High resolution spectroscopy with a femtosecond laser frequency comb

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Abstract. The output of a mode-locked femtosecond-laser is used for high resolution spectroscopy of Cs in an atomic beam. The laser is referenced directly to a stable RF signal from the NIST time-scale. By changing the laser's repetition rate, the Cs D_1 and D_2 transitions are detected with high resolution.

The introduction of the femtosecond laser optical frequency comb (FLFC) created a new era of precision frequency metrology. It has been used as a tool for optical frequency calibration and measurement, atomic clock comparisons and microwave synthesis. However, in those experiments , the actual atomic physics is done with highly coherent CW lasers and the FLFC is the link between these lasers and the frequency standards (atomic clocks, GPS-based frequency references, or microwave oscillators). The direct output of mode-locked lasers has been used successfully for two-photon spectroscopy [1,2]. In this paper, we demonstrate high-resolution single-photon spectroscopy using directly the FLFC output as a laser source, and perform optical frequency measurements that can successfully compete with the best measurements done using CW lasers, but with significantly simplified experimental setup. Specifically, we use a FLFC to excite single-photon transitions in neutral ^{133}Cs, and we use this to measure the optical frequencies between several energy levels in neutral ^{133}Cs.

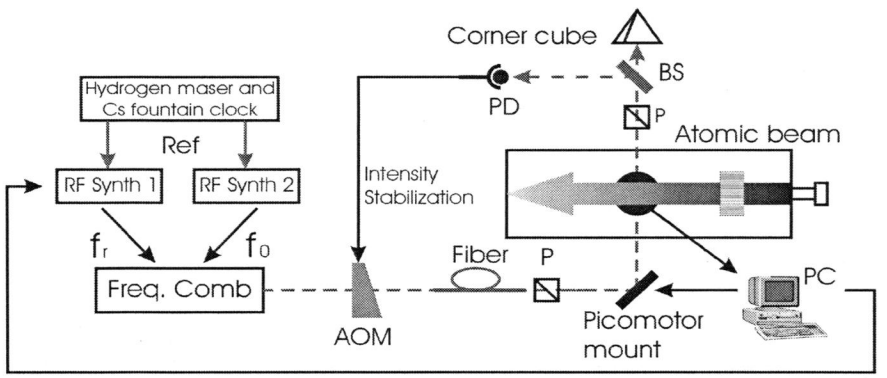

Fig.1. Experimental Setup.

In the present experiment (shown in Fig. 1), a self-referenced Ti:sapphire femtosecond laser frequency comb having 1 GHz repletion rate is used [3,4]. With established techniques [4,5], the repetition rate f_r and the offset frequency f_0 of the femtosecond laser are phase-locked to frequency synthesizers referenced to a stable Hydrogen maser, which is calibrated by a cesium atomic fountain clock [6]. The fractional frequency instability of the comb teeth is equivalent to that of the Hydrogen maser, given by ~ $2\times10^{-13}\tau^{-1/2}$, with τ the integration time measured in seconds. When averaged for several hours, the frequency of each tooth of the femtosecond comb can be known relative to the cesium primary frequency standard with fractional uncertainty approaching a few parts in 10^{-15}. Part of the femtosecond laser output is sent via a single-mode fiber to a highly-collimated atomic beam. The laser spectrum measured at the fiber output is shown in Figure 2.

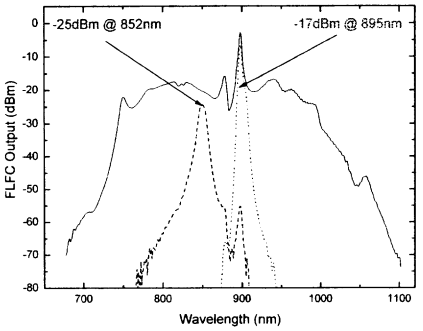

Fig.2. Femtosecond laser spectral output without interference filter (line), a 850nm band pass filter (dashed line) and 900nm band pass filter (dotted line).

The collimated laser beam excites a Cs atomic beam [7], which it crosses perpendicularly. Fluorescence from the excited Cs atoms is detected, digitized and stored on a computer as the synthesizer controlling f_r is scanned by the same computer. Fluorescence signals are readily observed with broadband (i.e. 750-1000 nm) excitation of the Cs atoms; however, interference filters are used to narrow the laser output spectrum to the region of interest and reduce the background noise. The laser intensity is stabilized using an acousto-optic modulator placed before the optical fiber.

Using an optical filter, the spectral width of the FLFC is narrowed in the vicinity of the Cs D_1 line ($6s\ ^2S_{1/2}$ - $6p\ ^2P_{1/2}$) at 895nm. The interference filter transmission is shown in Figure 2, and the transmitted power of ~25 nW per mode at 895nm is sufficient to excite the transitions. The four different components are due to transitions between F_g=3,4 – F_e=3,4 and are shown in Figure 3. Due to the presence of a comb tooth every 1 GHz, the fluorescence signals also repeat every 1 GHz change in optical frequency, corresponding to a change in f_r of ~3kHz. The different D_1 line components (which are separated optically by ~9 GHz) are identified using their measured optical frequencies [8], the FLFC offset frequency f_0 and the repetition rate f_r. The background is due to scattered laser light from the numerous comb components transmitted through the interference filter but not resonant with the atomic transitions.

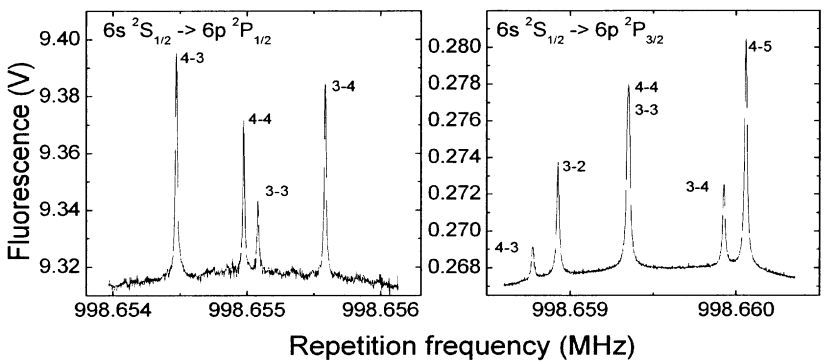

Fig.3 Fluorescence spectra of the D_1 (left) and D_2 (right) lines in ^{133}Cs as a function of the repetition frequency f_r of the femtosecond laser.

In the case of the D_2 line ($6s\ ^2S_{1/2}$ - $6p\ ^2P_{3/2}$), the FLFC spectrum is narrowed in the vicinity of 852nm using a different interference filter (the transmission of which is also shown in Figure 2). The intensity of the femtosecond laser in the vicinity of this atomic line is much lower (4nW per mode at 852nm), which explains the lower peak amplitudes and the lower background. The observed spectral features are due to transitions between F_g=3,4 and F_e=2,3,4,5. Due to dipole transition selection rules, only 6 components are expected. Because of the particular values of offset frequency f_0 and the repetition rate f_r, two of the spectral features overlap, as denoted in Figure 3.

While we can envision more sophisticated identification algorithms, in this preliminary measurement we rely on previous knowledge of the optical frequencies to determine the different spectral components and the mode number of the comb component which is resonant with each component. Due to the large repetition rate of the femtosecond laser (1GHz), such identification is possible knowing the optical frequencies with precision of several 10's of MHz. Another requirement for absolute optical frequency measurements is to reduce the Doppler shift associated with the atomic beam–laser beam misalignment. This is done using information from spectra obtained with a single laser beam compared to two counter-propagating laser beams [9].

As an example of the precision that can be obtained in a relatively short measurement time, the optical frequency measurement of $F_g=3 - F_e=4$ transition of the D_1 line is shown in Figure 4. The optical frequency of this transition, as measured in [8], has been subtracted from the data. The dashed area represents the uncertainty in the transition optical frequency, obtained in [8]. The present results give very good agreement within the measurement uncertainty and show great promise for future high-resolution spectroscopy done directly with self-referenced optical frequency combs.

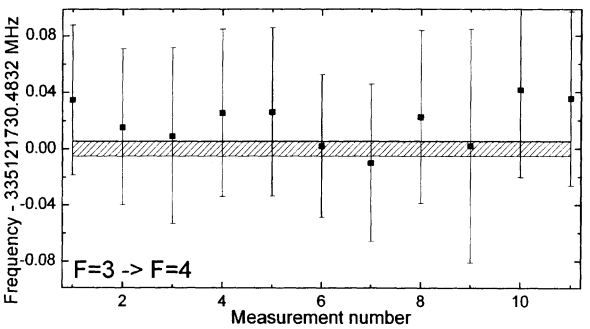

Fig.4. Optical frequency measurements of $6s\ ^2S_{1/2}$ (F=3) – $6p\ ^2P_{1/2}$ (F=4) transition using the FLFC.

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