Fast Focal Plane Array Detector and Readout for Pulsed Opto-Thermal Radiometry

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Mid-infrared focal plane array spectroscopic or spatial imaging of opto-thermal transient emission is reported. Pulsed near-surface optical heating of arbitrary unprepared room temperature surfaces produce depth-resolved transient thermal emissions in the mid-infrared chemical fingerprint spectral region. Two optical configurations, both offering a significant advance in pulsed photothermal radiometry, may be realised: (1) an opto-thermal spectrograph capturing entire time-resolved emission spectra with each laser excitation shot; and (2) an opto-thermal camera producing thermal emission transient spatial line images, again, with each optical stimulus. A high-speed time-gated focal plane array detector forms the centrepiece of this new instrumentation; its adaptation, in relation to the measurement of sequenced transient phenomena, is the subject of this paper.

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The potential of transient thermal emission spectroscopy in photothermal radiometry was first recognised in the late 1980's, preceded some years earlier by Tam and Sullivan's measurement of impulse excitation spectra. Development of Opto-thermal Emission Radiometry, which has shown that microsecond time-resolved thermal emission transients exhibit micron depth-resolved characteristic spectral features within near surface layers, has since embraced crude forms of spectral selectivity in both its pulsed excitation and radiant thermal response. Experimental spectroscopic techniques have used either: (a) interference filters, or (b) a scanned grating monochromator or (c) time-domain Fourier transform interferometry. Although broadband (∆λ/λ≈0.1) interference filters allow adequate thermal resolution for delicate in-vivo samples such as skin, an analytical technique demands greater spectral resolution. Alternatively, dispersive monochromator throughput is insufficient with single element cryogenic photon detectors. The step-scanning interferometer, currently undergoing further development, is aimed at applications requiring full transient information content while tolerating measurement times of the order of ten minutes.

This paper describes and discusses the properties and control techniques of a parallel-capture serial-readout high-speed focal plane array (FPA) imaging sensor for pulsed photothermal radiometric applications. Depending on optical configuration, such a system will record thermal emission transient intensity either across mid-infrared spectra from a single point on the sample surface or along a line across the surface, with each laser shot, in the form of single or multiple time-resolved slices.

Applications

With the ability to measure absorption spectra in the mid-infrared chemical analysis fingerprint region (5–15 µm), FPA spectroscopy offers the potential for non-destructive depth profiling of chemical composition homogeneity within arbitrary near-surface layers at near-ambient temperature, within seconds. Ultimately, this new form of imaging is aimed at in-vivo skin research, within the epidermis. This would encompass transdermal drug diffusion (pharmaceutical), quantification of the effects of externally applied chemicals (health & safety), hydration (cosmetics), wound healing (medical research), simultaneous comparison of skin lesions with adjacent healthy tissue (diagnostics), etc.

In the short term, thermal resolution is limited by current detector performance, restricting applications to less temperature sensitive materials within industrial non-destructive evaluation.

Detection criteria

Time-resolved emission spectra contain predominantly optical absorbance information at early stages of the transient response. To resolve such features, broadband excitation modulation resulting from impulse excitation must be matched by wide-bandwidth detection of thermal emission. Late response times contain features affected only by thermal diffusion, giving a slowly decaying transient tail that requires de-coupling after detection in order to avoid distortion. Conventional thermovision cameras with a single detector element, rotating scanning mirrors and 30 Hz typical frame rate have a serial detection horizontal scan time of ≈0.25 ms. Such a camera would amalgamate depth and spectral or spatial information. Separation of the two dimensions necessitates parallel capture by the use of a staring multi-element array. Commercial cameras of this type are slow: microbolometer detector elements have thermal response times of around 10 ms; pyroelectric arrays are inherently ac-coupled and suffer from microphonics. Amongst the photon detectors, indium antimonide arrays are in common use but have a 5.5 µm cut-off wavelength when cooled.

Choice of technology is therefore confined to mercury cadmium telluride (MCT) or lead chalcogenide by two prerequisites: 5–15 µm spectral response and sub-microsecond temporal response. Consequently, we are developing a first prototype high-speed opto-thermal imaging capability using new, relatively low cost, staring array sensor technology developed by the Thin Film Physics Group, ETH Zürich.
Experimental

**FPA detector and readout**

The infrared sensor is shown in Fig. 1 and consists of a 2×128-element photovoltaic detector array with a cut-off wavelength of 10.5 μm at 80 K. It was fabricated in a lead chalcogenide (Pb1−xSnxSe) layer grown by molecular beam epitaxy on a silicon substrate. In this hybrid version, the FPA chip is wire-bonded to four readout chips, all mounted on a ceramic substrate and forms a 48 mm square module located within the detector's liquid nitrogen dewar.

The readout (Fig. 2) comprises four 64-channel preamplifiers, addressable multiplexers and output drivers. Each preamplifier channel incorporates in its first stage a low-noise JFET-input resettable charge-sensitive amplifier with offset zeroing. An intermediate stage combines correlated double sampling for low-frequency 1/f noise reduction, a switched-capacitor filter that performs discrete-time triangular weighting and a gated integrator. Finally, analog signal amplitudes are read from the sample-and-hold isolating amplifiers. Each stage employs operational-amplifier techniques with differential inputs, active current sources and active loads. Logic-input comparators drive all 4×64 MOSFET switches pertaining to each control function.

**FPA control - overview**

To drive the sensor array and readout chips three external agents are required: (i) digital pulse trains forming accurate control timing sequences, (ii) adjustable, but clean and stable, analog voltage references and (iii) dc power supplies. A programmable stand-alone Digital Control PCB governs the parallel operation of all 256 preamplifier channels; their resetting, integration time-gating and sampling. It also addresses the four multiplexers that serially select each channel of the four corresponding preamplifier chips. An Analog PCB supplies adjustable dc voltage references to various stages within each preamplifier channel. Analog samples from the multiplexers are received and boosted by buffer-amplifiers prior to data acquisition. Digital and analog FPA circuits are powered by dc feeds from their respective control PCBs. See Fig. 3.

Energy sensing of the laser pulses and their synchronisation with transient measurements are jointly performed by an integrating photodiode trigger. A desktop computer, equipped with a 20 MS s−1 PCI bus data acquisition card from ADLink Technology Inc., captures and stores opto-thermal data for subsequent processing, analysis and visual display. Control programs are generated or edited on the computer, then downloaded to the Digital Control PCB via an RS232 link.

Signal integrity is optimised by physically separating analog and digital circuits, both on the readout module and outwith the dewar, while screened PCB enclosures attached to the dewar provide immunity to electromagnetic interference (EMI) from pulsed laser and other sources. Mixed mode simulations of logic and preamplifier channel operation were conducted using Electronic Design for Windows (EDWin). Having proved critical circuit features, EDWin was again used to generate the layout and artwork for 'production standard' boards, using ground plane and transmission line techniques.

**FPA control - software/hardware**

A single mouse click is all that is required to perform photothermal transient imaging, however, as with other cameras, several steps precede the final viewing; in this case, using Hewlett-Packard Visual Engineering Environment (HPVEE) graphical user-interface control panels. These provide access to a suite of interconnected programs that generate the timing sequences, download their contents, control the data acquisition card and, finally, present the stored measurement data.

The first step generates and stores on disk a FPA control sequence data file consisting of 1 024 pairs of 8-bit bytes, with the binary value of each bit representing the ON or OFF state of a particular MOSFET switch. The HPVEE program translates...
pop-up dialog box entries that specify, for example, delay time, integration time, number of measurement samples, etc. into a 2048-byte array. Confidence in the integrity of a control program, before download, is assured with graphical simulations of current edits. These take the form of timing diagrams representing the sixteen lines of control data.

Next, a selected data file is downloaded via an RS-232 link to the Digital Control PCB, where each received byte is stored in random access memory (RAM) and echoed back for error checking. The final byte changes the board's function to repetitively cycle through the contents of the RAM each time a laser flash trigger pulse arrives, outputting sixteen different control functions from two interlaced 8-bit latches. The detector assembly then operates without external control, apart from the transient synchronising trigger pulses.

The final control program is entered with that 'single mouse click' on a 'Start' button. A graphical interface first allows the operator to set the number of measurement sequences (sample groups of one or more time-resolved samples of each pixel, from each transient decay, plus a background sample - Fig. 4) to be captured as an aggregate running average, offsetting time cost against S/N improvement. Data acquisition is triggered by a rising edge on the multiplexer address line D0, which signals the start of a readout sequence that was itself initiated by optical excitation. Analog-to-digital conversion is clocked by the Digital Control PCB output latch clock, ensuring one synchronised analog sample per pixel. Following each transient sample, a 197 ms hardware timeout triggers an associated background sample containing an array of background spectral amplitudes. Such dual-sample sequences are repeated for successive 5 Hz laser flashes, with background data array elements subtracted from their corresponding transient data counterparts. Thus, both background irradiation and pixel offsets are corrected on-the-fly. The PC displays a sampled image of averaged intensity against emission wavelength (or distance).

**Optics**

The planned opto-thermal spectrograph will consist of a diffraction grating monochromator, two spherical mirrors and the thermal emission detector. The first mirror collects a limited solid angle of radiant background-plus-transient broadband thermal emission from its focal point on the sample and directs it in a parallel beam towards the grating. The second mirror collects all spectrally deflected beam angles from the grating and resolves each component by focusing them along the detector's 6.4 mm linear array.

Time-resolved spatial line images of thermal emission transients will be captured by replacing the grating and mirrors with a compound germanium lens. The thermal emission solid angle described by the lens aperture is then focused directly onto the sensor array. Assuming lens aberrations are properly corrected, diffraction-limited minimum blur spot size in the image plane gives an image optical resolution of

\[ R_{\text{eq, imag}} = \frac{2.44\lambda_{\text{em}} F}{\ln 2} = 17 \mu m, \]  

where emission wavelength \( \lambda_{\text{em}} \) is 10 \( \mu m \) and the lens \( f \)-number (\( F \)) is 0.7. Detector resolution \( R_D \) is governed by effective element size, which is octagonal and 30 \( \mu m \) across. The equivalent resolution of the imaging system in the image focal plane is given by

\[ R_{\text{eq, imag}} = \sqrt{R_o^2 + R_D^2} = 34.5 \mu m, \]

indicating that the lens is appropriately matched to the detector. Therefore, for an approximate shortest object distance of 0.5 m, the optimum spatial resolution in the sample focal plane is given by the ratio of distances from the lens, of sample (≈ 0.5 m) to image (≈ 70 mm) multiplied by \( R_{eq} \) giving a value of 0.25 mm.
Results and Discussion

The overriding factor limiting the performance of FPA imaging of transient phenomena is noise. Both spectral and spatial resolutions are limited by S/N since, with low energy excitation and dispersed emission, individual pixel signals are likely to be below noise level, requiring a trade-off between averaging of adjacent pixel signals and/or consecutive transient responses at the post-processing stage. Some of the noise sources pertaining to the system described here are dealt with below. Others, less specific to this paper, such as pixel non-uniformity can be found elsewhere.

Integration time

Integration time is controlled by the time taken to clock through a programmed number of address locations in RAM. The quartz crystal oscillator that drives the system clock is hard-wired to the preamplifiers, unencumbered by software interrupts and has a stability of a few parts per million, which is insignificant compared with the 12-bit A/D resolution of one part in 4 096.

A/D sampling error

To find the sampling error significance, the A/D resolution is compared with the smallest (noise-equivalent) output signal voltage, \( \text{NEA}_\phi \). Differentiating Stefan's law for a 300 K blackbody small temperature change, \( T \pm \text{NEA}_T \)

\[
\text{NEA}_M = 3\sigma T^2 \sin M \text{NEA} T \tag{3}
\]

where \( M \) is the photon exitance over all wavelengths and \( \sigma \) is the Stefan-Boltzmann constant \((1.52 \times 10^{-4} \text{ photon s}^{-1} \text{m}^{-2} \text{K}^{-3})\). The relationship for photon irradiance \( E_q \) of a detector pixel with area \( A_\phi \), from a Lambertian extended source is

\[
E_q = \frac{\text{NEA} \phi}{A_\phi} = \text{NEA} \phi \sin^2 \theta \tag{4}
\]

where \( \phi \) is the detector pixel photon flux and \( \theta \) (\( \approx 30 \) degrees) is the half angle of view of the extended source. Substituting for \( \text{NEA}_M \) in Eq.(4), and using published values \( \text{of} \ 30 \text{ mK (with 200 \mu s integration time) NEA} \) and 50% quantum efficiency, the noise-equivalent number of electrons generated by each pixel in 100 \( \mu \text{s} \) is \( 1.52 \times 10^7 \). With preamplifier first-stage feedback of 20 \( \text{pF}, \) this equates to a peak-to-peak \( \text{NEA} \phi \), of 3.5 \( \text{mV} \). Since the data acquisition card input range is \( \pm 5 \text{volts} \), 12-bit A/D resolution is 2.4 \( \text{mV} \), which is just sufficient.

EMI

During preliminary trials without properly screened PCBs or wiring, noise levels were sixty times greater than expected after compensating for responsivity losses due to unoptimised biasing and timing. This illustrates the vulnerability of the system to EMI. Future development of the FPA detector readout could include the addition of integrated control electronics, with programmable detector bias adjustment. This would eliminate both 30-way ribbons that presently connect to the external control PCBs along with most of the 180 electro-mechanical connections (excluding solder joints) that may lead to unreliability and contribute to low-frequency \( 1/f \) noise. The design of the Digital Control PCB was a system level choice, made with these considerations.

Bandwidth

Comparison with commercial 2-D FPA cameras should take account of integration time, which could be equal to the frame rate, i.e. 33 ms instead of 100 \( \mu \text{s} \). The resultant 15 Hz bandwidth would improve NEAT by a factor of 18.

Summary

Although the system described is not yet complete, its development is presented in order to encourage discussion of a significant new imaging method. Remaining work will entail use of time-resolved spectroscopy calibration curves that enable corrections for loss of spectral sensitivity due to non-instantaneous sampling and diminishing absorbance change with mean depth or delay. Non-linear pixel responsivity may have to be compensated in addition to the offset correction already described, although the transient temperature enhancements are small relative to background and dark current offset, making this unlikely. Construction of the optics will involve consideration of thermal resolution of the complete system: its throughput and dispersive effects. User interface improvements that are envisaged include raw and processed data presentation, graphical displays of depth-resolved spectra and comparisons with data from library files.

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References:


Note: The equation \( q \) in Eq.(4), and using published values \( \text{of} \ 30 \text{ mK (with 200 \mu s integration time) NEA} \) and 50% quantum efficiency, the noise-equivalent number of electrons generated by each pixel in 100 \( \mu \text{s} \) is \( 1.52 \times 10^7 \). With preamplifier first-stage feedback of 20 \( \text{pF} \), this equates to a peak-to-peak \( \text{NEA} \phi \), of 3.5 \( \text{mV} \). Since the data acquisition card input range is \( \pm 5 \text{volts} \), 12-bit A/D resolution is 2.4 \( \text{mV} \), which is just sufficient.