THz Quantum Cascade Sources based on Intra-cavity Frequency Mixing in Passive Nonlinear Sections

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Abstract—**We report terahertz quantum cascade laser sources based on intra-cavity difference-frequency generation in passive nonlinear sections. Current devices provide terahertz output up to a heat sink temperature of 210 K.**

I. Introduction And Background

THE terahertz (THz) spectral range (λ = 30-300 μm) still lacks a compact electrically pumped room temperature semiconductor source. Advances in THz quantum cascade lasers[1] (QCLs) have shown promise in elevating the operational temperature of these devices, but cryogenic cooling is still necessary for operation. THz QCL sources based on intracavity difference-frequency generation (DFG) in dual-wavelength mid-infrared (mid-IR) QCLs may present a viable alternative to THz QCLs for generating THz radiation at room temperature[2]. Devices in Ref. 2 utilized intersubband nonlinearity $\chi^{(2)}$ with population inversion, integrated with laser transitions. The value of $\chi^{(2)}$ in this approach is determined by the population inversion across the laser transition, which is clamped to values $\Delta N \approx 2\times10^{15}$ cm^{-3} at the laser threshold. Additionally, $\chi^{(2)}$ with population inversion will intrinsically have optical transitions at two laser frequencies. This leads to gain competition between two mid-infrared pumps and results in their operation in different TM waveguide modes, which reduces the DFG efficiency[3].

Here we present an alternative design of THz QCL sources based on DFG, using a passive nonlinear section at the exit facet, designed for giant second-order nonlinear susceptibility. The active region of such lasers may be designed to minimize gain competition between mid-IR pumps. Furthermore, the passive nonlinear section is expected to enforce operation of the pumps in the same waveguide mode through absorption saturation mechanism. Theoretical analysis shows that the new design of THz DFG QCL sources may lead to higher THz conversion efficiencies compared to that in devices based on $\chi^{(2)}$ with population inversion, while producing only minor additional losses to the pump lasers.

II. Results

Devices composed of lattice matched InGaAs/InAlAs were grown by molecular beam epitaxy on an InP substrate. A 500 nm thick nonlinear layer (NL) tailored to have resonant optical nonlinearity for DFG, associated with intersubband transitions, is grown on top of a QCL active region designed to emit at λ_1 = 8.4 μm and λ_2 = 9.5 μm. The NL sections were further patterned with 10μm-wide trenches every 50μm, to facilitate current transport to the active region below. We note that THz radiation generated more than a few hundred microns away from the exit facet is completely absorbed by free-carrier absorption in mid-IR QCLs. Tapering is introduced to improve THz radiation outcoupling[2].

The value of $\chi^{(2)}$ of this passive structure for THz DFG is estimated to be 1.08×10^6 pm/V. This leads to a theoretical conversion efficiency of $\eta = W_{THz}/W_1W_2 \approx 63$ μW/W^2, compared to 40 μW/W^2 for the active design in Ref. 2. If the passive design were to operate at the same wavelength (60 μm) as the active design, the conversion efficiency of this passive design would increase to ≈ 90 μW/W^2. Experimental results are presented in Fig. 1. The THz peak power output at 80K was measured to be approximately 100 nW, leading to an internal conversion efficiency of 0.8 μW/W^2. Absorption measurements of the nonlinear section indicate that intersubband transitions there are not in full-resonance with pump laser frequencies. Fully-optimized devices are expected to provide THz output closer to theoretical estimates.

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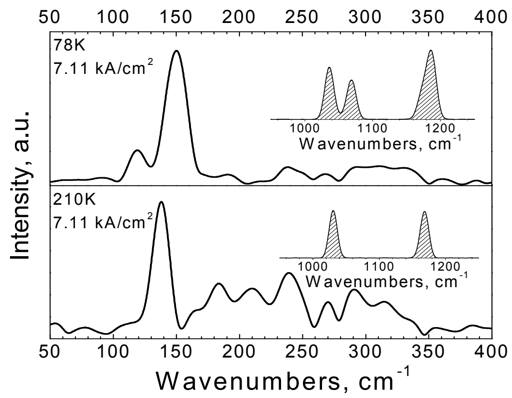

Figure 1. Terahertz spectra at both 78 K and 210 K of a device with high-reflectivity back facet coating and nonlinear section length of 175 μm. Emission centered at $\omega_3 \approx$ 4.2 THz. Inset shows the emission spectra for the mid-infrared pumps, $\lambda_1 \approx$ 8.4 μm and $\lambda_2 \approx$ 9.5 μm.

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