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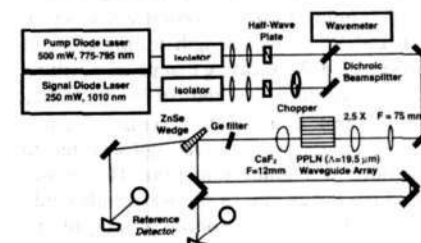
Trace gas spectroscopy using a periodically poled LiNbO₃ waveguide based mid-infrared difference frequency sensor

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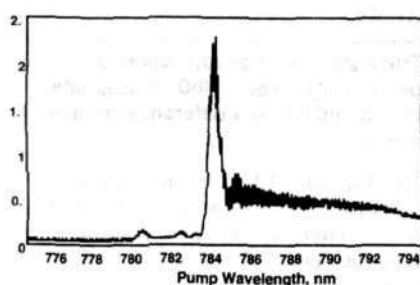
Mid-infrared laser absorption spectroscopy is a promising technique for environmental trace-gas detection because many important air contaminants have strong absorption bands in that spectral region. To access the 3–5 μm spectral region a convenient technique is difference frequency mixing in a non-linear material, which allows the frequency shifting of readily available near infrared diode laser sources. Periodically poled LiNbO₃ (PPLN) has desirable characteristics for such difference frequency mixing, including engineerable phase matching and a high non-linear coefficient (d_{eff}). The use of a tapered waveguide written onto the PPLN, leads to a further enhancement of the conversion efficiency of PPLN.^{1,2}

The DFG spectrometer employed in this work uses two commercial semiconductor lasers: a discrete master oscillator power amplifier tunable from 775 to 795 nm ('pump'), and a grating-stabilized tapered high-power oscillator at 1010 nm ('signal') as shown in Fig. 1. To simulate operating conditions expected of a compact low-power instrument, both lasers were operated at power levels below 150 mW. Each laser beam passed through an optical isolator, a half-wave plate and a telescope, emerging as a collimated, vertically polarized beam of near circular symmetry. The telescopes were adjusted such that the emerging beam diameters were roughly equal (~ 2.2 mm) for optimal simultaneous coupling into a waveguide. The laser beams were combined by a dichroic beamsplitter and focused at the input face of a channel waveguide array by a microscope objective.

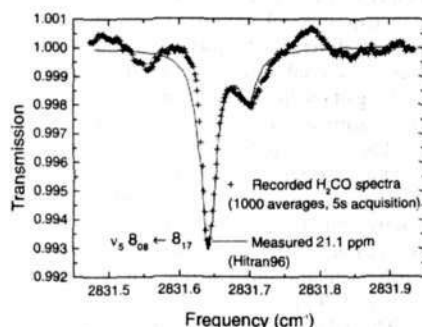
The key component of the DFG source, a $15 \times 10 \times 0.5$ -mm PPLN waveguide array, was fabricated by patterned proton exchange in molten benzoic acid for 36 hours at 160°C, and annealing in air for 38 hours at 340°C. It contained 75 channel waveguides arranged in groups of five for easy reference. All waveguides had the output channel width of 9 μm . Three out of five waveguides had their input ends preceded by a combination of a



CThK44 Fig. 1. Schematic diagram of a diode-pumped difference-frequency spectrometer using a PPLN waveguide.^{3,4}



CThK44 Fig. 2. Wavelength tuning curve at 3.5 μm : guided and unguided idler in PPLN waveguide.



CThK44 Fig. 3. Acquired H_2CO spectra (30 ppm H_2CO in N_2 , $P_{\text{total}} = 93$ torr, $L = 0.9$ m).

2-mm-long, $5 \rightarrow 9 \mu\text{m}$ linear width taper and a 1-mm-long, 5- μm -wide mode filter. The taper and the mode filter were segmented with a period of 20 μm . The segment duty cycle in the mode filter was 20%, while in the taper it increased parabolically from 20% to 100% (non-segmented).

To increase the absorption sensitivity for spectroscopy, balanced detection using a beam splitter and two photovoltaic InSb detectors was used. Repetitive frequency scanning of $\sim 0.4 \text{ cm}^{-1}$ was achieved by the use of a 200 Hz triangular wave voltage modulation applied to the piezo element of the extended cavity diode pump laser. Data was acquired by the use of two miniature (PCMCIA) 16 bit A-D cards with a sampling rate of 120 kHz. To allow simultaneous acquisition of the detector dark voltages in every frequency sweep, a chopper was operated synchronously with the frequency modulation.

The coupling efficiencies into the waveguide were 26% and 35% for the pump and signal wavelengths respectively. Hence for incident powers of 100 mW in each beam, 2.5 μW of radiation at 3.5 μm was generated corresponding to a conversion efficiency of 250 $\mu\text{W}/\text{W}^2$. A wavelength tuning curve is shown in Fig. 2 indicating that phasematching occurs at a pump wavelength of 784 nm ($\lambda_{\text{signal}} = 1010 \text{ nm}$). The broad phasematching feature at longer pump wavelengths is due to unguided waveguide radiation. The phase-matching bandwidth of the waveguide could be extended by synchronous tuning of the pump and signal wavelengths.

Figure 3 shows a spectrum of a 30 ppm calibrated H_2CO mixture in nitrogen at a pressure of 93 torr in a 90 cm long single pass

absorption cell. The measured concentration was 21.1 ppm as compared to a calibrated value of 30 ppm. This is due to one of the pump lasers operating in several longitudinal frequencies and which also leads to the observed baseline irregularities. From Fig. 3 it can be seen that the baseline noise corresponds to an absorption of 2×10^{-4} , or a minimum detectable concentration of 0.54 ppm.m.

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