



## Technology Focus: Sensors

### A Short-Range Distance Sensor with Exceptional Linearity

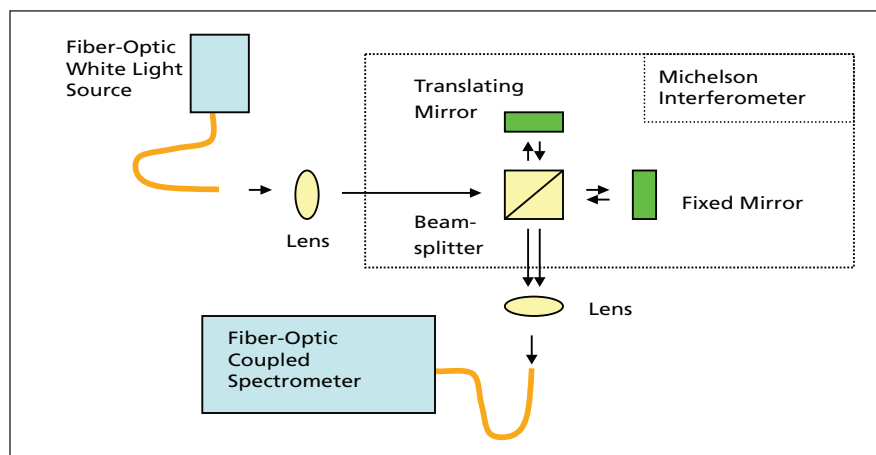
Potential uses exist in the areas of micromachining and nanotechnology.

*John F. Kennedy Space Center, Florida*

A sensor has been demonstrated that can measure distance over a total range of about 300 microns to an accuracy of about 0.1 nm (resolution of about 0.01 nm). This represents an exceptionally large dynamic range of operation — over 1,000,000. The sensor is optical in nature, and requires the attachment of a mirror to the object whose distance is being measured.

This work resulted from actively developing a white light interferometric system to be used to measure the depths of defects in the Space Shuttle Orbiter windows. The concept was then applied to measuring distance. The concept later expanded to include spectrometer calibration.

In summary, broadband (i.e., white) light is launched into a Michelson interferometer, one mirror of which is fixed and one of which is attached to the object whose distance is to be measured. The light emerging from the interferometer has traveled one of two distances: either the distance to the fixed mirror and back, or the distance to the moving mirror and back. These two light beams mix and produce an interference pattern where some wavelengths interfere constructively and some destructively. Sending this light into a spectrom-



The **Distance Sensor** is based on the wavelength variations of the light transfer through a Michelson interferometer. Collimated white light is launched into an interferometer composed of a fixed mirror and a translating mirror aligned with a beamsplitter. Light reflected from each mirror makes its way to a small spectrometer where the optical intensity can be measured as a function of wavelength.

eter allows this interference pattern to be analyzed, yielding the net distance difference between the two paths.

The unique feature of this distance sensor is its ability to measure accurately distance over a dynamic range of more than one million, the ratio of its range (about 300 microns) to its accuracy (about 0.1 nanometer). Such a large linear operating range is rare and arises here because both amplitude and phase-matching algo-

rithms contribute to the performance. The sensor is limited by the need to attach a mirror of some kind to the object being tracked, and by the fairly small total range, but the exceptional dynamic range should make it of interest.

*This work was done by Stephen Simmons and Robert Youngquist of Kennedy Space Center. For more information, contact the Kennedy Space Center Technology Transfer Office at (321) 867-7171. KSC-13382*

### Miniature Trace Gas Detector Based on Microfabricated Optical Resonators

Ultra-sensitive detection of molecules is available with a modified whispering gallery mode resonator.

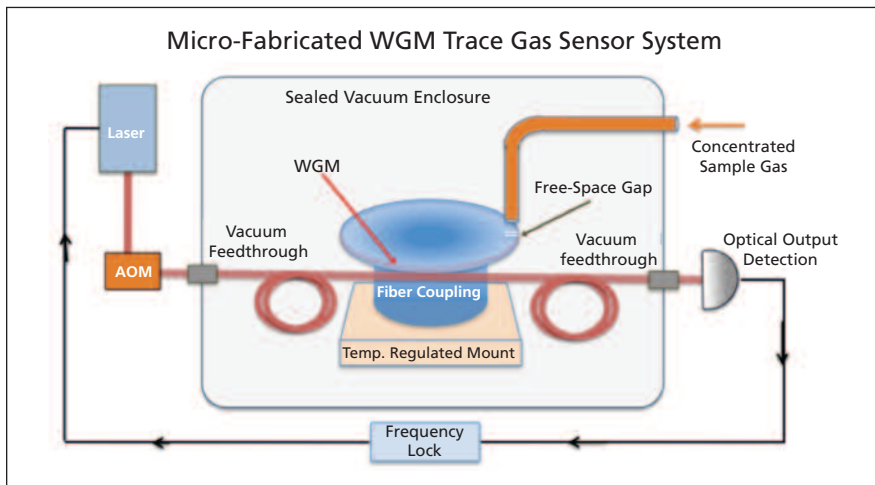
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While a variety of techniques exist to monitor trace gases, methods relying on absorption of laser light are the most commonly used in terrestrial applications. Cavity-enhanced absorption techniques typically use high-reflectivity mirrors to form a resonant cavity, inside of which a sample gas can be analyzed. The effective absorption length is aug-

mented by the cavity's high quality factor, or  $Q$ , because the light reflects many times between the mirrors. The sensitivity of such mirror-based sensors scales with size, generally making them somewhat bulky in volume. Also, specialized coatings for the high-reflectivity mirrors have limited bandwidth (typically just a few nanometers), and the delicate mir-

ror surfaces can easily be degraded by dust or chemical films.

As a highly sensitive and compact alternative, JPL is developing a novel trace gas sensor based on a monolithic optical resonator structure that has been modified such that a gas sample can be directly injected into the cavity. This device concept combines ultra-high  $Q$



The Trace Gas Detection System features a concentrated sample gas flowing to the free-space gap in the microfabricated disc, packaged inside a compact sealed enclosure with external laser and detection electronics. Also shown is a SEM image of a high- $Q$  calcium fluoride disc that has been augmented with a notch using FIB.

optical whispering gallery mode resonators (WGMR) with microfabrication technology used in the semiconductor industry. For direct access to the optical mode inside a resonator, material can be precisely milled from its perimeter, creating an open gap within the WGMR. Within this open notch, the full optical mode of the resonator can be accessed. While this modification may limit the obtainable  $Q$ , calculations show that the re-

duction is not significant enough to outweigh its utility for trace gas detection. The notch can be milled from the high- $Q$  crystalline WGMR with a focused ion beam (FIB) instrument with resolution much finer than an optical wavelength, thereby minimizing scattering losses and preserving the optical quality. Initial experimental demonstrations have shown that these opened cavities still support high- $Q$  whispering gallery modes.

This technology could provide ultra-sensitive detection of a variety of molecular species in an extremely compact and robust package. With this type of modified WGMR, one can inject a gas sample into the open gap, allowing highly sensitive trace molecule detection within a roughly 1-cm volume. Other critical components of the instrument, such as the detector and a semiconductor laser, could be directly packaged with the resonator so as to not significantly increase the size of the device.

Besides its low mass, volume, and power consumption, the monolithic design makes these resonators intrinsically robust devices, capable of handling significant temperature excursions, without moving parts to wear out or delicate coatings that can be easily damaged. A sensor could integrate with microfluidics technology for a chip-scale device. It could be mounted to the end of a deployable arm, or inserted into a borehole. Also, a network of individual sensors could be dispersed to monitor conditions over a wide region.

*This work was done by David C. Aveline, Nan Yu, Robert J. Thompson, and Dmitry V. Strelakov of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-47173*

## Commercial Non-Dispersive Infrared Spectroscopy Sensors for Sub-Ambient Carbon Dioxide Detection

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Carbon dioxide produced through respiration can accumulate rapidly within closed spaces. If not managed, a crew's respiratory rate increases, headaches and hyperventilation occur, vision and hearing are affected, and cognitive abilities decrease. Consequently, development continues on a number of CO<sub>2</sub> removal technologies for human spacecraft and spacesuits. Terrestrially, technology development requires precise performance characterization to qualify promising air revitalization equipment. On-orbit, instrumentation is required to identify and eliminate unsafe conditions. This necessitates accurate *in situ* CO<sub>2</sub> detection.

Recursive compensation algorithms were developed for sub-ambient detection of CO<sub>2</sub> with commercial off-the-shelf (COTS) non-dispersive infrared (NDIR) sensors. In addition, the source of the exponential loss in accuracy is de-

veloped theoretically. The basis of the loss can be explained through thermal, Doppler, and Lorentz broadening effects that arise as a result of the temperature, pressure, and composition of the gas mixture under analysis.

The objective was to develop a mathematical routine to compensate COTS CO<sub>2</sub> sensors relying on NDIR over pressures, temperatures, and compositions far from calibration conditions. The routine relies on a power-law relationship for the pressure dependency of the sensors along with an equivalent pressure to account for the composition dependency. A Newton-Raphson iterative technique solves for actual carbon dioxide concentration based on the reported concentration. Moreover, first principles routines were established to predict mixed-gas spectra based on sensor specifications (e.g.,

optical path length). The first principles model can be used to parametrically optimize sensors or sensor arrays across a wide variety of pressures/temperatures/compositions.

In this work, heuristic scaling arguments were utilized to develop reasonable compensation techniques. Experimental results confirmed this approach and provided evidence that composition broadening significantly alters spectra when pressure is reduced. Consequently, a recursive compensation technique was developed with the Newton-Raphson method, which was subsequently verified through experimentation.

*This work was done by Michael J. Swickrath and Molly S. Anderson of Johnson Space Center, Summer McMillin of Jacobs Technology, and Craig Broerman of Hamilton Sundstrand. Further information is contained in a TSP (see page 1). MSC-25343-1*