Beam Pattern Investigation of Terahertz Quantum Cascade Lasers

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Abstract—Far-field beam pattern measurement results of in-house fabricated 1 mm long THz QCLs with ridge widths of 30 µm and 100 µm are presented. Both devices show diffractive-like beam patterns in the elevation direction (perpendicular to semiconductor heterojunction plane). In the in-plane direction (parallel to semiconductor heterojunction plane), the device with a wider ridge width (100 µm) shows a quasi-Gaussian-like beam profile. A radio-frequency (RF) design simulator (HFSS) is deployed to simulate far-field beam pattern of the QCL devices. The simulation results are in good agreement with the experimental results.

1. INTRODUCTION

Terahertz (THz) quantum cascade lasers (QCL) are becoming a major technology for THz compact, coherent and single-frequency radiation sources, after first demonstrated in 2002 [1]. Recently QCLs with maximum operating temperature up to 164 K in pulse mode and 117 K in continuous mode [2] and wavelengths down to 1.2 THz ($\lambda = 250$ µm) have been reported [3]. Such a source has many potential applications, particularly in spectroscopy, imaging, and local oscillators for heterodyne receivers. Almost for all of the THz QCL applications, a well-defined and narrow beam is required. Such a beam pattern also focuses all of the output power onto a small arbitrary surface. However considering the wavelength of THz laser emission (30 µm to 300 µm), the sub-wavelength dimensions of laser ridge facet suggests that output beam pattern is not a Gaussian beam anymore, but rather becomes a diffractive-like pattern. This paper first briefly reviews the THz QCL fabrication process. Then the experimental results of the device output beam pattern will be presented and discussed.

2. PROCESSING

THz QCLs are fabricated by growing multiple periods of GaAs/Al$_{0.15}$Ga$_{0.85}$As quantum wells (MQW) using molecular beam epitaxy (MBE) followed by patterning laser ridge using photolithography techniques. Due to the time limitation of MBE growth duration, the active region of a QCL device is typically not thicker than 10 µm. Thicker wafers also exhibit higher level of defect densities in active region, which limits the optical gain required for lasing. The heterostructure design used for MQW is based on resonant longitudinal-optical phonon scattering to depopulate the lower lasing level with three-well active module [4]. The QCL waveguide is fabricated using metal-metal structure by low temperature In-Au wafer bonding and subsequent wafer removal. Various ridge widths of the devices can be defined in subsequent device fabrication processing. An air-bridge structure is used to fabricate the QCL ridge with a 100 µm width (see Figure 1(a)). This structure provides a 250 µm wide contact pad for multiple Au wires bonding. We use bottom of the wafer as ground contact. The carrier substrate is n$^+$ GaAs, yielding very small contact resistance. The sample is then cleaved into 1 mm long Fabry-Perot resonator laser bars. Figure 1(b) shows the quality of cleaved facets. Laser bar finally is Indium soldered top-side up on a copper package. Facet of lasers is accurately placed as close as possible to the edge of the mount. In the last step, device is wire bonded connecting the top contact of the device to the package pins and placed on a cryostat cold finger for measurements. Figure 2 shows the characterization results of one fabricated QCL, which operates above liquid Nitrogen temperature. The inset of Figure 2 shows the laser spectrum at 10 K. The QCL device lases in single mode with a frequency of 3.39 THz (wavenumber 112.9 cm$^{-1}$), which corresponds to a free-space wavelength of $\lambda = 88.6$ µm.

3. BEAM PATTERN MEASUREMENT RESULTS AND DISCUSSION

After mounting QCL bars on the package, the devices are placed in a closed cycle liquid Helium cooled cryostat. The laser radiation passes through a polyethylene window, which is around 70%
Figure 1: (a) schematic diagram of the cross-section of an air-bridge structure THz QCL ridge, (b) scanning electron microscopy (SEM) of a fabricated THz QCL with an air-bridge structure.

Figure 2: THz light intensity vs. current of a fabricated QCL at different temperatures. The threshold current density is around 0.6 kA/cm$^2$ at temperatures of 20–80 K. The inset shows the lasing spectrum of the device.

transparent in terahertz frequencies, and is detected by a liquid-He cooled Silicon Bolometer (IR Lab. Inc., Model HDL-5). The space between the cryostat and the detector is purged with dry nitrogen to minimize moisture absorption. The THz signal, after passing through a polyethylene window of the bolometer, is collected by a Winston cone that is placed inside the bolometer dewar and the beam is focused onto the detector. The electrical signal from the Si bolometer is fed into a lock-in amplifier and acquired using a computer. In order to measure the far field radiation pattern, the Bolometer detector is placed on a rotating stage to move along a circle centered at the QCL device under test with a radius of 10 cm ($>1000\lambda$). An iris with opening diameter of 2 mm is installed in front of the bolometer window for a sufficient angular resolution. The QCL device is electrically biased using an HP 8114A pulse generator in pulse mode (repetition rate 500 Hz and duty cycle 10%). Figure 3 shows the schematic diagram of the measurement setup.

Figure 3: Schematic diagram of the setup for THz QCL beam pattern measurement.
The output beam pattern of a THz QCL is first assumed to be approximated as a Gaussian beam profile, in which the electric field and intensity distribution at each given distance from the emission source is described by a Gaussian function. Defining the spot size boundary to be where the intensity drops to $1/e^2$ of the value at the beam center, the radius of the spot size at a distance $z$ from the source is given by

$$w(z) = w_0 \sqrt{1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2} \approx \frac{\lambda z}{\pi w_0}$$

(1)

where $w_0$ is the beam radius at beam waist and $\lambda$ is the wavelength of radiation [5]. $w_0$ is typically equal to the beam radius at the emission facet of the source, that is, the radius of the radiation source. The intensity profile of the beam at a cross-sectional plane is defined by the following Gaussian function as

$$I(r) = I_0 e^{-2r^2/w^2}$$

(2)

where $I_0$ is the intensity of beam at the center, $r$ is the radial distance from the beam center and $w = w(z)$. So the (full width at half maximum) FWHM radius can be calculated by finding the radius at which the exponential factor in (2) drops to one half. The divergence angle ($\theta$) of a beam can be defined as FWHM radius divided by $z$,

$$\theta = \frac{FWHM/2}{z} = 0.58 \times \frac{\lambda}{\pi w_0} \times (rad) = 33.7 \times \frac{\lambda}{\pi w_0} \times (^{\circ})$$

(3)

Equation (3) can be used to estimate the beam profile of the THz emission of QCL devices. For example, the QCL device, shown in Figure 2 has a cross-sectional size of $10 \times 100 \mu m^2$, emitting at $\lambda = 88.6 \mu m$, the divergence angles are calculated to be 19 (in-plane direction) and 190.1 (elevation direction) degrees (!). The calculated divergence angle in the elevation direction is over 180 degrees, which indicates the beam is so diffractive in the elevation direction and the Gaussian beam model may not be a good approximation any more.

Figure 4 shows the beam pattern measurement results for the 100 $\mu$m wide QCL, in both in-plane (theta) and elevation (phi) directions. The beam pattern in the in-plane direction exhibits multiple peaks besides the main peak at zero degree. It shows that the beam pattern can not be approximated by a single-mode Gaussian profile. Nevertheless, the FWHM of the main peak is measured to be 18 degree, agreeing well with the calculated result from Gaussian model approximation. In the elevation direction the beam patterns are much more complicated, which is due to strong beam diffraction. Because of omnidirectional radiation from both front and rear facets of the device, the fringes observed in Figure 4(b) are constructed by interference of coherent radiation from the front and rear facets, and hence spread over a wide angular range.

A radio-frequency (RF) design simulator (HFSS), from Ansoft, was deployed to simulate far-field beam pattern of the QCL devices. A QCL ridge with a metal-metal waveguide, as depicted in Figure 1(a), is simulated using the simulator. In the simulation model, a semi-insulating GaAs layer is used as the active region of the device, which is quite good approximation due to similar electric permittivity of GaAs and Al$_{0.15}$Ga$_{0.85}$As. The active region is sandwiched between two 1 $\mu$m gold layers with the bulk conductivity of 41 MS/m. Due to absence of a gain medium in the simulated structure; the active region is excited by an electromagnetic (EM) wave with a suitable frequency.

The simulation results of the far field pattern of a QCL with a 100 $\mu$m wide ridge are shown in the Figure 4 (upper curves). The simulation results shows a central peak with a quasi-Gaussian beam profile that has a FWHM of 16 degree along the in-plane direction, which is in good agreement with both the measured value (18 degree) and the calculated value from Gaussian beam approximation (19 degree). The simulated beam fringes in both in-plane and elevation directions match with measurement results within an angular range of $-30$ to 30 degree. Beyond this angular range the THz emission beam of the device might be blocked/deflected by the cryostat window, leading to discrepancies between the experimental data and the simulation results. The non-symmetrical shape of the in-plane profile at $\pm 25$ degree (Figure 4(a)) can be attributed to the asymmetrical device configuration — the air-bridges are only on one side of the ridge (Figure 1), which may influence the beam emission on that side. Discrepancy between the experimental and simulation results is also observed for the portion below the laser/package interface plane (negative Phi angles), where some peaks are missing in the measurement results. This could be attributed to the presence...
of the metallic package underneath of the QCL devices that may strongly alter the radiation patterns at negative angles in the elevation direction. In the positive elevation direction (the portion above the laser/package interface plane), simulated far-field pattern shows fairly good consistence with the experimental data. The agreement between RF calculations and the measurement results suggests that an EM model based on Maxwell’s equations predicts behavior of THz QCL beam more accurately than the simple Gaussian beam approximation approach does.

![Figure 4](image)

Figure 4: THz QCL beam pattern measurement and simulation results for 100 µm wide and 1 mm long ridge, (a) In-plane angle, Theta; (b) elevation angle, Phi.

4. CONCLUSIONS

The laser beam pattern of the THz QCL devices was investigated experimentally and theoretically. Both the measurement data and the simulation results show strong diffraction-like profiles of the far-field pattern because of the sub-wavelength dimensions of the laser structure. Along the in-plane direction, a central peak with a quasi-Gaussian profile is observed. The diffraction behavior of the beam pattern is more significant in the elevation direction, which could be attributed to the interference of coherent radiation from both facets of the device. The experimental results are in fairly good agreement with simulation results.

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REFERENCES