structural components, it is difficult or impossible to obtain exact temperature compensation of frequency through selection of S_2.

According to the present proposal, to make it possible to obtain exact temperature compensation, one would add a component having a nonlinear stiffness to the mechanical load path and would place the entire resonator-and-compensator assembly on a thermoelectric controller, in an oven, or both. Then the temperature dependence of frequency would be approximately quadratic and the net derivative of frequency with respect to temperature would be given by

$$df/dT \approx \partial f/\partial T + (\partial f/\partial F)S_2E_2(\alpha_2 - \alpha_1) + A\Delta T$$

where A is a parameter that characterizes the nonlinearity to lowest order in temperature and ΔT is the difference between the present temperature and some other temperature, which could be a target temperature. To find the target temperature that gives exact temperature compensation, one sets the derivative equal to zero and solves for ΔT:

$$\Delta T \approx -A^{-1}[\partial f/\partial T + (\partial f/\partial F)S_2E_2(\alpha_2 - \alpha_1)]$$

The oven and/or the thermoelectric controller could be used to set the temperature to the exact compensation temperature. Even if the exact values of A, $\partial f/\partial T$, $\partial f/\partial F$, S_2, E_2, α_1, and α_2 were not known in advance, one could still determine the exact compensation temperature by measuring frequency as a function of temperature and finding the lowest point on the approximately quadratic frequency-versus-temperature curve.

This work was done by Anatoliy Savchenkov, Andrey Matsko, Dmitry Strekalov, Lute Maleki, Nan Yu, and Vladimir Iltchenko of Caltech for NASA's Jet Propulsion Laboratory.

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to:

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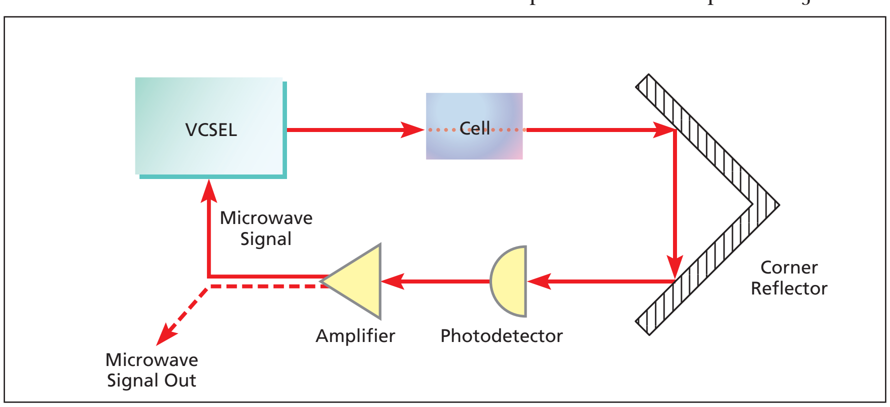
Refer to NPO-44567, volume and number of this NASA Tech Briefs *issue, and the page number.*

Dynamic Self-Locking of an OEO Containing a VCSEL

This is an alternative scheme for developing small, low-power atomic clocks.

NASA's Jet Propulsion Laboratory, Pasadena, California

A method of dynamic self-locking has been demonstrated to be effective as a means of stabilizing the wavelength of light emitted by a vertical-cavity surface-emitting laser (VCSEL) that is an active element in the frequency-control loop of an optoelectronic oscillator (OEO) designed to implement an atomic clock based on an electromagnetically-induced-transparency (EIT) resonance. This scheme can be considered an alternative to the one described in "Optical Injection Locking of a VCSEL in an OEO" (NPO-43454), *NASA Tech Briefs*, Vol. 33, No. 7 (July 2009), page 33. Both schemes are expected to enable the development of small, low-power, high-stability atomic clocks that would be suitable for use in applications involving precise navigation and/or communication.



This **Optoelectronic Oscillator** is a compact, relatively simple implementation of an atomic clock. The cell contains the optically absorbing atoms upon which the clock is based.

To recapitulate from the cited prior article: In one essential aspect of operation of an OEO of the type described above, a microwave modulation signal is coupled into the VCSEL. Heretofore, it has been well known that the wavelength of light emitted by a VCSEL depends on its temperature and drive current, necessitating thorough stabilization of these operational parameters. Recently, it was discovered that the wavelength also depends on the microwave power coupled into the VCSEL. This concludes the background information.

From the perspective that led to the conception of the optical injection-locking scheme described in the cited prior article, the variation of the VCSEL wavelength with the microwave power circulating in the frequency-control loop is regarded as a disadvantage and optical injection locking is a solution of the problem of stabilizing the wavelength in the presence of uncontrolled fluctuations in the microwave power. The present scheme for dynamic self-locking emerges from a different perspective, in which the dependence of VCSEL wavelength on microwave power is regarded as an advantageous phenomenon that can be exploited as a means of controlling the wavelength.

The figure schematically depicts an atomic-clock OEO of the type in question, wherein (1) the light from the VCSEL is used to excite an EIT resonance in selected atoms in a gas cell (e.g., ^{87}Rb atoms in a low-pressure mixture of Ar and Ne) and (2) the power supplied to the VCSEL is modulated by a microwave signal that includes components at beat frequencies among the VCSEL wavelength and modulation sidebands. As the VCSEL wavelength changes, it moves closer to or farther from a nearby absorption spectral line, and the optical power transmitted through the cell (and thus the loop gain) changes accordingly. A change in the loop gain causes a change in the 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 operational 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 this invention. Inquiries concerning rights for its commercial use should be addressed to:

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Refer to NPO-43751, volume and number of this NASA Tech Briefs *issue, and the page number.*

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 Center. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18417-1

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 narrow 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 intensity (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.