Optical frequency metrology and its contribution to the determination of fundamental constants

R. Holzwarth, J. Reichert, Th. Udem, and T. W. Hänsch

Max-Planck-Institut für Quantenoptik,
Hans-Kopfermann-Str. 1, 85748 Garching, Germany
Tel ++49-89-32905-262, Fax ++49-89-32905-200
E-mail: rlh@mpq.mpg.de, Website: http://www.mpq.mpg.de/~ haensch/chain/chain.html

The fine structure constant α is one of the most fundamental constants of nature. Because α scales all electromagnetic interactions, it can be determined by a variety of independent physical methods. Different values measured with comparable accuracy disagree with each other by up to 3.5 standard deviations and the so far most accurate value from the electron $g-2$ experiment uses extensive QED calculations. A new way to determine α is based on the accurately known Rydberg constant R_∞ according to:

$$\alpha^2 = \frac{2R_\infty}{c}\frac{h}{m_e} = 2R_\infty \times \frac{2f_{rec}c}{f_{D_1}^2} \times \frac{m_{Cs}}{m_p} \times \frac{m_p}{m_e}$$

The Rydberg constant is determined from optical frequency measurements on atomic Hydrogen with the highest precision of all natural constants. The 1S-2S transition frequency measured at Garching together with the measurement of another transition, e.g. the 2S-8D or 2S-12D transition measured in the Group of F. Biraben [1] allows one to derive the Rydberg constant and the 1S Lamb shift.

In addition to the Rydberg constant a number of different quantities relying on several other frequency measurements are needed. Experiments are underway in Stanford in S. Chu's group to measure the photon recoil shift $f_{rec} = f_{D1}^2 h/2m_{CS}c^2$of the cesium D_1 line. Together with the proton–electron mass ratio m_p/m_e, that is known to 2×10^{-9} [2] and even more precise measurements of the cesium to proton mass ratio m_{CS}/m_p in Penning traps, that have been reported recently [3], our frequency measurement of the cesium D_1 line provides the missing link for the determination of α.

To measure this frequency we have developed a new technique to determine large optical frequency differences with the help of femtosecond laser pulses. For an ideal mode-locked laser emitting a periodic train of pulses of identical waveform the output can be described in the frequency domain by a Fourier series. The elements of this series correspond to the longitudinal laser modes whose frequencies would thus be high harmonics of the pulse repetition rate f_r. In a real laser the optical phase is shifted, by say $\Delta\varphi$, from pulse to pulse with respect to the envelope as illustrated in fig. 1. This is because the group velocity, which determines the round trip time, is generally not identical with the phase velocity of the pulse carrier frequency. However, if $\Delta\varphi$ stays constant, we still expect a comb of equidistant mode frequencies, spaced by the repetition frequency f_r, but with each frequency displaced from a multiple nf_r by

an offset frequency $f_o = \Delta\varphi/2\pi T$, where $T = f_r^{-1}$ is the pulse roundtrip time. This broad frequency comb can be used like a ruler to phase coherently measure large differences between laser frequencies [4].

In our experiment we compare the frequency of the cesium D_1 line with the 4th harmonic of a transportable methane stabilized He-Ne laser. The frequency of this laser has been calibrated at the PTB and in our own laboratory against microwave cesium atomic clocks to within a few parts in 10^{13}. To measure the frequency of the Cesium D_1 line a frequency difference of 18 THz between the 4th harmonic of the He-Ne laser and the Cesium line at 895 nm had to be bridged (see fig. 2). To probe the transition we have used a standard saturation spectroscopy setup [5].

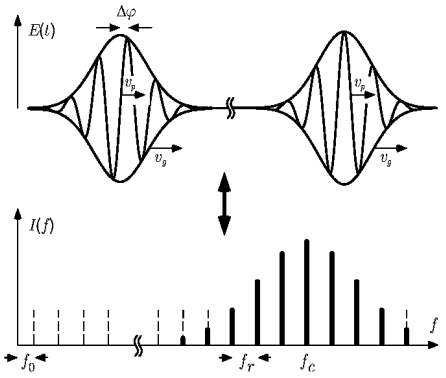

Fig. 1. Two consecutive pulses of the pulse train emitted by a mode locked laser and the corresponding spectrum.

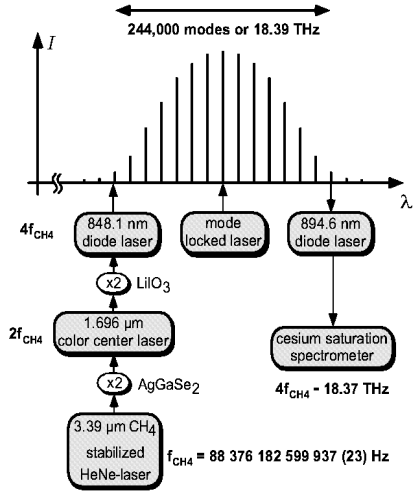

Fig. 2. Frequency chain that allows the comparison of the precisely known methane stabilized He-Ne laser at 88 THz with the cesium D_1 line at 895 nm.

This femtosecond frequency comb turned out to be quite a powerful tool for precision spectroscopy. Using novel microstructured photonic crystal fibers the useful width of these combs can be further enlarged to more than one optical octave. With such a broad spectrum we have recently measured directly the interval between a laser frequency f and its second harmonic 2f. Such a frequency chain allows the direct comparison of radio and optical frequencies [6].

Future applications of precise optical frequency measurements include the search for variations in the fundamental constants and the test of CPT invariance with anti-hydrogen now underway at CERN.

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[6] R. Holzwarth et. al., to be published.