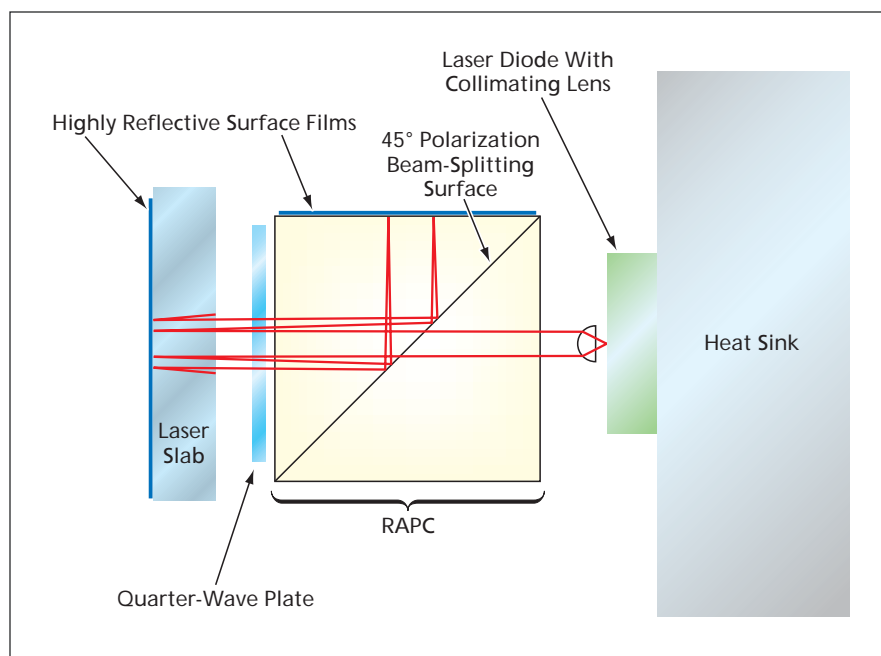


flection of pump light from a highly reflective thin film on the side opposite the side through which the pump light enters. In two-pass pumping, a Nd:YAG slab having a thickness of 2 mm (which is typical) absorbs about 84 percent of the 809-nm pump light power, leaving about 16 percent of the pump light power to travel back toward the laser diodes. This unused power can cause localized heating of the laser diodes, thereby reducing their lifetimes. Moreover, if the slab is thinner than 2 mm, then even more unused power travels back toward the laser diodes.

The four-pass optical coupler captures most of this unused pump light and sends it back to the laser slab for two more passes. As a result, the slab absorbs more pump light, as though it were twice as thick. The gain and laser cavity beam quality of a smaller laser slab in conjunction with this optical coupler can thus be made comparable to those of a larger two-pass-pumped laser slab.

The four-pass coupler (see figure) consists of a right-angle polarization cube (RAPC) with a quarter-wave plate on the side facing the laser slab and highly reflective film coating one of the perpendicular sides. The RAPC transmits p-polarized light (light polarized parallel to the plane of incidence) and reflects s-polarized light (light polarized perpendicular to the plane of incidence). Each laser diode emits a collimated beam and is oriented so that the beam is p-polarized (vertically polarized in the figure). The p-polarized beam passes through the RAPC, and then through the quarter-wave plate, which converts it to a rotationally polarized beam. The beam then passes into the laser slab for



The Four-Pass Coupler is interposed between the laser diodes and the laser slab. This view is along the longitudinal laser axis. The laser diodes, of which only one is shown here, are arranged in a row parallel to the axis.

a first pump pass, reflection, and second pump pass in the usual manner.

The pump light remaining after the second pass leaves the laser slab and travels back into the RAPC via the quarter-wave plate, which converts this light to s polarization. This s-polarized beam is reflected from the internal 45° polarization beam-splitting surface of the RAPC, sending the beam to the reflective coated RAPC surface at normal incidence. After reflection from this surface, this beam is reflected by the 45° surface toward the laser slab and is converted to rotational polarization by the quarter-wave plate. The beam then

makes two more passes through the laser slab in the usual manner.

Any pump beam power remaining after the fourth pass is converted to p polarization by the quarter-wave plate and travels back to the laser diode. However, when the coupler is designed correctly in conjunction with the other laser components, the fraction of pump power returning to the laser diode is too small to exert a significant adverse effect on the laser-diode lifetime or performance.

*This work was done by Donald B. Coyle of Goddard Space Flight Center. Further information is contained in a TSP (see page 1). GSC-14961-1*

## Low-Resolution Raman-Spectroscopy Combustion Thermometry

**This method offers advantages over related prior Raman-spectroscopy-based methods.**

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A method of optical thermometry, now undergoing development, involves low-resolution measurement of the spectrum of spontaneous Raman scattering (SRS) from N<sub>2</sub> and O<sub>2</sub> molecules. The method is especially suitable for measuring temperatures in high-pressure combustion environments that contain N<sub>2</sub>, O<sub>2</sub>, or N<sub>2</sub>/O<sub>2</sub> mixtures (including air).

Methods based on SRS (in which scattered light is shifted in wavelength by amounts that depend on vibrational and rotational energy levels of laser-illuminated molecules) have been popular means of probing flames because they are almost the only methods that provide spatially and temporally resolved concentrations and temperatures of multiple molecular species in turbulent

combustion. The present SRS-based method differs from prior SRS-based methods that have various drawbacks, a description of which would exceed the scope of this article. Two main differences between this and prior SRS-based methods are that

- It involves analysis in the frequency (equivalently, wavelength) domain, in contradistinction to analysis in the in-

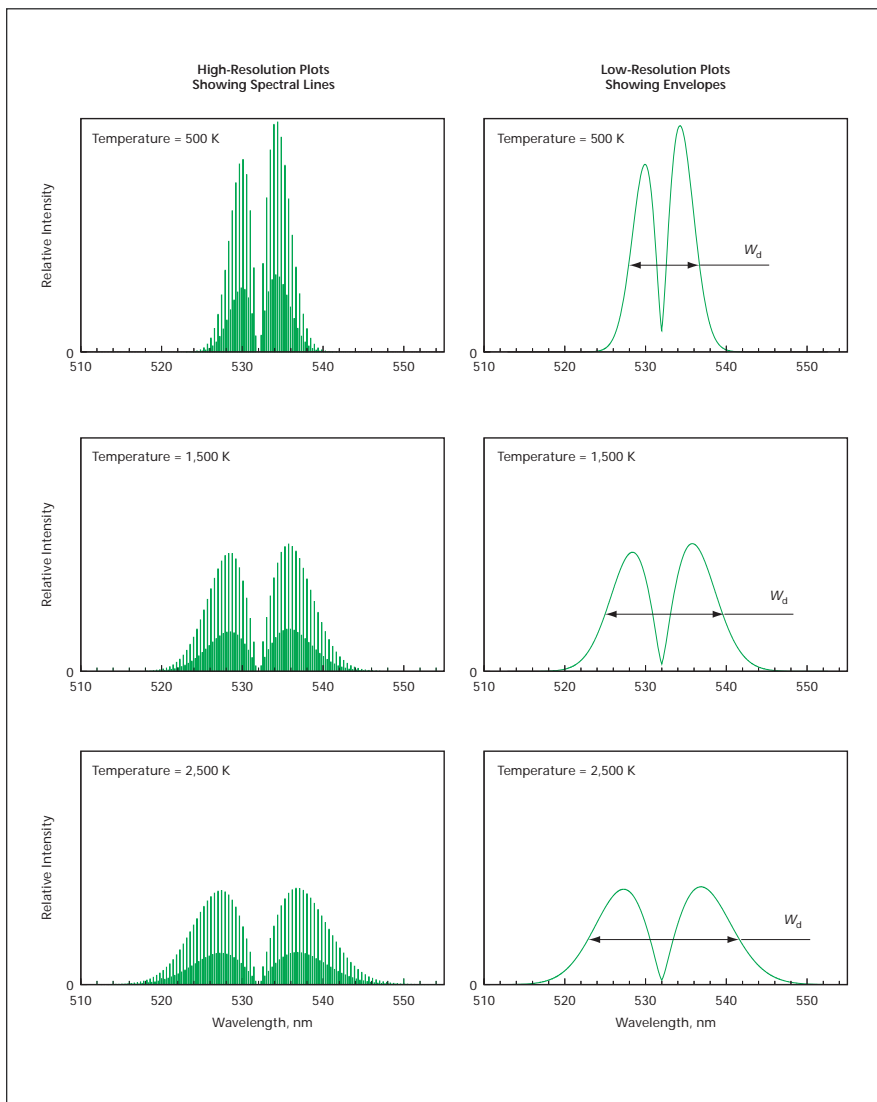


Figure 1. Rotational Raman Spectra of pure  $N_2$  at three temperatures were calculated to show how  $W_d$  increases with temperature.

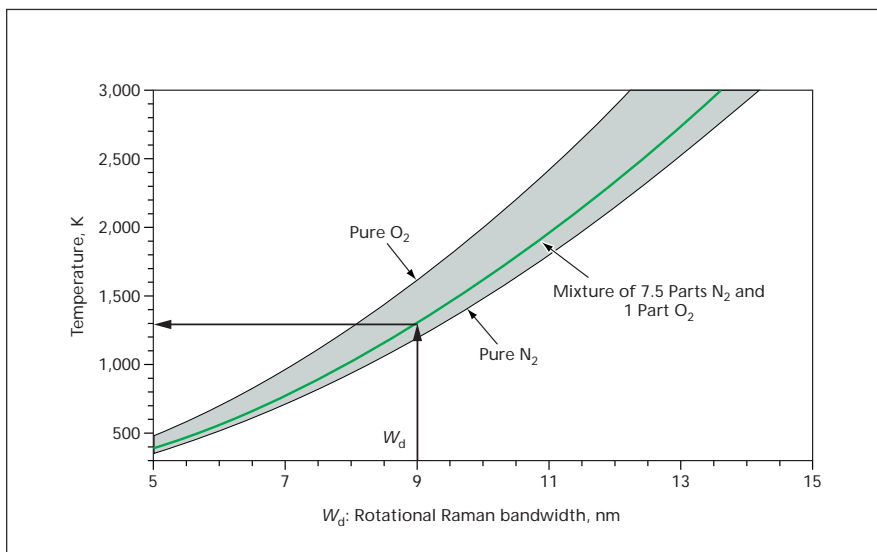


Figure 2. The Conversion Formulas for Pure  $N_2$  and  $O_2$  are represented by the lower and upper boundaries, respectively, of the shaded region. For an  $N_2/O_2$  mixture, the conversion formula lies between these boundaries.

tensity domain in prior methods; and

- It involves low-resolution measurement of what amounts to predominantly the rotational Raman spectra of  $N_2$  and  $O_2$ , in contradistinction to higher-resolution measurement of the vibrational Raman spectrum of  $N_2$  only in prior methods.

Analysis in the frequency domain reduces the effects of uncertainties in the spectral-response calibration and permits greater signal-to-noise ratios by excluding the noise contributed by intensity or amplitude fluctuations. One advantage of utilizing the rotational Raman spectral bands is that they are much stronger than are the vibrational Raman spectral bands. In particular, in this method, one utilizes the rotational  $N_2$  bands near the laser wavelength. The deliberate choice of lower resolution makes it acceptable to use wider spectrograph slits and thereby to collect more light to obtain greater signal-to-noise ratios. A further advantage of lower resolution is the independence of the spectra on pressure broadening effects.

According to theoretical simulations, the rotational Raman spectrum of  $N_2$  widens with increasing temperature (see Figure 1). This is because at higher temperature, greater proportions of rotational states having higher energies become excited. Consequently, it should be possible to establish a relationship between the width  $W_d$  of the envelope of the rotational Raman spectrum and the temperature and to express this relationship as a conversion formula for determining the temperature from  $W_d$  of a measured spectrum; this is the basic principle of the present method. The method as described thus far would be simple, were it not for the facts that (1) the rotational Raman spectra of  $N_2$  and  $O_2$  overlap and (2) almost any practical combustion system contains  $N_2$  and  $O_2$ . The net effect of the superposition of the  $N_2$  and  $O_2$  rotational Raman spectra is to produce a taller, narrower version of the spectrum of pure  $N_2$ , the amount of narrowing depending on the relative proportions of  $N_2$  and  $O_2$ .

To account for this narrowing, it becomes necessary to generate and use a more comprehensive conversion formula, as illustrated in Figure 2. First, the envelopes of rotational SRS spectra of  $N_2$  and  $O_2$  are calculated theoretically over a range of temperature at a certain pressure to obtain the conversion formulas for  $N_2$  and pure  $O_2$ . Then a blended conversion formula is obtained as a weighted average, wherein the weighting factors

are determined by the relative proportions of  $N_2$  and  $O_2$  as measured or calculated by independent means. (The independent means could be measurements of vibrational Raman spectra of  $N_2$  and  $O_2$  or a chemical-equilibrium calcula-

tion.) Finally, the measured  $W_d$  is inserted into the blended conversion formula, yielding the temperature.

*This work was done by Quang-Viet Nguyen of Glenn Research Center and Jun Kojima of Ohio Aerospace Institute.*

*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-18100-1.*

## Temperature Sensors Based on WGM Optical Resonators

### Differences between temperature-dependent frequencies of resonances would be measured.

NASA's Jet Propulsion Laboratory, Pasadena, California

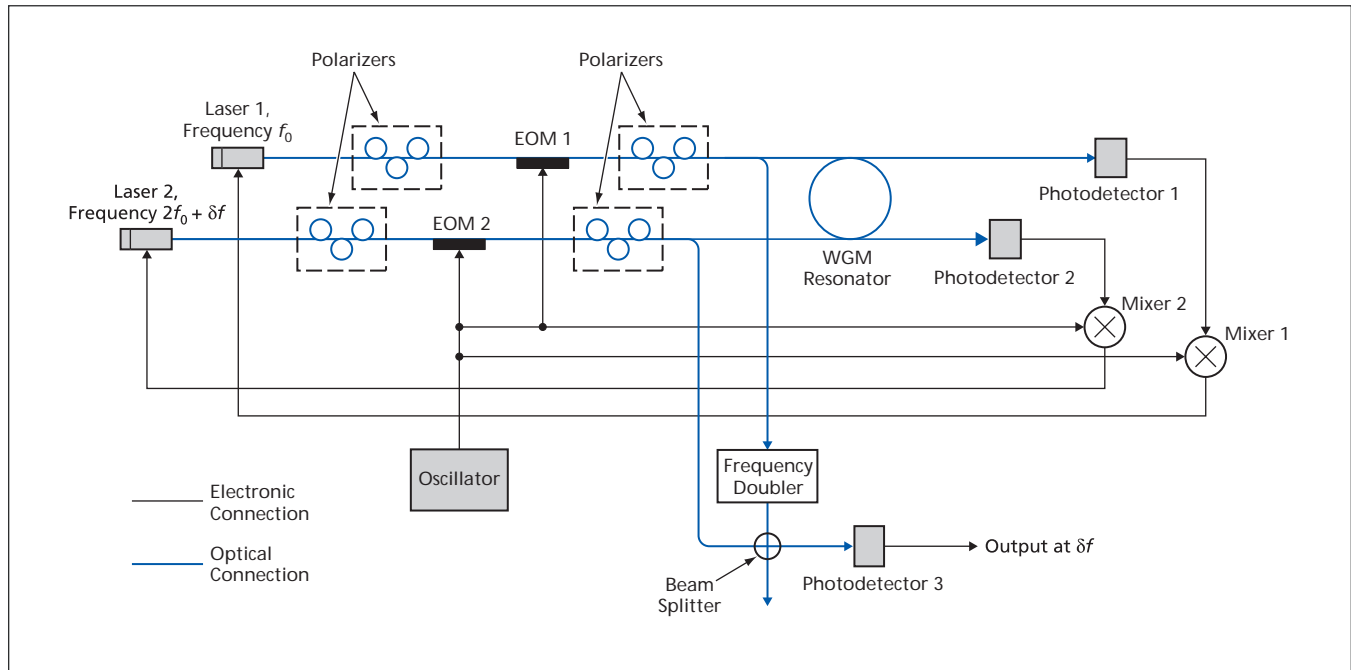
A proposed technique for measuring temperature would exploit differences between the temperature dependences of the frequencies of two different electromagnetic modes of a whispering-gallery-mode (WGM) optical resonator. An apparatus based on this technique was originally intended to be part of a control system for stabilizing a laser frequency in the face of temperature fluctuations. When suitably calibrated, apparatuses based on this technique could also serve as precise temperature sensors for purposes other than stabilization of lasers.

A sensor according to the proposal would include (1) a transparent WGM dielectric resonator having at least two different sets of modes characterized by different thermo-optical constants and (2) optoelectronic instrumentation for measuring the difference between the temperature-dependent shifts of the res-

onance frequencies of the two sets of modes. The figure schematically depicts an example of such a sensor. Laser 1, operating at frequency  $f_0$ , would be locked to a mode in the first of the two sets of WGM modes to be exploited; the mode locking would be accomplished by established means that would include photodetector 1, an oscillator, polarizers, mixer 1, and electro-optical modulator EOM 1. Laser 2, operating at frequency  $2f_0 + \delta f$ , would be locked to a mode in the second of the two sets of WGM modes to be exploited; in this case, the mode locking would be accomplished by established means that would include photodetector 2, the oscillator, mixer 1, and electro-optical modulator EOM 2.

Part of the modulated output of laser 1 would be fed through a frequency doubler to obtain a modulated beam at frequency  $2f_0$ . In a beam splitter, the  $2f_0$

output from the frequency doubler would be combined with part of the modulated output of laser 2 at  $2f_0 + \delta f$ . The interference between these combined beams would cause the output of photodetector 3 to include a component at the heterodyne frequency,  $\delta f$ , which would have the desired temperature dependence. Inasmuch as  $f_0$  and  $\delta f$  could readily be chosen to place  $\delta f$  within a suitable radio-frequency range and means for measuring radio frequency precisely are readily available, it would be straightforward to measure  $\delta f$ . Then the temperature could be calculated by inversion of the known temperature dependence of  $\delta f$ . It has been estimated that for a typical  $CaF_2$  WGM resonator having a resonance quality factor ( $Q$ ) of  $2 \times 10^{10}$ , the temperature-measurement sensitivity would be characterized by a temperature increment of about  $40 \mu K$  for a frequency increment



The Lasers Would Be Mode-Locked to resonance frequencies  $f_0$  and  $2f_0 + \delta f$ , respectively, of the WGM resonator. The heterodyne frequency,  $\delta f$ , would vary with temperature and, therefore, would be measured for use as an indication of temperature.