microwave power and, thus, in the VCSEL wavelength. It is possible to choose a set of design and operational parameters (most importantly, the electronic part of the loop gain) such that the OEO stabilizes itself in the sense that an increase in circulating microwave power causes the VCSEL wavelength to change in a direction that results in an increase in optical absorption and thus a decrease in circulating microwave power. Typically, such an appropriate choice of opera-

tional parameters involves setting the nominal VCSEL wavelength to a point on the shorter-wavelength wing of an absorption spectral line.

This work was done by Dmitry Strekalov, Andrey Matsko, Nan Yu, Anatoliy Savchenkov, and Lute Maleki of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). Further information is contained in a TSP (see page 1).

In accordance with Public Law 96-517, the contractor has elected to retain title to

Internal Water Vapor Photoacoustic Calibration

John H. Glenn Research Center, Cleveland, Ohio

Water vapor absorption is ubiquitous in the infrared wavelength range where photoacoustic trace gas detectors operate. This technique allows for discontinuous wavelength tuning by temperature-jumping a laser diode from one range to another within a time span suitable for photoacoustic

calibration. The use of an internal calibration eliminates the need for external calibrated reference gases. Commercial applications include an improvement of photoacoustic spectrometers in all fields of use.

This work was done by Jeffrey S. Pilgrim of Vista Photonics, Inc. for Glenn Research Cen-

Mid-Infrared Reflectance Imaging of Thermal-Barrier Coatings
Apparatus successfully monitors extent of hidden subsurface delamination.

John H. Glenn Research Center, Cleveland, Ohio

An apparatus for mid-infrared reflectance imaging has been developed as means of inspecting for subsurface damage in thermal-barrier coatings (TBCs). The apparatus is designed, more specifically, for imaging the progression of buried delamination cracks in plasma-sprayed yttria-stabilized zirconia coatings on turbine-engine components. Progression of TBC delamination occurs by the formation of buried cracks that grow and then link together to produce eventual TBC spallation. The mid-infrared reflectance imaging system described here makes it possible to see delamination progression that is invisible to the unaided eye, and therefore give sufficiently advanced warning before delamination progression adversely affects engine performance and safety.

The apparatus (see figure) includes a commercial mid-infrared camera that contains a liquid-nitrogen-cooled focal-plane indium antimonide photodetector array, and imaging is restricted by a nar-

row bandpass centered at wavelength of 4 μm. This narrow wavelength range centered at 4 μm was chosen because (1) it enables avoidance of interfering absorptions by atmospheric OH and CO_2 at 3 and 4.25 μm, respectively; and (2) the coating material exhibits maximum transparency in this wavelength range. Delamination contrast is produced in the mid-infrared reflectance images because the introduction of cracks into the TBC creates an internal TBC/air-gap interface with a high diffuse reflectivity of 0.81, resulting in substantially higher reflectamce of mid-infrared radiation in regions that contain buried delamination cracks.

The camera is positioned a short distance (≈12 cm) from the specimen. The mid-infrared illumination is generated by a 50-watt silicon carbide source positioned to the side of the mid-infrared camera, and the illumination is collimated and reflected onto the specimen by a 6.35-cm-diameter off-axis paraboloidal mirror. Because the collected images are of a steady-state reflected inten-

sity (in contrast to the transient thermal response observed in infrared thermography), collection times can be lengthened to whatever extent needed to achieve desired signal-to-noise ratios.

Each image is digitized, and the resulting data are processed in several steps to obtain a true mid-infrared reflectance image. The raw image includes thermal radiation emitted by the specimen in addition to the desired reflected radiation. The thermal-radiation contribution is eliminated by subtracting the image obtained with the illumination off from the image obtained with the illumination on. A flat-field correction is then made to remove the effects of non-uniformities in the illumination level and pixel-to-pixel variations in sensitivity. This correction is performed by normalizing to an image of a standard object that has a known reflectance at a wavelength of 4 μm. After correction, each pixel value is proportional to the reflectance (at a wavelength of 4-μm) at the corresponding location on the specimen.
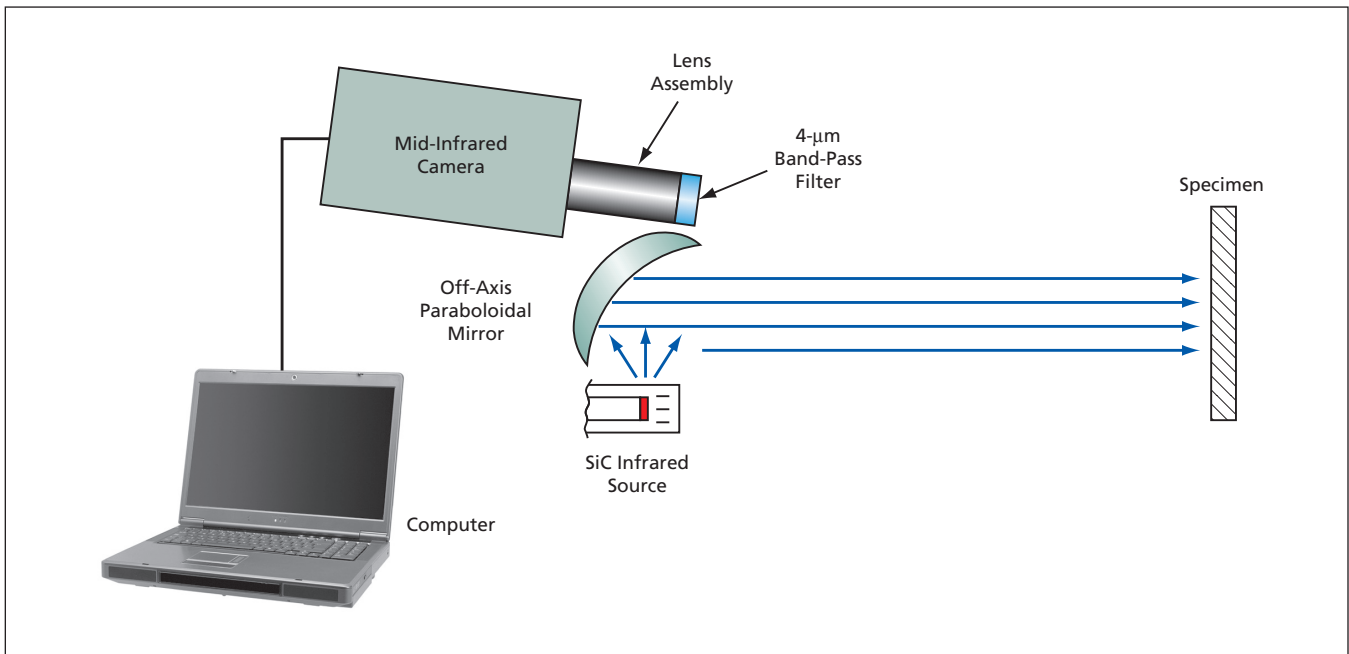
A **TBC-Coated Specimen Is Imaged** using reflected mid-infrared radiation at a wavelength of 4 µm. At this wavelength, subsurface delamination progression in the TBC that is invisible to the unaided eye becomes visible in the mid-infrared reflectance image.

Mid-infrared reflectance imaging of specimens that were thermally cycled for different numbers of cycles was performed and demonstrated that mid-infrared reflectance imaging was able to monitor the gradual delamination progression that occurs with continued thermal cycling. Reproducible values were obtained for the reflectance associated with an attached and fully delaminated TBC, so that intermediate reflectance values could be interpreted to successfully predict the number of thermal cycles to failure.

This work was done by Jeffrey I. Eldridge of Glenn Research Center and Richard E. Mar- *tin of Cleveland State University. Further information is contained in a TSP (see page 1).*

Improving the Visible and Infrared Contrast Ratio of Microshutter Arrays
Microshutters are used in the fabrication of integrated circuits and MEMS devices.

Goddard Space Flight Center, Greenbelt, Maryland

Three device improvements have been developed that dramatically enhance the contrast ratio of microshutters. The goal of a microshutter is to allow as much light through as possible when the shutters are in the open configuration, and preventing any light from passing through when they are in the closed position. The ratio of the transmitted light that is blocked is defined here as the contrast ratio.

Three major components contribute to the improved performance of these microshutters:

1. The precise implementation of light shields, which protect the gap around the shutters so no light can leak through. It has been ascertained that without the light shield there would be a gap on the order of 1 percent of the shutter area, limiting the contrast to a maximum of 100.

2. The precise coating of the interior wall of each microshutter was improved with an insulator and metal using an angle deposition technique. The coating prevents any infrared light that finds an entrance on the surface of the microshutter cell from being emitted from a sidewall. Since silicon is in effect transparent to any light with a wavelength longer than ≈1 micrometer, these coatings are essential to blocking any stray signals when the shutters are closed.

3. A thin film of molybdenum nitride (MoN) was integrated onto the surface of the microshutter blade. This film provides the majority of light blockage over the microshutter and also ensures that the shutter can be operated over a wide temperature range by maintaining its flatness.

These improvements were motivated by the requirements dictated by the James Webb Space Telescope NIRSpec instrument. The science goals of the NIRSpec require observing some of the very faintest objects in a given field of view that also may contain some very bright objects. To observe the faint objects, the light from the bright objects — which could be thousands of times brighter — must be completely blocked. If a closed microshutter is even slightly transmissive, a very bright object will still transmit a small signal,