Stable Single Mode Terahertz Semiconductor Sources at Room Temperature

M. Razeghi[a]

[a]*Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, IL 60208, USA. razeghi@eecs.northwestern.edu*

Terahertz (THz) range is an area of the electromagnetic spectra which has lots of applications but it suffers from the lack of simple working devices which can emit THz radiation, such as the high performance mid-infrared (mid-IR) quantum cascade lasers (QCLs) [1] based on InP technology [2]. The applications for the THz can be found in astronomy and space research, biology imaging, security, industrial inspection, etc. Unlike THz QCLs based on the fundamental oscillators, which are limited to cryogenic operations, semiconductor THz sources based on nonlinear effects of mid-IR QCLs do not suffer from operating temperature limitations, because mid-IR QCLs can operate well above room temperature. THz sources based on difference frequency generation (DFG) utilize nonlinear properties of asymmetric quantum structures, such as QCL structures.

For a fixed second order power conversion efficiency, the output THz power increases quadratically with the increase of mid-IR power. Therefore, DFG based THz QCLs can benefit significantly from the recent dramatic power improvement of mid-IR QCLs. Shown in Fig. 1 (a) is the power performance of a broad area QCL emitting around 4.4 – 4.5 μm. The device operates at room temperature in pulsed mode with a pulse width of 200 ns and a duty cycle of 0.2%. The peak output power reaches 120 W. If this mid-IR power level can be realized with a DFG device, the THz power output is expected to be enhanced by four orders of magnitude compared to a watt level mid-IR source. This means milliwatt terahertz power is well within reach with a DFG approach in QCLs, at least in room temperature pulsed mode operation. As for room temperature continuous wave (cw) operation, the highest achieved output power is 5.1 W at a wavelength around 4.9 μm (Fig. 1(b)). Although this is much lower than the pulsed mode operation, it is still possible to achieve cw THz power in μW level. As continuous effort is put in improving the mid-IR power level, we are expecting a better situation for the THz emission in both pulsed and cw operations.

Another concern with the nonlinear approach is the linewidth of the THz emission. The conventional implementation of DFG in QCL with a Fabry-Perot (FP) cavity does not have spectrum control. Because the mid-IR pump sources are multimode, the frequency difference in THz is also multimode with a typical linewidth about 1 THz. In order to obtain spectrum purification in the pumping sources, we have designed a dual-period DFB grating and demonstrated the feasibility to obtain single mode operation for both mid-IR and THz frequencies. In this work, double exposure holographic lithography (HL) was used to define the dual-period DFB grating on top of the contact layer. Fig. 2 shows the measured mid-IR and THz spectra for such a DFB device at room temperature. Single mode emission around 4 THz is obtained (Fig. 2(b)) due to single mode operation of the two pumping sources shown in Fig. 2(a). In contrast, the FP device emits a broad-band multi-wavelength THz spectrum due to the multimode operation of the mid-IR sources. The linewidth of the THz signal from the DFB device is 6.6 GHz, which is mainly limited by the resolution 3.75 GHz (0.125 cm^{-1}) of the spectrometer. The wavelength is nearly constant at different currents, with a significantly smaller current-tuning coefficient of 1.5 GHz/A compared to the mid-IR pumping signals (11.4 GHz/A). This is expected because the wavelength tuning for DFB lasers is determined by the change of the refractive index as a function of temperature. Since the two mid-IR wavelengths are so close to each other, their refractive indices change at a similar rate as a function of temperature. As result, the THz difference frequency signal has about one order of magnitude smaller tuning rate than the corresponding mid-IR signals.

Fig. 3 shows the mid-IR and THz power performances at room temperature. The maximum mid-IR peak power of the DFB device is around 1.2 W and 0.8 W for the two wavelengths. A maximum THz peak power of 8.5 μW is obtained. The THz power conversion efficiency is about 10 μW/W2 for all working currents.

In conclusion, we demonstrate room temperature THz emission at 4 THz from dual-period DFB QCLs based on intracavity DFG. Stable single mode operation is obtained with a high power output of 8.5 μW and a power conversion efficiency of 10 μW/W2.

References

[1] M. Razeghi, "High-performance InP-based mid-IR quantum cascade lasers," *IEEE J. Sel. Top. Quantum Electron.*, vol. 15, pp. 941-951, 2009.

[2] M. Razeghi, *The MOCVD Challenge: A survey of GaInAsP-InP and GaInAsP-GaAs for photonic and electronic device applications*, Second Edition, Taylor and Francis/CRC Press, 2010.

[3] Q. Y. Lu, N. Bandyopadhyay, S. Slivken, Y. Bai, and M. Razeghi, "Room temperature single-mode terahertz sources based on intracavity difference-frequency generation in quantum cascade lasers," *Appl. Phys. Lett.*, vol. 99, pp. 131106, 2011.

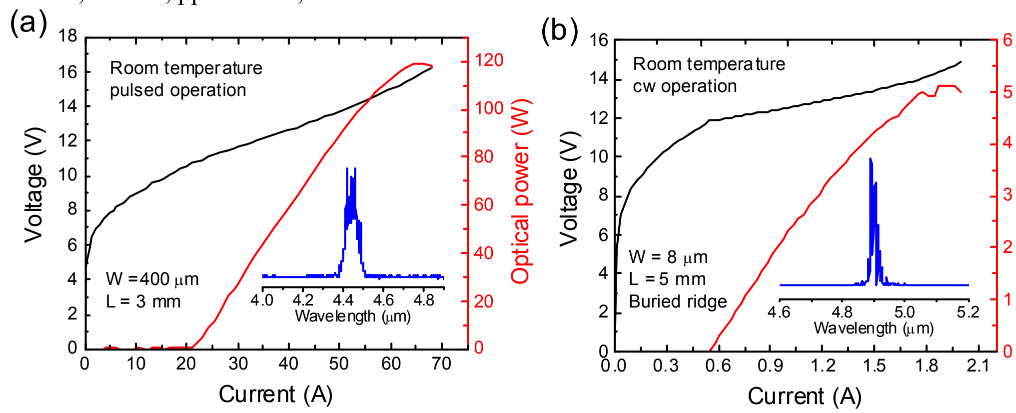

Fig. 1 (a) Room temperature pulsed mode operation of a mid-IR QCL and (b) room temperature cw operation of a buried ridge mid-IR QCL. The insets are the lasing spectra measured close to the threshold.

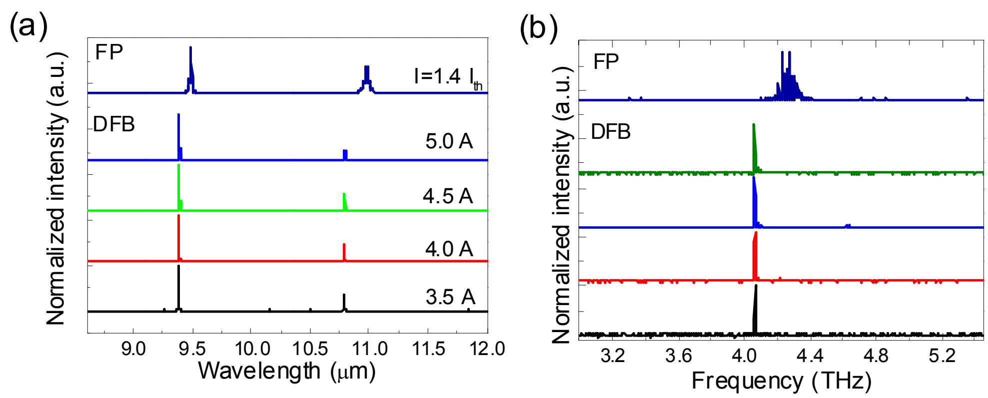

Fig. 2 Room temperature mid-IR (a) and THz (b) spectra at different currents for the dual-period DFB device and its FP counterpart. I_{th} is the threshold current of the FP device.

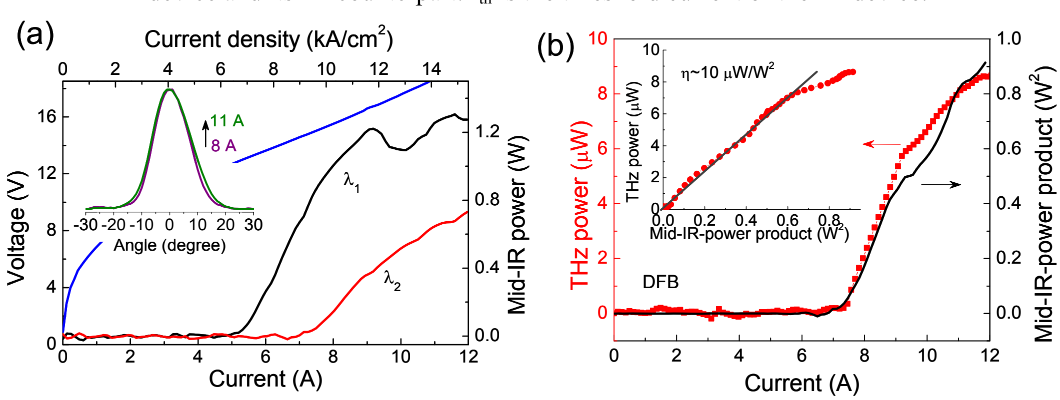

Fig. 3 Room temperature mid-IR (a) and THz (b) power performances for the dual-period DFB device. The inset of (a) is the total-power far fields for the two mid-IR wavelengths. The inset of (b) shows the mid-IR-to-THz power conversion efficiency.