Use of 2.7-THz Quantum Cascade Laser and Microbolometer Camera for Imaging of Concealed Objects

Barry N. Behnken and Gamani Karunasiri
Department of Physics, Naval Postgraduate School, Monterey, CA, USA

Danielle Chamberlin and Peter Robrish
Agilent Laboratories, Santa Clara, CA, USA

Jérôme Faist
Institute of Physics, University of Neuchâtel, Neuchâtel, Switzerland

Imaging in the terahertz regime (0.3-10 THz) is currently conducted primarily through the use of antenna-coupled semiconductor detectors or superconducting bolometers. These detection schemes are often bulky and unable to support real-time imaging due to their dependence upon complex scanning mechanisms. For imaging applications it is desirable to employ focal plane arrays (FPAs) which leads to more compact systems. Microbolometer FPAs, which produce images based on temperature change due to infrared absorption, have a broad wavelength response and, unlike photon-based FPAs, can be operated at room temperature. While advances in microbolometer technology allow real-time imaging in the 7-13 μm wavelength range with high sensitivity, the ability to detect THz radiation with such devices is relatively unknown. In this poster, we present the successful imaging of various objects using a 2.7 THz (110 μm) quantum cascade laser source and optically modified microbolometer camera.

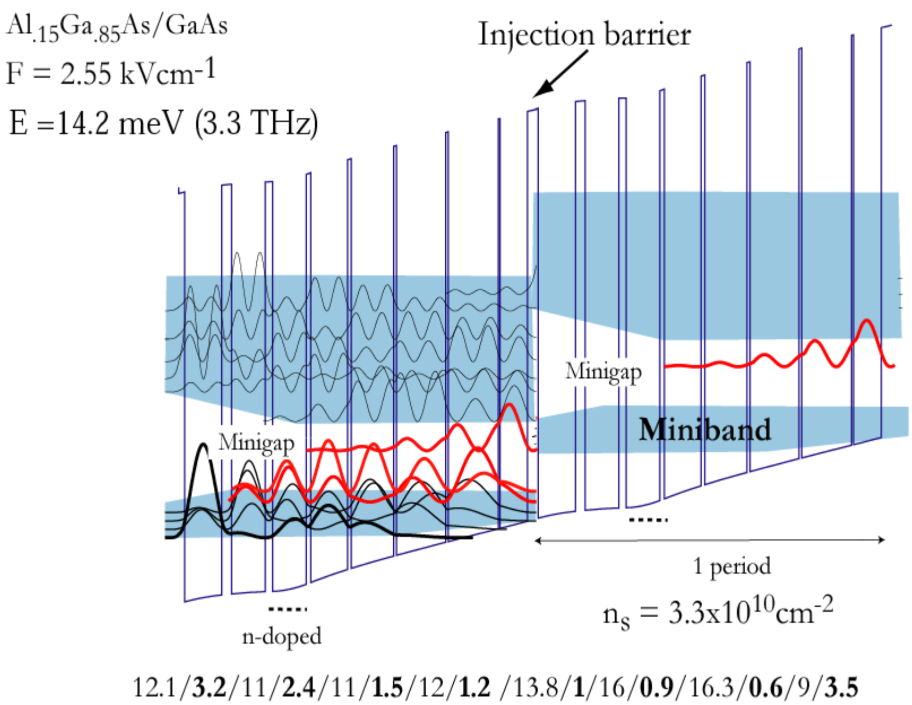
Introduction

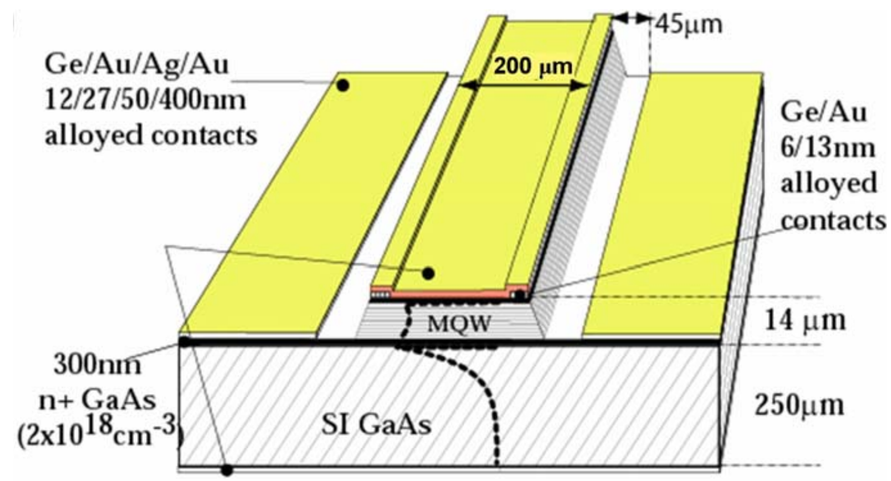
Due to its unique spectral characteristics, radiation in the 0.3-10 THz spectral range has gained recent popularity as a new and potentially powerful medium for next-generation imaging technology. Equipped with a proper illuminating source and sensor, THz imaging systems are capable of stand-off imaging of concealed objects and of human body tissue—particularly cancerous growths, which can elude x-ray based imaging detection. Such detection agility is due to the fact that THz wavelengths are short enough to provide sub-millimeter resolution capability, but are also long enough to penetrate non-metallic materials. Additionally, many explosive materials absorb strongly in the THz frequency range—suggesting numerous applications in the stand-off spectroscopic analysis and identification of concealed explosives. Due to a dearth of THz-tuned sensors and sources, however, this frequency range has not been fully exploited to date. The use of uncooled microbolometer cameras for THz imaging using a quantum cascade laser (QCL) source has potential applications for real time security imaging in this frequency range.

Quantum Cascade Laser (QCL)

The QCL used in these experiments, fabricated via molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate, consists of a 14 μm thick multiple quantum well (MQW) active region comprised of 120 periods. To mitigate heating in the active region, the laser was nominally operated at a 200-300 kHz repetition rate and, depending upon the imaging scheme used, a duty cycle of 8-15%. The measured I-V characteristics of the laser showed that the impedance at lasing is about 3 Ω. Due to the high current and short pulse width required to drive the QCL, impedance matching to the 50 Ω pulse generator was accomplished by incorporating a step-down transformer into the electrical circuit.

QCL Power output: $$P = \frac{\mathbf{N}\,\eta\, h\,\nu\,(I - I_{th})}{2e}$$ N: # of periods

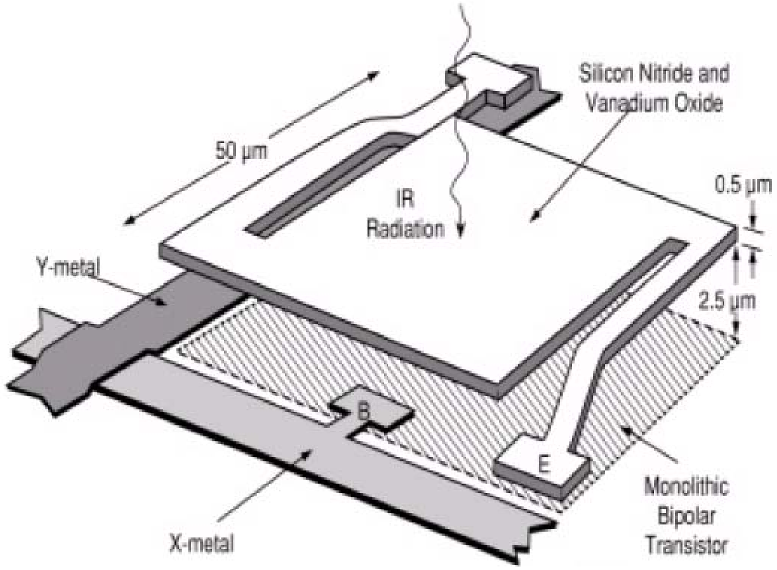




Microbolometer Detection System

The detection system is a commercially-available, uncooled 160x120 pixel microbolometer focal plane array camera (IR-160, Infrared Systems) designed for imaging in the 7-13 μm wavelength range. The pixels are constructed, using conventional MEMS techniques, of a composite film of vanadium oxide (VO_x) and silicon nitride (Si_3N_4) with dimensions 50x50 μm^2. The camera has a dynamic range of 66 dB, noise equivalent power (NEP) of approximately 10 pW/√Hz and noise equivalent temperature difference (NETD) of less than 100 mK with f/0.8 optics.

The Infrared Systems IR-160 microbolometer camera



Source: *Uncooled Infrared Imaging Arrays & Systems*, by Kruse & Skatrud

NETD Calculations

For the 1-5 THz range, $h\nu < kT$. Planck's radiation law can be approximately solved by using $\nu_{lo} \approx 0$ in the power integral.

$$P(T) = \int_{\nu_{lo}}^{\nu_{hi}} \frac{2\pi kT}{c^2} \nu^2 \, d\nu \approx \int_{0}^{\nu_{hi}} \frac{2\pi kT}{c^2} \nu^2 \, d\nu \approx \frac{2\pi kT}{3c^2} \nu_{hi}^3$$

ν_{lo}: 1 THz, ν_{hi}: 5 THz

F_{no}: f-number of the lens element

A: area of a single pixel of the FPA

ε_s, ε_t : emissivity of the source/target

L: spectral irradiance of the source

P(T): exitance of the target in 1-5 THz

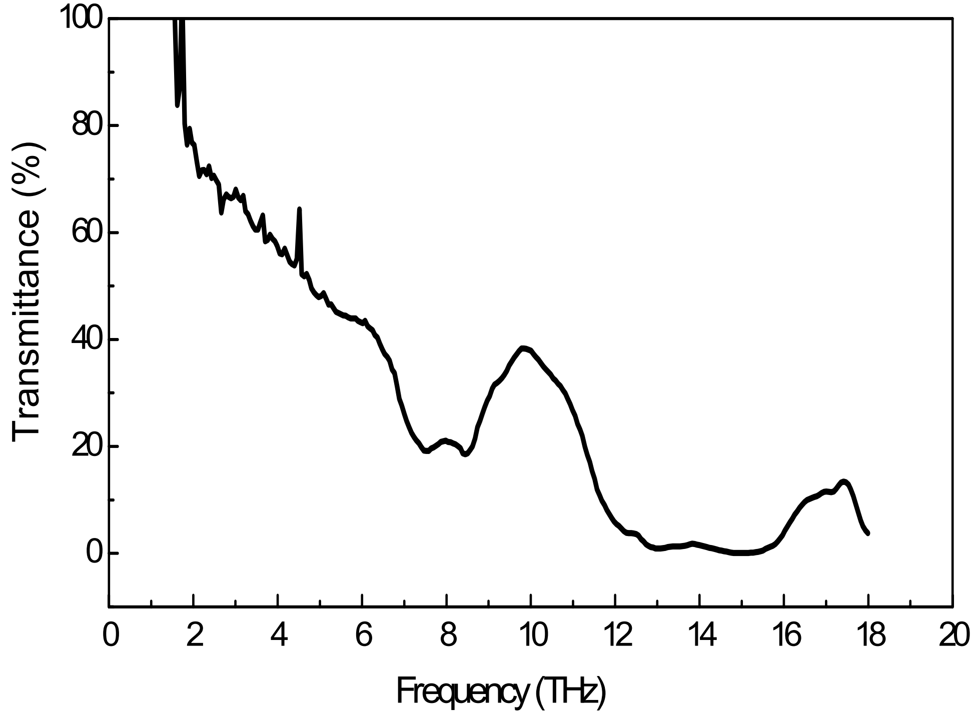
$$L = \frac{\varepsilon_t P(T)}{\pi}$$

$$\mathrm{NETD} = \frac{4F_{no}^2}{A\varepsilon\pi\left(dL/dT\right)}\mathrm{NEP} = \frac{6c^2 F_{no}^2}{A_{\mathrm{det}}\varepsilon\,\pi\,k\,\varepsilon_t \nu_{hi}^3}\mathrm{NEP} \approx 1.6\,\mathrm{K}$$

The total incident power density over the 1-5 THz region of approximately 12 W/m^2 at 300 K (compared with ~ 4,100 W/m^2 for the IR range of 8-12 μm).

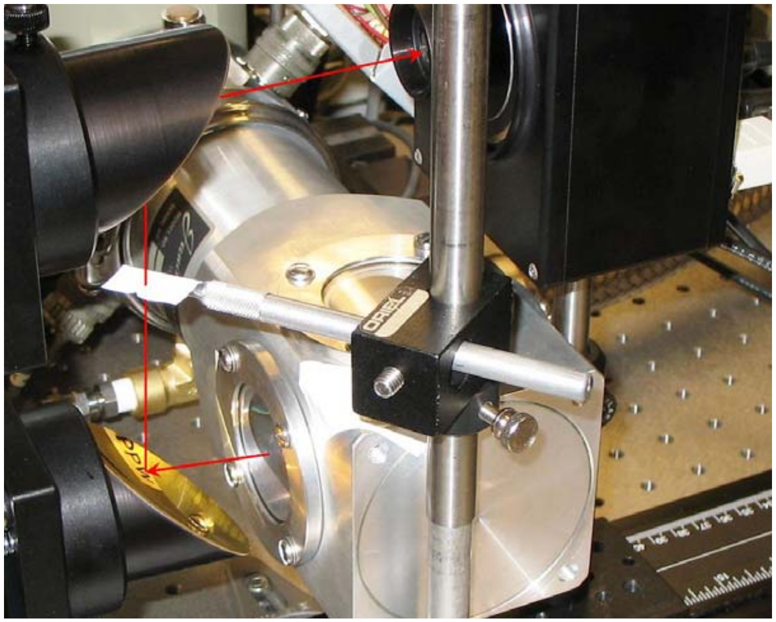
THz Optics

Due to the relatively long wavelengths involved, modifications to the camera's optics were necessary to maximize the amount of THz radiation received by the focal plane array. Initial measurements using the original germanium lens indicated that an applied anti-reflection coating heavily attenuated the incident THz beam. To correct this deficiency, the Ge lens was replaced with a 1-inch diameter, 20-mm focal length bi-convex lens made of picarin (PPL-1"-20mm-BC, Microtech Instruments). Picarin, which has a transmittance of approximately 65% for radiation oscillating at 2.7 THz, was also used as the source material for the window to the cryostat.

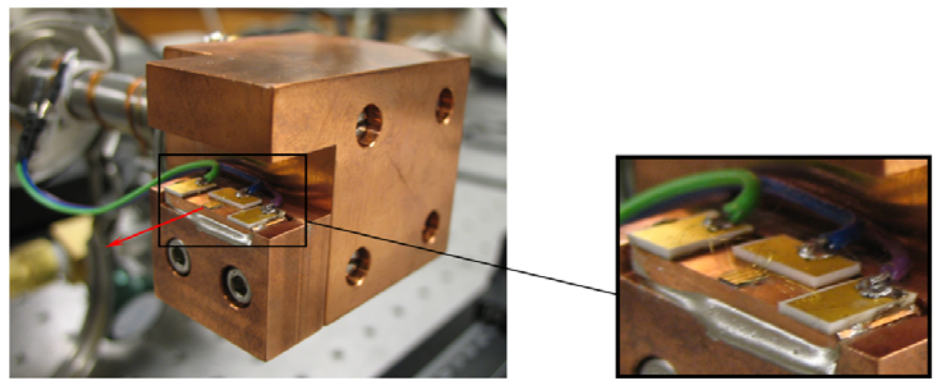


Measured transmittance of a picarin window as a function of THz frequency.

Optical Configuration

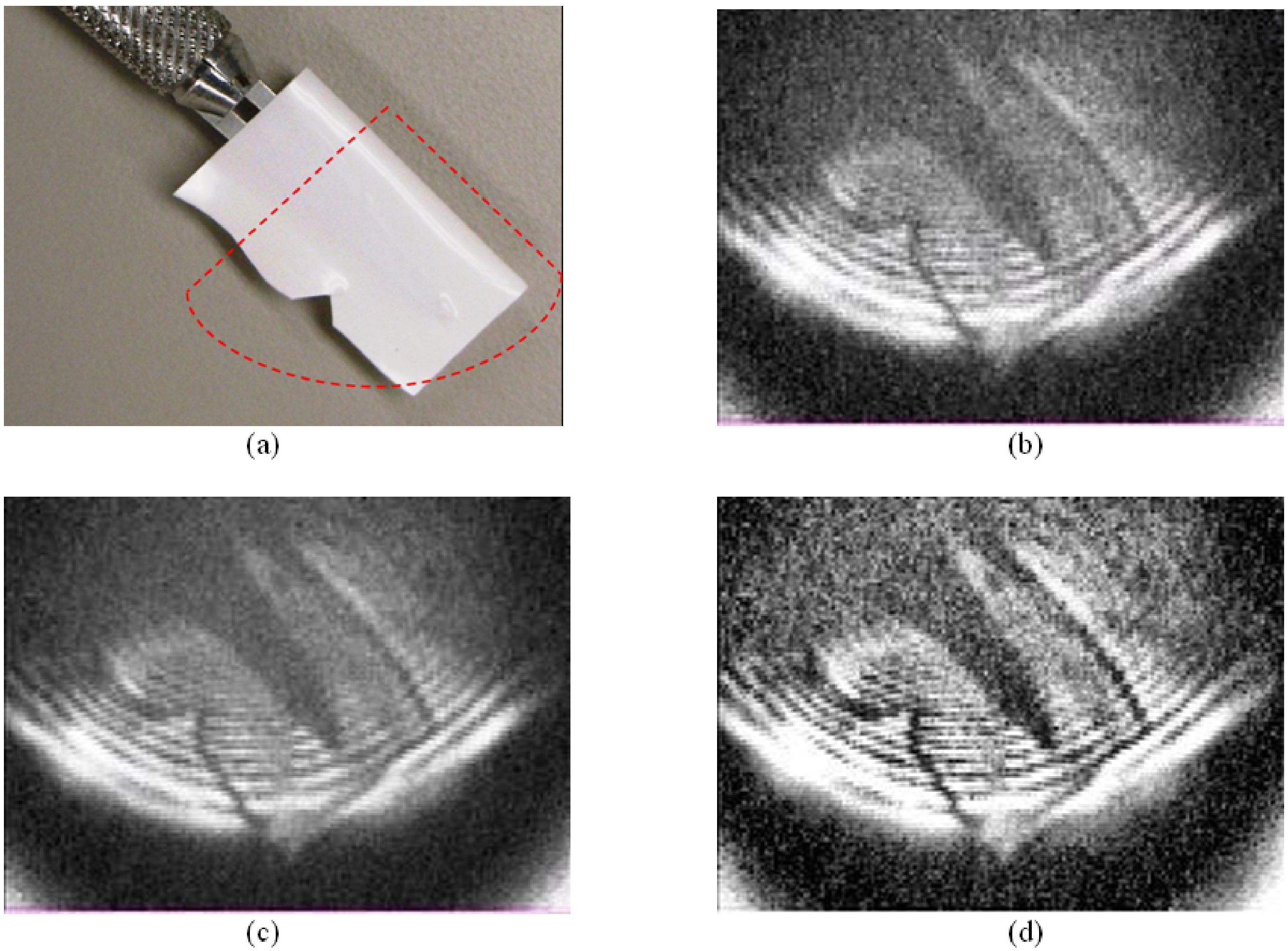


Optical configuration used for THz imaging. Lower and upper mirrors (50.8 mm and 101.6 mm focal length, respectively) are used to focus and steer the THz beam emerging from the picarin window of the cryostat to the focal plane array of the microbolometer.



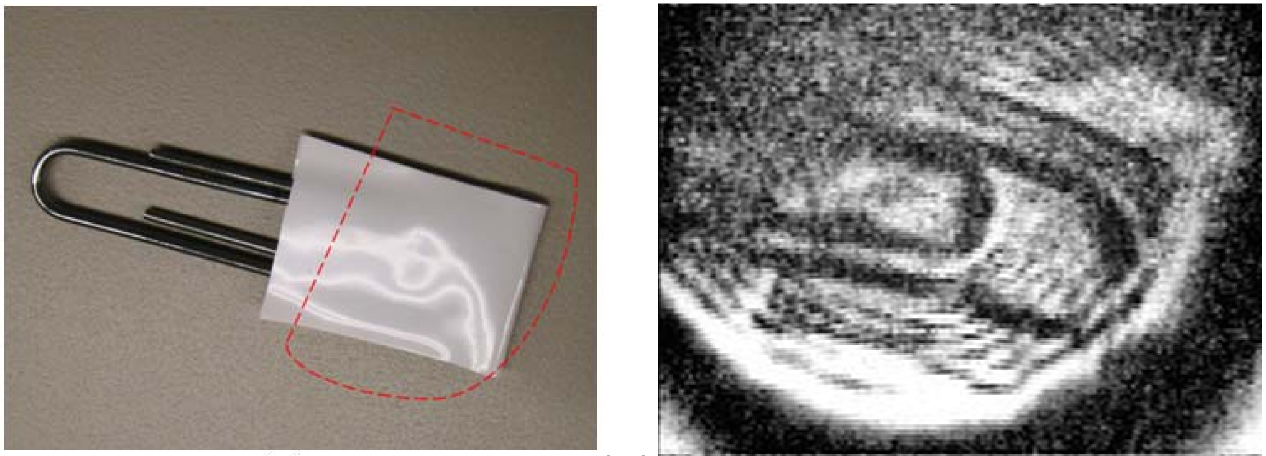
QCL assembly used within cryostat in present study (with external cold head housing removed). Laser element is affixed to a copper carrier to facilitate transfer of thermal energy away from the laser. When lasing, beam is emitted outward, from QCL edge, along direction of red arrow (inset).

Imaging Results

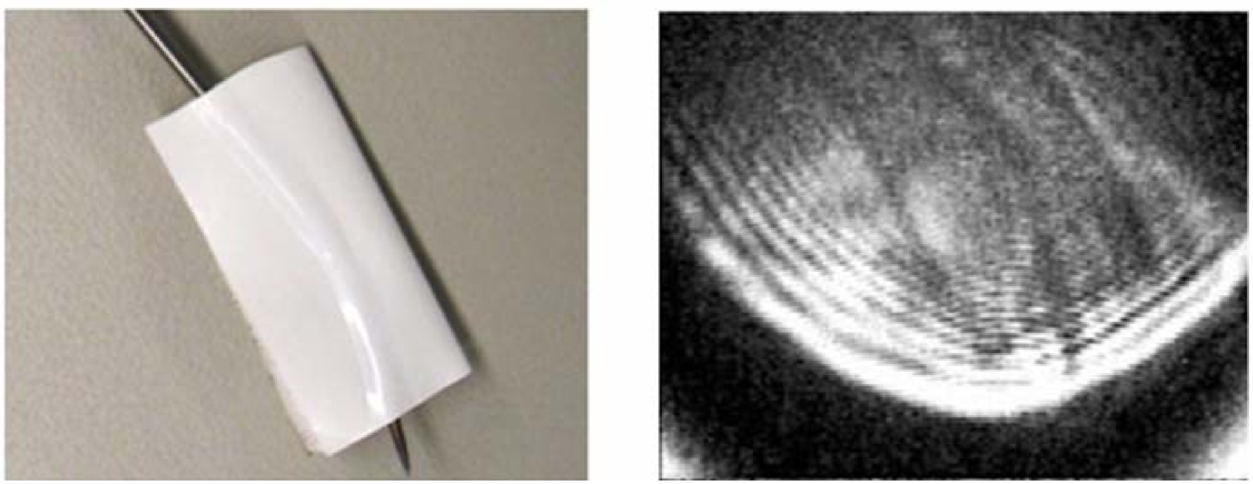


Imaging of a small utility knife blade wrapped in opaque plastic tape. (a) Conventional digital photograph. Red dotted region represents approximate area of illumination. (b) Single frame image of blade assembly illuminated with 2.7 THz QCL radiation and imaged with microbolometer camera. (c) Image generated by computationally averaging 50 individual frames. (d) Figure (c) refined using MATLAB image processing utility software.

Imaging Results (cont)



(a)



(b)

Imaging of metallic objects using QCL/microbolometer imaging scheme. Figures on left are digital photographs of objects wrapped in plastic tape; figures on right are 50-frame averages of THz images enhanced with MATLAB noise reduction algorithms. (a) Paper clip. (b) Dentist's pick.