Continuous-wave modulation of a femtosecond Ti:sapphire oscillator
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Over the last two decades the invention of and developments in femtosecond lasers have had a big impact on a diverse range of scientific fields including biological imaging, nanotechnology, and ultrafast spectroscopy [1]. A critical development in the evolution of these lasers was the discovery of methods to broaden their frequency spectrum, which has typically been done using self-phase-modulation inside a photonic crystal fiber. Using such broadening an octave-wide spectrum can be produced which allows $f - 2f$ spectroscopy and locking of the carrier-envelope phase (CEP) of the comb [1]. In this talk, we describe a new method to broaden the frequency spectrum of a femtosecond laser oscillator [2]. The method relies on continuous-wave (CW) optical modulation of the femtosecond oscillator at a rate of 90 terahertz (THz) using Raman based four-wave mixing [3]. We prepare the optical modulator by driving deuterium (D$_2$) molecules to a highly coherent vibrational state using intense CW pump and Stokes laser beams inside a high finesse cavity. Once coherent vibrations are established, we can send any carrier laser through the cavity and produce frequency downshifted (Stokes) and upshifted (anti-Stokes) sidebands. The carrier beam does not need to be resonant with the cavity; the modulation is produced in a single pass. In particular, a femtosecond Ti:sapphire laser oscillator whose spectrum is centered at 800 nm is frequency modulated to produce upshifted and downshifted sidebands centered at wavelengths of 650 nm and 1.04 $\mu$m, respectively. The steady-state single-pass efficiency of our modulator is $\sim 10^{-6}$ and transient (10 $\mu$s-time-scale) single-pass efficiency is $\sim 10^{-4}$ (the efficiency is the ratio of the generated frequency upshifted sideband power to the incident carrier power). Figure 1 shows the modulated Ti:sapphire output observed on a grating spectrometer over the 600-900 nm spectral range, clearly showing the frequency upshifted anti-Stokes sideband.

![Figure 1: The modulated Ti:sapphire spectrum at the output of the cavity as recorded on a grating spectrometer, clearly showing the incident Ti:sapphire spectrum as well as the frequency upshifted anti-Stokes sideband. The plots are obtained for two different modes of operation for the Ti:sapphire laser: (a) without mode-locking (and therefore narrow spectrum), (b) with mode-locking. The solid blue lines are the spectrum analyzer scans showing the Ti:sapphire and the frequency upshifted spectrum simultaneously. The solid orange lines are separate scans of the initial unmodulated Ti:sapphire spectrum that are normalized in order to more clearly display the input spectral features.](image)

References