Mid-Infrared Optical Frequency Combs based on Difference Frequency Generation for Dual-Comb Spectroscopy

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Abstract: Dual optical frequency combs at 2.8-3.4 μm with powers >210 mW were produced with femtosecond fiber-lasers and difference frequency generation. Interferograms between the combs have been demonstrated as a step towards mid-infrared dual-comb spectroscopy.
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1. Introduction

The development of optical frequency combs (OFCs) in the mid-infrared (MIR) has been the subject of intense interest [1]. One of the main motivations comes from the possibility of accessing the strong vibrational fundamental bands of molecular gases, where OFC spectroscopy combines fast-acquisition, high-resolution, precision and broadband coverage. In this direction, new and attractive techniques such as dual-comb [2] and VIPA spectroscopy [3] have been developed in combination with OFC sources. Important applications include atmospheric and greenhouse gas studies or hazard gas sensing and identification in the presence of additional background species.

Here we report the development and characterization of two MIR optical frequency combs centered at 3.0 microns produced by difference frequency generation in a single-pass PPLN crystal. Significantly, one of the combs employs a polarization maintaining fiber oscillator [4] and amplifiers, we generate more than 200 mW of idler MIR power covering 2.8 to 3.4 μm, for pump power of 1.4 W at 1 micron, and signal power of 120 mW at 1.5 μm. The multiheterodyne with the second comb at a repetition rate difference of ~100 Hz produced interferograms which demonstrate the coherence required for future dual-comb spectroscopy.

2. Mid-Infrared Optical Frequency Dual Combs - Design and Characterization

Two MIR OFCs have been constructed using schemes similar to those reported in refs. [5, 6, 7]. Since they are generated from a single Er oscillator, a key advantage is the cancellation of the carrier-to-envelope offset frequency by the DFG process. One of our combs uses polarization maintaining fibers and amplifiers, providing higher stability and robustness. This MIR OFC is based on a 100 MHz PM fiber erbium oscillator generating 5 mW at 1550 nm, with design similar to the one described in [4]. It is amplified and spectrally broadened to produce a few mWatt of light around 1060 nm using 3 cm of a highly nonlinear fiber (HNLF). This is amplified in a double-clad Yb fiber amplifier, and subsequently sent to a grating compressor, to produce a pump beam with 150 fs pulses and average power up to 5 watts within 1030-1080 nm. This beam is directed to a 3 mm-long PPLN crystal where it is mixed with 120 mW, 150 fs pulses from the amplified Er oscillator at 1520-1620 nm. We use a single-grating crystal with periods varying from 27.9 to 31.6 μm. The second MIR OFC is based on a commercial Er oscillator (Menlo), and is designed in a similar way using non-PM fibers and a 1-mm long PPLN crystal. Its repetition rate is adjusted to provide a low frequency repetition rate difference with respect to the other oscillator. For these preliminary experiments, both oscillators were free-running, although the offset-free nature of the MIR combs should require simplified stabilization of only the comb repetition rates.

Figure 1a shows typical spectra of both MIR combs, extending from 2.8 to 3.4 microns. This range nearly reflects the spectra of pump and signal beams, except at the longer wavelengths where additional spectral bandwidth is expected. The narrow absorption peaks that can be seen in these spectra, recorded in high-resolution MIR optical spectrum analyzer, are due to atmospheric water absorption in a 1.5 m path length. The inset shows a portion of the absorption spectrum of two isotopomers of acetylene (C_2H_2 and $^{13}C_2H_2$).

Figure 1b shows a power plot for the PM MIR comb, as a function of pump power at 1060 nm for a signal power of 120 mW at 1550 nm. Although our Yb amplifier can provide higher powers, we have limited it here to avoid

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damage to the crystal, since the waist size (20 µm) was kept close to the optimum value. The obtained MIR power of 215 mW (for P_{pump} = 1.4 W and P_{signal} = 120 mW) can still be scaled up in the present setup. Figure 1c is the MIR power recorded over a few hours, for the PM comb, showing a fractional standard deviation of 3.5%. This variation arises from temperature and pressure driven changes in the optical path lengths, none of which are presently environmentally isolated.

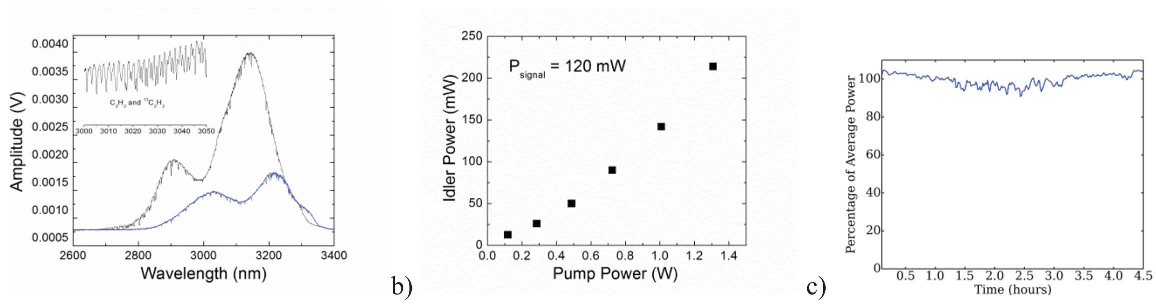

Figure 1. a) Typical MIR spectra produced by the PM (black) and non-PM (blue) fiber combs. Inset shows a spectrum of C_2H_2 and $^{13}C_2H_2$ as measured with the same MIR spectrum. b) Power plot for the PM MIR OFC. c) Power stability for the PM MIR OFC.

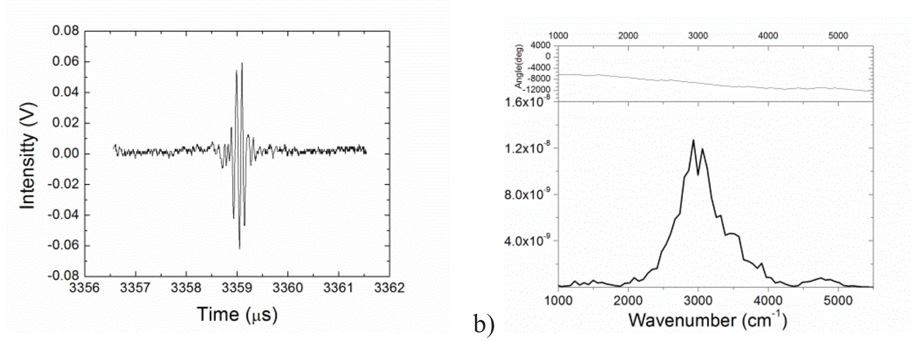

Figure 2. a) Interferogram obtained in dual-comb MIR spectroscopy, using free-running oscillators. B) FFT of the interferogram, after conversion from time delay to displacement.

3. Coherence between free-running combs and prospects for dual-comb spectroscopy

Figure 2a shows a single-shot interferogram obtained from the multiheterodyne between the full bandwidth of both MIR combs. The MIR beams have been combined in a 50/50 CaF_2 beamsplitter and directed to a fast InAs biased photodetector. The generated voltage is amplified in a 200 MHz amplifier and sent to a fast scope. The repetition rate difference, Δf_{rep}, between the Er oscillators has been adjusted to ~100 Hz. Figure 2b shows the FFT of the interferogram. The band centered at 3000 cm^{-1} shows good agreement with the convolved optical spectra of the two combs. Since the sampling duration of Fig 2(a) is relatively short and the oscillators have not been stabilized, we do not expect to resolve the comb lines in the present configuration, but nonetheless our systems show good prospects for high-resolution dual-comb spectroscopy [1] with high power in the MIR.

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