Tunable, fiber coupled spectrometer based on difference-frequency generation in periodically poled lithium niobate

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Abstract: A Yb-fiber amplifier seeded by a 1083 nm DBR diode laser is fiber coupled with an external cavity diode laser (814 nm to 870 nm) and difference-frequency mixed in a periodically poled lithium niobate crystal (3.25 μm to 4.4 μm). Phase matching characteristics and the spectroscopic detection of several trace gases using this compact sensor will be reported.

OCIS code: (190.2620) Frequency conversion; (300.6340) Spectroscopy, infrared;

Introduction

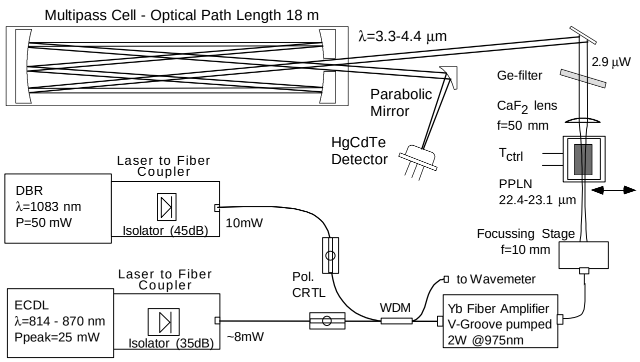
The recent development of compact mid-IR sources using frequency-converted near infrared diode laser using periodically-poled lithium niobate has been demonstrated to be applicable for the sensitive, selective and real time detection of many trace gas species in the mid-IR spectroscopic "fingerprint" region [1-3]. The optical architecture however has been based on discrete optical elements and is therefore susceptible to vibrations and temperature drifts if operated in a non-laboratory environment. In this paper we describe the development of a fiber coupled difference-frequency mixing mid-IR source with inherent robustness, high conversion efficiency and wide tunablity, packaged in a portable suitcase.

Sensor configuration

This spectroscopic mid-IR source reported here is tunable from 3.25 μm to 4.4 μm. The device uses as pump sources an external cavity (814 nm to 870 nm) and a distributed Bragg reflector (DBR, P=50mW, λ=1083 nm) diode laser seeding a Ytterbium doped fiber amplifier pumped by a 975 nm, P=2 W diode laser (Fig.1)[4,5]. Both lasers are coupled into a single mode fiber and combined by a wavelength division multiplexer (WDM). The linear polarization output from the fiber for a **e**+**e**→**e** nonlinear mixing process in the PPLN crystal is maintained by using two polarization controllers in the fiber delivery system. Coarse frequency tuning of the ECDL is achieved by rotation of 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 modulation of the DBR diode laser. The fiber amplifier boosts the seed pump power of 10 mW at 1083 nm to 540 mW.

Quasi-phase matching and DFG tuning characteristics

Firstly, an aspheric lens (f=8 mm; 0.5NA) was used for imaging the fiber output into the 19 mm



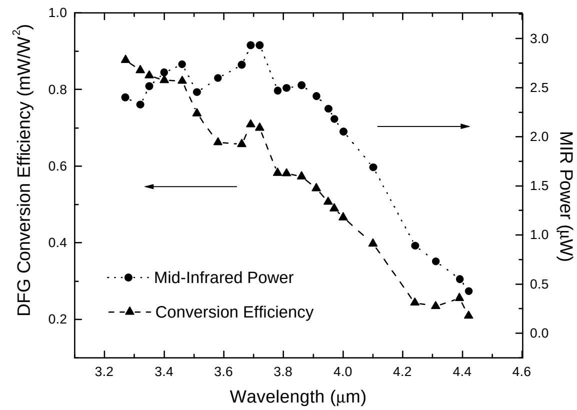


Fig.1: Optical set-up of a fiber coupled widely tunable DFG spectrometer

Fig. 2: Conversion efficiency and tuning characteristics of a DFG spectrometer

long PPLN crystal resulting in a DFG conversion efficiency of 0.35 mW/W^2. The theoretical DFG conversion efficiency yields ~1.4 mW$\cdot$ W^{-2} [3]. However, using this lens, chromatic aberration is causing an incomplete spatial overlap of the two pump beams. Subsequently, using an achromatic focusing lens (f=10 mm; 0.25NA), the dispersion and refraction effects of the two pump beams imaged into the PPLN crystal were compensated and an experimental value of 0.74 mW/W^2 at a wavelength of 3.5 µm 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.

Fig. 2 shows the obtained conversion efficiency and MID-IR power as a function of the generated MID-IR wavelength with a maximum mid-infrared power of 2.9 µW (@3.7 µm).

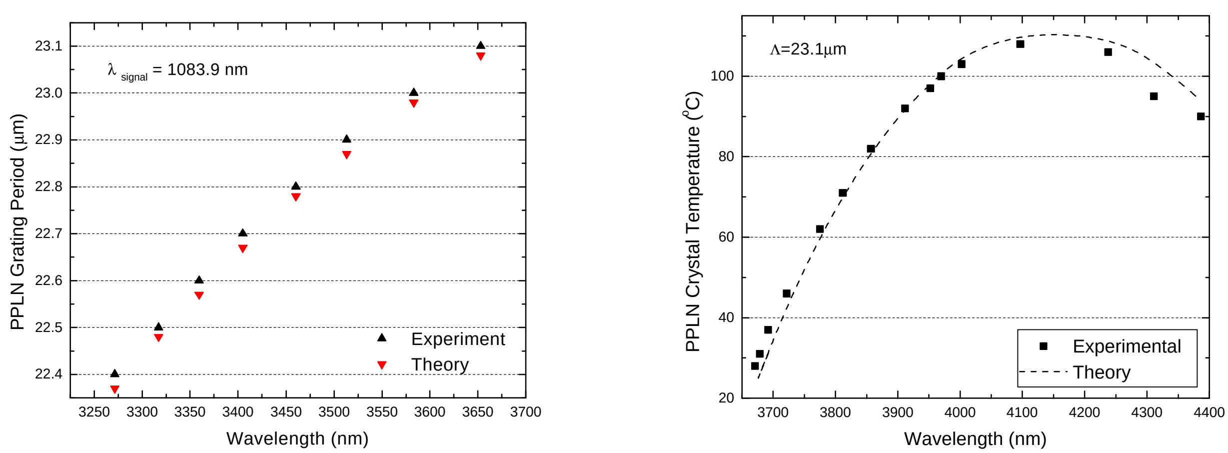


Fig. 3: Two quasi-phase matching approaches by changing the nominal grating period (a) or temperature tuning at a fixed nominal grating period (b)

QPM properties of the multi-channel PPLN crystal (Λ=22.4 – 23.1 µm; 0.1 µm steps) were investigated using 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 μm channel of the PPLN crystal was aligned to the optical axis and temperature tuning applied to phase match the signal, pump and DFG beams from 3.65 to 4.4 μm (Fig. 3).

Spectroscopic performance and real time detection

Detection of CO_2, N_2O, CH_4, H_2CO and NO_2 was used to determine the spectroscopic performance of this sensor. Fig. 3 shows a spectrum of a methane absorption line of the ν_3-band at 3038.51 cm^{-1}. Assuming a cross section of $S=8.919\times10^{-20}$ cm / molecule given by the 1996 Hitran database a concentration of 1811.5 ppb was established for a calibrated value of 1772.7 ppb (NOAA). A standard deviation of ± 2% was established from continuous measurements of a NOAA air standard [6] for a 0.5 hour long period.

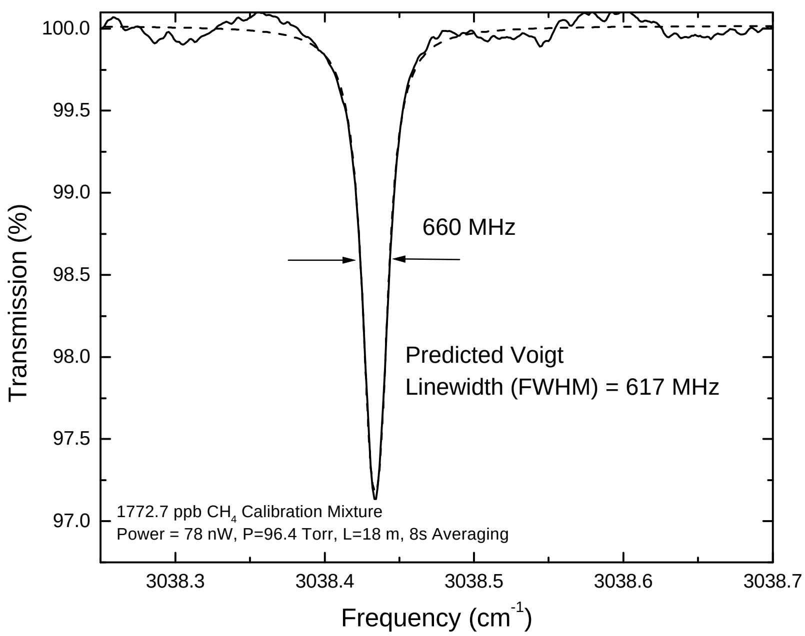


Fig. 4: Methane absorption line at 3038.52 cm^{-1} acquired from a calibrated gas mixture

The sensor, including driver electronics and optics, was mounted on a single breadboard measuring 45 cm x 45 cm x 12 cm and tested for an extended time period of time. Room laboratory air was sampled through the multi-pass cell at a pressure of 95 torr, maintained by a vacuum flow controller. Fig. 5 shows the detected methane concentration and the generated mid-IR power as a function of time. This long-term experiment shows reliable operation of the fiber coupled spectroscopic source of both the generated mid-IR power as well as the inherent frequency stability for a time interval of 18 hours.

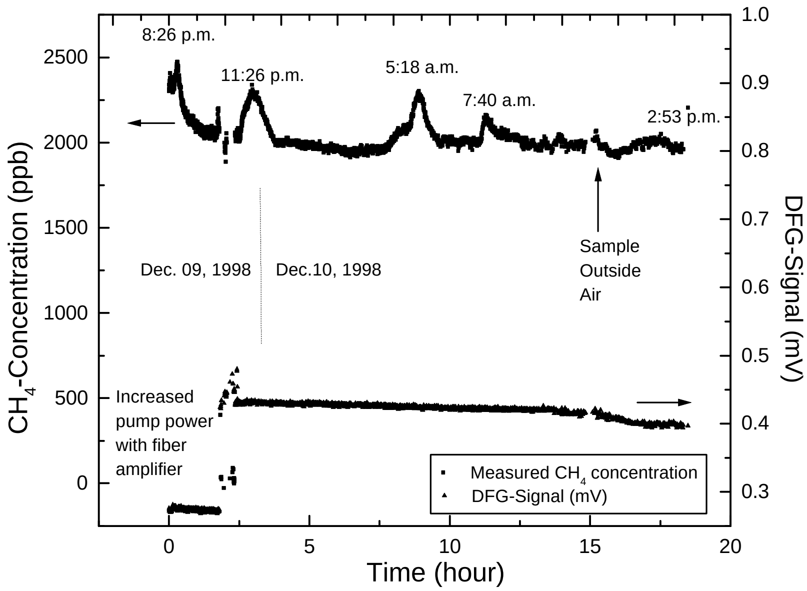


Fig.5: Long-term sampling of laboratory and outside air (upper trace) and mid-IR power for a 18 hour time interval

In conclusion, a robust, compact and widely tunable fiber coupled mid – IR sensor suitable for the real-time detection of various trace gases is described. For continuous and effective quasi-phase matching over the ECDL tuning range, a PPLN crystal with a fan-out design grating will allow rapid tuning and acquisition of different absorption lines. Improvement of the focussing conditions into the PPLN crystal and a higher power fiber amplifier can further increase the conversion efficiency and the mid-infrared DFG power, respectively. The sensor architecture is also suitable for difference-frequency generation of longer IR wavelengths using quasi-phase matched GaAs with a transparency range from 2 μm to 16 μm [7].

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