CMN5.pdf

Dual Frequency Combs at 3.4 μm with Subhertz Residual Linewidths

E. Baumann, F. R. Giorgetta, I. Coddington, W. C. Swann, N. R. Newbury
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305
esther.baumann@nist.gov

Abstract: Two coherent 1.5 µm frequency combs are transferred to 3.4 µm by difference-frequency generation with a 1064 nm cw laser. From a multi-heterodyne measurement, the residual linewidth between the comb teeth is resolution-limited at 200 mHz.

OCIS codes: 300.6340 (Spectroscopy, infrared), 320.7090 (Ultrafast lasers)

Frequency combs have proven to be a powerful tool in a diverse range of applications, most recently including broadband precision molecular spectroscopy [1-4]. However, standard frequency comb sources cover the visible to near-infrared portion (up to 2 µm) of the spectrum and do not extend out further to the mid-infrared (MIR), 2 µm – 5 µm region, where many fundamental molecular absorption lines are found. Therefore, there have been a number of efforts to extend frequency combs to the MIR to support spectroscopic applications [5-7]. These MIR frequency combs could be used as a wavelength reference for MIR swept laser spectroscopy [8] or directly in dual-comb spectroscopy [1-3]. Here, we generate a MIR frequency comb through difference-frequency generation (DFG) in a periodically poled Lithium Niobate (PPLN) ridge waveguide [9] between a cw 1064 nm laser source and two Er-fiber-laser frequency combs at 1.5 µm. The two fiber-laser combs are phase-locked tightly together with less than a radian of optical phase noise in a bandwidth from subhertz up to the Nyquist frequency. We demonstrate that the corresponding residual linewidth between teeth of the generated 3.4 µm combs is resolution-limited for our 5 second observation period at 200 mHz. Based on our results, we will also discuss the prospects for dual-comb spectroscopy in the 3 µm region.

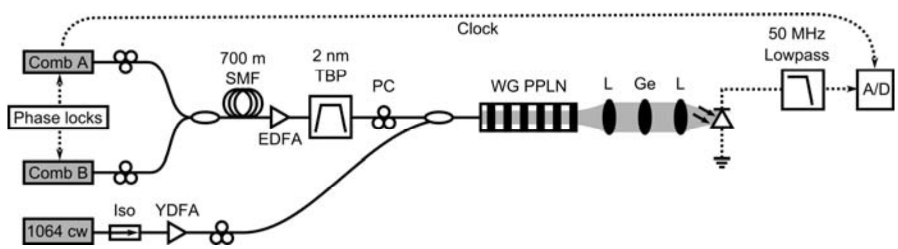

Fig. 1: DFG comb setup. Combs A and B are each Er-fiber-laser frequency combs that are phase-locked together with sub-radian phase noise. Their output is stretched, amplified, filtered, and then converted to around 3.375 µm in a ridge waveguide PPLN. The 1064 nm laser is a cw fiber laser. EDFA: Erbium-doped fiber amplifier, SMF: single-mode fiber, TBP: tunable bandpass, PC: polarization control, L: CaF lens, Ge: Germanium filter.

Our approach follows [5] and exploits the availability of fiber-coupled ridge waveguide PPLN with a conversion efficiency of ~5%/W. The setup is shown in Fig. 1. CW light from a 1064 nm fiber-laser source is amplified to 200 mW and fiber-coupled into the ridge waveguide. Here, the frequency of the 1064 nm laser was free-running, but its linewidth could be narrowed to Hertz level by phase-locking it to a stabilized fiber-comb or to a cavity. The outputs of two coherent Er-fiber frequency combs are combined, stretched by use of 700 m of SMF to reduce the peak power, amplified, and then filtered in a tunable bandpass filter with a passband that exceeds slightly the phase-matching bandwidth of the PPLN at a given temperature. The combined average comb power impinging on the PPLN is 2 mW. Given the 200 mW of 1064 nm light and 5%/W conversion efficiency of the PPLN, the resulting DFG power per comb is estimated at 10 µW over approximately 2000 comb teeth yielding 5 nW/tooth. Higher comb tooth powers could be achieved by including additional amplification after the filter; however, this power is

CMN5.pdf

sufficient to measure the linewidth of the comb teeth. The two 3.4 µm combs are detected on an InAs detector with a dark-current-limited noise equivalent power (NEP) of 15 pW/Hz$^{1/2}$.

To measure the comb linewidth, we use a multi-heterodyne approach. The repetition rates of the two combs (labeled A and B in Fig. 1) are centered at 100 MHz but differ slightly by 3.142 kHz. Heterodyning of comb A and B leads to an rf comb with a spacing of 3.142 kHz between the comb teeth. Fig. 2 shows the heterodyne beats for a filter setting at 1556 nm. We clearly observe the individual rf beats between pairs of comb teeth from 3.37 µm to 3.38 µm. The conversion wavelength window is given by the quasi-phasematching condition of the PPLN; the window's center wavelength can be shifted by tuning the PPLN temperature. As expected, the residual linewidths of the beat notes between the combs are conserved through the DFG. For the full 5 seconds of data acquisition (limited by the on-board memory of the digitizer), we find a resolution limited linewidth of 200 mHz. Therefore, the absolute linewidth of the 3.4 µm comb will be limited by the absolute linewidth of the 1.5 µm combs and 1 µm laser, both of which could be reduced to Hertz levels or below by use of cavity-stabilized lasers.

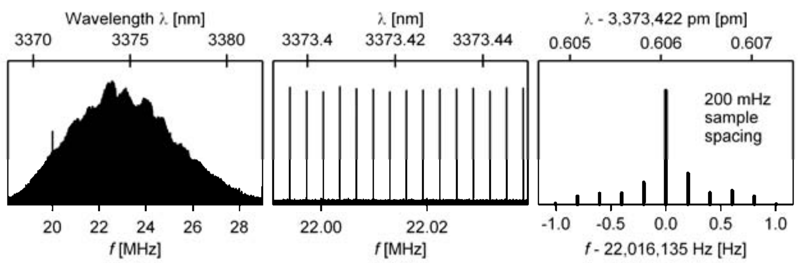

Fig. 2: RF beats between the comb lines of combs A and B for a difference in repetition rate of 3.142 kHz. The origin of the bottom abscissa lies at 3346 nm, where the teeth of both combs A and B overlap. The left panel shows the full rf spectrum, limited by the phase-matching of the PPLN (there is a spurious spike around 20 MHz). The top axes give the wavelength of the corresponding optical comb. The ripple is attributed to etaloning effects. The middle panel is the same rf spectrum expanded ~250× in the horizontal scale showing the clearly separated rf heterodyne signals from individual pairs of comb teeth. The right panel shows a single heterodyne beat, which has a resolution-limited linewidth of 200 mHz.

A fully phase-locked 1064 nm laser would provide Hertz level absolute linewidths at 3.4 µm, which would be useful for precision optical frequency metrology. However, the tight residual coherence between the 3.4 µm combs is already sufficient for dual-comb spectroscopy, because it permits long coherent averaging periods. Therefore, although a swept laser system will always provide much superior SNR, it is interesting to consider the SNR achievable in use of the combs directly in dual-comb spectroscopy. Fortunately, some of the SNR loss inherent in the 1% conversion to 3.4 µm, and in the large detector NEP, can be overcome by a combination of pre-amplification of the 1.5 µm comb and through Felgett's advantage common to Fourier spectroscopy [10]. We will discuss the SNR achievable with this system.

References

[1] I. Coddington, W. C. Swann, and N. R. Newbury, Coherent multiheterodyne spectroscopy using stabilized optical frequency combs, Phys. Rev. Lett. **100**, 013902 (2008).
[2] F. Keilmann, C. Gohle, and R. Holzwarth, Time-domain mid-infrared frequency-comb spectrometer, Opt. Lett. **29**, 1542–1544 (2004).
[3] A. Schliesser, M. Brehm, F. Keilmann, and D. van der Weide, Frequency-comb infrared spectrometer for rapid, remote chemical sensing, Opt. Express **13**, 9029–9038 (2005).
[4] M. Thorpe and J. Ye, Cavity-enhanced direct frequency comb spectroscopy, Appl. Phys. B **91**, 397–414 (2008).
[5] P. Maddaloni, P. Cancio, and P. De Natale, Optical comb generators for laser frequency measurement, Measurement Science and Technology **20**, 052001 (19pp) (2009).
[6] S. Bartalini, P. Cancio, G. Giusfredi, D. Mazzotti, P. De Natale, S. Borri, I. Galli, T. Leveque, and L. Gianfrani, Frequency-comb-referenced quantum-cascade laser at 4.4 µm, Opt. Lett. **32**, 988–990 (2007).
[7] C. Erny, K. Moutzouris, J. Biegert, D. Kuhlke, F. Adler, A. Leitenstorfer, and U. Keller, Mid-infrared difference-frequency generation of ultrashort pulses tunable between 3.2 and 4.8 µm from a compact fiber source, Opt. Lett. **32**, 1138–1140 (2007).
[8] A. F. Dirk Richter and P. Weibring, Difference frequency generation laser based spectrometers, Laser & Photonics Reviews **3 (4)**, 343–354 (2008).
[9] M. Asobe, O. Tadanaga, T. Yanagawa, T. Umeki, Y. Nishida, and H. Suzuki, High-power mid-infrared wavelength generation using difference frequency generation in damage-resistant Zn : LiNbO3 waveguide, Electron. Lett. **44**, 288–290 (2008).
[10] P. R. Griffiths and J. A. Haseth, *Fourier Transform Infrared Spectrometry* (Wiley-Interscience, 2007).