

Robust broadly tunable mid-infrared spectrometer based on difference-frequency generation for gas sensing applications

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The recent development and characterization of a fiber coupled difference-frequency spectroscopic source tunable from 3.25 μm to 4.3 μm will be reported. This device uses as pump sources an external cavity diode laser (ECDL) operating from 814 nm to 870 nm and a 1083 nm distributed Bragg reflector (DBR) diode laser injection seeded Ytterbium doped fiber amplifier (Fig. 1) [1, 2]. Both diode lasers are coupled into a single mode fiber and combined by a wavelength division multiplexer (WDM). The linear polarization output from the fiber for an $e+e \rightarrow e$ nonlinear mixing process in the PPLN crystal is maintained by using two polarization controllers in the fiber delivery system. Gross frequency tuning of the ECDL is achieved by pivoting its diffraction grating relative to the optical axis of the laser cavity. Fine tuning and scanning of single or multi-component absorption lines of up to ~ 25 GHz is accomplished by current modulating the DBR diode laser. The Yb fiber amplifier pumped by a 975 nm, 2W diode laser boosts the available DBR seed pump power of 10 mW to ~ 540 mW.

Finding the optimum focusing into the PPLN crystal proved to be difficult. The theoretical conversion efficiency assuming a Gaussian beam shape yields $\sim 1.4 \text{ mW}\cdot\text{W}^{-2}$ [3]. An aspheric lens ($f=8$ mm; 0.5 NA) was used for imaging the fiber output into the 19 mm long PPLN crystal resulting in a measured conversion efficiency of $0.35 \text{ mW}\cdot\text{W}^{-2}$.

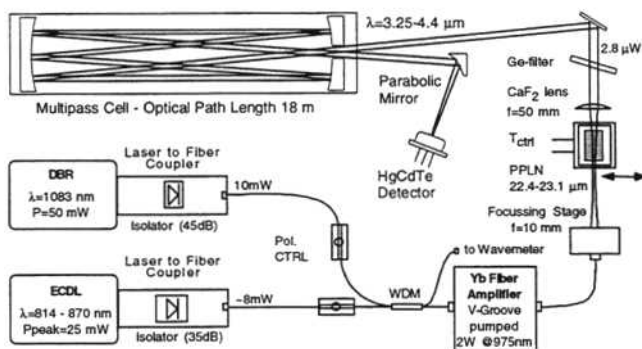


Figure 1: Optical set-up of a fiber coupled widely tunable DFG spectrometer.

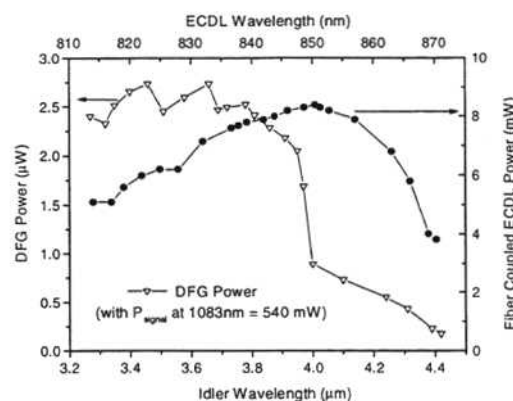


Figure 2: DFG Power and tuning characteristics of a DFG based mid-IR spectroscopic source.

Using an achromatic focusing lens ($f=10$ mm; 0.25 NA), the dispersion and refraction effects of the two pump beams imaged into the PPLN crystal were compensated and an experimental value of $0.74 \text{ mW} \cdot \text{W}^{-2}$ at a wavelength of $3.5 \text{ } \mu\text{m}$ was obtained. However, the small aperture (0.25) of the imaging lens causes diffraction effects and limits optimal focusing of the pump and signal beams.

Figure 2 shows the generated mid-IR power as a function of the mid-IR wavelength with a maximum mid-infrared power of $2.8 \text{ } \mu\text{W}$ (@ $3.46 \text{ } \mu\text{m}$).

QPM properties of the multi-channel PPLN crystal ($\Lambda=22.4 \text{ } \mu\text{m}$ to $23.1 \text{ } \mu\text{m}$; $0.1 \text{ } \mu\text{m}$ steps) were investigated applying two approaches. Firstly, the PPLN crystal was translated perpendicular to the optical axis to phase match the pump (ECDL) and signal (DBR) wavelengths for the respective nominal grating period at a constant temperature of 24.5°C . Secondly, the $23.1 \text{ } \mu\text{m}$ channel of the PPLN crystal was aligned to the optical axis and temperature tuning was used to phase match the signal, pump, and DFG beams from 3.65 to $4.4 \text{ } \mu\text{m}$ (Figure 3). The use of a new fan-out grating design for the PPLN crystal with effective periods ranging from $22.4 \text{ } \mu\text{m}$ to $23.3 \text{ } \mu\text{m}$ may provide continuous quasi-phase matching from $3.25 \text{ } \mu\text{m}$ to $4.4 \text{ } \mu\text{m}$ with a single mixing crystal.

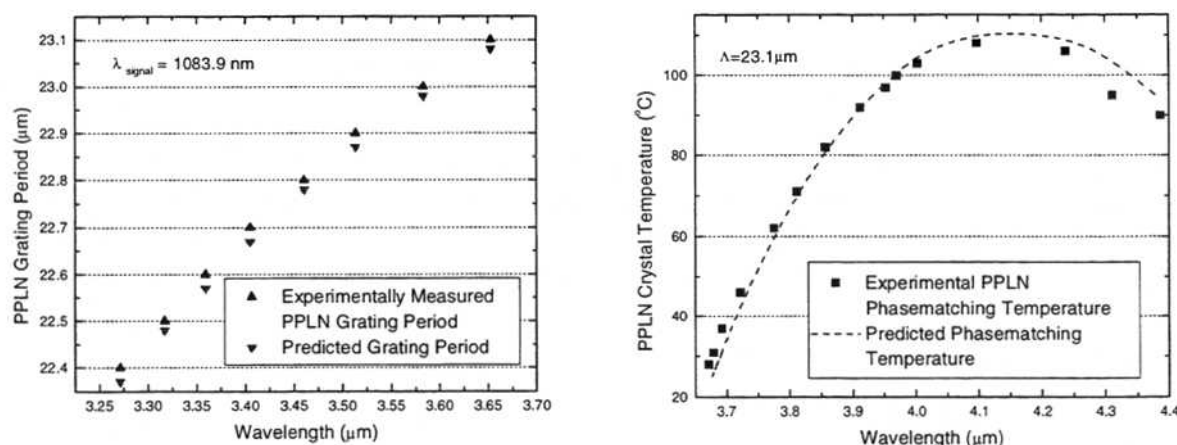


Figure 3: Two quasi-phase matching approaches by changing the nominal grating period (a) or temperature tuning at a fixed nominal grating period (b).

The spectra of CO_2 , N_2O , CH_4 , and H_2CO were used to determine the spectroscopic performance of this sensor. Figure 4 shows the CH_4 spectrum in the Q branch at $\sim 3018 \text{ cm}^{-1}$. As a monitoring test, a CH_4 absorption line at 3028.751 cm^{-1} [4] was used to detect ambient atmospheric levels. Using a cross section of $S=8.919 \times 10^{-20} \text{ cm}^2 / \text{molecule}$ given by the 1996 Hitran database, a concentration of 1811.5 ppb was established in comparison to the calibrated value of 1772.7 ppb for a NOAA air standard for the sample [5]. A standard deviation of $\pm 2\%$ was established from continuous measurements of this NOAA air standard for a 0.5 hour period.

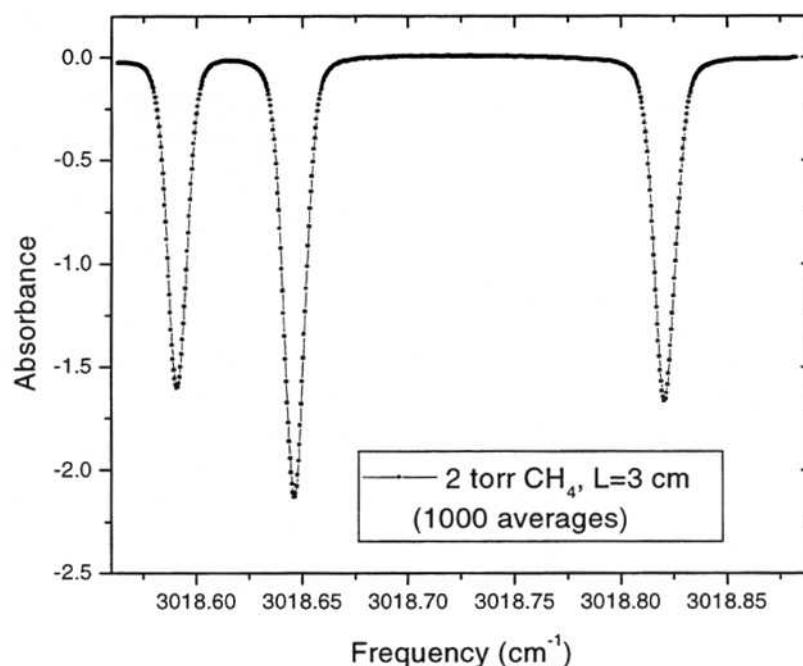


Figure 4: High resolution spectrum of CH₄ in the Q-Branch at 3018 cm⁻¹.

In summary, a robust, potentially compact and widely tunable fiber coupled mid-IR sensor suitable for the real-time detection of various trace gases will be described. Improvement of the focusing conditions into the PPLN crystal and a higher power (1 to 2) W fiber amplifier can further increase the conversion efficiency and the useful mid-infrared DFG power, respectively.

References:

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5. Courtesy of E. Dlugokencky, NOAA, Climate Monitoring & Diagnostic Laboratory, Boulder, CO.