

Active hyperspectral imaging using a quantum cascade laser (QCL) array and digital-pixel focal plane array (DFPA) camera

Anish Goyal,¹ Travis Myers,¹ Christine A. Wang,^{1,*} Michael Kelly,¹ Brian Tyrrell,¹
B. Gokden,² Antonio Sanchez,¹ George Turner,¹ and Federico Capasso²

¹MIT Lincoln Laboratory, 244 Wood St., Lexington, MA 02420, USA

²Harvard University, School of Engineering and Applied Sciences, 29 Oxford St., Cambridge, MA 02138, USA

*wang@LL.mit.edu

Abstract: We demonstrate active hyperspectral imaging using a quantum-cascade laser (QCL) array as the illumination source and a digital-pixel focal-plane-array (DFPA) camera as the receiver. The multi-wavelength QCL array used in this work comprises 15 individually addressable QCLs in which the beams from all lasers are spatially overlapped using wavelength beam combining (WBC). The DFPA camera was configured to integrate the laser light reflected from the sample and to perform on-chip subtraction of the passive thermal background. A 27-frame hyperspectral image was acquired of a liquid contaminant on a diffuse gold surface at a range of 5 meters. The measured spectral reflectance closely matches the calculated reflectance. Furthermore, the high-speed capabilities of the system were demonstrated by capturing differential reflectance images of sand and KClO₃ particles that were moving at speeds of up to 10 m/s.

©2014 Optical Society of America

OCIS codes: (110.4234) Multispectral and hyperspectral imaging; (140.3290) Laser arrays; (140.3298) Laser beam combining; (140.3600) Lasers, tunable.

References and links

1. M. Eismann, *Hyperspectral Remote Sensing* (SPIE, 2012).
2. A. K. Goyal, M. Spencer, M. Kelly, J. Costa, M. DiLiberto, E. Meyer, and T. Jeys, "Active infrared multispectral imaging of chemicals on surfaces," *Proc. SPIE* **8018**, 80180N (2011).
3. F. Fuchs, S. Hugger, M. Kinzer, R. Aidam, W. Bronner, R. Losch, Q. Yang, K. Degreif, and F. Schnurer, "Imaging standoff detection of explosives using widely tunable mid-infrared quantum cascade lasers," *Opt. Eng.* **49**(11), 111127 (2010).
4. M. C. Phillips and B. E. Bernacki, "Hyperspectral microscopy of explosives particles using an external cavity quantum cascade laser," *Opt. Eng.* **52**(6), 061302 (2013).
5. C. A. Kendziora, R. M. Jones, R. Furstenberg, M. Papantonakis, V. Nguyen, and R. A. McGill, "Infrared photothermal imaging for standoff detection applications," *Proc. SPIE* **8373**, 83732H (2012).
6. M. Diem, P. R. Griffiths, and J. M. Chalmers, eds., *Vibrational Spectroscopy for Medical Diagnosis* (Wiley, 2008).
7. K. Yeh, M. Schulmerich, and R. Bhargava, "Mid-infrared microspectroscopic imaging with a quantum cascade laser," *Proc. SPIE* **8726**, 87260E (2013).
8. A. Mukherjee, Q. Bylund, M. Prasanna, Y. Margalit, and T. Tihan, "Spectroscopic imaging of serum proteins using quantum cascade lasers," *J. Biomed. Opt.* **18**(3), 036011 (2013).
9. P. H. Ng, S. Walker, M. Tahtouh, and B. Reedy, "Detection of illicit substances in fingerprints by infrared spectral imaging," *Anal. Bioanal. Chem.* **394**(8), 2039–2048 (2009).
10. R. Bhargava, R. S. Perlman, D. C. Fernandez, I. W. Levin, and E. G. Bartick, "Non-invasive detection of superimposed latent fingerprints and inter-ridge trace evidence by infrared spectroscopic imaging," *Anal. Bioanal. Chem.* **394**(8), 2069–2075 (2009).
11. N. J. Crane, E. G. Bartick, R. S. Perlman, and S. Huffman, "Infrared spectroscopic imaging for noninvasive detection of latent fingerprints," *J. Forensic Sci.* **52**(1), 48–53 (2007).
12. F. Capasso, C. Gmachl, D. L. Sivco, and A. Y. Cho, "Quantum cascade lasers," *Phys. Today* **55**(5), 34 (2002).
13. Daylight Solutions, Inc., www.daylightsolutions.com; Block Engineering LLC, www.blockeng.com.
14. B. G. Lee, M. A. Belkin, C. Pflugl, L. Diehl, H. A. Zhang, R. M. Audet, J. MacArthur, D. P. Bour, S. W. Corzine, G. E. Huffler, and F. Capasso, "DFB quantum cascade laser arrays," *IEEE J. Quantum Electron.* **45**(5), 554–565 (2009).

15. P. Rauter, S. Menzel, A. K. Goyal, B. Gokden, C. A. Wang, A. Sanchez, G. W. Turner, and F. Capasso, "Master-oscillator power-amplifier quantum cascade laser array," *Appl. Phys. Lett.* **101**(26), 261117 (2012).
16. P. Rauter, S. Menzel, A. K. Goyal, C. A. Wang, A. Sanchez, G. W. Turner, and F. Capasso, "High-power arrays of quantum cascade laser master-oscillator power-amplifiers," *Opt. Express* **21**(4), 4518–4530 (2013).
17. P. Rauter, S. Menzel, B. Gokden, A. K. Goyal, C. A. Wang, A. Sanchez, G. Turner, and F. Capasso, "Single-mode tapered quantum cascade lasers," *Appl. Phys. Lett.* **102**, 181102 (2013).
18. B. G. Lee, J. Kinsky, A. K. Goyal, C. Pflügl, L. Diehl, M. A. Belkin, A. Sanchez, and F. A. Capasso, "Beam combining of quantum cascade laser arrays," *Opt. Express* **17**(18), 16216–16224 (2009).
19. A. K. Goyal, M. Spencer, O. Shatrovov, B. G. Lee, L. Diehl, C. Pfluegl, A. Sanchez, and F. Capasso, "Dispersion-compensated wavelength beam combining of quantum-cascade-laser arrays," *Opt. Express* **19**(27), 26725–26732 (2011).
20. M. Kelly, R. Berger, C. Colanero, M. Gregg, J. Model, D. Mooney, and E. Ringdahl, "Design and testing of an all-digital readout integrated circuit for infrared focal plane arrays," *Proc. SPIE* **5902**, 59020J (2005).
21. B. Tyrrell, R. Berger, C. Colanero, J. Costa, M. Kelly, E. Ringdahl, K. Schultz, and J. Wey, "Design approaches for digitally dominated active pixel sensors: Leveraging Moore's Law scaling in focal plane readout design," *Proc. SPIE* **6900**, 69000W (2008).

1. Introduction

Active hyperspectral imaging (A-HSI) is a method for the classification and mapping of materials based on their optical properties [1]. By the term "active", we mean that the scene of interest is actively illuminated (e.g., using a laser) rather than depending upon the ambient radiation. A-HSI in the mid-infrared (MIR) portion of the optical spectrum is of particular interest because the strong and unique absorption features associated with the roto-vibrational modes of molecules allows for chemical identification. MIR A-HSI has a wide range of applications including chemical agent detection [2], explosives detection [3–5], biomedical imaging [6–8], and forensics [9–11]. As compared to alternative detection methods, MIR A-HSI enables scanning with high-areal coverage rates and high sensitivity while the laser intensity at the target remains eye safe. A-HSI systems can be configured in a variety of ways. In this work, the scene is illuminated with a wavelength-tunable laser and an image of the scattered radiation is captured by a camera. The resulting hyperspectral image cube (HSI cube) comprises a sequence of frames, with each frame corresponding to an image of the scene at a different illumination wavelength.

Practical MIR A-HSI systems have been enabled by the development of quantum cascade lasers (QCLs) which are compact and efficient sources of tunable MIR radiation [12]. External-cavity (EC) QCLs are now commercially available to span the entire MIR and which can tune across $>100\text{ cm}^{-1}$ of optical bandwidth within 10's of milliseconds [13]. While this capability is impressive, some applications require even faster tuning. Therefore, we have been developing multi-wavelength QCL arrays [14–17] because of their advantages over EC-QCLs which include: (1) extremely high-speed electronic tuning, (2) higher average power by driving multiple lasers either simultaneously or in an interleaved fashion, and (3) compact and rugged designs with no moving parts. By applying wavelength beam combining (WBC) methods to QCL arrays, the beams from each laser in the array can be spatially overlapped to interrogate a common target [18, 19]. In this work, we use for the first time a WBC-QCL array as the illumination source in an A-HSI demonstration.

The camera incorporates a digital-pixel focal plane array (DFPA) imager in which an analog-to-digital converter (ADC) is associated with each pixel of the HgCdTe detector array [20, 21]. This circuit architecture allows for very fast frame readout to enable high-speed HSI. Also, the DFPA has features to mitigate the effect of the passive thermal background which are of critical importance in a practical MIR A-HSI system since the thermal background radiation is often larger than the active return. In particular, the DFPA has the ability to synchronously detect the laser return and also to perform *on-chip* subtraction of the passive thermal background as will be described. The same on-chip processing functions also enable on-chip spectral classification.

In the following sections, characteristics of the QCL array and the DFPA camera are first described. Then HSI cubes are captured of a contaminated surface at a range of 5 meters. Finally, the QCL array and DFPA camera are used to generate differential reflectance images within a measurement time of $4.1\text{ }\mu\text{s}$ per frame to distinguish between particles of sand and

KClO₃ in a sample that is moving at speeds of up to 10 m/s. To the best of our knowledge, this is the highest speed acquisition of a differential reflectance image and is enabled by combining the unique properties of the QCL array and DFPA camera.

2. Wavelength-beam-combined QCL array

The tapered QCL arrays used in this work were fabricated as described in detail previously [17]. Figure 1(a) shows a photomicrograph of the QCL array. The array includes 15 operational QCLs in which each QCL comprises a tapered gain section coupled to a straight distributed Bragg reflector (DBR) section. Both sections of each laser in the array are individually addressable. The 2-mm-long tapered-gain sections have a tapering half-angle of 1.3° and output aperture of 110 μm that narrows down to 13 μm at its interface with the DBR section. The 2-mm-long DBR section has a DBR period that varies from device-to-device along the array such that the Bragg wavelength varies linearly with position from $\lambda = 9.21$ to 9.78 μm ($\nu = 1086$ to 1022 cm^{-1}). In this work, the QCLs are operated as DBR tapered oscillators (DBR-TOs) by driving only the tapered section such that the laser cavity is formed between the DBR and the uncoated output facet. The DBR section is not driven when the device is lasing.

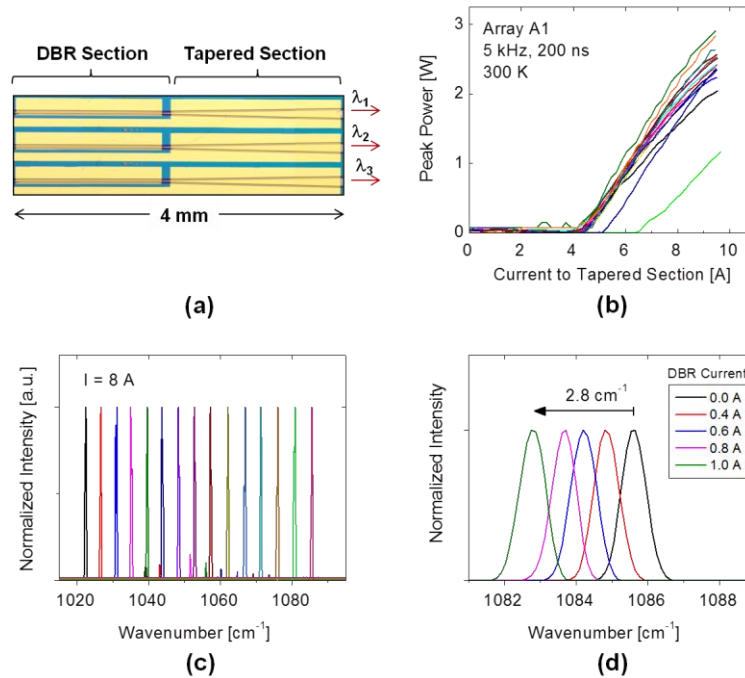


Fig. 1. (a) Photomicrograph of laser array. Each laser in the array is comprised of a DBR section coupled to a tapered section with each section being individually addressable. The tapered section is driven with a current pulse to achieve lasing while the DBR section remains unpumped. (b) Peak output power versus current for each of the 15 lasers in the array. (c) Normalized emission spectra for each laser in the array. (d) Demonstration of fine tuning of the wavelength by pre-biasing the DBR section. For these measurements, the spectrometer resolution is $\sim 0.5 \text{ cm}^{-1}$.

Figure 1(b) plots the output power versus current for the 15 lasers under pulsed conditions (200 ns, 5 kHz) at room temperature. All lasers achieve peak powers > 2 W except for laser #3 which reaches only 1.1 W. The output power is very uniform across the array as compared to QCL arrays based on distributed-feedback (DFB) lasers [14]. Figure 1(c) plots the normalized emission spectra for all lasers at a current of $I = 8$ A as measured using a Fourier-transform infrared (FTIR) spectrometer with 0.1 cm^{-1} resolution. The lasers were designed to be equally

spaced in wavelength and are measured to have a spacing of $\Delta\lambda = 40.6 \text{ nm}$ ($\Delta\nu \approx 4.5 \text{ cm}^{-1}$). The actual laser wavelength versus position deviates from a linear fit by less than $\pm 1.9 \text{ nm}$ ($\pm 0.2 \text{ cm}^{-1}$). The lasers typically operate on ~ 2 longitudinal modes separated by 0.4 cm^{-1} which corresponds to the longitudinal Fabry-Perot modes of the 4-mm-long devices. The full-width half-maximum (FWHM) spectral widths are $<0.6 \text{ cm}^{-1}$ for all devices. A spurious mode that may be associated with a higher-order lateral mode is observed 16 cm^{-1} on the high-frequency side of the primary lasing peak that has an intensity $>8 \text{ dB}$ below the primary peak. For the data presented later, the lasers were driven at an output power of only $\sim 300 \text{ mW}$ (average power of $\sim 0.3 \text{ mW}$) to avoid damaging the array. At these lower powers, the lasers often operated on a single longitudinal mode and the spurious mode is suppressed by $>30 \text{ dB}$ relative to the primary lasing wavelength.

DBR-TO QCLs are highly suited for spectroscopic applications that require moderate spectral resolution. In addition to being able to achieve high peak powers in near-diffraction-limited beams, the emission wavelength is stable because it is determined by the photonic bandgap of the DBR. When driving only the tapered gain section, the emission spectrum is found to fall within a fixed spectral window of $<0.6 \text{ cm}^{-1}$ independent of drive current and pulse length. Master-oscillator power-amplifier (MOPA) QCLs have been demonstrated with peak powers of up to 10 W in a single-longitudinal-mode making them suitable also for high-resolution spectroscopy [16]. However, a disadvantage of the MOPA for this application is that they exhibit a thermally induced frequency chirp when driven under long-pulse conditions. Furthermore, they are sensitive to the influence of facet reflections making it difficult to control the emission wavelength. In order to perform spectroscopy with a higher spectral resolution than is given by the $\Delta\lambda = 40.6 \text{ nm}$ ($\approx 4.5 \text{ cm}^{-1}$) spacing between adjacent lasers in the QCL array, it is possible to adjust the emission wavelength of each laser by thermally tuning the DBR section with a sub-threshold current pulse [18]. Figure 1(d) plots the emission spectrum for laser #15 when the DBR section was driven for $4 \mu\text{s}$ with a current pulse and then, after a 100-ns -delay, driving the tapered section above threshold for 200 nsec . As expected, the laser frequency decreases with increasing drive current to the DBR due to a thermally induced shift in the Bragg frequency. A shift of -2.8 cm^{-1} is obtained at a DBR drive current of 1 A . It was possible to achieve a shift of -6.8 cm^{-1} at a drive current of 1.5 A (not shown). However, under these conditions the DBR section lases on its own prior to lasing of the tapered section.

Figure 2(a) shows a photograph of the QCL array after being mounted epi-side up onto a temperature-controlled copper heatsink and attaching a cylindrical microlens ($f = 75 \mu\text{m}$, $f/0.5$, anti-reflection-coated germanium) to collimate the emission in the fast axis. For the results presented here, lasers were characterized under pulsed conditions (200 ns , 10 kHz). Unless otherwise noted, beam dimensions and divergences are reported in terms of their full-width-at- $1/e^2$ ($\text{FW}1/e^2$). As shown schematically in Fig. 2(b), the array was beam combined using a transform lens ($f = 100 \text{ mm}$) and a diffraction grating (75 g/mm , $12.4\text{-}\mu\text{m}$ -blaze). The electric field of the incident radiation is parallel to the grating grooves and the grating diffraction efficiency is $\sim 70\%$. The beam size after the diffraction grating is $18.8 \text{ mm} \times 15.9 \text{ mm}$ in the lateral and transverse dimensions, respectively. Assuming that the beam is diffraction-limited, one infers a lateral beam size at the laser facet of $94 \mu\text{m}$ which is consistent with the $110\text{-}\mu\text{m}$ -wide output aperture of the tapered laser. As described in [16], adiabatic expansion of the optical mode within the tapered section results in a non-astigmatic beam with a low divergence thereby obviating the need for micro-optics to collimate the beam in the lateral dimension. The lateral far-field profile after the diffraction grating, as shown in Fig. 2(c) for laser #14, closely approximates a Gaussian with beam divergence of 0.60 mrad . The divergence for lasers in the array varies from 0.59 to 0.94 mrad with an average value of 0.71 mrad . The larger divergence for some lasers is likely due to their broader spectrum of up to 0.6 cm^{-1} being dispersed by the diffraction grating.

Figure 2(d) plots the pointing error in the lateral (beam-combining) dimension for each element in the array relative to a fixed reference direction [19]. The error bars represent the

$\text{FW1}/e^2$ beam divergence. The peak-to-peak pointing error of 0.53 mrad is dominated by the quadratic component of the non-linear dispersion of the diffraction grating as has been reported previously [19]. Note that the quadratic pointing error is not an intrinsic limitation of WBC but can be reduced by better matching of the WBC optics to the laser array. For example, if different optics were used (75 g/mm, $f = 200$ mm) with the existing array, the quadratic component of the pointing error could be reduced by a factor of $\sim 10 \times$. Alternatively, since a 1-cm^{-1} shift in wavelength for any laser results in a 0.55-mrad shift in pointing, the pointing error can be perfectly corrected by appropriately tuning the wavelength of each laser in the array by pre-biasing the DBR section as described earlier. For a system with pointing errors, the beams from different lasers will walk-off from one another as they propagate. The beam walk-off is given by $\Delta x = \Delta\theta \cdot R$ where $\Delta\theta$ is the difference in pointing between two beams and R is the distance to the target. Assuming that a relative walk-off of up to 20% can be tolerated then, for the current WBC-QCL array with beam size of $D = 18.8$ mm and $\Delta\theta = 0.53$ mrad, the maximum range is 6.8 meters. To achieve longer ranges, the beam can be expanded using a telescope to increase the effective range by the factor m^2 where m is the telescope magnification.

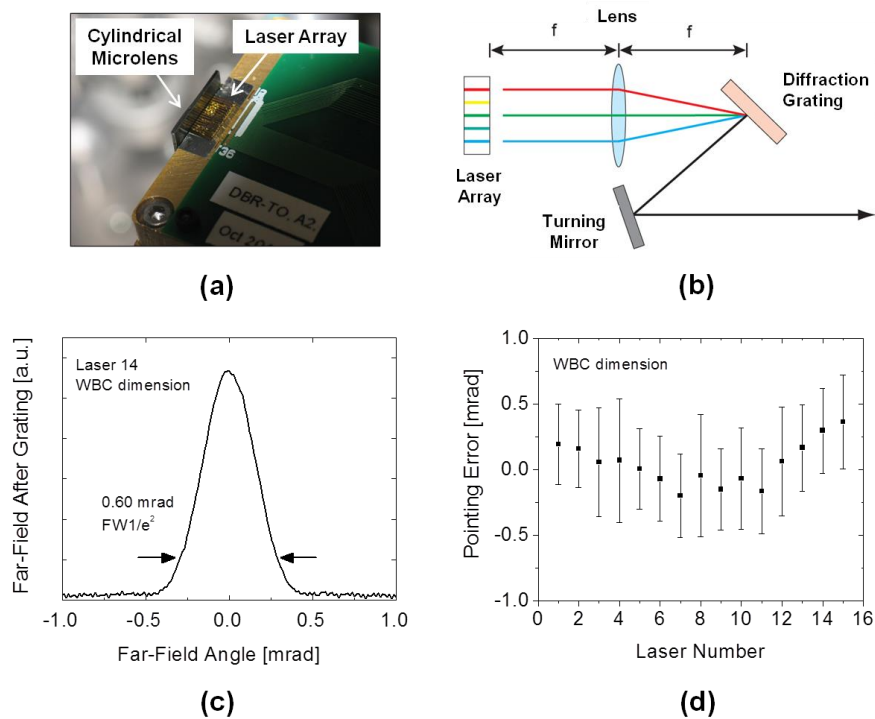


Fig. 2. (a) Photograph of QCL array bonded to a copper heat sink with attached cylindrical microlens to collimate the emission in the transverse (fast) dimension. (b) Wavelength-beam-combining configuration that utilizes an $f = 100$ mm transform lens and 75 g/mm diffraction grating. (c) Far-field profile after the diffraction grating of laser #14. (d) Pointing error in the WBC dimension for each element in the array. The error bars represent the $\text{FW1}/e^2$ beam divergence and the peak-to-peak pointing error is 0.53 mrad.

3. DFPA camera

The camera used for A-HSI is based on DFPA technology [20]. The DFPA uses a 256×256 HgCdTe detector array with $30\text{-}\mu\text{m}$ pixel pitch that is bump-bonded to a custom read-out integrated-circuit (ROIC). Unlike conventional analog FPAs, the DFPA incorporates an analog-to-digital converter (ADC) underneath each pixel. The ADC of the DFPA operates by counting the number of times a small capacitor is charged by the HgCdTe photodiode current.

Every time the capacitor's voltage exceeds a threshold, a comparator is triggered causing the capacitor to discharge and the event to be recorded by an up/down counter. The 14-bit counter can be dynamically enabled or disabled. Furthermore, the counter can be dynamically configured to either add or subtract counts. At the end of an acquisition period, the digital values associated with the counter are read-out through fast digital shift-register operations.

The DFPA architecture enables a variety of unique capabilities that are relevant for A-HSI systems. Two capabilities of the DFPA are especially relevant for the measurements presented here because they suppress the passive thermal background. This is important because the passive background is often larger than the active return. First, the DFPA can time-gate the response with sub-microsecond resolution by enabling the counter to count only while the laser is illuminating the scene. Between pulses, counting is not enabled and the intra-pulse passive thermal background does not contribute to the signal and, therefore, to additional noise. The DFPA can be programmed to add an arbitrary number of pulses. The second important capability is called passive background subtraction. Typically, subtraction of the passive background is achieved by taking two frames, with and without laser illumination, and differencing the images at the computer. Not only does this increase the number of frames that must be read from the camera, any motion of the object between frame reads (typically on the order of ~ 1 msec) will result in imperfect registration of the images. The DFPA, however, can perform high-speed background subtraction on-chip. This is accomplished simply by the counting down between laser pulses for a time equal to the count-up time while the laser was on to result in a counter value that represents only the active signal of interest. Combining time-gating with background subtraction significantly reduces the deleterious effects of the passive thermal background.

A demonstration of these benefits is shown in Fig. 3. Figure 3(a) shows a conventional thermal image of a hand in which the integration time is 100 μ s. The hand is illuminated with a QCL with average power of only about 0.3 mW. During acquisition of the image, a single laser pulse illuminates the surface but its intensity is too low to be visible. Figure 3(b) demonstrates the benefits of time-gating and multi-pulse integration. Here, the camera is configured to integrate 50 pulses with an integration window of 2 μ s per pulse to increase the active return relative to the passive background. Even with time-gating, the laser beam is barely visible because the passive background is ~ 3 times stronger than the active return. Figure 3(c) demonstrates the benefit of combining time-gating with on-chip background subtraction. During each laser pulse, the DFPA integrates the active return plus the passive background for 2 μ s. After the laser pulse, the DFPA subtracts the passive background for 2 μ s. This process is repeated 50 times to integrate the signal over multiple laser pulses and yields an image of the active return only. An additional benefit of on-chip background subtraction is that the active return can occupy the full dynamic range of the imager (e.g., 14 bits) without losing headroom to the passive signal.

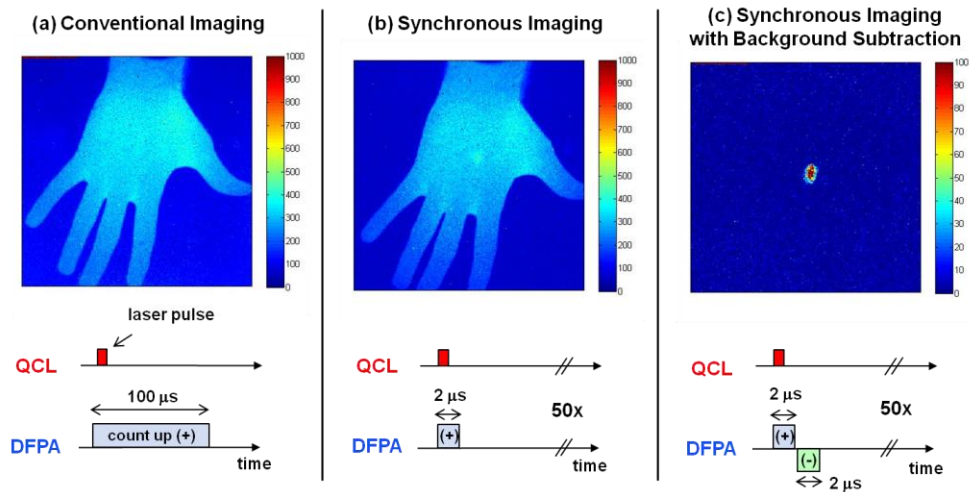


Fig. 3. (a) A conventional thermal image of a hand which is illuminated by a QCL. The single laser pulse during the 100- μ s-long integration period is too weak to be visible. (b) Synchronous detection image that utilizes time gating to integrate over 50×2 - μ s-long pulses while the laser is on to increase the active return by a factor of 50 compared to the conventional image. (c) On-chip background subtraction is combined with time gating to extract only the active return. As compared to Fig. 3(b), the passive background is subtracted on-chip such that the stationary signal is nulled.

4. Hyperspectral imaging demonstration

Results are presented of A-HSI using the beam-combined QCL array and DFPA camera. The laser was operated with an average power of only ~ 0.3 mW. The DFPA was operated as described in the previous section to integrate the active return from 50 laser pulses with on-chip background subtraction for each illumination wavelength. The sample consists of a roughened glass slide that was gold coated and upon which a thin layer of diethyl phthalate (DEP) was applied. The distance to the sample was 5 meters and the sample was angled by a few degrees to avoid a strong specular reflection from the surface of the liquid. The DFPA camera was fitted with a long focal-length lens ($f = 200$ mm, $f/1.4$) such that the spatial resolution at the target is 0.75 mm. Figure 4(a) shows images of the sample when illuminated at two different wavelengths. At 1049 cm^{-1} , the DEP is weakly absorbing and the reflectance is about 30% relative to a clean diffuse-gold substrate. When laser is tuned to 1072 cm^{-1} , where the DEP is strongly absorbing, the reflectance approaches zero.

A hyperspectral image cube containing 27 wavelengths was captured. 14 lasers within the WBC-QCL array (one laser failed) were driven under normal conditions to generate reflectance images with a spectral step size of $\sim 4.5\text{ cm}^{-1}$. To achieve a finer spectral step size of $\sim 2.3\text{ cm}^{-1}$, 13 of the lasers were tuned by pre-biasing the DBR section as described earlier. Since the wavelength tuning results in a ~ 1.2 -mrad angular shift of the laser pointing, the turning mirror shown in Fig. 2(b) was adjusted to compensate. Figure 4(b) plots the measured reflectance within the DEP film relative to the reflectance of a clean sample of diffuse gold. The reflectance was averaged over a region corresponding to roughly 200 pixels in order to reduce speckle noise. The measurements compare favorably with the calculated reflectance assuming double-pass absorption in the DEP given by $R = A \exp(-2\alpha t)$ where α is the absorption coefficient of DEP [2] and t is the film thickness. The best least-squares fit to the data is obtained with $A = 0.48$ and $t = 7.04\text{ }\mu\text{m}$. The fitted value for A is in reasonable agreement with the calculated value of $A = 16/(n+1)^4 = 0.35$ which assumes a constant value for the refractive index of DEP of $n \approx 1.6$ and takes into account the factor of n^2 increase

in solid-angle of the scattered radiation due to refraction at the liquid-to-air interface as well as the double-pass transmission losses at this interface. This expression for A captures to first-order the factors that reduce the reflectance from a liquid on a diffusely reflecting metallic substrate. Second-order effects, such as the wavelength dependence of the refractive index of DEP [2] and the fact that the film thickness cannot be described by a single value since the substrate is rough, are not captured in this simple calculation.

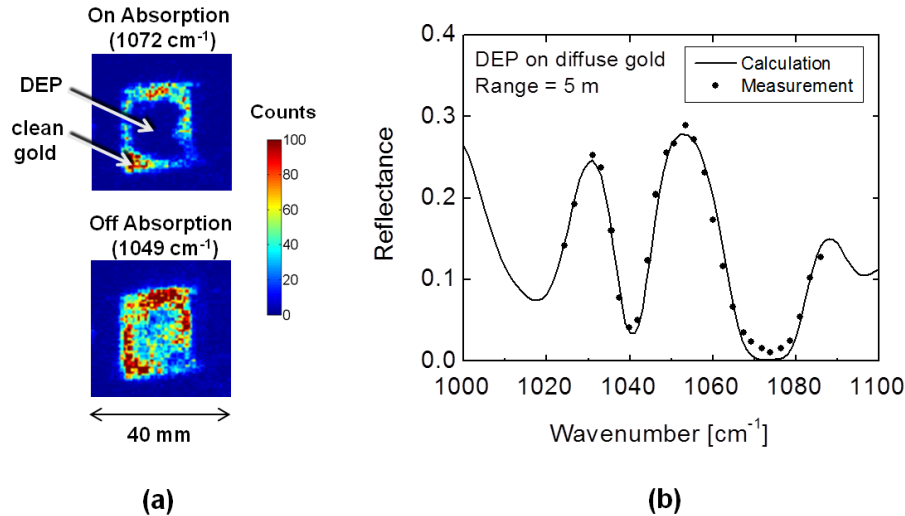


Fig. 4. (a) Reflectance images of a diffusely reflecting gold sample that is partially coated with a film of DEP at a range of 5 meters. Images are at two wavelengths that are either weakly or strongly absorbed in the DEP. (b) The measured reflection spectrum compared with calculations for a film thickness of $7.04\ \mu\text{m}$. The measured data was derived from a hyperspectral image cube with 27 frames. A spectral step size of $\sim 2.3\ \text{cm}^{-1}$ (which is finer than the $\sim 4.5\ \text{cm}^{-1}$ spacing between adjacent lasers in the QCL array) was achieved by thermally tuning the wavelength of each laser by pre-biasing the DBR section.

5. High-speed differential imaging

High-speed, differential reflectance measurements were made of particles of KClO_3 and sand (i.e., silica) while moving at high speed at a standoff distance of 10 cm. These materials were chosen because a differential spectral measurement will yield opposite signs for the result. Figures 5(a) and 5(b) show the experimental setup in which 3×3 arrays of both KClO_3 and sand were adhered to double-sided tape and the sample was then attached to a rotating chopper wheel. This deterministic arrangement of particles was chosen to simplify interpretation of the results. Two wavelengths from the beam-combined QCL array were incident onto the sample at a $\sim 30^\circ$ to the sample normal. The scattered light was captured by the DFPA camera using a telescope configuration such that the spatial resolution is $60\ \mu\text{m}$. Figure 5(d) shows the timing diagram for the measurement. When the sample is illuminated at $\lambda_1 = 9.8\ \mu\text{m}$, the DFPA counter adds the signal for $2\ \mu\text{s}$. Then after a $0.1\text{-}\mu\text{s}$ -delay, the second laser is driven to illuminate the sample at $\lambda_2 = 9.3\ \mu\text{m}$ during which time the DFPA counter subtracts the signal for $2\ \mu\text{s}$. This second step subtracts both the active return at λ_2 and the passive background. Figure 5(c) shows the reflectance spectra for bulk powders of KClO_3 and sand as measured using an FTIR spectrometer. Based on the bulk spectra, KClO_3 particles will have a positive value for the differential reflectance, while the sand will have a negative value. Not shown is the reflectance spectrum of the tape which is relatively constant over this wavelength range. Measurements were made in a single shot (no averaging over multiple laser pulses) such that the differential reflectance image is acquired within $4.1\ \mu\text{s}$ corresponding to an effective shutter speed of $1/244,000$ th of a second.

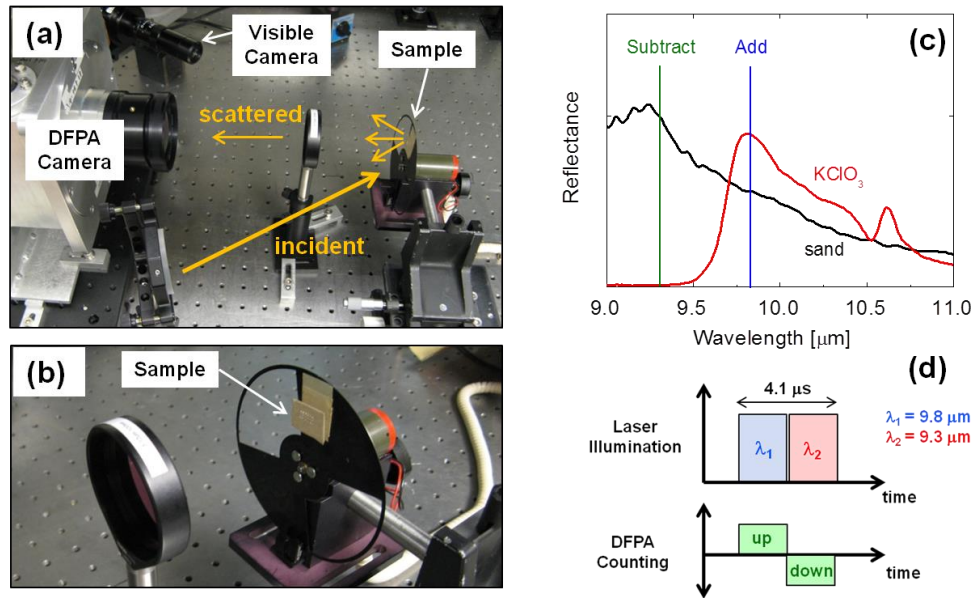


Fig. 5. (a) Photograph of the experimental setup in which the sample is mounted to a rotating chopper wheel and is illuminated by two lasers from the beam-combined QCL array. The scattered radiation is captured by the DFPA camera. (b) Closer view of the sample mounted to the chopper wheel. (c) Reflection spectra of bulk KClO_3 and sand powders as measured using an FTIR spectrometer. Indicated are the illumination wavelengths which are added and subtracted at the DFPA camera. (d) Timing diagram for the QCL array and DFPA camera showing how the signal is added at the DFPA when the sample is illuminated at λ_1 , and then subtracted when illuminated at λ_2 . The total measurement time is $4.1 \mu\text{s}$.

Figure 6 shows the differential reflectance image along with the visible image acquired with the camera seen in Fig. 5(a). The visible camera has a shutter speed of $1/10,000$ th of a second. In Fig. 6(a), the sample is stationary. In the differential reflectance image, the red and blue particles correspond to the KClO_3 and sand, respectively, which have positive and negative values, respectively, for the differential reflectance. The sample was then rotated such that the linear speed at the center of the sample reached 10 m/s and camera images were captured once per revolution of the chopper wheel. Figure 6(b) shows images taken while the sample was moving at 10 m/s . Since the measurement time for the differential reflectance image is $4.1 \mu\text{s}$, blurring due to rotation of the sample is only $41 \mu\text{m}$ which is less than the spatial resolution of $60 \mu\text{m}$. Since the particles occupy multiple pixels, differential reflectance images of the stationary and moving particles are almost identical. For the visible image with a $100\text{-}\mu\text{s}$ integration time, the scene blurs by 1 mm when the particles are moving at 10 m/s .

A video associated with Fig. 6 ([Media 1](#)) shows the sample as it is rotating. In the video, image capture is synchronized with the rotation of the sample. As the rotational speed of the sample increases, the visible image is seen to blur while the differential reflectance image remains sharp. At the highest rotational speed, which corresponds to a linear speed of 10 m/s , the mechanical system becomes unstable and results in the observed shaking of the scene. As stated earlier, each frame is the result of a single-shot measurement taken within a measurement time of $4.1 \mu\text{s}$. To the best of knowledge, this represents the highest speed acquisition of a differential reflectance image.

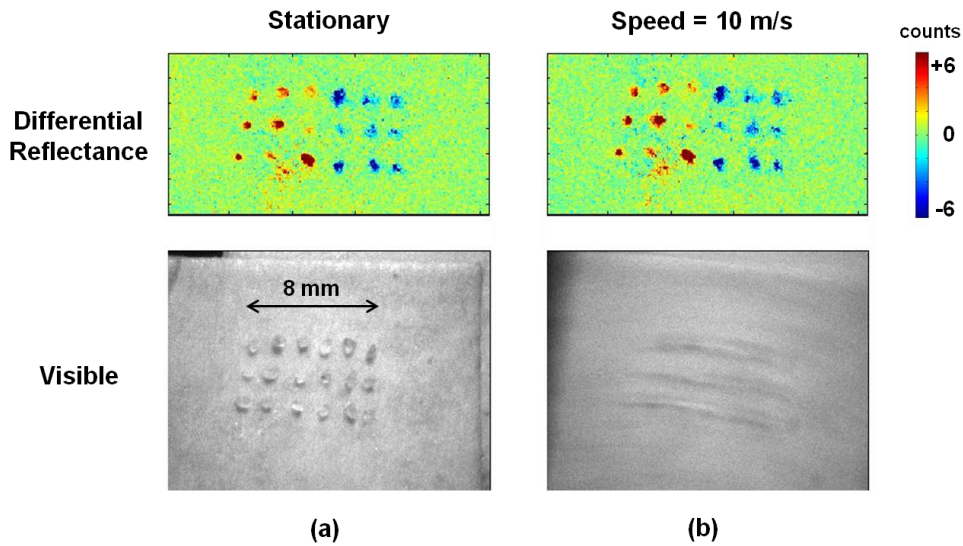


Fig. 6. Comparison of differential reflectance images (top) and visible images (bottom) for the particles when (a) stationary and (b) moving at linear speeds of 10 m/s ([Media 1](#)). The differential reflectance images show KClO_3 particles with a net positive value which is rendered as red. The sand particles have a net negative value which is rendered as blue. Since the image acquisition time for the differential reflectance image is only 4.1 μs , the image does not significantly blur even when the sample is moving at speeds of 10 m/s. The visible image, however, with the acquisition time of 100 μs is significantly blurred.

7. Summary

In summary, the benefits of cooperatively operating a beam-combined QCL array with a DFPA camera for MIR A-HSI are demonstrated. This technology pairing allows for high-speed acquisition of HSI cubes to map large areas rapidly because the QCL array is capable of high-speed wavelength tuning while the DFPA camera is capable of high frame rates. Furthermore, the on-chip time-gating and background-subtraction capabilities of the DFPA camera mitigate the deleterious effects of the passive thermal background while allowing the imaging of moving objects. HSI cubes of the spectral reflectance from a liquid contaminant on a diffusely reflecting gold surface were captured. The measured and calculated signatures are in good agreement. Also, proof-of-principle *on-chip* spectral classification was demonstrated by cooperatively operating the QCL array and DFPA camera to classify particles moving at speeds of up to 10 m/s. Although this demonstration involved a simple difference image between two wavelengths, this approach to on-chip spectral classification can be generalized to the case of multiple wavelengths in order to increase the sensitivity and specificity of classification.

Acknowledgments

The authors acknowledge the assistance of Leo Missaggia for packaging. The Lincoln Laboratory portion of this work was sponsored by the Office of the Assistant Secretary of Defense for Research and Engineering under Air Force contract No. FA8721-05-C-0002. The opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government. FC and BG acknowledge partial financial support from the Defense Threat Reduction Agency Joint Science and Technology Office for Chemical and Biological Defense (Grant No. HDTRA1-10-1-0031).