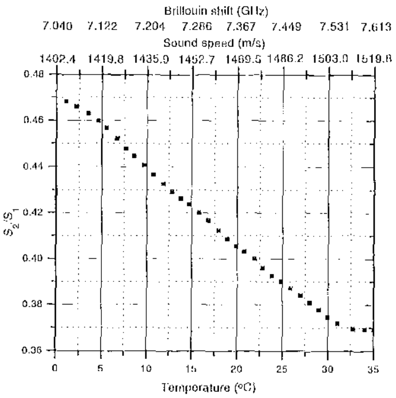


CThM63 Fig. 2. Observed signal as a function of temperature for pure water. The auxiliary axis at the top shows the corresponding Brillouin shift and sound speed.

technique[2,3] to provide single-longitudinal-mode operation from pulse to pulse. The laser pulse from the Nd:YAG laser is transmitted into the water sample to generate Brillouin scattering, then the Lidar return is collected, collimated and then passed through an absorption cell containing $^{127}I_2$. The laser frequency is tuned so that its second harmonic at 532 nm lies on a strong absorption line of $127I_2$; consequently, this first absorption cell absorbs all of the elastically scattered light (zero frequency shift). The transmitted light from the $^{127}I_2$ cell, consisting of the Brillouin shifted components, is divided by a 50-50 beamsplitter into two equal parts, one of which is detected and provides the normalization signal S_1. The second half passes through an absorption cell containing $^{129}I_2$ and is detected to give the signal S_2. The edges of molecular absorption lines of $^{129}I_2$ provide the high spectral resolution that is needed for an accurate determination of the Brillouin shifts. Specifically, as the Brillouin frequency shift(ν_B) increases (decreases) the transmission of the $^{129}I_2$ cell decreases (increases) and hence S_2/S_1 decreases (increases). Simple normalization provides a signal S that depends only on the Brillouin shift and is independent of variations in the amplitude of the Lidar return. Specifically, we measured the signal $S = S_2/S_1$ as a function of temperature of the water sample, because temperature, sound speed (ν_s), and Brillouin shift (ν_B) are uniquely related in pure water.[4] Figure 2 shows the first laboratory data by single shot from tests implementing the concept shown schematically in Fig. 1, with an additional axis at the top showing the corresponding Brillouin shift and derived sound speed. By evaluating the errors at each point, the sound speed was determined to an accuracy of ~75 cm/s. For this data, we used a sample of pure water (0.0‰ salinity) that is ~50 cm deep. There are two important factors limiting the accuracy of our obtained data. First, our temperature measurements were made using a normal thermometer with an accuracy of ±0.2°C; a new thermometer with an accuracy of ±0.02°C has recently been obtained for future work. Another factor limiting the accuracy is inherent in any detection system using normalization based on two different detectors. Each detector has a different response, which leads to a measurement of $S = S_2/S_1$ that is also dependent on the different responses. We are solving this problem by implementing a two-shot averaging scheme. We are also developing a technique to stabilize the laser frequency more precisely. With these improvements, we expect a sound speed accuracy of 25 cm/s by our edge technique for the actual ocean measurements.

1. D.A. Leonard and H.E. Sweeney, *Remote sensing of ocean physical properties: A comparison of Raman and Brillouin techniques,* **925,** 407–414 (1988).
2. S.W. Henderson, E.H. Yuen, E.S. Fry, "A fast resonance detection technique for single frequency operation of injection seeded Nd:YAG lasers," Opt. Lett. **11,** 715–717 (1986).
3. Edward S. Fry, Qiquan Hu, Xingfu Li, "Single-frequency operation of an injection seeded Nd:YAG laser in high noise and vibration environments," Appl. Opt. **30,** 1015–1017 (1991).
4. Edward S. Fry, Yves Emery, Xiaohong Quan, Jeffrey W. Katz, "Accuracy limitation on Brillouin lidar measurements of temperature and sound speed in the ocean," Appl. Opt. **36,** 6887–6894 (1997).

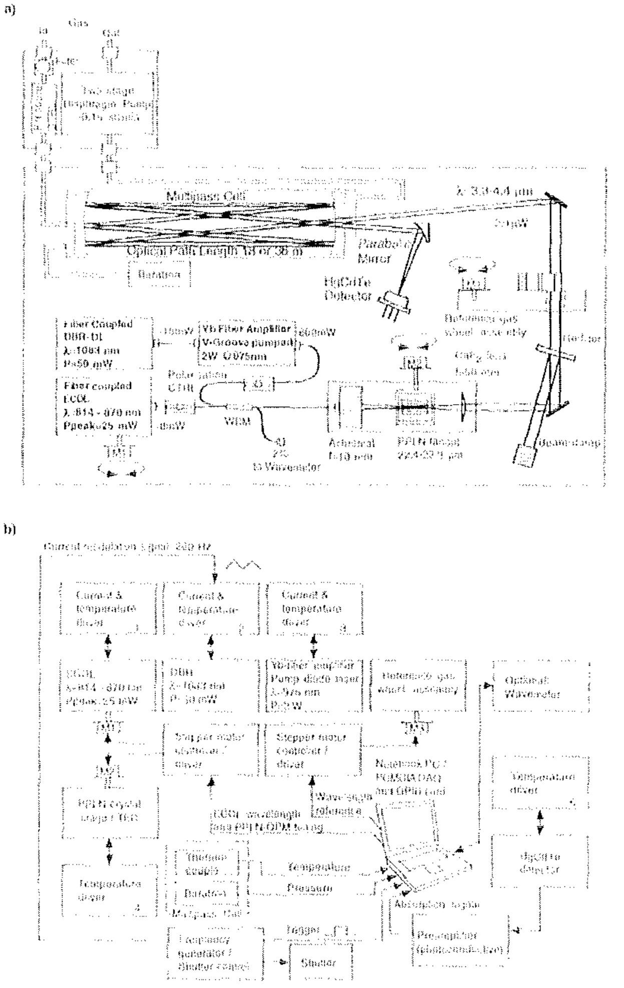
CThM64

Development of an automated multispecies gas sensor using diode laser pumped difference-frequency generation

Dirk Richter, David G. Lancaster, Frank K. Tittel, *Rice Quantum Inst., Rice Univ., Houston, Texas 77251-1892, USA; E-mail: fkt@rice.edu*

Selective and sensitive mid-IR multi-species gas detection is an attractive tool for many real world applications. Narrow-linewidth mid-IR absorption gas sensors based on difference-frequency mixed near-IR solid-state and diode lasers have been shown to be an effective tool for molecular species detection.[1-3] In real-world applications such gas sensors can be exposed to considerable temperature fluctuations and vibrations. Depending on the application, such sensors may have to cope with large dynamic changes of the gas concentration and with other potentially interfering gases.

In this work we report an automated, compact sized, portable gas sensor that uses widely tunable mid-IR difference-frequency laser



CThM64 Fig. 1. DFG-based multispecies gas sensor device architecture depicting both the optical (a) and electronic (b) subassemblies.

generated light applied to multispecies gas detection using direct extractive absorption spectroscopy. Fig. 1a shows the optical schematic and Fig. 1b the electronic diagram of the automated sensor controlled by a notebook PC. A unique feature of this DFG-based mid-IR source is the electronically controlled continuous phase-matching of the pump lasers (814 nm–870 nm pump; 1083-nm signal). This is achieved using a noncritically quasi-phase-matched periodically poled lithium niobate crystal ($L = 2$ cm) with a fan-out type grating ($\Lambda = 22.4$ to 23.3 μm).

Other key sensor features include fast response (~10 sec), high sensitivity (~2×10^{-4}), selectivity (linewidth ~60 MHz), reliable autonomous long-term operation (weeks) and alignment using fiber-coupled diode laser pump sources, a large dynamic range (ppbv-ppmv) and wide continuous stepper motor driven spectral tuning from 3.3 to 4.4 μm. This allows us to access many molecular absorption lines and to select different individual absorption lines that are most appropriate depending on a selected target gas and composition. Calibrated reference gas cells of 5-cm length can be rotated automatically into the absorption beam path and provide frequency/wavelength calibration. In this manner any frequency drift can be compensated by tuning of the external cavity diode laser by a stepper motor with a measured precision of 0.02 cm^{-1}. The entire sensor is operated by LabVIEW software with expert feedback algorithms, which are able to provide real time optimization of the spectral tuning and quasi-phase-matching conditions to the environment. The automated DFG-based sensor has been successfully tested in both laboratory and nonlaboratory environments with remote control operation via a telephone line interface.

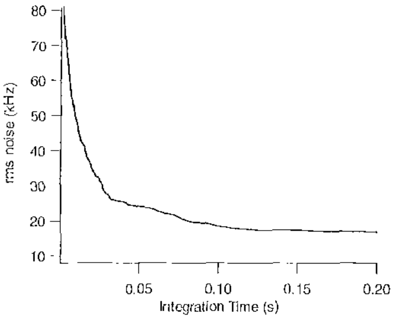
1. Th. Toepfer, K.P. Petrov, Y. Mine, D. Jundt, R.F. Curl, F. K. Tittel, "Room Temperature Mid-Infrared-Laser Sensor for Trace Gas Detection," Appl. Opt. **36**, 8042–8049 (1997).
2. D.G. Lancaster, D. Richter, R.F. Curl, F.K. Tittel: "Real-time measurements of trace gases using a compact difference-frequency-based sensor at 3.5 μm," Appl. Phys B—Special Issue: Environmental Trace Gas Detection using Laser Spectroscopy, **67** 3, 339–345 (1998).
3. D.G. Lancaster, D. Richter, F.K. Tittel, "Portable fiber coupled diode laser based sensor for multiple trace gas detection," Appl. Phys. B—Lasers and Optics, DOI 10.1007/s003409900115 (1999).

CThM65

A frequency stabilized laser array for use in displacement metrology

J. Marc Pedulla, Richard D. Deslattes,
John R. Lawall, Yann Le Coq,[*] *NIST, 100 Bureau Dr., Gaithersburg, Maryland 20899-8422, USA; E-mail: marc.pedulla@nist.gov*

We have developed a frequency stabilized laser system to supply light to measure atomic distance displacements of a stage moved in real time. Each laser in the array provides enough power (~1 mW) for four Michelson interferometers whose accuracy requires a frequency stability of 20 kHz. In addition, each laser must be stable on both short and long time scales due to the real time control requirements.



CThM65 Fig. 1. RMS noise of the iodine-stabilized laser as a function of integration time.

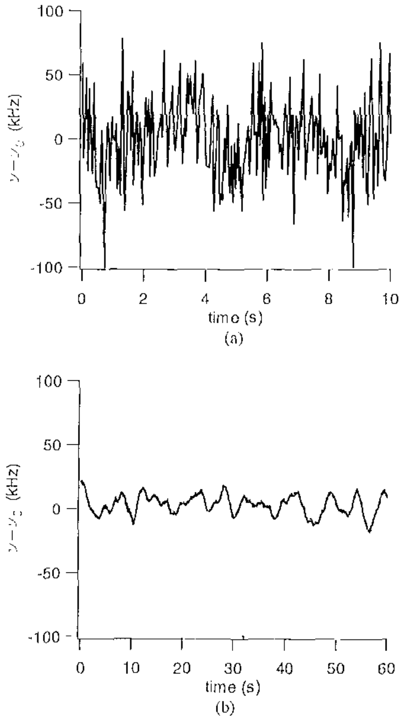
The iodine-stabilized laser is the standard method of realizing the international definition of the meter in the visible and has an absolute accuracy of ~3×10^{-11} (12 kHz). Unfortunately, this laser is not suitable for fast measurements because its frequency is modulated by 6 MHz p-p at 8.3 kHz in order to lock to an iodine transition. In addition, it is very susceptible to optical feedback and only supplies ~100 μW of power.

We combine the long-term stability of the iodine-stabilized laser with the short-term stability and relative high power of sealed-cavity HeNe laser tubes by frequency-locking the sealed-cavity tubes to the iodine-stabilized laser using a digital feedback control loop. After we outfitted the sealed-cavity tubes with heaters to control their frequency by thermal expansion, we built-in two layers of thermal isolation to reduce environmental effects.

Cyclic averaging is used to remove the 6-MHz modulation by averaging an integral number (approximately 200) of complete cycles of the 8.3-kHz signal from the iodine-stabilized laser. Even after cyclic averaging, the iodine-stabilized laser must be further averaged to attain the cited accuracy of 3×10^{-11}.

In order to determine the amount of averaging necessary, frequency deviations of the iodine-stabilized laser were measured by setting up a disequilibrated Mach-Zender interferometer in vacuum and recording the phase fluctuations. This data was time-averaged with increasing integration times and we determined that 24 ms of averaging is needed to reduce the error in the iodine-stabilized laser to between 20–30 kHz rms (Fig. 1).

To measure the quality of the frequency lock, two identical sealed-cavity lasers were independently frequency-locked to the iodine-stabilized laser. The beat frequency (offset to zero) between the iodine-stabilized laser and one sealed-cavity tube [Fig. 2(a)] as well as the beat between the two sealed-cavity tubes is recorded [Fig. 2(b)]. As expected from the 24-ms integration time, the standard deviation between the iodine-stabilized laser and the sealed-cavity tube is 33 kHz while that between the two sealed-cavity tubes is 10 kHz.



(a)

(b)

CThM65 Fig. 2. (a) Beat between the iodine-stabilized laser and a sealed cavity tube ($\sigma = 33$ kHz). (b) Beat between two sealed-cavity tubes ($\sigma = 10$ kHz).

The modular nature of our setup allows additional lasers to be added with minimal effort creating an array of lasers with sufficient power (1 mW) and accuracy (10 kHz) to perform atomic scale displacement measurements. These lasers have resolution better than the iodine-stabilized laser at short time scales and perform as well as the iodine-stabilized laser over longer times.

[*] *Lab. C. Fabry de l'Inst. d'Optique, France*

CThM66

8–12 micron OPO pumped by a 2.09-micron holmium laser

Suresh Chandra, Michael E. Wager,
Toomas H. Allik,[*] Wayne W. Hovis,[**]
Science Applications International Corporation, 4031 Colonel Glenn Highway, Dayton, OH, 45431; E-mail: chandras@saic.com

There is a great need to develop continuously tunable coherent sources for chemical sensing lidar applications in the 8–12-μm atmospheric transmission window. Many different optical parametric oscillator (OPO) schemes have been attempted to meet this need. Desirable properties for such an OPO include; continuously tunability, good beam quality and conversion efficiency, single-stage OPO conversion and a high moderate repetition rate.

This paper presents an OPO that meets most of these requirements. The OPO is based