Efficient Terahertz-wave Generation in Mid-infrared Quantum-cascade Lasers with a Common Dual-upper-state Active Region

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***Abstract*— We report the performance of room temperature, single mode terahertz sources based on intracavity difference frequency generation in mid-infrared quantum cascade lasers with a common dual-upper-state (DAU) active region. As a result of designing of DAU active region for giant optical nonlinearity, the DAU devices with a dual-period buried distributed feedback grating operate in two single-mode mid-infrared wavelengths at 10.7 µm and 9.7 µm, and produce single-mode THz output at ~2.9 THz with a side mode suppression ratio of ~25 dB. A high mid-infrared to THz conversion efficiency of 0.8 mW/W^2 is obtained at room temperature.**

I. INTRODUCTION

THE 1-5 THz spectral range is very important for many applications, such as imaging, chem/bio sensing, heterodyne detection, and spectroscopy. However, this spectral range still lacks high performance compact semiconductor sources operable at room temperature. Recently, THz sources based on intracavity difference-frequency generation (DFG) [1] in dual-wavelength mid-infrared (mid-IR) quantum cascade lasers (QCLs) have been demonstrated. The performances of these devices have improved considerably [2-4] and they have recently achieved mW-level peak THz output power in pulsed mode and a few microwatt THz output in continuous-wave at room temperature [4]. In order to obtain higher THz power and higher mid-IR to THz conversion efficiency, improvements in the active region design are crucially important. Currently, two wavelength stacks of active regions were utilized for the THz DFG QCLs [1-4]. Here, we present a THz DFG-QCL with identical dual upper-state active regions. Our proof-of-concept devices demonstrate single-mode THz emission with high mid-IR and THz conversion efficiency of 0.8 mW/W^2 at room temperature.

II. DESIGN OF ACTIVE REGION

For efficient THz generation, the following criteria for a gain medium should be, in general, satisfied: (1) large dipole matrix elements associated with transitions involved in generation of intersubband nonlinear susceptibility $\chi^{(2)}$, (2) large population inversion, and (3) broad gain spectrum. In the active region with single upper laser state [1-4], optical nonlinearity for DFG is created by designing anticrossing between the lower laser states in miniband, resulting in one set of three subband states that produce giant $\chi^{(2)}$ for DFG. On the other hand, in the dual-upper-state active regions [5], several triplets of states contribute to resonant $\chi^{(2)}$ for DFG as shown in Fig. 1. As a result, an efficient THz conversion through DFG process is expected to be achieved in the DAU QCLs. The waveguide core in our proof-of-concept devices consists of DAU active region designed for emission around 10 µm [6], which are also designed to have large nonlinearity $|\chi^{(2)}|$ for DFG. Assuming the parameters described in Ref. [2], we obtain $|\chi^{(2)}|$~23 nm/V at the designed electric field, which is higher than the average value for the dual-stack bound-to-continuum type active region. In addition, in order to obtain high mid-IR laser performance the wavefunction of state 4 is engineered to be highly diagonal for both active regions.

All the layer structures were grown on an undoped InP substrate by metal organic vapor phase epitaxy technique. The growth starts with a 400 nm thick InGaAs current spreading layer (Si, 1.5×10^{18} cm^{-3}) and a 5.0 µm thick n-InP (Si, 1.5×10^{16} cm^{-3}) is used as a lower cladding layer. The lattice matched InGaAs/InAlAs active regions with 50 cascade stages were used as the emitting region and sandwiched between a 0.25µm thick n-$In_{0.53}Ga_{0.47}As$ layer (Si, 5×10^{16} cm^{-3}) and a 0.45µm thick n-$In_{0.53}Ga_{0.47}As$ layer (Si, 5×10^{16} cm^{-3}). Two separate buried grating sections were defined for two wavelength emission [3] and etched 250 nm deep into upper n-$In_{0.53}Ga_{0.47}As$ guide layers. The upper cladding layer consists of a 5 µm thick n-InP (Si, 1.5×10^{16} cm^{-3}) followed by a 15 nm thick n$^+$- InP (Si, ~10^{18} cm^{-3}) cap layer. The waveguide was designed for efficient extraction of THz radiation via Cherenkov emission into the substrate [2, 3]. After the growth, the wafer was processed into ridge waveguide and front facet is polished into 20^o to facilitate the THz output.

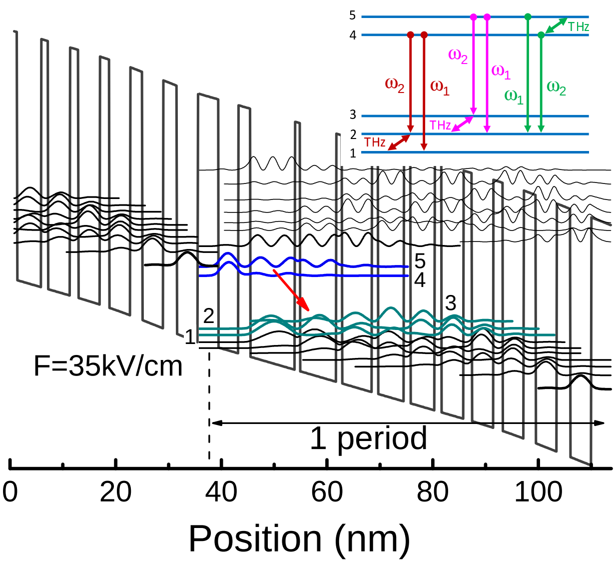

Fig. 1 Band diagram and moduli squared of the relevant wavefunctions for one period of active region biased at 35kV/cm. Schematic description of the DFG process is shown in inset.

III. Results

The pulsed current-light output (I-L) characteristics for mid-IR and THz signals for a 12 µm-wide, 3 mm-long device at room temperature are shown in Fig 2. The DFB laser exhibits a mid-IR peak power of ~400 mW and an approximately 20 µW of THz peak power at 2% duty cycle. Despite homogeneous active region structure, the laser operated two wavelength emission at λ_{long}=10.7 µm and λ_{short}=9.7 µm. Threshold current densities were observed to be 2.5 kA/cm^2 and 3.7 kA/cm^2 for λ_{long} and λ_{short} respectively. After the lasing at shorter wavelength λ_{short}, the output power at longer wavelength λ_{long} decreases with increasing the output power at λ_{short}, likely due to gain competition between the two pumps. The combined mid-IR power increases as a function of input current until the rollover point.

The THz power versus a product of the two mid-infrared pump powers at room temperature is shown in Fig 3. The mid-IR to THz power conversion efficiency is observed to be ~0.8 mW/W^2, which is highest in THz DFG-QCLs. As a comparison, figure 3 also shows a performance of a heterogeneous bound-to-continuum device with the same cladding structure. Obviously, the higher mid-IR to THz conversion efficiency is obtained for the DAU device. The high conversion efficiency of the DAU device is attributed to higher values of nonlinear susceptibility $\chi^{(2)}$, compared to that of heterogeneous-type devices. The conversion efficiency decreases as a function of temperature, possibly due to the increase in transition linewidth broadening factors and the corresponding reduction in the value of optical nonlinearity. The THz spectrum of the present device, shown in Fig. 3 inset, exhibits single-mode operation at 2.9 THz with a side mode suppression ratio of ~25 dB. The frequency of the single mode THz spectrum was in good agreement with the spacing of mid-IR pump spectra.

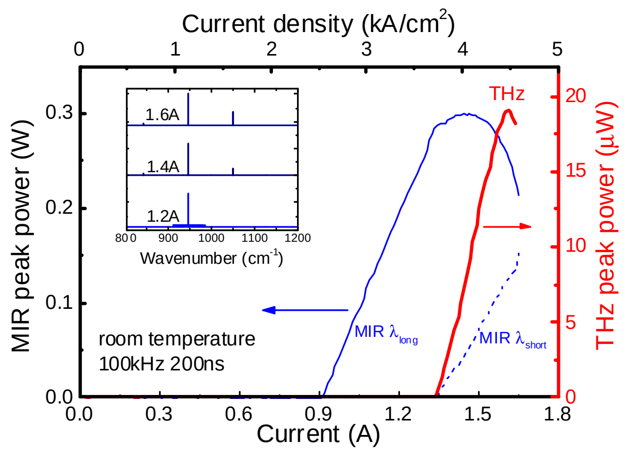

Fig. 2 Pulsed current-light output characteristics of a 3.0 mm-long, 12 µm wide buried hetero-structured device for THz peak power and the mid-IR pump power. Solid blue line is the emission centered at 940 cm^{-1} and dashed blue line is emission at 1040 cm^{-1}. The laser was operated at room temperature with 200 ns pulses at 100 kHz. Inset shows room temperature mid-IR emission spectra of the device, taken at various currents.

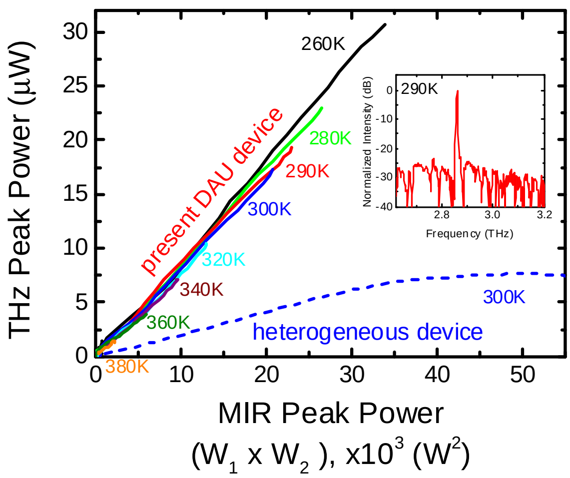

Fig. 3 THz peak power versus the product of mid-infrared pump powers, for various temperatures. The result of heterogeneous bound-to-continuum device at 300K is also shown as a comparison (dashed line). Inset shows room temperature THz emission spectrum.

IV. Conclusion

We discussed the performance of room temperature, single frequency terahertz quantum cascade laser sources based on the homogeneous DAU active region design. The devices provide THz output at 2.9 THz with a record-high mid-IR-to-THz conversion efficiency of 0.8 mW/W^2 at room temperature reported for THz DFG-QCLs with emission frequency below ~3 THz to date. The DAU active region design may offer advantages for intra-cavity terahertz generation in mid-IR QCLs over heterogeneous-type active region designs in terms of higher values of optical nonlinearity for THz DFG.

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