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Frequency divide-and-conquer approach to producing octave-wide frequency combs and few-cycle pulses in the mid-IR[1]

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I will present a new technique for extending frequency combs to the highly desirable yet difficult-to-achieve mid-IR spectral range. The technique is based on subharmonic optical parametric oscillation (OPO) that can be considered as a reverse of the second harmonic generation process. The frequency comb of a pump laser is transposed to half of its central frequency and simultaneously spectrally augmented, thanks to an enormous gain bandwidth of the OPO near degeneracy, as well as due to massive cross-coupling between the laser and the OPO frequency comb components. Using ultrafast erbium (1.56 microns) or thulium (2 microns) -based fiber lasers as a pump and using thin, sub-mm-long, quasi phase-matched lithium niobate [1] or gallium arsenide [2] crystals, we produce frequency combs centered correspondingly at 3.1 or 4 micron subharmonic of the pump frequency. With the properly managed OPO cavity group velocity dispersion, octave-wide frequency combs spanning 2.5 - 6 micron range were achieved. Due to the doubly-resonant operation, the threshold of such a system is low (typically 10 mW) and by several experiments including measuring frequency beats between the OPO comb teeth and a narrow-linewidth CW laser and by interfering the outputs of two identical but distinct OPOs pumped by the same laser [3], we established that the frequency comb from a subharmonic OPO is phase-locked to that of the pump laser. Pulse duration measurements show that for the optimal intracavity dispersion conditions, we generate sub 5-cycle pulses at the subharmonic of the pump. I will also talk about applications of our mid-IR frequency combs to trace gas detection, where part-per-billion sensitivity of molecular detection is achieved [4] as well as about Fourier spectroscopy using a dual-comb system consisting of two phase-locked lasers. [1] N. Leindecker, A. Marandi, R.L. Byer, K. L. Vodopyanov, "Broadband degenerate OPO for mid-infrared frequency comb generation," Opt. Express 19, 6296-6302 (2011). [2] N. Leindecker, A. Marandi, R.L. Byer, K. L. Vodopyanov, J. Jiang, I. Hartl, M. Fermann, and P. G. Schunemann "Octave-spanning ultrafast OPO with 2.6-6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser," Opt. Express 20, 7047-7053 (2012). [3] A. Marandi, N. Leindecker, V. Pervak, R.L. Byer, K. L. Vodopyanov, "Coherence properties of a broadband femtosecond mid-IR optical parametric oscillator operating at degeneracy," Opt. Express 20, 7255-7262 (2012). [4] M. W. Haakestad, T. P. Lamour, N. Leindecker, A. Marandi, and K. L. Vodopyanov, "Intracavity trace molecular detection with a broadband mid-IR frequency comb source," J. Opt. Soc. Am. B 30, 631-640 (2013).

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