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CThO5 **3:30 pm**

Surface micromachined scanning confocal microscope

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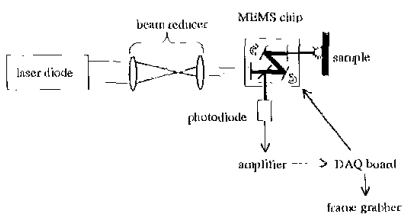
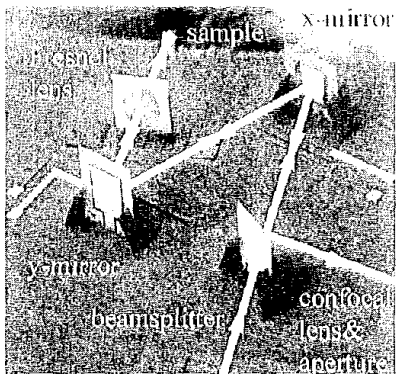
Confocal scanning microscopy has recently emerged as a significant new technique, which exhibits several advantages over conventional optical microscopy.[1] Because confocal images are devoid of out-of-focus blur it allows noninvasive, optical sectioning of intact specimen. There has been an ongoing effort to reduce the size of the imaging head, to enable its use in endoscopy, CD read heads, and *in vivo* medical imaging.

The confocal microscope system, shown in Fig. 1, has a 0.65-μm laser diode as the light source. The beam on arriving at the chip passes through an aperture and a beam splitter and is then scanned in the *x*- and *y*- directions by two mirrors and is focused on the sample by an objective lens. The reflected light from the sample retraces the path and is reflected by the beam splitter into a confocal lens, which focuses the beam onto a detector. The presence of a pinhole aperture at the focusing spot of the second lens ensures the confocal operation of the microscope. The photocurrent from the detector is processed to produce an image.

Silicon surface micromachining has been used to fabricate the compact optical system incorporating low-inertia scanners. Figure 2 is a scanning electron microscope (SEM) photograph showing a part of the system. Both scanning mirrors stand vertically on the silicon substrate and are actuated by combdrives. These MEMS structures were fabricated using the MCNC-MUMPS foundry process. The MUMPS process includes two structural layers of polycrystalline silicon: a 2-μm-thick POLY1 layer and a 1.5-μm-thick POLY2 layer. The mirrors and the lenses are fabricated using a 3.5-μm-thick polysilicon, whereas the beam splitter has only the POLY1 layer. Details of fabrication of scanning mirrors have already been published by Kiang *et al.*[2] Gold is evaporated onto the surface of the mirrors to increase reflectivity.



CThO5 Fig. 1. Schematic of the confocal microscope system.



CThO5 Fig. 2. SEM of the scanning mirrors and the objective lens.

Electrostatic combdrives are used as actuators as they provide high resonance frequencies. The *x*- and *y*- mirrors are 250 μm × 250 μm and 320 μm × 300 μm with resonant frequencies of 3.5 kHz and 2 kHz, respectively. The maximum angular deflection of these mirrors, 1.5° and 3° respectively, was obtained with a 25 V difference applied to the two electrodes. The Fresnel lenses in this system have a numerical aperture of 0.16 and a focal length of 1 mm for the objective lens and 300 μm for the confocal lens. The spot size and depth of focus are 3 μm and 25 μm, respectively.

Images of metallic grating on glass substrates have been obtained using external lenses, instead of the on-chip Fresnel lenses, as this allows the focusing of the laser beam to 1-μm spot size. Efforts are underway to obtain images of integrated circuits and to fabricate a high-NA on-chip lens.

This system design, in conjunction with low temperature wafer bonding techniques, which can be used to bond the laser and the detector onto the chip, can be used to develop a monolithic micro-scanning confocal microscope on a Si-chip. Unlike previous designs[3] this system, being completely surface micromachined, provides ease of fabrication and allows mass production using conventional photolithography techniques.

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CThO6 **3:45 pm**

Trace gas detection in ambient air with cw and pulsed QC lasers

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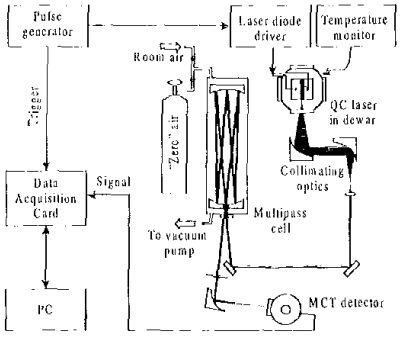
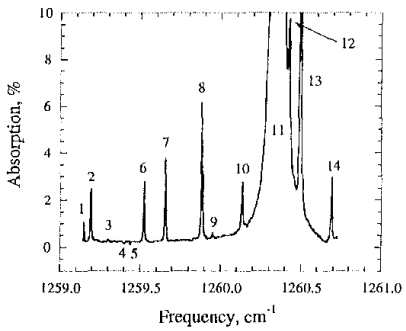
Recently developed quantum-cascade lasers[1] have been shown to be useful tunable single-frequency light sources for laser-based absorption spectroscopy in the important mid-IR region.[2–5] In this work, we demonstrate the application of cw and pulsed single-frequency QC-DFB lasers to the sensitive detection of CH_4, N_2O, C_2H_5OH (ethanol) and different isotopic species of H_2O in ambient air will be reported. In order to determine the ethanol concentration from its dense infrared spectrum, a new approach based on a linear correlation technique was applied.

A schematic of the cw QC-DFB laser based gas sensor configuration is shown in Fig. 1. A commercial multipass cell aligned for a 100-m optical path was used. The pressure in the cell was set to 20–40 Torr. To improve the sensitivity, a "zero-air" background subtraction technique[6] was also used. Spectra of ambient air and a pollutant-free "zero air" were alternatively taken with the sequential subtraction of the zero-air signal from the ambient air signal. In most of the measurements, pure air with an addition of 5% CO_2 was used as a zero gas. The laser radiation was detected with a liquid nitrogen cooled photovoltaic MCT detector. The QC laser frequency was fast-tuned with current, which was supplied in 120–235-μs ramped pulses (quasi-cw operation) at a 800 to 1000 Hz repetition rate. Frequency scans were typically over a 2 cm^{-1} range. The variation of the laser duty cycle resulted in a variation of laser operating temperature and frequency offset.

An example of the absorption spectrum of ambient air obtained with such a cw QC-based gas sensor is shown in Fig. 2. The estimated sensitivity is 2.5 ppb for CH_4, 1.0 ppb for N_2O, 63 ppt for H_2O and 125 ppb for C_2H_5OH. In experiments with a near-room temperature pulsed QC laser, 7 to 10 ns current pulses were



CThO6 Fig. 1. Schematic of the cw QC-DFB based gas sensor.



CThO6 Fig. 2. An example of an absorption spectrum of room air obtained with a 100-m pathlength multipass cell and a zero-air background subtraction technique. The assignment of the strong spectral lines is shown: $H_2{}^{16}O$ - 1, 11, 13; N_2O - 2, 3, 10; CH_4 - 6, 7, 8, 14; $H_2{}^{18}O$ - 9; HDO - 12; and CO_2 in the reference zero-air that appears as a negative absorption - 4, 5.

applied to the laser. Fast frequency tuning was obtained using a sub-threshold ramped current, as in Ref. 5. The first experiments with a pulsed QC laser indicate a line broadening caused by frequency chirping due to the pulsed drive current. The narrowest laser linewidth was obtained with the shortest achievable pulses of 7 ns resulting in a FWHM of 0.016 cm^{-1} (480 MHz).

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CThO7 **4:00 pm**

Sub-ppb detection of trace gas species with a high-power diode-pumped cw difference-frequency sensor

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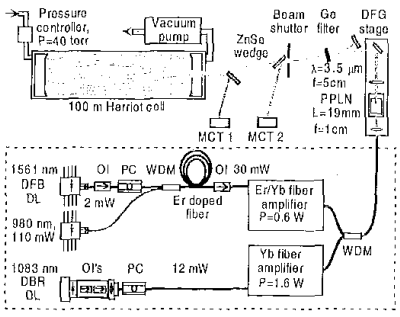
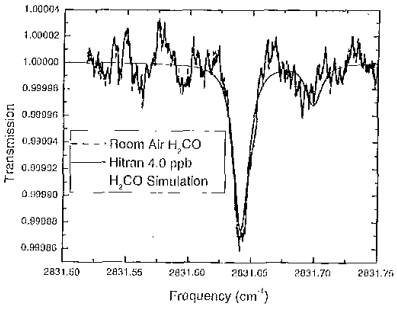
A significant issue in urban air quality is the ability to measure particular trace and pollutant gases in real time with high sensitivity and specificity. One such species is H_2CO that although at low concentrations of 2–20 ppb, is a precursor to atmospheric ozone production. H_2CO is produced by the photochemical breakdown of volatile organic carbon molecules and can also be a byproduct from incomplete combustion processes. In major urban environments, such as Los Angeles, New York and Houston, monitoring of H_2CO distribution and its daily concentration cycle is important in modeling complex ozone chemistry.

For high sensitivity optical monitoring of fundamental H_2CO ro-vibrational lines, cryogenically cooled Pb salt diode lasers operating near 2831 cm^{-1} (3.5 μm) can be used.[1] Although difference-frequency-based sensors have advantages such as noncryogenic operation, intrinsic wavelength stability and high beam quality, their low cw power (<5 μW) has limited their minimum detection sensitivities to date.[2] To increase the difference-frequency power produced in such a sensor we have developed an architecture based on two frequency-stable diode lasers at 1.1 and 1.5 μm, which are amplified by high-power Yb and Er/Yb fiber amplifiers,[3] respectively. To date we have generated up to 0.7 mW of narrow-band (<60 MHz) mid-infrared radiation. This higher power capability allows the use of an optical-noise-reducing dual-beam absorption configuration employing two DC-coupled Peltier-cooled HgCdTe detectors and an extended 100-m absorption pathlength achieved with a low-volume Herriot cell.

Figure 1 is a schematic of the sensor configuration. The mixing lasers are a fiber pigtailed 2-mW 1561-nm DFB diode laser and a 50-mW 1083-nm DBR diode coupled into single-mode fiber. A Er^{3+}-doped fiber preamplifier increases the 1561-nm seed power to 30 mW to saturate the gain in the 0.6-W Er/Yb



CThO7 Fig. 1. Difference-frequency-based formaldehyde sensor using dual beam spectroscopy OI: optical isolator, WDM: wavelength division multiplexer, PC: polarization controller.



CThO7 Fig. 2. Observed and simulated transmission spectrum of H_2CO in air (L = 100 m).

fiber amplifier while the 1083-nm diode directly seeds the 1.6-W Yb amplifier. To combine the two wavelength channels into a single fiber a wavelength division multiplexer (WDM) is used. The difference-frequency mixing occurs on a separate optical stage, where the fiber delivered beam is imaged into the 19-mm PPLN crystal (M = 11), by a 1-cm focal-length achromat lens. The primary beam is directed to a MCT detector after the multipass cell, and a reference beam incident on the second MCT is acquired from a ZnSe wedge placed in the beam before the multi-pass cell. This dual beam technique allows the strong etalons that arise from the lens and PPLN crystal in the difference-frequency mixing stage to be eliminated by ratioing the two beams. The two channels are acquired simultaneously by the use of two A-D data acquisition cards. Spectral lineshapes are acquired by direct current modulation of the 1560-nm diode (triangular waveform at 0.1 to 1 kHz). This technique improves the absorption sensitivity to $\sim 2 \times 10^{-5}$. Figure 2 is a formaldehyde absorption spectrum near 2831.6 cm^{-1} obtained from room air for a pathlength of 100 m, a pressure of 40 torr and an average of 5000 spectra acquired over 140 s. A Hitran92 4.0 ppb H_2CO simulation is overlaid on the experimentally obtained spectrum. The residual displays a σ of $\pm 1.3 \times 10^{-5}$, corresponding to a single shot detection sensitivity of ± 0.4 ppb.

This work demonstrates a significant increase in both power and sensitivity over previously reported DFG based spectroscopic sources, and thereby will permit high sensitivity and real-time trace gas sensing.

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