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# Thermoelectric-cooled terahertz quantum cascade lasers

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**Abstract:** We demonstrate the first lasing emission of a thermo-electrically cooled terahertz quantum cascade laser (THz QCL). A high temperature three-well THz QCL emitting at 3.8 THz is mounted to a novel five-stage thermoelectric cooler reaching a temperature difference of $\Delta T$ = 124 K. The temperature and time-dependent laser performance is investigated and shows a peak pulse power of 4.4 mW and a peak average output power of 100 µW for steady-state operation.



## 1. Introduction

Since the first demonstration of terahertz quantum cascade lasers (THz QCLs), there has been a continuous research toward higher temperature devices that do not require cryogenic cooling [1,2]. An alternative to THz QCLs is the generation of THz radiation using difference-frequency mixing in mid-infrared QCLs, which enables operation at room temperature, however, this technology is limited to low output powers [3, 4]. In contrast, THz QCLs enable output powers above 1 W [5], but are restricted by their operating temperature. The current published $T_{max}$ record is 199.5 K [6], using a three-well GaAs/$Al_{0.15}Ga_{0.85}As$ LO-phonon depletion scheme active region. Recently, a new temperature record was presented, showing lasing up to 201.5 K for a two-well design, which is based on the LO-phonon depletion scheme [7]. With the LO-phonon depletion scheme, an efficient depopulation of the lower laser level is achieved also at high temperatures [8]. In the past, a significant effort has been devoted to increasing the $T_{max}$, including different active region designs [9–12] and novel material systems [13–17] with lower effective electron masses to increase the optical gain, but up to now, the operating temperature is still limited to 200 K. Nevertheless, this temperature can be achieved with $LN_2$ cooling [18] and easily be reached with cryocoolers [19], however both cooling techniques have their drawbacks. The need of cryogenic liquids restricts the device mobility, whereas cryocoolers generate mechanical vibrations, through the closed-cycle compressors, which have to be considered in setups with external optics and cavities [20]. The technology of thermoelectric cooling based on the Peltier effect overcomes both of these drawbacks and enables cooling without cryogenic liquids or moving mechanical parts. Therefore, THz QCLs operation using a thermoelectric cooler (TEC) is a milestone in the THz technology. In this paper we show the first demonstration of a three-well THz QCL operated with a TEC, which is enabled by using a high temperature active region lasing up to 196 K [12] and a five-stage TEC with an optimized housing and water cooling system.

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## 2. Characterization of the thermoelectric cooler

The thermoelectric effect (Peltier effect) creates a heat transfer by applying a voltage and thus generates a temperature difference between the two sides of the Peltier element. In a further step, a thermoelectric cooler (TEC), or Peltier cooler, consists of multiple n- and p-type semiconductors, which are placed thermally in parallel to each other and electrically in series [21]. The TECs are widely used for different applications including the cooling of laser diodes and integrated circuits [22]. In MIR QCLs, TECs are used to increase the laser performance, specially in continuous wave operation [23,24]. The temperature difference of a single thermoelectric module is limited due to an intrinsic heating of the device induced by ohmic losses. To further increase the temperature difference between the hot and cold side, multistage devices are used.

In this presented work, we have used a set of four five-stage TEC model 4xTB-5-(198-91-44-20-10) from Kryotherm LLC, to achieve a high temperature difference with a significant heat load. The thermal management of the whole setup requires good heat conductivity and similar coefficients of thermal expansion for all used components. Additionally, the thermal short circuit from the chip to the electronics has to be minimized. The housing and the dimensions of the TEC are designed to dissipate a heat load of 2 W at a temperature of 180 K to allow the operation of a THz QCL in pulse mode with a high enough duty cycle to easily detect the emitted light. For efficient cooling of the hot side of the TEC, a compact water cooling system was designed to keep the housing and bottom plate at room temperature. The housing itself is under vacuum to increase thermal isolation and to avoid vapor condensation on the QCL. For laser mounting, a copper plate is attached to the cooled side of the TEC and the THz QCL is indium soldered on a C-mount which is screwed to the copper plate. To characterize the temperature performance of our TEC, the temperature (cold side) inside the housing is measured as a function of the applied input current (see Fig. 1(a)), where the cooling water temperature is kept at a constant value of 19 °C. At an input current $I_{TEC}$ = 15 A and an applied voltage of $V_{TEC}$ = 32.1 V the minimum

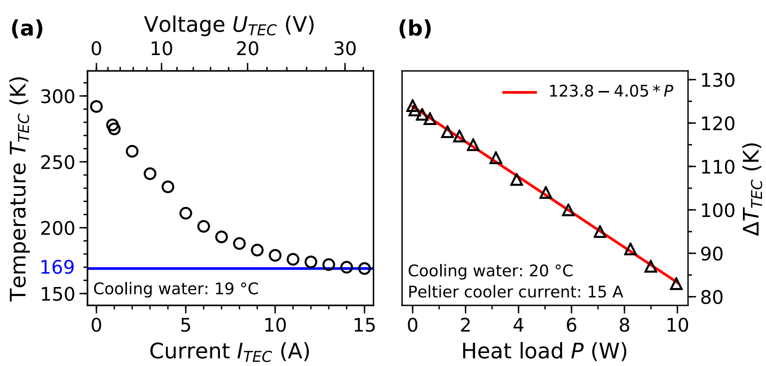


Fig. 1. Thermoelectric cooler characteristics. (a) Temperature as a function of the applied current. A minimum of 169 K is reached at a current of 15 A and an applied voltage of 32.1 V. (b) Heat load dependent temperature difference between the cooling water and copper mount.

temperature of −103.8 °C = 169.4 K is reached. An important feature to characterize is the TEC temperature behaviour under different heat loads applied at the copper mount on the cold side. This is important to verify a stable laser operation of the THz QCL, because their output power decreases at higher heat sink temperatures. At the optimum driving condition of the TEC ($I_{TEC}$ = 15 A) an ohmic resistance on the copper mount is used to apply a heat load up to 10 W. The additional introduced heat from the ohmic resistance reduces the temperature difference of the cooling water and the copper mount in the TEC ($\Delta T_{TEC} = T_{water} - T_{mount}$). Figure 1(b) shows a linear temperature difference decrease of 4.05 K $W^{-1}$ for higher heat load powers after the TEC reaches thermal stability. For a heat load of 2 W, a temperature difference of 115.7 K is still reached resulting in an absolute heat sink temperature of 177.4 K which is below the desired temperature of 180 K.

## 3. Terahertz QCL device

The used THz QCL active region is based on a 3-well design with GaAs wells and $Al_{0.24}Ga_{0.76}As$ barriers and is described in more detail in previous publications [12, 25]. The laser ridges are processed in a copper-copper waveguide to ensure high optical mode confinement, low optical losses and thus high operating temperatures. The used laser ridge (2600 µm x 60 µm) is indium soldered on a copper C-mount and first tested in a standard helium (He) flow cryostat to characterize the performance for temperature up to 190 K. The laser light is collected with a parabolic mirror and guided into a fourier transform infrared spectrometer to analyze the emitted light. To minimize additional device heating effects, the QCL is operated in pulsed mode with a duty cycle of 0.5 %. Figure 2(a) shows the lasing performance for temperatures from 160 K up to the maximum temperature of 190 K. In this temperature range the laser threshold current is increasing from 1.6 A up to 1.9 A. At maximum intensity, the applied voltage for all

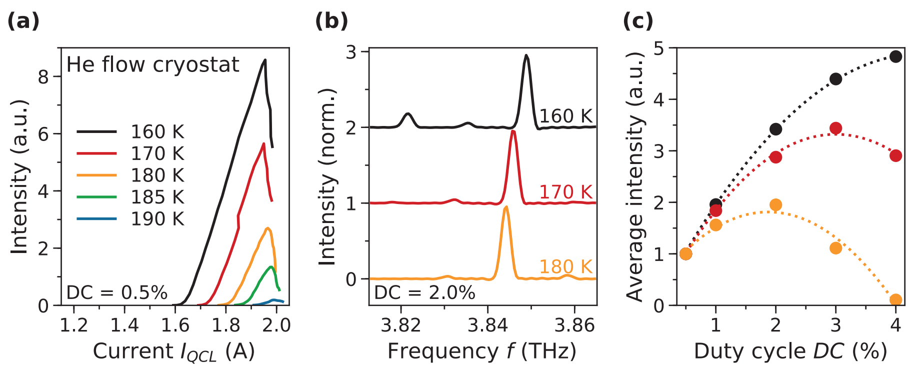


Fig. 2. THz QCL performance in He flow cryostat. (a) Measured light-current curves up to a maximum temperature of 190 K in pulsed operation (0.5 % duty cycle). (b) Spectra at 160, 170 and 180 K show a strong lasing mode at around 3.85 THz. (c) Average lasing intensity versus duty cycle for heat sink temperatures of 160, 170, and 180 K.

temperatures is 24 V, resulting in an electrical peak input power of 45 W. In this temperature range (160–180 K) the laser has a strong lasing mode at 3.85 THz which shows a slight red shift for higher operating temperatures (see Fig. 2(b)). The influence of the self heating during laser operation is obtained by measuring the average intensity for 0.5–4 % duty cycles and heat sink temperatures of 160, 170 and 180 K (Fig. 2(c)). For higher heat sink temperatures, the maximum average intensity is reached at a lower duty cycle, because the self heating during laser operation has a stronger effect at higher temperatures.

## 4. Performance of the thermoelectric-cooled terahertz QCL

After device characterization in the He flow cryostat the C-mount, including the QCL, is mounted on the copper plate inside the TEC. At maximum cooling power and at a minimum heat sink temperature of 169 K, the QCL is operated with a duty cycle of 2 %. The THz radiation is out-coupled through a 2 mm thick TPX window and detected with a calibrated power meter. For a duty cycle of 2 % (250 ns pulse length, 80 kHz repetition rate, double modulated), the average electrical power of the QCL is ~0.5 W, resulting in an increase of the heat sink temperature to

171 K. At this temperature, the QCL shows a peak pulse power of 4.4 mW and a lasing threshold

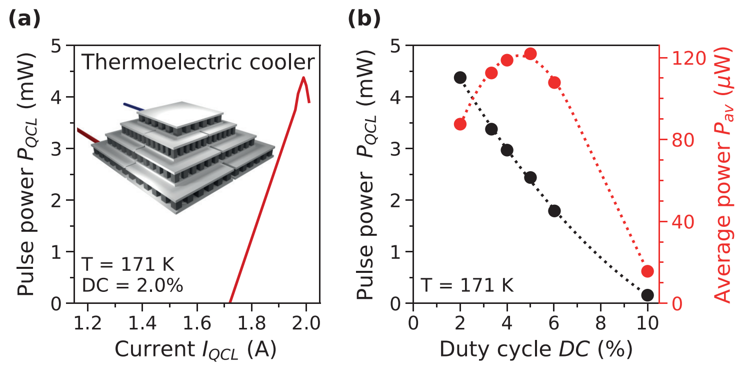


Fig. 3. THz QCL performance cooled with the thermoelectric cooler. (a) Light-current behaviour in pulsed mode and an operating temperature of 171 K (TEC input: 15 A, 32.1 V). (b) Pulsed and average power of the QCL at different duty cycles. A maximum average power of 120 µW is reached at a duty cycle of 5 %.

current of 1.7 A (see Fig. 3(a)), which is in good agreement with the threshold current obtained in the He flow cryostat. Figure 3(b) shows the dependence of the pulse peak output power $P_{QCL}$ as a function of the duty cycle. The pulse length is kept constant at 250 ns with a repetition rates up to 400 kHz (10 % duty cycle). For each measurement, the QCL is only operated for a short period of time to exclude an increase of the heat sink temperature, which therefore can be kept constant at a temperature of 171 K for all different duty cycles. For increasing duty cycles the generated heat is not dissipated fast enough, which leads to a temperature increase of the QCL active region and therefore to a reduced single pulse peak output power (black dots). On the other hand, the average laser power $P_{av}$ (red dots) increases, but only up to a duty cycle of 5 %, where the reduced peak power dominates over higher repetition rates. For duty cycles higher than 10 %, the increased temperature of the active region is already too high and laser operation can't be observed anymore.

Beside the temperature increase of the QCL active region, the heating of the whole TEC has to be considered, specially when it comes to steady-state operation. Due to the fact that most of the electrical input power of the QCL is converted into heat, this energy will heat up the TEC up to an equilibrium point, where the input energy is equal to the dissipated heat. To obtain the laser output power of the QCL at this equilibrium temperature, the signal decay over time is measured for different duty cycles (see Fig. 4). At time t = 0 s the TEC has its minimum temperature T = 169 K and the average output power $I_0$ has its maximum at a duty cycle of 5 % (compare to Fig. 3(b)). The signal shows an exponential decay over time with an offset $I_\infty$, which is the laser intensity at the equilibrium temperature, depicted in the inset of Fig. 4. While for the initial operation the QCL reaches with a duty cycle of 5 % an average power of 120 µW, at steady-state operation (thermal equilibrium) the highest peak average power is slightly reduced to 100 µW at a duty of 3–4 %.

## 5. Conclusion

We show the feasibility of a thermoelectrically cooled THz QCL, which is a fundamental step towards portable hand-held THz spectroscopy. This we achieved by combining a high temperature active region lasing up to 196 K with a five-stage thermoelectric cooler. The high average output power of 100 µW from the complete assembly exceeds the requirements for THz spectroscopy. To further increase the performance of a thermoelectrically cooled THz QCL setup, higher operating temperatures for the laser would benefit in two ways. If $T_{max}$ of the laser is above the

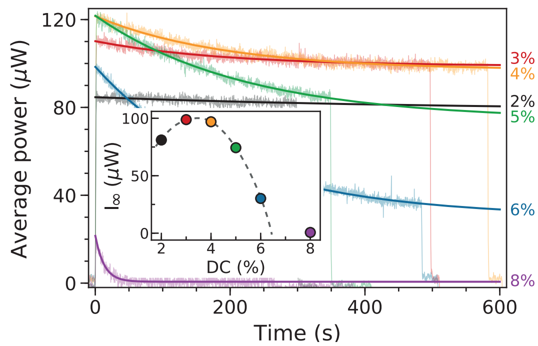


Fig. 4. Signal decay due to the laser operation and heat sink temperature increase for different duty cycles. At 3–4 % duty cycle a maximum average power of 100 µW is reached at the equilibrium temperature. The inset shows the output power $I_{\infty}$ at steady-state operation.

temperature of the TEC, the laser can operate with a higher output power. On the other hand, the requirements for the TEC would be reduced drastically. By increasing the operating temperature from 170 K to 200 K, the electric input power of the TEC could be reduced by over a factor of 5. This would diminish the amount of cooling water, reduces the total assembly dimensions and further improves portability.

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