Femtosecond laser frequency combs: optical synthesizers for precision spectroscopy and frequency metrology

S. Diddams, A. Bartels , T. Fortier , E. Ivanov*, K. Kim, J. McFerran*, W. H. Oskay, G. Wilpers, C. W. Oates, J. C. Bergquist and L. Hollberg**
Time and Frequency Division, National Institute of Standards and Technology
325 Broadway M.S. 847, Boulder CO 80305

V. Gerginov and C. E. Tanner
Department of Physics, University of Notre Dame, Notre Dame, IN 46556-5670

A femtosecond laser frequency comb (FLFC) is the broadband (octave-spanning) evenly-spaced array of optical frequencies that is present in the output of a femtosecond mode-locked laser [1,2]. Such frequency combs immediately found wide-spread use in optical frequency metrology and emerging optical atomic clocks, and now their role in a variety of other precision measurements is beginning to emerge. Beyond a general review of FLFC s and their generation and control, in this talk we will cover the following topics.

Properties of FLFC s stabilized to optical cavities and atomic transitions. Of relevance to high resolution spectroscopy is our demonstration that when phase-locked to a suitably narrow CW laser, the individual elements of a Ti:sapphire-based FLFC (spanning ~550 1000 nm) can have linewidths at or below 1 Hz. Thus, one can use the FLFC to translate the linewidth and stability of a single well-stabilized CW laser to virtually any color. In related experiments, we have further verified that the frequency position of the FLFC elements relative to the CW reference laser can be known with an uncertainty approaching one part in 10^{19}. These results lead us to conclude that the FLFC is a reliable tool for optical atomic clocks of the future and for laboratory-based tests of the equivalence principle (e.g. searches for time-variations of fundamental constants).

Synthesis of low noise microwave frequencies. Beginning with a CW laser stabilized to a high-Q optical resonator, we can use the FLFC to phase-coherently divide the optical carrier down to a microwave frequency at the repetition rate, f_r, of the femtosecond laser. Electronic microwave signals (at f_r or one of its harmonics) are then generated in the photocurrent of a high-speed detector that is illuminated by the optically-stabilized femtosecond pulse train. In this manner we have demonstrated the generation of a 10 GHz microwave signal having instability of $\sim 3\times 10^{-15}$ in 1 second of averaging and unprecedented low phase noise close to the carrier. The residual noise of the FLFC indicates that instabilities at or slightly below 1×10^{-15} (1 s averaging) should be achievable with the present system.

High-resolution spectroscopy directly with the FLFC. In the applications described above, the FLFC functions as a synthesizer or link between optical standards or the optical and microwave domains. However, we have recently demonstrated that even the few nanowatts contained in a single element of the FLFC can be used for high-precision spectroscopy of the D_1 and D_2 lines in Cs. In this application, we reference the FLFC to a stable microwave source of known frequency and perform parallel, multi-color spectroscopic measurements by scanning f_r of the femtosecond laser. The result is a measurment precision that is immediately competitive with the best measurments employing CW lasers, but with a significantly simplified experimental setup. We have further demonstrated that the FLFC can be directly locked to Cs transitions, thus providing a simple optical clock.

present address: Gigaoptics GmbH, Louis-Raverat Str. 23, 63165 M lheim am Main, Germany
also with: Los Alamos National Lab, Physics Division, P-23, Los Alamos, NM 87545
* present address: School of Physics, University of Western Australia, Nedlands, 6009, Australia
** present address: PTB, Bundesalle 100, D-38116 Braunschweig, Germany

References

[1] T. Udem, R. Holzwarth, T. W. H nsch, *Nature*, **416**, 233 (2002).
[2] see contributions in *Femtosecond optical frequency comb: principle, operation and applications*, S. Cundiff and J. Ye, (eds.), (Kluwer, Newell, MA), 2005.

0-7803-8973-5/05/$20.00 ©2005 IEEE