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Tub4.4 - LASER LEVEL SELECTION IN TERAHERTZ QUANTUM CASCADE LASERS

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Laser Level Selection in Terahertz Quantum Cascade Lasers

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***Abstract*—The active region of a terahertz quantum cascade laser with two optical transitions is studied. The population of upper laser states, which correspond to 3.4 and 3.8 THz, are investigated at different operating temperatures and in a strong magnetic field.**

***Index Terms*—quantum cascade laser, terahertz, intersubband transitions**

I. Introduction

Quantum cascade lasers (QCLs) are mid-infrared and terahertz unipolar semiconductor lasers where the optical transitions are designed through bandgap engineering [1], [2]. Terahertz QCL emission is energetically below the reststrahlen band (5–20 meV) and is the only solid state laser in this range of the chemical fingerprint region [3]. Currently, THz QCLs have achieved several milestones: lase in pulse mode operation up to 200 K [4], pulsed operation output power of 2.4 W [5], and octave spanning emission [6]. Detailed knowledge of the electronic states and the scattering mechanisms is required for designing high temperature operation, thermoelectric cooling, and broadband lasers active regions, desired for frequency combs [7] and ultra short pulse generation in QCLs [8]. Broadband active regions are created using heterogeneous active regions [9], two or more active regions grown epitaxially, which requires additional bias dependent design parameters.

THz QCLs are sensitive to design changes and thus ideal for studying intersubband (ISB) states and transitions [10]. Applied magnetic fields, parallel to the growth direction, allow the probing of ISB transitions and scattering mechanisms through the suppression of non-radiative relaxation channels. This control has resulted in reduced GaAs/AlGaAs THz QCL lasing threshold J_{th} [11] and increase the maximum operating temperature T_{max} to 225 K at 19.3 T [12]. Materials with a lower effective mass require a reduced magnetic field: 11 T for InGaAs/GaAsSb enables 190 K operation [13] and 12 T for InGaAs/InAlAs enables 195 K operation [14]. The interface roughness scattering, prevalent in the 1 monolayer thick barriers in the InAs/AlAsSb THz QCLs is suppressed above 4.4 T, which enables lasing at 5 K [15].

II. Experiment and Results

The active region studied was a high-temperature three-well GaAs/AlGaAs THz QCL with two upper laser levels. The design is identical to the GaAs/$Al_{0.21}$GaAs active region that reached a T_{max} of 196 K at a frequency of 3.8 THz [16]. The QCL is processed into a 2550 μm × 120 μm ridge with the metal-metal waveguide geometry with 15 μm Ni side absorbers added in the processing to suppress higher order lateral modes.

Figure 1(a) shows the band structure of the investigated structure at two lasing biases. The two upper laser levels are labeled $|4\rangle$ and $|3\rangle$, with the lower laser level labeled $|2\rangle$. Level $|1\rangle$ is the extractor level, coupled to the LO-phonon transition. The optical transitions $|3\rangle \rightarrow |2\rangle$ and $|4\rangle \rightarrow |2\rangle$ are labeled LT_{32} and LT_{42}. At 12.2 kV cm^{-1}, the LT_{42} transition around 3.8 THz has a larger matrix element and thus stronger emission than the LT_{32} transition, shown in figure 1(b). At 12.5 kV cm^{-1}, the LT_{42} and LT_{32} transitions have similar matrix elements and at higher biases the LT_{32} transition is stronger. Figure

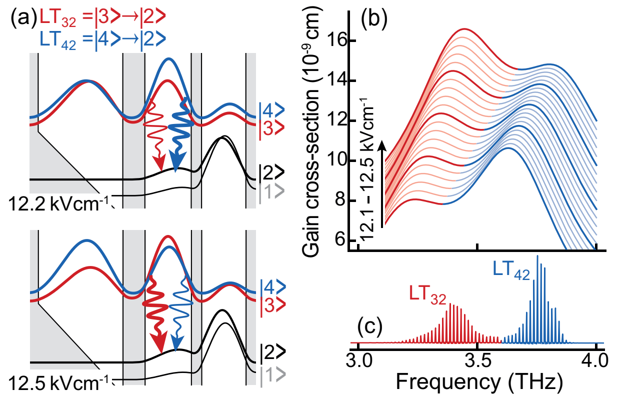

Fig. 1. (a) Active region at two different bias fields. The LT_{42} transition has a larger matrix element than LT_{32} at the lower bias, which changes at the higher bias. (b) Calculated spectra gain cross-section. (c) Emission spectrum at 5 K.

1(c) shows the simultaneous emission spectrum of the two transitions with similar integrated intensity. The emission intensity is dependent on the population of the two levels. This behavior agrees with the calculated band structure, but further studies are required to determine the interactions between the two upper levels, their population, injection, and scattering process.

The temperature dependent L-J-V device behavior is shown in figure 2(a). The lasing threshold J_{th} increases typically with the heat sink temperature, while the peak output power and dynamic range decrease. The figure 2(b) shows the emission spectra at 5, 80, and 140 K for different current densities. At all temperatures, the LT_{42} is the first emission, due to the greater dipole matrix element z_i. With increasing bias, the LT_{32} emerges at low temperatures, while it is largely suppressed at higher temperatures.

To determine whether the two laser states occur next to each other in the same active region or in neighboring periods, a magnetic field of $0{-}7.5$ T was applied to the QCL. Here, smaller laser ridges ($1900\,\mu$m $\times$ $90\,\mu$m, with $10\,\mu$m Ni side absorbers) were used. The threshold current density J_{th} decreases with increasing magnetic field, which is due to the reduction in the reduction in scattering processes. Above 6 T, the J_{th} increases again and the output power falls, due to continued suppressed scattering. Applying the magnetic field results in first the reduction in emission of LT_{32} and then at higher fields the emission of LT_{42}. The magnetic field is hindering the scattering from level $|4\rangle \rightarrow |3\rangle$. Due to the low energy separation between $|4\rangle$ and $|3\rangle$, this is an efficient scattering process without the magnetic field. The LT_{42} emission increases with the applied magnetic field up to 4.1 T, as the scattering to level $|3\rangle$ is suppressed.

III. Conclusions

The emission spectra for a 3-well terahertz QCL was studied with respect to the two upper laser states $|3\rangle$ and $|4\rangle$, LT_{32} 3.4 and LT_{42} 3.8 THz. The individual population and scattering effects for the states were investigated at different temperatures

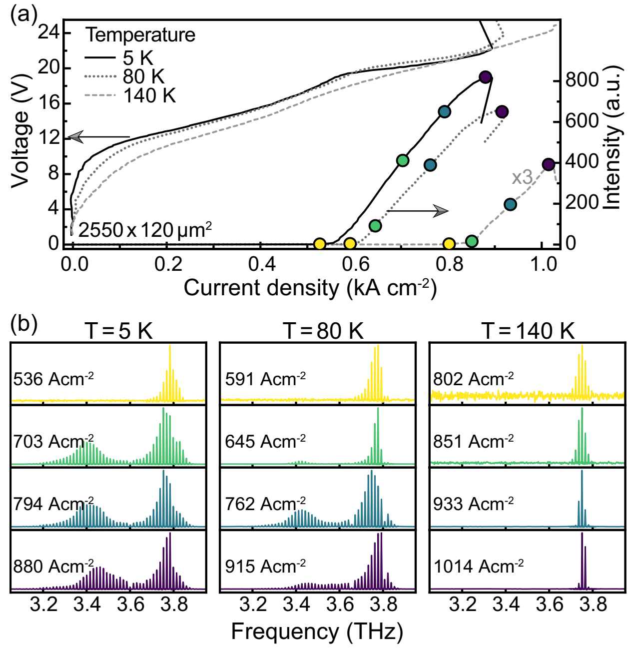

Fig. 2. (a) L-J-V measurement for 5, 80, 140 K. (b) Emission spectra at the different current densities for the corresponding temperatures.

and magnetic fields. At elevated temperatures, the upper laser state $|3\rangle$ is thermally depopulated, resulting in the reduction of the LT_{32} emission. In a magnetic field, the elastic scattering from $|4\rangle \rightarrow |3\rangle$ is suppressed, resulting in a stronger LT_{42} emission.

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