Mid-IR frequency comb upconversion spectroscopy

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We present a mid-infrared frequency comb generated via difference frequency mixing of a Yb femtosecond fiber laser. After passing through a methane gas sample, the MIR comb is upconverted and dispersed onto a CCD for detection.
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A laser frequency comb in the mid-infrared (MIR) wavelength range could make an ideal candidate for a trace gas detection light source, combining the broad spectral coverage and precise knowledge of the frequency comb modes with the strong infrared absorption features of many molecules [1-3]. Our approach to generating a mid-infrared frequency comb uses difference frequency mixing [4] from an amplified ytterbium fiber laser (Fig.1) [5]. The amplified frequency comb has average power of 2.5W at a repetition rate of 100MHz, with spectrum and pulse duration as shown in Fig. 2a. A portion of this power is focused into a photonic crystal fiber (PCF) to broaden the output spectrum as shown in Fig. 2b. The longest wavelengths (from 1300nm-1700nm) are due to Raman soliton propagation in the PCF. We recombine this Raman shifted peak with the original spectrum (Fig. 1), and focus onto a 2mm long periodically poled lithium niobate crystal (PPLN 1) having periods chosen generate mid-infrared through difference frequency mixing. The wavelength of the Raman-shifted spectral peak can be tuned by adjusting the power incident on the PCF (as shown in Fig. 2c for a series of different input powers), allowing the MIR comb to be tuned over a wide range (Fig 2d), with up to 35mW of average power. Advantages of this approach to MIR generation include broad tunability, scalability via further amplification in Yb fibers, and a MIR comb that is offset frequency free.

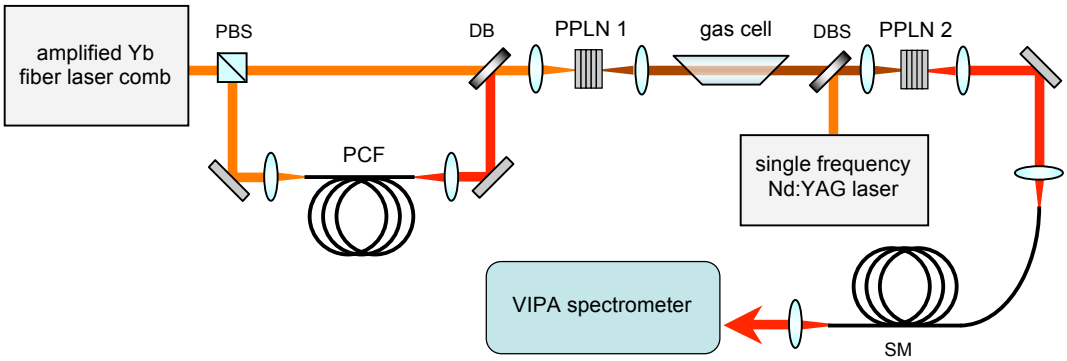

Fig.1. Diagram of the experimental setup. PBS polarizing beam splitter, DBS dichroic beam splitter. PCF photonic crystal fiber, SMF single mode fiber, PPLN periodically poled lithium niobate.

The MIR comb light was used to interrogate a methane gas cell with a path length of 11.7cm and methane pressure of 65 Torr. Fig. 3a shows the large bandwidth at a single Raman-shift setting with a monochromator trace of the unnormalized absorption transmission through the methane. In order to truly take advantage of the high resolution possibilities of mid-infrared spectroscopy using frequency combs, we need to be able to resolve the individual comb lines. Previous work in the visible and near-infrared regions [2, 6] used a two-dimensional technique combining a standard diffraction grating and a highly dispersive virtually imaged phased array (VIPA). Limitations in optical coating technology and MIR detector arrays restrict this approach to the visible and near-infrared ranges, and so we use a second nonlinear stage to upconvert the MIR spectrum back to ~800nm. The MIR light is combined with a 500mW, 1064nm CW Nd:YAG laser and focused onto a second PPLN crystal (see Fig. 1), generating a few nW of upconverted signal. The available second PPLN is 3.5mm long, limiting the upconversion phase matching bandwidth to only a portion of the full spectrum from Fig. 3a, but we expect a shorter PPLN should be able to recover the entire MIR bandwidth. Fig. 3b shows preliminary results obtained with VIPA imaging. Coarse VIPA alignment with a 795nm CW laser demonstrates spectral resolution of ~8 GHz, which is presently too low to resolve our 100MHz spaced comb lines. However, this result demonstrates the strong potential for this MIR comb upconversion technique, requiring only modest efficiency to be compatible with standard silicon CCD

technology rather than expensive and less sensitive MIR cameras or microbolometers. We expect that a combination of VIPA optical alignment improvements and upconverted comb tooth filtering will allow the comb modes to be individually resolved.

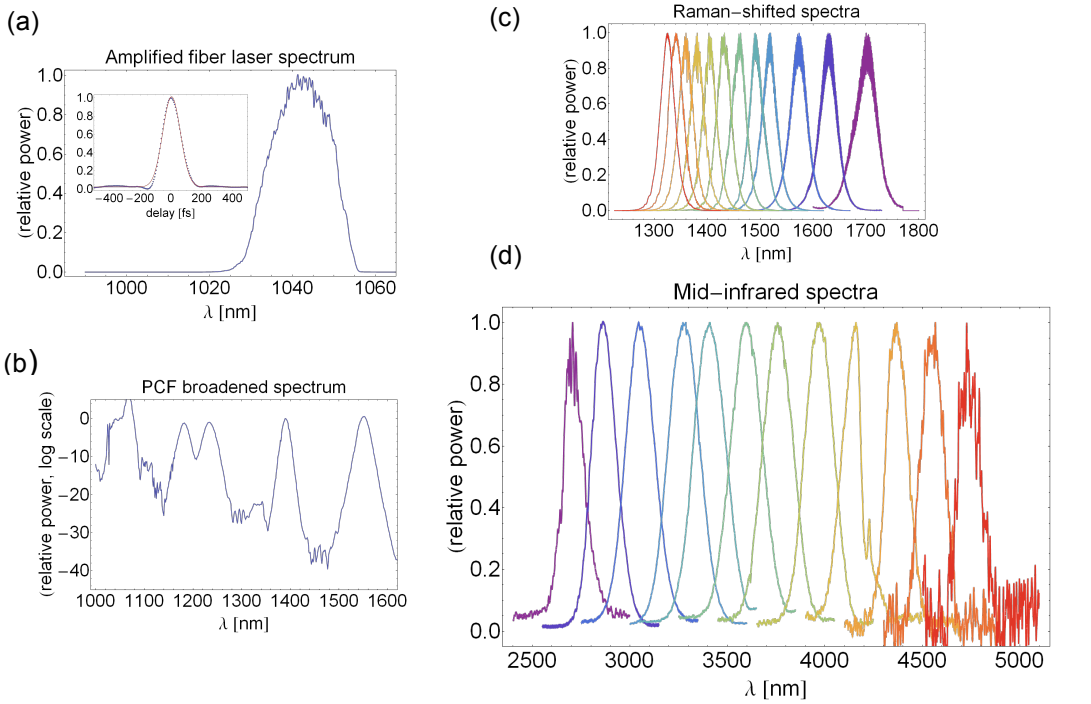

Fig.2. (a) Spectrum from amplified fiber laser, with inset showing ~130fs pulse duration. (b) Broadened spectrum. (c) Raman shifted spectra from PCF. (d) MIR spectra from difference frequency mixing between the amplified laser spectrum and the corresponding Raman peaks from (c).

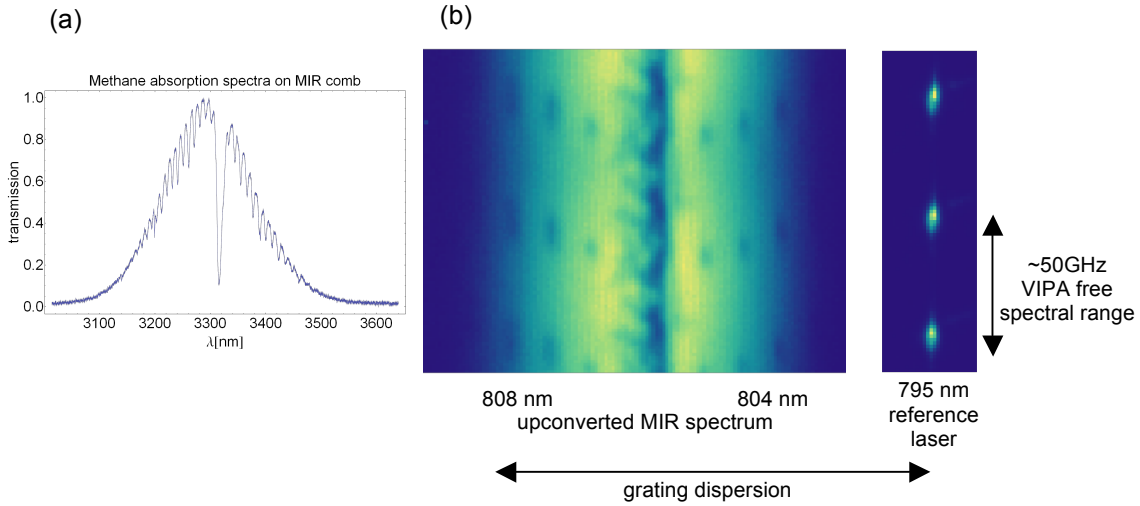

Fig. 3. (a) Monochromator trace of methane transmission with MIR comb. (b) CCD image of the upconverted spectrum using a VIPA and grating spectrometer. The dark central band corresponds to the strong absorption of methane near 3310nm, and the dark spots match the evenly-spaced weaker absorption features of part (a). Present resolution is ~ 8GHz.

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