Compact high power mid-IR spectroscopic source based on difference frequency generation in PPLN

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Abstract: An all solid-state, fiber coupled spectroscopic source based on difference frequency generation (DFG) in periodically poled lithium niobate (PPLN) is reported that generates up to 0.7 mW continuous wave (cw), tunable mid-infrared power at 3.3 μm with a linewidth of < 60 MHz.
OCIS Codes: (190.2620) Frequency conversion; (300.6340) Spectroscopy, infrared

Introduction

The motivation for this work has been to develop a continuous wave DFG based sensor for sensitive, selective and real-time detection of trace gas species in ambient air at ppb levels in the spectroscopically important fingerprint region where most molecules posses characteristic ro-vibrational spectra. Various DFG pump source combinations have been investigated. Early DFG pump configurations were based on discrete optics but have now been replaced by fiber coupled diode laser sources and fiber amplifiers providing a more robust architecture, higher DFG pumping power and superior conversion efficiency based on fiber imaged near diffraction limited gaussian beams (Fig.1). Furthermore, advanced PPLN architectures such as fan-out grating structures provide continuous quasi-phase matching for DFG sources using widely tunable pump sources, e.g. external cavity diode or multi-section DFB InGaAsP diode lasers.

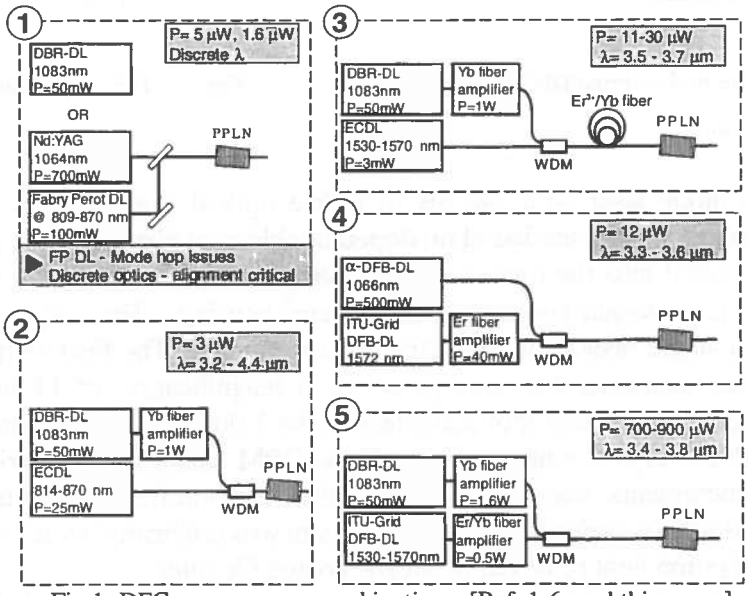

Fig.1: DFG pump source combinations. [Ref. 1-6, and this paper].

The use of optical telecommunications diode lasers and fiber technology combined with nonlinear optical parametric frequency conversion has resulted in a very robust compact gas sensor design, suitable for room temperature operation comparable to cryogenically cooled tunable Pb salt laser spectrometers [7]. Sensitive dual beam spectroscopy of CH_4 with an absorption sensitivity ($\pm 1\sigma$) of $\pm$ 2.8 $\times$ 10^{-5} was demonstrated using a Herriot cell with an effective 80 m path length using the DFG based sensor.

Configuration of spectroscopic source

A schematic of the spectroscopic source architecture is shown in Fig. 2. This mid-infrared source utilizes low power diode lasers at 1 and 1.5 μm, which seed 1.6 W Yb and 0.6 W Er/Yb fiber amplifiers, respectively. The signal seed source is a 1083 nm DBR diode laser, coupled into a single mode fiber to seed the Yb fiber amplifier via a -45 dB opto-isolator [5]. A 2 mW fiber pigtailed 1560 nm DFB

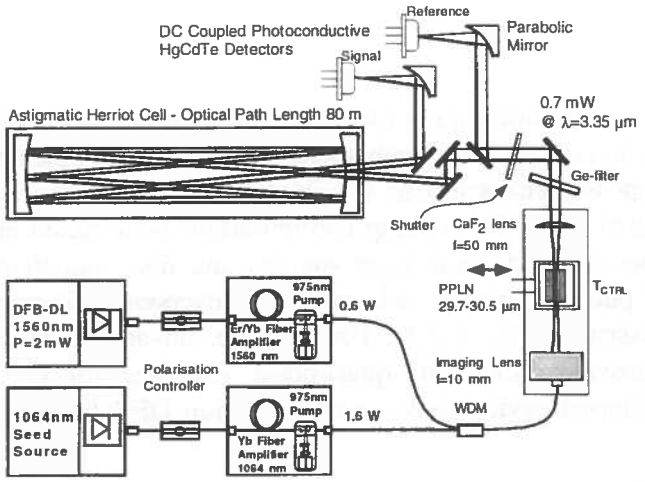

Fig. 2: Schematic of the mid-infrared DFG based spectroscopic source.

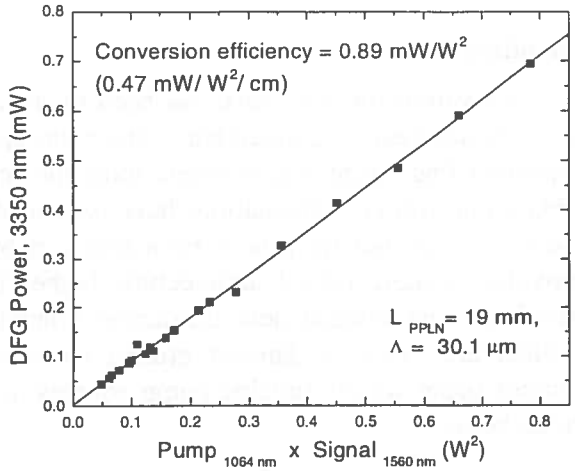

Fig. 3: DFG conversion efficiency

telecommunications diode laser with -80 dB of in-line optical isolation was used as the second seed source. The rare earth amplifiers are based on doped double-clad fibers that are pumped by single 975 nm 4 W diode lasers coupled into the outer hexagonal cross-section cladding by a V-groove configuration [8]. Each amplifier is packaged into an 8 $\times$ 10 $\times$ 2 cm^3 housing. The output from each fiber amplifier was combined into a single fiber by use of a fiber beam coupler. The fiber output was then imaged by a f =10 mm AR coated achromat lens configured for a magnification of 11 into a 19 mm long PPLN crystal, resulting in estimated beam spot diameters of the 1.06 μm and 1.56 μm beams of 63 and 89 μm, respectively. The PPLN crystal which contained nine QPM channels with periods ranging from 29.7 to 30.5 μm in 0.1 μm increments, was mounted on a Peltier element for temperature control and AR coated for pump, signal, and idler wavelengths. The DFG beam was collimated by a f = 5 cm CaF_2 plano-convex lens and the residual pump light removed by an AR coated Ge filter.

The reference beam for dual beam spectroscopic measurements was provided by the front surface 29% reflection from an uncoated ZnSe wedge placed in the beam at 45°. This beam was then directed to an

off-axis f = 3 cm parabolic mirror where the radiation was focussed onto the HgCdTe (MCT) reference detector. The remaining radiation was directed through an astigmatic Herriot cell, configured for a path length of 80 m before being directed onto a second MCT detector (data channel). The MCT detectors are operated in a photoconductive mode and is dc coupled to pre-amplifiers with 3 dB bandwidths of 200 kHz. Each detector has an area of 1 mm^2 and is operated at a temperature of -65°C by use of integrated 3-stage Peltier cooling elements.

The data for spectroscopic measurements was recorded by 2 separate 16 bit, A-D PCMCIA cards sampling in parallel at 200 kHz and interfaced to a laptop Pentium II PC running LabVIEW (National Instruments) and Windows98. A beam shutter after the Ge-filter allowed the dark voltage of each detector to be measured.

Fig.3 shows the conversion efficiency as a function of the pump power product, incident on the PPLN crystal. The diode laser pump and DFG powers were alternately measured with a calibrated thermopile detector. A maximum DFG power of 0.7 mW was generated and corresponds to a conversion efficiency of 0.47 $mW \cdot W^{-2} \cdot cm^{-1}$, which compares reasonable with the theoretically expected conversion efficiency of 0.76 $mW \cdot W^{-2} \cdot cm^{-1}$. This power value was corrected for optical reflection losses at the CaF_2 lens and germanium filter, the uncorrected value is 0.55 mW.

Spectroscopic performance

A spectrum of room air acquired over a 0.8 cm^{-1} scan range is shown in Fig. 4 which covers two H_2O lines and the $^{12}CH_4$ P(3) ν_3 ro-vibrational lines. A molecular concentration of 2021 ± 21 ppb CH_4 in air was calculated by fitting a Voigt line-shape to each CH_4 peak, and the resulting integrated line-shape areas were compared with those obtained from a cylinder of calibrated air containing 1772.7 ppb CH_4.

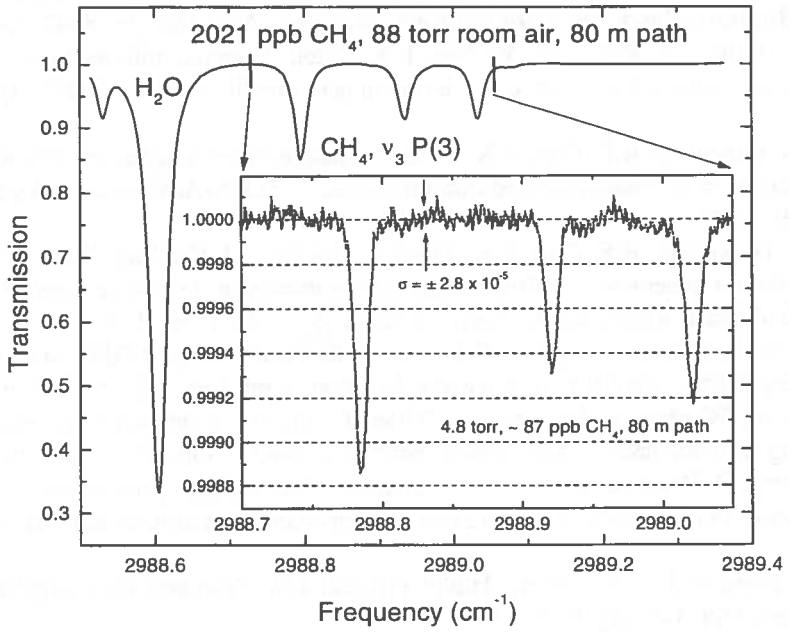

Fig. 4: Room air spectrum of the CH_4 P(3) ν_3 ro-vibrational lines at P = 88 torr and 2 H_2O lines. The inset is a low pressure CH_4 spectrum in the same spectral region (~87 ppb of methane in nitrogen)

The ±21 ppb error is attributable to the zero baseline estimation for each methane peak fitted arising from the superposition of the 5 primary absorption peaks and 3 weaker peaks. The inset to Fig. 4 is a reduced frequency range spectrum of a low CH_4 concentration (~87 ppb) in nitrogen at a cell pressure of 4.8 torr, and is an average of 1000 spectra (10 s average and 200 Hz detection bandwidth). This spectrum was acquired to display the P(3) ro-vibrational lines and baseline noise on the same scale, as well as reduce the effect of pressure broadening on the lineshapes. The baseline noise has a $\pm 1\sigma$ magnitude of $\pm 2.8 \times 10^{-5}$ (0.0028%) can be attributed to detector-preamplifier 1/f noise. Hence, a normalized detection sensitivity of 4.0×10^{-6} $Hz^{-1/2}$ and an estimated CH_4 detection sensitivity of 4.3 ppb·m·$Hz^{-1/2}$ (54 ppt for L = 80 m) is obtained.

During initial characterization of the sensor, a spiking behavior in the 1 μm pump power was observed. As a precaution to the diode laser seed source, an inherently optically isolated monolithic ring type Nd:YAG laser operating at 1064 nm was used for studying these effects. We attributed this behavior to a combination of stimulated Brillouin scattering (SBS) and Rayleigh scattering occurring in the pump beam delivery fiber, which produced backward propagating pulses that were subsequently amplified in the high gain Yb amplifier, thereby leading to power instability. To eliminate the SBS effects in the fiber, the delivery fiber was shortened from 7 m to 1.5 m, which increased the calculated threshold for SBS from 1.6 W to 7.3 W respectively, assuming a 5.7 μm field diameter in the fiber [9]. The effects of SBS and Rayleigh scattering can also be eliminated by use of an optical isolator placed at the output of the Yb amplifier and increasing the input seed laser power to saturate the fiber amplifier. Future work will focus on the use of dual-beam wavelength modulation spectroscopy [10] to further improve sensitivity and packaging of the sensor to permit long term monitoring of trace gases such as CH_4 and H_2CO with replicate prescion of sub-ppb levels for potential field applications.

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