An active infrared sensor system gives industry a new non-contact testing method.

IR monitoring has been used routinely in industry for years. Thermal imagers monitor production processes to help manufacturers avoid damage, optimize processes, or plan mid-process repairs. Until recently, though, IR monitoring was a passive affair, involving detectors used to measure thermal radiation emitted by the environment. We can obtain much more information by active sensing—aiming a pulse source such as a gas explosion source, IR-radiation source, or a mechanical wave at a surface; capturing the resultant thermal emission; and correlating the data by time and position (see figure 1). Applications include thin film metrology, as well as weld inspection for in situ quality control.

Real-time imaging of the transient thermo-opto behavior of opaque bodies allows us to capture time-gated data for a spatial resolution on the order of micrometers. To be commercially viable, though, the method requires an economical detector that offers sufficient performance. Conventional thermal vision cameras have a serial scan time and must amalgamate depth and lateral information. Separation of the two spatial dimensions calls for parallel capture, using a staring multi-element array. Commercial staring cameras are slow; microbolometers, for example, have thermal response times of around 10 ms. Pyroelectric arrays are inherently AC devices and thus suffer from noise. Among the photon detectors, indium antimonide arrays have an undesirable 5.5-µm cut-off wavelength when cooled, and the cost of mercury cadmium telluride technology is prohibitive for industrial processes.

To address these drawbacks, we have developed a mid-infrared camera capable of capturing transient thermal emission responses of sample surfaces with each flash of an energy pulse. The snapshot detector consists of a cooled lead chalcogenide staring focal plane array (FPA) with a 256-element linear format, 3- to 9-µm spectral response, and multiplexed output parallel read-out. The sensor is able to measure early (optical) and late (optical and thermal) responses from a surface, integrated over intervals of microseconds, achieving micrometer resolution. It
measures performance in terms of thermal resolution versus signal integration time; for example, 316 mK for 100 µs sample widths.

Many applications need fast readout, high-precision synchronization, and high sensitivity in defined spectral bands. For a sensor to perform diverse tasks like film thickness measurement in multilayer coatings, in situ weld quality control, or crack detection, the device needs high flexibility in integration time, readout time, and spectral response.

The new sensor allows the user to communicate with each sensor element of the array by computer. The user can select integration time as well as the readout time, optimizing performance for the application. We can also integrate sensors with different spectral responses in the same array.

To obtain good results, the detector element area has to be very small, so that the sensitivity with microsecond integration times is not fundamentally limited. Non-uniformity, read noise, and 1/f noise dominate with room temperature samples. Obtaining a good response requires elevated sample temperatures (e.g., 200K bias), relatively high excitation pulse energy (300 mJ), and robust samples with high emissivity and low diffusivity. The method is well suited to applications such as automated welding and plasma spraying, which could benefit from through-plume visibility for rapid, non-invasive evaluation of surface properties.

**An integrated package**

The complete camera unit consists of the infrared optics, the hybrid sensor array, and the control electronics. To measure multiespectral high-speed signals emitted from a surface after an energy pulse, the hybrid sensor array incorporates a $128 \times N$ element focal plane array, where $N$ runs from one to 96 (see figure 2). The device is fabricated in a lead chalcogenide (Pb$_1-x$Sn$_x$Se) layer grown by molecular-beam epitaxy on a silicon substrate. The sensitivity can be “tuned” within the range from 3 to 10 µm. Each detector pixel has its own amplifier channel whose outputs are connected to a programmable electronic unit. All signals are sampled in parallel-capture with serial-read-out mode.

The entire package of circuits is integrated in the image focal plane chip. Because the photon energy collected by the effective area ($7 \times 10^{-10}$ m$^2$) of each detector element per sample is very small, the resultant signal currents require amplification. Placing the preamplifiers as close to the detectors as possible minimizes the output impedance for driving further stages.

After the system captures the 2-D data array (see figure 3), software adds the data from successive scaled scans to another, zero-initialized 2-D array called the signal. The scaling factor is in the form of an integer variable that can be modified between measurements. It includes a 12-bit A/D conversion factor that gives a magnitude in volts. Averaged data is made available for
further processing and presentation by dividing the signal array by the number of measurement scans in the ‘average of scans’ object.

A trace of the signal for each scan provides real-time visualization of the averaging process on baseline-skimmed read-out sequences. To achieve this, the routine subtracts values of the baseline row of the 2-D variable from each read-out row of the detector array. To retrieve the magnitude scale, we divide the accumulating signal values by their rolling scan numbers.

The system also includes an optics alignment subroutine. A further data acquisition refinement that helps to find transitory small signals buried in noise limits the displayed data to eight centrally situated pixels and repeats them eight times. The benefit appears to be that deflections registered by pixels along a straight line result in a more statistically well-behaved distribution over several pixels for a signal with a thermal response component as compared to pure noise. Fleeting, slightly curved responses occurring anywhere across a 1.25 Hz updated display are difficult to distinguish. They are more easily perceived in the form of a repeated pattern across the whole display.

a growing presence

The system is designed for multilayer coating metrology such as in situ control of thermal or physical vapor deposition coatings, as well as for crack and corrosion detection. For nondestructive crack testing, the pulse triggers milli-Kelvin heating in the area of interest, then the sensor captures and analyzes the data. Restricting the probe effect to the area of interest requires two excitation sources: mechanical waves for detecting the area of a crack, and a short-wave radiation source for pinpointing it. The pulse sources are focused on the test zone, and deliver thermally measurable signals from layer depths of interest as low as 2 mm. The thermal emissions come to the surface through heat conduction in a few milliseconds as a function of the pulse energy and the synchronized signal capture. The variation of the thermophysical data of materials requires appropriate synchronization between the pulse source and the integration time of the sensor.

Another example where this non-contact testing comes in handy is in testing elevator structures in aircraft tails. The task here consists of determining moisture or adhesion flaws in the planking of the carbon composite honeycomb cells within the structure. Testers need to detect cells with a water content of more than 10% or with adhesion flaws affecting an area greater than 100 mm². The tests must be carried out on the finished component and the data captured and stored for future use.

The equipment consists of an IR camera, a pulse source, and the necessary hardware and software. Because of differences in heat flow, all the hollow spaces in the honeycomb construction are clearly and distinctly visible and can be imaged to a depth resolution of 4 mm. The system reveals adhesion faults in the planking and delamination inside the carbon-fiber layers.

Interpreting camera data with confidence required extensive testing of the control software and hardware. Having optimized the control and shown some weaknesses in the basic recommended timing diagrams, we systematically examined the performance of the FPA camera and the system as a whole, ending with some early time-resolved pulse opto-thermographs and an estimate of noise performance. Detailed analysis of numerous tests allowed us to optimize the system and gain confidence in the quality of our photothermal measurements.

The new sensor concept allows us to collect opto-thermograms using multiple time gating to measure spectral responses generated by a shock energy pulse source, integrated over very short time intervals. It allows nondestructive testing (NDT) at any point in the production process, improving quality control and increasing throughput. It provides the development engineer an efficient and rational test technique, and is growing in importance as an option for NDT and early damage detection.

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