Frequency tuning of THz bound-to-continuum QCLs

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***Abstract*—A novel mechanism is presented for tuning the emission frequency of a THz bound-to-continuum Quantum Cascade Laser (QCL) through the application of a uniform thickness transformation applied to an existing laser design. Experimental results from a total of ten wafers are presented demonstrating a predictable shift in the emission wavelength. Wafers based on a design around 2.9 THz produced a frequency shift of 0.35 THz.**

I. INTRODUCTION

Terahertz quantum cascade lasers (QCLs) [1] operate on an intersubband transition allowing the energy of the transition to be engineered over a range of frequencies, presently from 4.8 THz [2] to 1.6 THz [3]. This ability to control the frequency of the QCL coupled with high output powers and narrow line width makes THz QCLs highly suited to heterodyne spectroscopy applications [4], of particular importance in the THz region where many molecules and compounds have distinct absorption lines [5] and there is a lack of compact high-power sources.

For such applications where a specific frequency is required it is desirable to have a method to alter the emission frequency of a QCL to match that of the application. Small shifts in emission frequency can be achieved with the distributed feed back (DFB) technique already demonstrated with terahertz QCLs [6], [7]. The range of this technique however is limited by the width of the gain curve.

An alternative approach is to modify the gain curve by changing the design of the structure. The design of a THz QCL for a specific frequency however is not trivial and it would be convenient to adjust a known design in a simple and predictable way rather than re-start the design process. Here we present a method to achieve this by adjusting each well and barrier by the same fractional amount, causing a change in the period length of a bound-to-continuum THz QCL resulting in a predicable shift in the emission frequency. The range over which we tune the frequency highlights the robustness of the bound-to-continuum design. The effect of this technique on other design types, such as phonon depopulation designs [8], should be a matter for further investigation.

II. EXPERIMENTAL

All wafers were grown on a Veeco ModGen II molecular beam epitaxy (MBE) reactor on semi-insulating GaAs substrates. The period length of each wafer was determined by high resolution X-ray diffraction, as shown in the inset to figure 1. The spacing of satellite peaks around the [004] lattice reflection was used to determine the period length in each structure [9] with an accuracy of 0.5%. The wafers were processed into $250\,\mu\mathrm{m}$ wide, 3mm long single plasmon waveguides, the method is described in ref. [10]. For the measurement devices were mounted in a helium flow cryostat. Electrical measurements were made in three terminal configuration, making use of the two bottom contacts to remove the voltage contribution of the highly doped n^+ channel. Spectra from the devices were taken using a Bruker IFS66v/S FTIR spectrometer with 7.5 GHz resolution.

III. SIMULATIONS

In the following simulations the QCL alignment condition was taken as the field at which the anti-crossing between the upper and injector states occurs as this resonance characterizes a maxima in conduction. As noted in [10] our lasers exhibit negligible frequency shifts with field suggesting that below full alignment there are two field domains present[1]. It is the aligned domain that we are identifying by using this simulation method.

Each structure is generated from the original design by all layers being multiplied by a constant to thicken or thin the structure. The modified structure is modelled self-consistantly at the alignment field to determine the emission frequency of the laser.

IV. 2.9 THZ LASERS

For this study we present eight wafers exhibiting period variation of a 2.9 THz [12] design. The period length of each sample was determined by high resolution X-ray diffraction. In Figure 1 we show results from the eight wafers and

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[1] Domain formation has been observed in GaAs/AlGaAs mid-IR QCLs [11].

simulations, all samples were taken from the center of the wafer. The simulation of the structures show a clear, near linear, trend suggesting that thicker structures emit at lower frequencies. There is very good agreement between data from wafers and simulations, the frequency of the wafers span a range of 0.35THz.

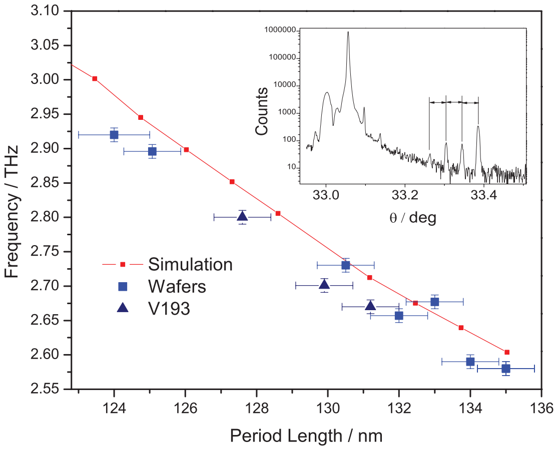

Fig. 1. The emission frequency of 10 devices taken from 8 wafers against period thickness. The connected (red) points is the prediction from simulations, square (blue) marks are wafers with the three devices from V193 marked as triangular points. The inset shows a typical X-ray rocking curve from a QCL wafer, the spacing of the satellite peaks is used to determine the period length.

Included with the eight wafers in figure 1 are three samples taken from a single wafer labelled V193, here we make use of the slight growth variations over a 3” wafer. The three samples were taken from the centre (c1), mid-way between centre and edge (c2) and from the edge (c3) of the wafer. Sample c1 had a mean period of 131.2 ± 0.8nm, c2 was 129.9 ± 0.8nm and c3 was 126.7 ± 0.8nm, showing that at the very edge of the wafer the structure becomes slightly thinner. The data from these samples fits well with that from the other wafers.

V. 2.0 THz LASERS

To investigate this frequency tuning method in another design two further wafers were grown. V305 was grown to a 2.0 THz recipe given in ref. [10] and V306 was grown with all wells and barriers reduced in thickness by 2.5%. The thicknesses were confirmed by high resolution X-ray diffraction measurements.

Spectra taken from the devices are show as an inset in figure 2. Laser spectra were taken at 10K to allow for temperature stability at high pump power. The emission frequency differs by 0.10 THz between the two structures in good agreement with a predicted shift of 0.15 THz.

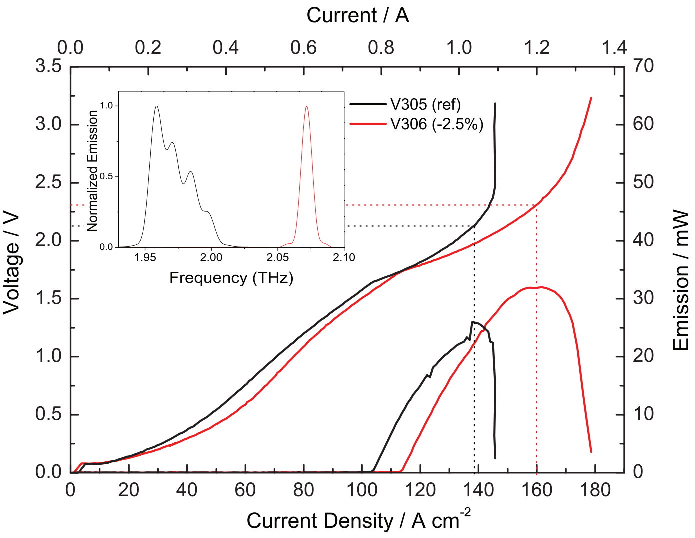

Fig. 2. The I-V and I-L plots for V305 and V306 at 4.4K are shown. The I-V of V306, the thinner structure, is characterized by a more conductive miniband, and larger dynamic range. The inset shows a spectral comparison of the two wafers near maximum power.

VI. CONCLUSIONS

Changing the period length of a THz bound-to-continuum quantum cascade laser can be used to controllably alter the emission frequency of a known active region. Data was presented from ten wafers demonstrating how this technique has been used to tune the emission frequency of two separate bound-to-continuum designs operating around 2.0 THz and 2.9 THz. In the case of our 2.9 THz design we tuned emission over a range of 0.35 THz.

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