the QCL injection current and the temperature of its active region, we made the narrow-band unsaturated gain curve of the diagonal transition spectrally superimposed on the broadband (saturated) vertical transition gain clamped at threshold. These results in the lasing wavelength being defined by the diagonal transition, along the lines of the lasing wavelength tuning phenomenon discussed in the model of Ref. 19. In our experiment, this interplay of saturated and unsaturated gain coefficients shows up as the lasing level switching from the vertical to diagonal transition. Due to the strong sensitivity of the diagonal transition energy on the bias field, by applying a carefully optimized pump current waveform, we achieve a transient narrowband emission of $\sim 2$ cm$^{-1}$ FWHM, which is blue-chirped over the spectral band as large as 25 cm$^{-1}$. In our realization, the wavelength sweeping time is limited by our pump source to a few microseconds, but generally it can be made much faster, even at the nanosecond scale. The proposed scheme is a demonstration of the high-speed spectral tuning of a narrow-band emission in the FP QCL. This technique can overcome limitations of temperature-tuned pulsed DFB QCLs or EC QCLs and provide a cost-effective, compact, and wide frequency-swept light source in the mid-IR range.

A standard InGaAs/InAlAs FP QCL (the sample labeled as #14556) operating at the wavelength of 8.15 $\mu$m, manufactured by Alpes Lasers, is used to demonstrate the frequency blue-chirped emission. This laser employs a double LO resonance epitaxial design N655 from Ref. 20. It is processed into a buried-heterostructure waveguide with an active region width of 9 $\mu$m and a cavity length of 3 mm, with an estimated FP cavity mode spacing of $\sim 0.5$ cm$^{-1}$. The laser cavity has a metal coated back facet with a high reflectivity of $\sim 98\%$, while the front facet is left uncoated with a reflectivity of $\sim 27\%$, resulting in a low threshold modal gain. The laser chip is mounted on AlN submount on a copper baseplate whose temperature is controlled with a Peltier cooler. In the experiments reported here, the laser is driven in either CW or pulsed regimes.

In order to optimize the laser driving parameters for level switching, the laser CW spectrum is measured as a function of injection current at various copper baseplate temperatures. A FTIR spectrometer is used to capture high-resolution lasing spectra of the QCL as a function of its operation conditions. Figure 1 shows CW lasing spectrum evolution with the current at three different operation temperatures at the copper baseplate: −20°C, 0°C, and 20°C. As expected, the baseplate temperature has a strong impact on the lasing threshold of the QCL measured to be of 0.54, 0.66, and 0.80 A for the three selected operating temperatures. In all cases, the spectrum is nearly single mode at the lasing threshold, but already at $\sim 50$ mA excess above the threshold, it suddenly turns into broadband multimode emission and continues to broaden gradually with the injection current. In agreement with the estimated free spectral range of the laser cavity, the measured adjacent mode spacing is $\sim 0.5$ cm$^{-1}$.

The multimode spectrum broadened over the $> 20$ cm$^{-1}$ spectral range spans over more than 40 lasing modes centered at the initial single lasing mode frequency. Such a spectral broadening phenomenon of the initial lasing mode at small excess above the lasing threshold can be attributed to the multimode Risken–Nummedal–Graham–Haken (RNGH) instability eased by the spatial hole burning in the FP QCL. This spectral broadening pattern is determined by the buildup of Rabi oscillations sidebands at the initial lasing mode.

However, the measured spectral maps in Fig. 1 do not always follow the expected behavior of gradual spectral broadening of the symmetric sidebands, as a square root of the pump excess above the instability point of the initial lasing mode. In the spectral map of Fig. 1(b) measured at the baseplate temperature of 0°C, starting from

![FIG. 1. Normalized CW lasing spectrum of the QCL #14556 as a function of current for three different temperatures: −20°C (a), 0°C (b), and 20°C (c). The spectral profile at each current is normalized by its maximum spectral power density. The spectral resolution is 0.2 cm$^{-1}$ and the current is changed in steps of 5 mA.](image)
the pump current of $\sim 0.77 \, \text{A}$, the center frequency of the sidebands now reveals a blue shift with the pump current (and bias field) of $\sim 62 \, \text{cm}^{-1}/\text{mA}$ until the current value of $0.87 \, \text{A}$. A similar blue chirped emission with the current variation is seen in Fig. 1(a) for a temperature of $-20 \, \text{°C}$ and for current above $\sim 0.85 \, \text{A}$. However, in this case, the spectral broadening vanishes abruptly and the lasing modes become spectrally confined within a narrow band. The laser spectrum now moves toward higher frequency with the current (and quadratically with the bias field) at the rate of $\sim 153 \, \text{cm}^{-1}/\text{mA}$. Such a spectral behavior has much in common with the energy shift due to the quantum confined Stark effect, which in QCLs is usually observed in diagonal intersubband transitions. However, in our case, the active QW region is designed for lasing on the vertical transition. The possibility of tunneling resonances and intersubband transition switching with the applied bias field has been noticed since the pioneering work of Kazarinov and Suris. Based on band structure modeling of the N655 epitaxial design from Ref. 18, the experimentally observed lasing behavior can be attributed to the interplay between the optical gain on the main transition clamped at threshold and unsaturated gain of the diagonal transition between the injector state and low lasing level. The spectral overlap is possible due to the combination of two conditions: (i) the vertical transition is almost insensitive to the QCE; (ii) at the same time, the diagonal transition is sensitive to it and its frequency varies over a wide range. In addition, the sensitivity of vertical transition to the bias field is reduced due to photon-assisted transport as well as clamping the gain transition “picture” (populations, scattering rates, etc.) in the configuration encountered at the lasing threshold. The QCL behavior, when two gain spectra start to overlap as a result of the tunneling resonance between the injector and upper lasing subband in the active QW region, can be considered along the model discussed in Ref. 19 on the interplay of two gain media in a laser. In our case, the interaction of the two optical gains is defined by the pump rate at each transition, gain saturation, and photon-assisted transport on the vertical transition, and by the excess of the small signal gain on diagonal transition. This interplay defines the resulting lasing wavelength. What is also important in our case is that it should define the net gain relaxation time $T_1$ as well. According to Ref. 18, the gain relaxation time on the diagonal transition could be half as long as the vertical one, which has a direct impact on the occurrence of multimode RNGH instability and strong spectral broadening.

At a higher temperature ($0 \, \text{°C}$ in Fig. 1(b)], the lasing threshold is reached at a higher current, while in general, the voltage drop decreases with the temperature. Therefore, within the bias field range leading to spectral overlap of the unsaturated gain on the diagonal transition and clamped gain on the vertical transition, the small signal gain on the diagonal transition is not that strong as at $-20 \, \text{°C}$. Correspondingly, its impact on the lasing behavior is weaker. On the contrary, at the baseplate temperature $-20 \, \text{°C}$, the contribution of the diagonal transition is stronger and, therefore, it significantly impacts the spectral properties, as well as the effective relaxation time $T_1$ of the net gain. Since the gain relaxation time $T_1$ on the diagonal injector-low active level transition is short, it gets harder to reach the RNGH multimode instability point. These simple considerations allow us to speculate about a possible origin of the narrowband blue-chirped emission at $-20 \, \text{°C}$ in Fig. 1(a) and broadband blue-chirped emission at $0 \, \text{°C}$ in Fig. 1(b) when both vertical and diagonal transitions contribute to lasing. A comprehensive model for transition switching will be developed elsewhere.

In the rest of this Letter, we focus at a practical application of the narrowband spectral tuning behavior in the quasi-CW operating FP QCL, to realize a high-speed wide-spectral-range frequency-swept mid-IR laser source. It turns out that all scattering time constants relevant to the gain in QCLs are on the picosecond scale or shorter. Therefore, sweeping the driving current over the blue-chirped CW emission range on a microsecond or even nanosecond scale allows one to realize a frequency-swept source. The key point is to find such quasi-CW operating conditions under pulsed current pumping so that the lasing frequency inherently shows blue shifts in time along the smooth rising slope of the injection current pulse.

Under the pulsed current operation, the average temperature rise in the active region of the QCL is different from CW operating conditions. It is strongly affected by the duty cycle of the pump pulse train. To simplify tuning and to independently adjust the current pulse amplitude, its waveform, and the baseplate temperature, a laser train with low duty cycle is used to produce negligible (on average) self-heating in the active region over the pulse train period.

Following the evolution of individual FP cavity modes in Fig. 1(b) with the current, we extract the heat spreading thermal resistance $R_T$ and the temperature rise in the active region of our QCL. Using the broadband multimode emission regime as in Fig. 1(b) and the separately measured thermal wavelength coefficient of 0.65 nm/K, what is comparable to the value reported in Ref. 28, the extracted $R_T$ in our laser is of 8.2 K/W. The estimated active region temperature rise is about 70 °C in the CW spectral tuning range of interest. Therefore, the baseplate temperature of 50 °C under the pulsed pump current and a low duty cycle should allow one to reproduce the CW spectral behavior seen in Fig. 1(b).

As a driver, we use a home-made current pulser producing a pulse train at 100 Hz repetition rate with 10 µs FWHM duration and $\sim 2$ µs rise time on the front edge, resulting in the duty cycle of 0.1%. An example of the current pulse and voltage drop waveforms can be found in Fig. 2(c). The transient spectral behavior of the QCL is characterized by a step-scan FTIR (Vertex 70, Bruker) with the output monitored on external infrared detector. In this study, we use DC-coupled detector PVI-4TE-10.6 from VIGO System SA and pre-amplified IR detector module Q-MACS IRDM-1GA from neoplas control GmbH.

The time-resolved spectrum is measured with 2.5 ns time sampling (the detector response time is 4.5 ns) and 1.0 cm$^{-1}$ spectral resolution (insufficient to resolve cavity modes). The time-resolved data were acquired over 12 µs window encompassing the excitation 10 µs pump pulse with an advance of 1 µs.

Figure 2 shows the spectrochronograms measured with the pulse amplitude of 1050 mA at three different temperatures on the copper baseplate (0 °C, 20 °C, and 50 °C). As expected, the time-resolved spectra are significantly influenced by the operating temperature. At all set temperatures, the laser spectrum starts with a strong single mode at threshold and it becomes broader above the threshold, in agreement with the trends seen in CW spectra of Fig. 1. The interplay of the diagonal and vertical transitions yielding a blue chirped emission is visible at all temperatures; however, its appearance is different. For the case when the two transition energies overlap throughout the current sweep in Fig. 2(c), showing a promising linear chirp behavior on a rising front of the current pulse as expected for the operating temperature of 50 °C. At low temperatures, because the voltage drop and
As result, at an intermediate pulse amplitude is insufficient to compensate for the behavior of the spectral overlap with temperature. As seen in Fig. 3(b), the maximum current pulse amplitude is insufficient to compensate for the behavior of the spectral overlap with temperature. At the lowest temperature of 0°C, the light emission shows just a slight inclination to the blue shift, which occurs at even longer delay, while the instantaneous spectrum is relatively broad during the entire duration of the current pulse.

The spectral properties of lasing modes in the blue-chirped emission regime of the pulsed FP QCL are further characterized in Fig. 3. This figure shows time-resolved measurements made with the resolution of 0.2 cm⁻¹ and at 40°C of the copper baseplate temperature for which the largest spectral sweeping range and the narrowest instantaneous spectral width are obtained. As in the previous measurements, the 2.5 ns time sampling is used, while the temporal resolution is limited by the detector response time of 4.5 ns. To aid the comparison with the normalized CW spectrum from Fig. 1(a), the instantaneous spectrum at each acquisition time point in Fig. 3(a) is normalized at its maximum spectral power density. The evolution of the time-resolved spectrum under the pulsed current operation reproduces the main trends of the CW spectrum evolution with the pump current. Within the initial 1 μs stage of the current pulse rising (corresponding to the time axis labels from 1 μs to 2 μs in Fig. 3), the laser exhibits a broadband emission caused by multimode RNGH instability. The lasing modes spread over the ~50 cm⁻¹ spectral range, from approximately 1200 cm⁻¹ to 1250 cm⁻¹, corresponding to excitation of about 100 longitudinal modes. Then, at a time axis label 2.88 μs, the multimode RNGH lasing regime instability is swiftly switched off and the lasing spectrum turns into a narrowband emission. The emission wavelength is highly sensitive to the applied bias field, as seen in Fig. 3(b). As discussed above, we attribute this spectral behavior to the diagonal transition from the injector to the low laser level with a very low gain relaxation time and, as a consequence, requiring a high pump current for occurrence of the multimode RNGH instability. Opposite to this, the vertical transition in the active QWs is characterized by a longer gain relaxation time and, hence, by a significantly eased excitation of the broadband multimode RNGH emission. Yet another difference between the two lasing transitions is in their apparent sensitivity to the QCSE energy shift. In Fig. 3(a), within the time window from 2.88 μs to 4.68 μs, the emission spectrum is linearly blue-chirped in time, shifting from 1216 cm⁻¹ to 1241 cm⁻¹ with just a few visible mode hops, thus performing a wide spectral sweep of 25 cm⁻¹ over 1.8 μs. For the rest of the pump pulse, starting at the time axis label of 4.68 μs right after the end of the self-frequency tuning, the laser returns to the steady-state regime of the broadband multimode emission. The dominant lasing mechanism switches back to the usual vertical transition with relatively long gain relaxation time and, hence, a small excitation current of the multimode RNGH instability. However, it must be noted that such a multimode emission is useless for spectroscopy applications. It can be eliminated by shortening the applied current pulse.

Figure 3(b) shows the evolution of the peak frequency of the lasing mode distribution during the blue-chirped emission plotted vs QCL bias. The right axis of the figure displays the corresponding instantaneous current indicated on a blue curve. The red curve depicts a second-order polynomial fit of the laser frequency vs the voltage drop, showing good agreement with the expected behavior due to the QCSE energy shift.

Figure 3(c) shows several instantaneous spectral snapshots taken during the blue-chirped emission. It can be seen that several modes are present simultaneously in the lasing spectrum. We expect that the number of modes can be minimized by varying the length of the gain chip and the lasing threshold conditions. For this particular QCL sample, we observe spectral width equivalent to four longitudinal modes on average [see Fig. 3(d)] corresponding to spectral FWHM of ~2 cm⁻¹. This is enough for mid-IR spectroscopy of congested spectra in aqueous solutions and high-pressure gasses or low-pressure gases with vibrational line separation of more than 2 cm⁻¹. The instantaneous optical power during the blue-chirped emission continuously grows with the pump current from 120 mW to 150 mW, providing attractively high spectral power density for various spectroscopic applications.

Figure 4 reports on blue chirped emission in another nominally identical QCL sample. The tuning range of 22 cm⁻¹ and the FWHM
of \( \sim 3 \text{ cm}^{-1} \) reproduce very close the results of the first sample (Fig. 3). The standard deviation of the wavelength and the FWHM over 20 repeated scans is much smaller than the average FWHM, while the standard deviation of FWHM itself is smaller than the cavity mode separation (0.5 cm\(^{-1}\)). Such close reproducibility of the blue-chirped emission in different, although nominally identical QCL samples, and the repeatability of the spectra with scanning, attests the feasibility of practical application of this effect in spectroscopy. The observed slight difference in the wavelength indicates the necessity for selection and calibration of individual QCLs. Concerning the temperature and current stability requirements and aging of the thermal resistance, those are not more crucial than in the commercial pulsed DFB QCLs. Interestingly, in contrast to DFBs, where device aging and temperature instabilities cause changes of mode hopping current over the tuning range, rendering DFB device unsuitable for spectroscopy, for blue-chirped FP QCLs, the mode hopping is not devastating, as it is always continuous (between adjacent modes) and is permanently present during the spectral scan. Shifting of mode hopping currents by one cavity mode has no impact on the wavelength scan range or spectral FWHM (see Fig. 4).

We have described a method to achieve a narrow-line blue-chirped emission from a standalone FP cavity QCL with double LO resonance design and operating at a wavelength of 8.15 \( \mu \text{m} \) at room...
temperature. The threshold gain, the current, and the operating temperature of the FP QCL play an important role in activation of the efficient switching of the lasing frequency from the vertical transition to the QCSE-sensitive diagonal transition. Once the lasing frequency is locked on the diagonal transition, the peak frequency of the laser is self-swept over a spectral range of 25 cm⁻¹ within a 1.8 μs time interval when the laser is driven by a current pulse train. Preliminary modeling results indicate that the lasing frequency locking range on the diagonal transition and, respectively, the spectral tuning range of the FP QCL can be increased by lowering cavity losses (to be published elsewhere). To avoid confusion, we stress that although almost all QCL designs are using injector-active region tunneling, not all of them are capable of demonstrating such spectral features. Presently, we observe the blue-chirped emission for one design and the effect is reproducible in about a half of QCL samples. An important future work should be devoted to optimization of doping, interface roughness, and operating temperature to achieve similar spectral behavior in other QCL designs.

We believe that the proposed frequency-swept mid-IR light source based on the QCSE energy shift in cost-effective FP QCLs has large potential for a wide range of industrial applications such as real-time trace gas sensing and monitoring of the semiconductor manufacturing process. This approach reduces dramatically the power consumption, complexity, size, and cost of the frequency-swept mid-IR light source, even in comparison to DFB and EC QCLs. Offering competitively attractive high spectral power density for spectroscopic applications, it combines some advantages of both DFB and EC QCLs. Thus, like DFB QCLs, it provides a rapid spectral frequency sweeping capability, which enables in situ monitoring. Like the EC QCLs, it allows spectral tuning over a few tens of wavenumbers. However, with the instantaneous spectral width of 25 cm⁻¹, it is not possible to resolve the structure of a single rovibrational absorption line of a molecule in a low-pressure gas cell like it is possible using DFB and EC QCLs, in particular for lightweight molecules. Thus, for some molecules (e.g., carbon tetrfluoride or sulfur dioxide), the challenge would be to measure a congested spectrum, ideally the entire vibrational band. On the other hand, there are many other gas molecules exhibiting main vibrational line separation of a few wavenumbers. Therefore, in comparison to narrow-band DFB QCLs offering a rapid tuning over the range of only 2 cm⁻¹, our FP QCL being rapidly swept over the spectral band of 25 cm⁻¹ may be more attractive for sensing gas molecules species with congested spectra distributed over a range of more than 2 cm⁻¹ or for detection of vibrational molecular spectra in high pressure gas cells or aqueous solutions. In this way, the proposed technique may offer an attractive alternative to the DFB and EC QCLs in various spectroscopic applications.

We thankfully acknowledge the valuable discussions with Dr. Norbert Lang (Leibniz Institute for Plasma Science and Technology) and Dipl.-Ing. Henrik Zimmermann (neoplas control GmbH, Greifswald, Germany). We are grateful to neoplas control GmbH for providing the IR detector module. This study is carried with the financial support from EUROSTARS project LEVES (Reference No. E112309).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

1. A. Schliesser, N. Picque, and T. W. Hansch, Nat. Photonics 6, 440–449 (2012).
2. P. Werle, F. Semer, K. Maurer, R. Kornmann, R. Mucke, and B. Jankert, Opt. Laser Eng. 37(2–3), 101–114 (2002).
3. R. I. Woodward, M. R. Majewski, D. D. Hudson, and S. D. Jackson, Appl. Phys. Lett. 4(2), 020801 (2019).
4. N. Lang, U. Macherti, H. Zimmermann, S. Glitsch, M. Wiese, J. Röpcke, and J. P. H. van Helden, Sensors 18(7), 2058 (2018).
5. K. A. Tillman, R. J. R. Maier, and D. T. Reid, Appl. Phys. Lett. 85(16), 3366 (2004).
6. C. Fischer and M. W. Sigrist, “Mid-IR difference frequency generation,” in Solid-State Mid-Infrared Laser Sources. Topics in Applied Physics, edited by J. T. Sorokin and K. L. Vodopyanov (Springer, Berlin, Heidelberg, 2003), Vol. 98.
7. J. C. Gauntner, V. Fortin, J.-Y. Carrée, S. Poulain, M. Poulain, R. Vallée, and M. Bernier, Opt. Lett. 41(8), 1756 (2016).
8. D. Grassani, E. Tagkoudi, H. Guo, C. Herkommer, F. Yang, T. J. Kippenberg, and C.-S. Brä, Nat. Commun. 10, 1533 (2019).
9. P. Burghoff, Y. Yang, J. L. Reno, and Q. Hu, Optica 3(12), 1362–1365 (2016).
10. E. L. Normand, M. McCallus, G. Duisbury, and N. Langford, Opt. Lett. 28(1), 16–18 (2003).
11. B. Grouze, B. Parvítte, J. Loly, and V. Zенинари, Opt. Lett. 34(2), 181–183 (2009).
12. K. Gurel, S. Schilt, A. Bismuto, Y. Bidaux, C. Tardy, S. Blaser, T. Gensch, and T. Sudmeyer, Photonics 3(3), 47 (2016).
13. J. Röpcke, P. B. Davies, S. Hamann, M. Hannemann, N. Lang, and J.-P. H. van Helden, Photonics 3(3), 45 (2016).
14. N. Lang, U. Macherti, S. Glitsch, H. Zimmermann, J. Röpcke, and J. H. van Helden, Contrib. Plasma Phys. 55(10), 758–773 (2015).
15. A. Bismuto, R. Terazzi, M. Beck, and J. Faist, Appl. Phys. Lett. 96, 141105 (2010).
16. M. Lang, S. Suchalkin, and M. A. Belkin, “Mid-infrared quantum cascade lasers with electrical control of the emission frequency,” IEEE J. Quantum Electron. 49(1), 60–64 (2013).
17. S. Suchalkin, G. Belenky, and M. A. Belkin, IEEE J. Sel. Top. Quantum Electron. 21(6), 1 (2015).
18. A. V. Antonov, D. I. Kuritsyn, A. Gajic, E. E. Orlova, J. Radovanovic, V. V. Vaks, and D. L. Boiko, arXiv:1711.10749 (2017).
19. N. Basov, IEEE J. Quantum Electron. 4(11), 855–864 (1968).
20. R. Terazzi, T. Gensch, A. Wittmann, and J. Faist, Phys. Rev. B 78, 155328 (2008).
21. A. Gordon, C. Y. Wang, L. Diehl, F. X. Kärtner, A. Belyanin, D. Bour, S. Corzine, G. Höfler, H. C. Liu, H. Schneider, T. Maier, M. Troccoli, J. Faist, and F. Capasso, Phys. Rev. A 77(5), 053804 (2008).
22. N. Vukovic, J. Radovanovic, V. Milanovic, and D. L. Boiko, IEEE J. Sel. Top. Quantum Electron. 23(6), 1–16 (2017).
23. N. Vukovic, J. Radovanovic, V. Milanovic, and D. L. Boiko, Opt. Quantum Electron. 48, 254 (2016).
24. N. Vukovic, J. Radovanovic, V. Milanovic, and D. L. Boiko, Opt. Express 24, 26911–26929 (2016).
25. R. F. Kazarinov and R. A. Suris, Semiconductors 5(4), 707–709 (1971), see https://www.researchgate.net/publication/257947712_Possible_amplification_of_electromagnetic Waves_in_a_semi-conductor_with_a_supercritical/1965026839968143606000000/download.
26. M. Mátys, P. Lugli, and C. Trauschek, J. Appl. Phys. 110(1), 013108 (2011).
27. D. L. Boiko, G. Guerrero, and E. Kapon, J. Appl. Phys. 100(10), 103102 (2006).
28. M. Brandstetter, A. Genner, C. Schwarzer, E. Mujaig, G. Strasser, and B. Lendl, Opt. Express 22(3), 2656–2664 (2014).