Development of Terahertz Sources Based on Intra-Cavity Difference-Frequency Generation in Quantum Cascade Lasers

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Abstract—**We report a demonstration of intra-cavity terahertz difference-frequency generation in a dual-wavelength mid-infrared quantum cascade laser with integrated giant optical nonlinearity. We will discuss the perspectives of this approach to produce a room temperature electrically pumped semiconductor source of terahertz radiation.**

The terahertz (THz) spectral range (λ=30-300µm) has long been devoid of compact electrically pumped room temperature semiconductor sources. Despite recent progress with terahertz quantum cascade lasers[1], existing devices still require cryogenic cooling. An alternative way to produce terahertz radiation at room temperature is difference-frequency generation (DFG) in a nonlinear optical crystal using infrared or visible pump lasers. Here we report a monolithically integrated dual-wavelength quantum cascade laser (QCL) with the active region engineered to possess giant second-order nonlinear susceptibility associated with intersubband transitions in coupled quantum wells. Our device produces THz radiation via intra-cavity DFG. Since mid-infrared QCLs have been shown to operate continuous-wave (CW) above room temperature, we believe that this approach can lead to a room temperature electrically pumped CW semiconductor THz source.

Our first proof-of-principle device is based on a heterostructure grown by the molecular beam epitaxy with an AlInAs/InGaAs material system lattice-matched to an InP substrate. The substrate is n-doped to 1.5×10^{17} cm^{-3}; the structure consists of 1.6 µm of InGaAs n-doped to 5×10^{16} cm^{-3}, followed by a 3.2 µm-thick active region, 1.5 µm of InGaAs n-doped to 5×10^{16} cm^{-3}, and 10 µm of InP n-doped to 10^{17} cm^{-3} (grown my MOVPE). Thick top waveguide cladding is used to make a dielectric waveguide for the THz wave. The active region contains of two sections: the top section is a 30-period structure based on bound-to-continuum design with integrated optical nonlinearity emitting at 8.7 µm and the bottom section is a 20-period structure based on two-phonon design emitting at 7.6 µm. We calculate that the main contribution to the optical nonlinearity for DFG comes from the triplet of states in the bound-to-continuum section shown in Fig. 1 and labeled "1", "3", and "4". We estimate the value of the nonlinear susceptibility for DFG process $\chi^{(2)}\approx4\times10^{5}$ pm/V. This very large value is typical for THz DFG processes in coupled quantum well systems[2].

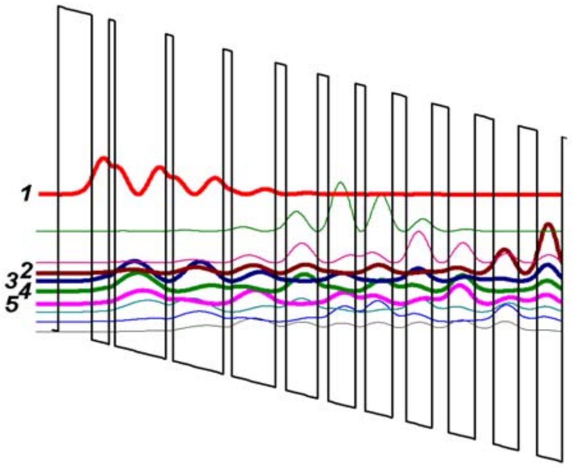

Fig. 1. Conduction band diagram of the bound-to-continuum section of the active region with integrated optical nonlinearity.

The devices were processed as deep-etched 20µm-wide 2mm-long ridge lasers; their back facet was coated with high-reflection coating. A typical mid-infrared emission spectrum from ridge waveguide devices is shown in the inset of Fig. 2 along with typical I-V and L-I characteristics. The devices operated in dual-wavelength mode up to 250K and still provided single wavelength emission ($\lambda\approx$7.6µm) at room temperature.

THz spectra from a representative device are shown in Fig. 3. The spectral position of the THz signal is in agreement with the difference of the frequencies of the mid-infrared pumps. The maximum DFG output power at 10K and 80K was comparable, and it was approximately a factor of 5 smaller at 150K, the maximum temperature at which DFG was observed. The decrease with temperature of the DFG signal can be attributed to the reduction of the mid-infrared pump powers with temperature. In particular, the product of the peak powers of the two mid-infrared pumps at 10K and 80K was

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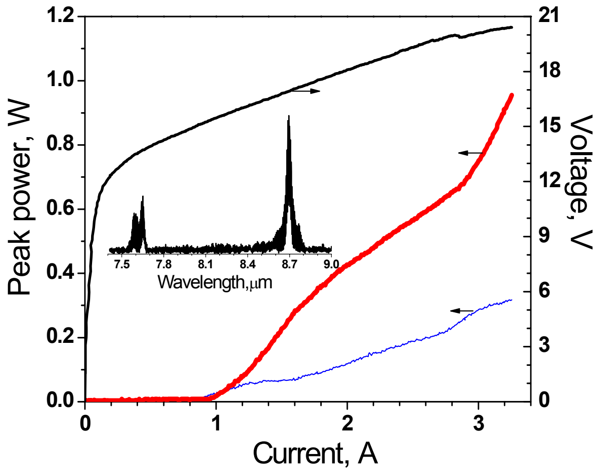

Fig. 2. L-I and I-V characteristics of a representative device obtained at T=10K. The peak powers of the 7.6μm (thin line) and 8.7μm (thick line) pumps are plotted. Inset shows the mid-infrared spectrum of the device operated in pulsed mode at high currents.

similar and that at 150K was smaller by approximately a factor of four. Figure 4 shows the dependence of the combined mid-infrared and THz DFG powers on the injection current and the dependence of the THz DFG power on the product of the mid-infrared pump powers. A linear dependence with the slope efficiency of 11 nW/W^2 is clearly seen. Overall, we have generated approximately 60nW of THz power, corrected for the estimated 10% collection efficiency, at T=80K.

We will also discuss our ongoing work improve the efficiency of THz DFG by achieving phase matching and employing surface emission schemes to extract THz radiation from the whole length of the device.

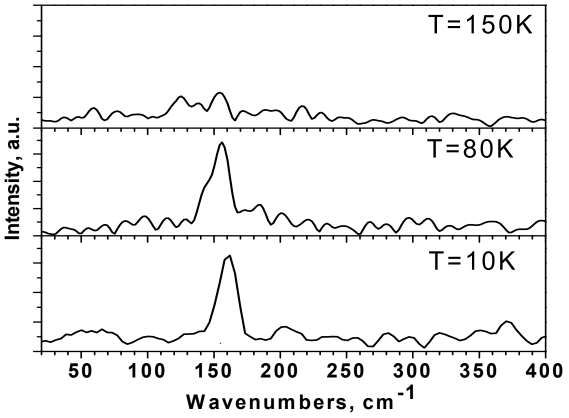

Fig. 3. Terahertz DFG emission spectra obtained at different temperatures.

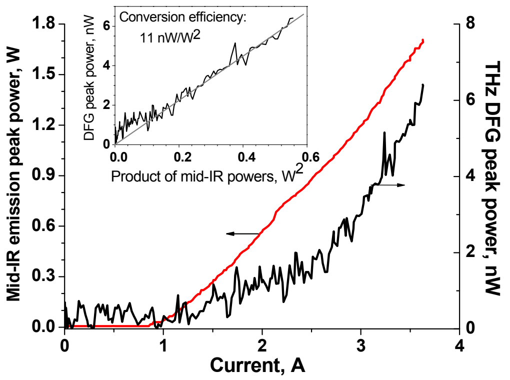

Fig. 4. L-I plots for THz DFG power and mid-infrared emission power for a representative device obtained at 10K. In the inset, DFG signal intensity is plotted versus the product of the two mid-infrared pump powers. The data is not corrected for collection efficiency of the setup.

REFERENCES

[1] Williams, B.S. *et al.* Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode. *Opt. Express* **13,** 3331-3339 (2005).

[2] Sirtori, C. *et al.* Far-infrared generation by doubly resonant difference frequency mixing in a coupled quantum well two-dimensional electron gas system. *Appl. Phys. Lett.* **65,** 445-447 (1994).