The Extreme Ultraviolet Frequency Comb and Prospects for X-ray Combs

T. K. Allison[1], D. C. Yost[1], A. Cingöz[1], A. Ruel[2], and M. E. Fermann[2], I. Hartl[2], and J. Ye[1]

[1]*JILA, National Institute of Standards and Technology and University of Colorado, Department of Physics, Boulder, CO 80309, USA.*

[2]*IMRA America, Inc., 1044 Woodridge Ave., Ann Arbor, MI 48105, USA.*

The application of precision laser spectroscopy techniques to the extreme ultraviolet (XUV) and x-ray spectral regions will enable many exciting endeavors, including precision tests of quantum electrodynamics [1], searches for variations of fundamental constants [2], and precision measurements of nuclear Mössbauer transitions. However, there currently exist no narrow linewidth cw lasers in the XUV or x-ray regions. Lack of a narrow linewidth cw source can be overcome by using a frequency comb [3], operating on the principle that a repetitive train of short pulses with definite phase relationship consists of a comb of narrow frequency lines spaced by the repetition frequency. In the visible and inrared regions, frequency combs have revolutionized frequency metrology by providing a direct link between optical frequencies and primary radio frequency standards.

A promising method for extending frequency comb spectroscopy to the XUV is high order harmonic generation of an infrared frequency comb at the focus of a high finesse cavity. A first generation system was able to achieve greater than 100 nW of average power up to the 21st harmonic at 51 nm [4,5]. Here we will present results of the power scaling of this technique using a new 80-W average power Yb fiber laser with 120 fs pulse duration at a repetition rate of 154 MHz [6]. The harmonic spectrum obtained at 5 kW intracavity power with 500 Torr of Xe backing pressure is shown in Fig. 2 (b). The inset shows the CCD image used to extract the line scan through the spectrum. Even with only 10% output coupling, we determine 3.7, 3.8, 1.3, 1.8, and 0.7 μW of average power for the 9^{th} through 17^{th} harmonics, respectively. The corresponding photon fluxes range from 2.2×10^{12} to 1.2×10^{11} photons/s for increasing harmonic orders. These preliminary results are very promising in terms of the scalability of high harmonic powers since a factor ~10 increase has been obtained with a relatively modest increase in intracavity peak

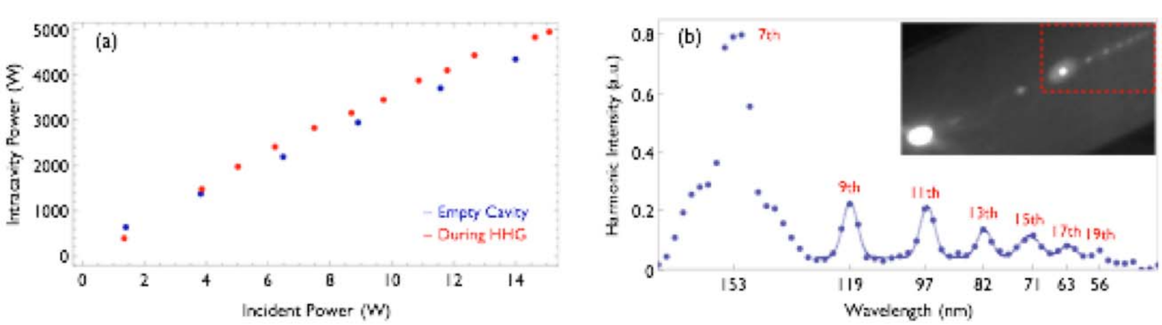

Figure 0: (a) Intracavity buildup. (b) The high harmonic spectrum. Inset shows the CCD image with the relevant harmonics in red box.

intensities. We will discuss these results and an ongoing effort to perform the first spectroscopy with the XUV comb at 82 nm in an Ar supersonic molecular beam.

The cavity enhancement technique could also potentially be used with similar average inracavity power to seed an echo enabled harmonic generation free electron laser [7,8], which requires only modest laser seed energies. In this scheme, electron bunch energy modulation would occur at a short undulator placed at the intracavity focus of the enhancement cavity. We will present some estimates of the feasibility of producing a frequency comb in the x-ray light accounting for sources of phase noise in the laser seeding and FEL processes.

[1] E. E. Eyler, D. E. Chieda, M. C. Stowe, M. J. Thorpe, T. R. Schibli, and Jun Ye,"Prospects for precision measurements of atomic helium using direct frequency comb spectroscopy", *Eur. Phys. J. D* 48, 43 (2008)

[2] W. G. Rellergert, D. Demille, R. R. Greco, M. P. Hehlen, J. R. Torgerson, and E. R. Hudson, Constraining the Evolution of the Fundamental Constants with a Solid-State Optical Frequency Reference Based on the ^{229}Th Nucleus. *Phys. Rev. Lett.* **104**, 200802 (2010).

[3] Jun Ye and S. T. Cundiff, Colloquium: Femtosecond Optical Frequency Combs, *Rev. Mod. Phys.* **75**, 325 (2003).

[4] I. Hartl., T. R. Schibli, A. Marcinkevicious, D. C. Yost, D. D. Hudson, M. E. Frmann, and Jun Ye, Cavity-enhanced similariton Yb-fiber laser frequency comb: 3×10^{14} W/cm^2 peak intensity at 136 MHz. *Opt. Lett.* **32**, 2870-2872 (2007)

[5] D. C. Yost, T. R. Schibli, and Jun Ye, Efficient Output Coupling of Intracavity High Harmonic Generation, *Opt. Lett.* **33**, 1099 (2008).

[6] A. Ruehl, A. Marcinkevicius, M. E. Fermann, and I Hartl. 80 W, 120 fs Yb-fiber Frequency Comb. *Opt. Lett.* **35**, 3015.

[7] G. Stupakov, Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation. *Phys. Rev. Lett.* **102,** 074801.

[8] D. Xiang and G. Stupakov, Echo-enabled harmonic generation free electron laser. *Phys. Rev. ST Accel. Beams, **12**, 030702.*