3.5 THz surface emitting distributed feedback QCL operated 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 local oscillator by pumping a superconducting hot-electron bolometer (HEB) mixer. The second order DFB surface emitting THz QCL, based on the Bragg gratings incorporated into the waveguide, shows single mode emission at 3.555 THz, which is only 4 GHz off from the hydroxyl (OH) line. This frequency can be slightly tuned by operating current or temperature. 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-metal waveguide QCLs, there are no interference patterns. All these make it possible to fully pump a superconducting NbN HEB mixer with a surface emitting DFB QCL at 60 K, and even at 70 K based on the estimated power.**

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 has the emission lines at terahertz frequencies such as 1.8, 2.5 and 3.5THz [1]. Among them, the 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 ultra high spectral resolution ($\nu/\Delta\nu>10^6$, where ν is the frequency), a heterodyne receiver based on a NbN HEB mixer will be ideal for detecting the OH line. Since such a mixer has shown a superior sensitivity up to 5.3 THz [2], suitable local oscillators (LO) at this particular frequency become the only obstacle. Solid state LOs based on multipliers have only been demonstrated up to 2 THz, but the output power drops severely with frequency due to reduced multiplication efficiency at high frequencies. Optically pumped FIR gas lasers are very bulky, huge power consumptive and have no strong molecular lines close to this specific frequency.

Recently developed terahertz quantum cascade lasers (QCLs) [3] become a promising candidate for LO in a heterodyne receiver. THz QCLs are based on quantum well structures, where the photon energy can be chosen by tailoring the thickness of the coupled wells and barriers, which makes such structures ideal for generation of arbitrary wavelength radiation. It has been demonstrated that a THz QCL is a suitable source for the application of LO in a heterodyne receiver system [4]. In addition, THz QCLs have shown excellent power stability [4], phase-lock capability [5], and narrow intrinsic linewidth [6], which meet the enssential requirements as LO.

Until now, most of the THz QCLs used for LO are based on a Fabry-Perot cavity. This cavity makes use of two facets as reflecting surfaces and a gain region in between. However, the edge-emission Fabry-Perot laser often gives multi-modes emission. It can generate single mode, but it is hard to control the emission frequency precisely. Furthermore, 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 [7,8]. For high-resolution spectroscopy applications, it is essential to control the single mode lasing at the exact targeting frequency. Recently a surface emitting DFB THz QCL was reported [9]. 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 having the advantage in both the frequency and beam pattern in comparison with a typical metal-metal waveguide Fabry-Perot QCL. And the improved beam pattern will also lead to a better beam coupling to the HEB mixer, which is essential for high temperature operation of QCL as LO since the emission power is limited in this case. Here we demonstrate this new type of surface emitting DFB QCL, operated at 3.55THz, as local oscillator by pumping a superconducting HEB mixer.

II. THz Surface Emitting DFB QCL

The surface emitting DFB QCL used in this experiment is developed by the MIT group and is described in reference. 9. The active region is based on a resonant-phonon depopulation scheme and a metal-metal waveguide is used for modal confinement. As shown in Fig.1, 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 indium soldered on a copper mount and is mounted on the cold stage of a helium-flow cryostat. The QCL consumes 4W DC power in continuous wave mode and emits a maximum output power of 1mW. This laser can also be operated at a relatively high temperature. As to be explained, the QCL working at 70K can still provide about 25% of its maximum power (Fig.2) and is estimated to have enough power to pump a HEB mixer at its optimal operating point.

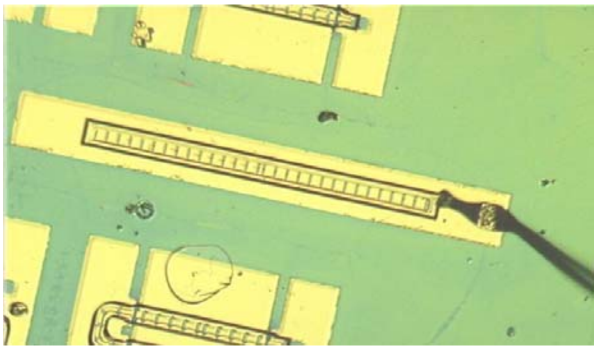


Fig. 1 Picture of a MIT surface emitting DFB QCL with a length of 754μm and a width of 40μm. Also shown is the Al wire bonding for biasing the laser

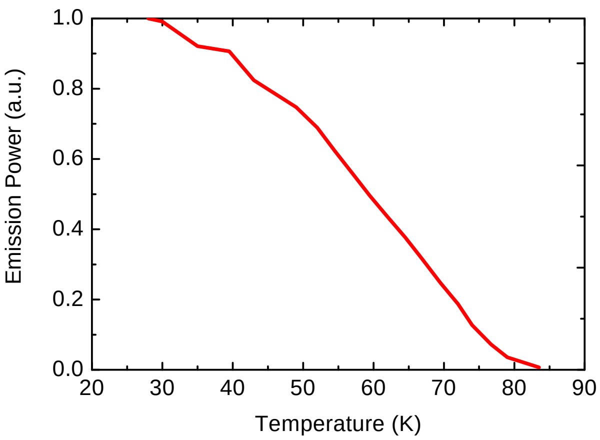


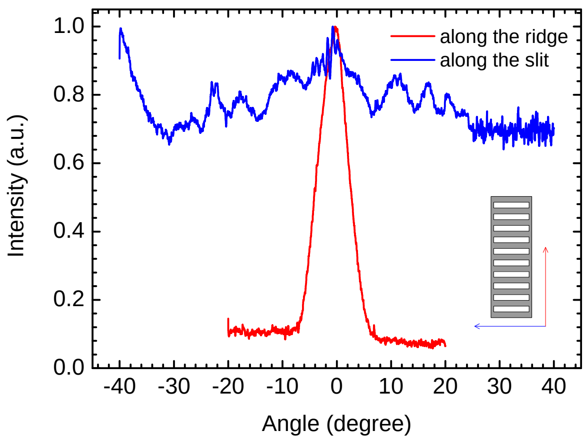
Fig. 2 Emission power of the surface emitting DFB QCL as a function of the bath temperature. The power is measured with a pyrodetector after focusing the beam by a HDPE lens (f=26.5mm).

III. Results

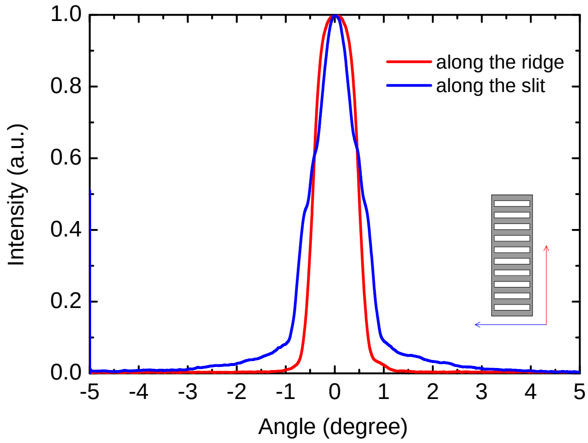
A. Far-field beam pattern

The beam pattern measurement setup was described in Ref. [10]. By using a room temperature pyrodetector and two PC controlled stepper motors, the radiation beam was measured in both horizontal and vertical directions spherically.

As shown in Fig.3a, the radiation beam was measured with the pyrodetector placed at a radial distance of 112mm. Along the laser's ridge direction, a single-lobed beam was observed, where the full width at half maximum (FWHM) is 7deg. However, along the laser's slit direction, the beam is highly divergent, which is mainly due to the subwavelength dimension in this direction. Compared with the beam patterns measured from meta-metal waveguide Fabry-Perot type QCLs [7,8], the surface emitting DFB QCL emits a directional beam in one direction. The other advantage is that there are no interference fringes in both directions. These features make it easy to couple the laser's radiation into a HEB mixer, which typically has a Gaussian beam [11]. Fig.3b shows the beam pattern measured after focusing by a HDPE lens (f=26.5mm). A single-lobed beam is found in both directions, where the FWHMs are less than 1 deg.



(a)

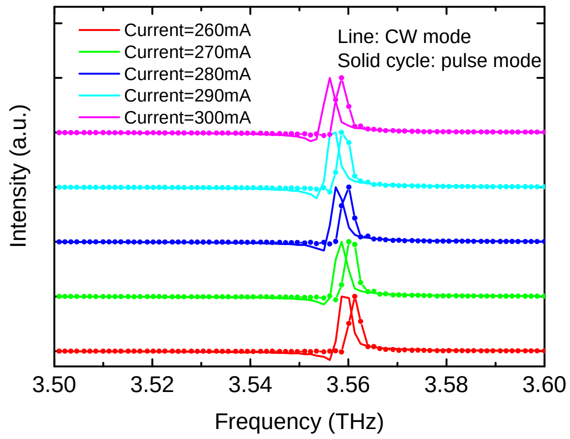


(b)

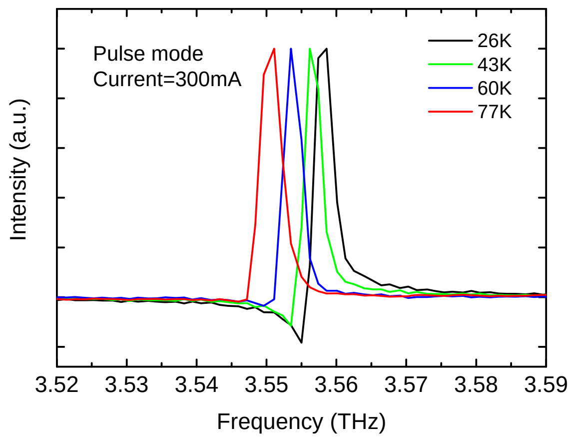
Fig. 3 Measured far-field beam pattern of the surface emitting DFB QCL. (a) Beam pattern measured directly in front of the QCL at a distance of 112mm. (b) beam pattern measured after the radiation focused by a HDPE lens.

B. Spectra characteristics

Emission spectra were measured using a Fourier-transform spectrometer (FTS) [12] with a resolution of 0.7GHz. This value is much larger than the intrinsic linewidth of a QCL, which is typically in the range of 6-30KHz. As shown in Fig.4, by changing the bias current, the surface emitting DFB QCL shows robust single mode emission over a wide operating range, which indicates a frequency tuning range of 5GHz. With increasing the bath temperature from 30K to 70K, a frequency tuning range of around 10GHz was measured in this case. It is interesting to note that the observed frequency range can cover the particular OH line at 3.551THz. This single mode lasing together with a relative large tuning range makes surface emitting DFB laser ideal for high resolution molecular line detection.



(a)

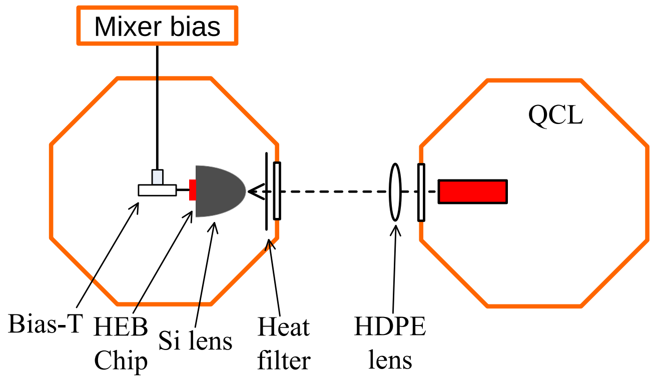


(b)

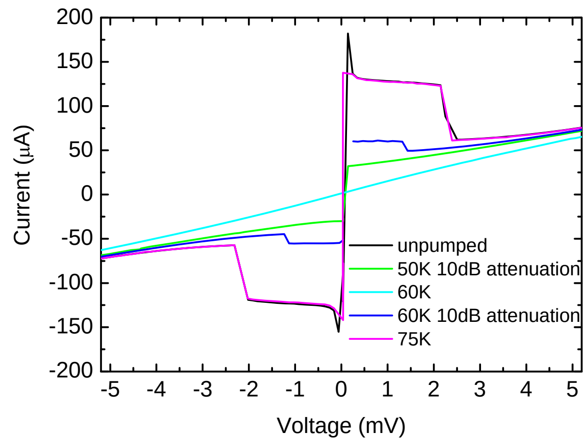
Fig. 4 (colour online) Measured emission spectra of the surface emitting DFB QCL. (a) Emission spectra measured at different bias current in pulsed and CW mode;(b) Emission spectra measured at different bath temperature in pulsed mode.

C. Coupling the radiation to the HEB mixer

We use a spiral antenna coupled NbN HEB mixer, which consists of a 2μm wide, 0.2μm long, and 5.5nm thick NbN bridge [2]. The HEB has a low-temperature normal-state resistance (R_N) of 83Ω, a critical temperature of 9.3K, and a critical current of 210μA at 4.2K.



(a)



(b)

Fig. 5 (colour online) (a) Schematic view of the QCL-HEB coupling experimental setup. (b) 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.

As shown in Fig.5, by placing the QCL and the HEB directly face to face, and using a HDPE lens (f=50mm) 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 60K is enough to fully pump the HEB (bringing the HEB fully in the normal state). This enables the QCL to operate as LO with a HEB mixer in a heterodyne receiver where a thin Mylar beam splitter is used to reflect the power to the HEB [4]. Based on the pumping curve at 60 K with additional 10 dB attenuator, and using the iso-thermal method [13], the LO power absorbed at the HEB itself is estimated to be 530 nW. Taking all known losses (the HDPE window, air, heat filter, Si lens) into account, we found that 4% of total emission power from the QCL is absorbed by the HEB. Although this is still a low value, the coupling efficiency is improved by a factor of 3 compared with that obtained with a metal-metal waveguide Fabry-Perot cavity QCL as described in Ref. 4, which is mainly due to the improved far-field beam pattern.

We did not perform the pumping measurement directly at 70 K. However, we can predict that this laser would be powerful enough to pump the HEB at 70 K. Figure 2 indicates that the output power of the QCL at 70K is about half the power generated at 60K. Based on the value of 530 nW at 60 K, we expect a power of 270nW at the HEB itself with the QCL at 70K. This value is more than the optimal LO power (140nW). 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 a space instrument because it is technically much easier to have such a cooler in comparison with a cooler for, e.g. 10 K.

IV. Summary

In conclusion we have made a set of measurements, like the beam pattern measurement, the spectral measurement, and pumping a HEB mixer, to demonstrate that the surface emitting DFB QCL working at 3.5 THz can be used as 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 60K, 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.

Acknowledgment

The work was partly supported by China Exchange Programme executed by KNAW and CAS, and by the AMSTAR+ project of RadioNet under FP7, and NWO.

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