

# 3.5 THz Quantum Cascade Laser at 70 K as local oscillator

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**Abstract**—We report a set of measurements to demonstrate a new type of surface emitting distributed feedback (DFB) quantum cascade laser (QCL) operated at 3.5 THz as a local oscillator by pumping a superconducting hot-electron bolometer (HEB) mixer. Based on the Bragg gratings incorporated into the waveguide, the second order DFB surface emitting THz QCL shows single mode emission at 3.555 THz, which is only 4 GHz off from the hydroxyl (OH) line. Because of the radiation being emitted from the surface, the far-field beam is much improved, with a divergent far field beam pattern only in one direction. We also notice that in the far field beam pattern, unlike conventional metal-waveguide QCLs, there are no interference patterns. All these factors make it possible to fully pump a superconducting NbN HEB mixer at 60 K, and even at 70 K based on the estimated power.

**Index Terms**—terahertz, quantum cascade laser, high temperature, far-field beam, hot electron bolometer

## I. INTRODUCTION

The hydroxyl (OH) radical has been identified to be a crucial probe for problems related to the atmosphere such as global warming and ozone destruction. The OH radical emission line at 3.551 THz has been identified as the best candidate for OH profile retrieval because of its brightness and isolation. With a nearly quantum noise limited sensitivity and an ultra high spectral resolution, a heterodyne receiver based on a superconducting NbN hot-electron bolometer (HEB) mixer

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will be ideal for detecting the OH line. Since such a mixer has shown a superior sensitivity up to 5.3 THz [1], suitable local oscillators (LO) at this particular frequency become the only obstacle for future development. Solid state LOs based on multipliers have only been demonstrated up to 2.5 THz, but the output power drops severely with frequency due to reduced multiplication efficiency at high frequencies. Also, bulky and power consumptive FIR gas lasers have no strong molecular lines close to this specific frequency.

Based on the quantum well structure, the photon energy of a quantum cascade laser (QCL) is determined by the thickness of the coupled wells and barriers, which makes such a structure ideal for generation of THz radiation. Until now, most of the THz QCLs used as LOs are based on a Fabry-Perot cavity. In order to achieve single mode lasing, the laser has to be narrow and often the width is much smaller than the wavelength. The latter causes a highly divergent beam with even strong interference fringes, which makes it difficult to couple the radiation to any phase sensitive detector like a HEB mixer. However, for a surface emitting DFB THz QCL [2], by incorporating the second order Bragg gratings into the waveguide, a single mode emission is coupled out from the surface. These characteristics make surface emitting DFB QCL that have advantages in both the frequency selection and with less divergent far-field beam. Moreover, due to relative large DC power dissipation of the laser, low temperature operation of QCLs with liquid-helium cooling is impractical for balloon-borne and space missions. Therefore, high temperature operation of the laser with a dry, liquid cryogen-free cooler, such as a pulse tube cryocooler or a Stirling cooler is crucial for instrumental applications.

## II. THz SURFACE EMITTING DFB QCL

The surface emitting DFB QCL used in this experiment is described in Ref. 2. The active region is based on a resonant-phonon depopulation scheme and a metal-metal waveguide is used for modal confinement. By introducing a second-order Bragg grating on the top surface of the waveguide, the radiation is coupled out from the top surface. The DFB grating enables robust single-mode operation over a large operating range. By using a Pi phase-shift in the center of the grating, a single-lobed far beam pattern is obtained.

The QCL is operated on the cold stage of a helium-flow cryostat. The QCL consumes 4 W DC power in continuous wave mode and provides a maximum output power of 1 mW. As to be explained, the QCL working at 70 K can still provide about 25% of its maximum power and is estimated to have

enough power to pump a HEB mixer at its optimal operating point.

### III. MEASUREMENT RESULTS

For the beam pattern measurement, by using a room temperature pyrodetector and two PC controlled stepper motors, the radiation beam was measured in both horizontal and vertical directions spherically.

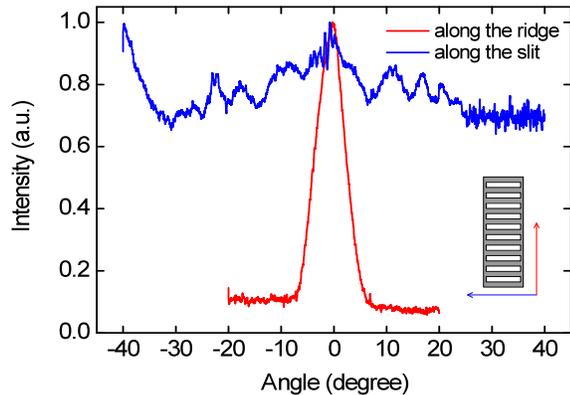


Fig. 1 Measured far-field beam pattern of the surface emitting DFB QCL, where beam pattern measured directly in front of the QCL at a distance of 112 mm.

As shown in Fig. 1a, the radiation beam was measured with a pyrodetector placed at a radial distance of 112 mm. Along the laser's ridge direction, a single-lobed beam was observed, where the full width at half maximum (FWHM) is 7 deg. However, along the laser's slit direction, the beam is highly divergent, which is mainly due to the subwavelength dimension of the waveguide in this direction. Compared with the beam patterns measured from meta-metal waveguide Fabry-Perot type QCLs [3], surface emitting DFB QCL emits a directional beam in one direction. Another advantage is that there are no interference fringes in either direction. These features caused a higher power coupling efficiency from the laser to a HEB mixer, which typically holds a Gaussian beam. For the beam pattern after focused using a HDPE lens, a single-lobed beam is found in both directions, where the divergence is less than 1 deg.

We use a spiral antenna coupled superconducting NbN HEB mixer, which consists of a 2  $\mu\text{m}$  wide, 0.2  $\mu\text{m}$  long, and 5.5 nm thick NbN bridge [1]. The HEB has a low-temperature normal-state resistance ( $R_N$ ) of 83  $\Omega$ , a critical temperature of 9.3 K, and a critical current of 210  $\mu\text{A}$  at 4.2 K.

As shown in Fig. 2, by placing the QCL and the HEB directly face to face, and using a HDPE lens ( $f=50$  mm) to focus the laser's radiation, the current-voltage characteristics of the HEB at different pumping levels are obtained. It is clearly shown that the emission power from the surface emitting DFB QCL working at 60 K is enough to fully pump the HEB (bringing the HEB fully in the normal state). This enables the QCL to be operated as the LO in a heterodyne receiver where a thin Mylar beam splitter is used to reflect the power to a HEB mixer.

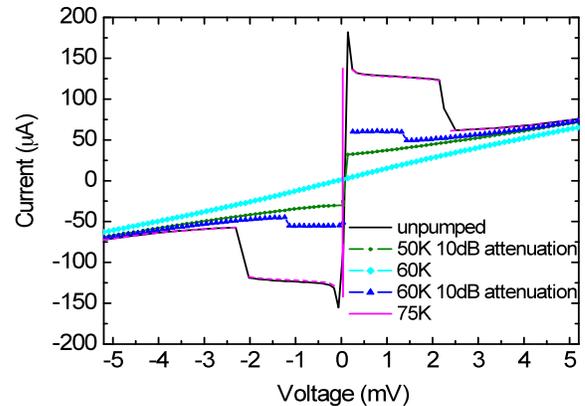


Fig. 2 Current-voltage characteristics of the HEB for different pumping levels caused by different operating temperature of the QCL. In some cases, an attenuation of the LO power is introduced in order to get a proper pumping curve.

Although no pumping measurement data were available at 70 K, we can predict that this laser would be powerful enough to pump the HEB at 70 K by using a thick Mylar Beam splitter or a Martin-Puplett interferometer (MPI). Since the output power of the QCL at 70 K is about half the power generated at 60 K. Based on the value of 530 nW at 60 K, we expect a power of 270 nW at the HEB itself with the QCL at 70 K. This value is more than the optimal LO power (140 nW). Since the beam is still highly divergent in one direction, further improvement can be made by placing the QCL closer to the cryostat window and using a short focal distance lens. The possibility of operating a QCL at 70 K or above is crucial for the application in balloon-borne and space missions because it is technically much easier to have such a cooler in comparison with a cooler for, e.g. 10 K.

### IV. CONCLUSION

In conclusion we have demonstrated using measurements of the beam pattern, spectra characteristics, and pumping a HEB mixer, that the surface emitting DFB QCL working at 3.5 THz can be used as the LO in a heterodyne receiver for the OH line detection. We found that the new laser gives a better beam pattern. The QCL can fully pump a HEB mixer at 60 K, suggesting that there is enough power even at 70 K. We emphasize that operating a QCL at a temperature of 70 K or above is practically important for a real instrument, in particular in space.

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