Ultra-narrow cesium dark resonance with mode-locked pump laser and high temperature buffer cell

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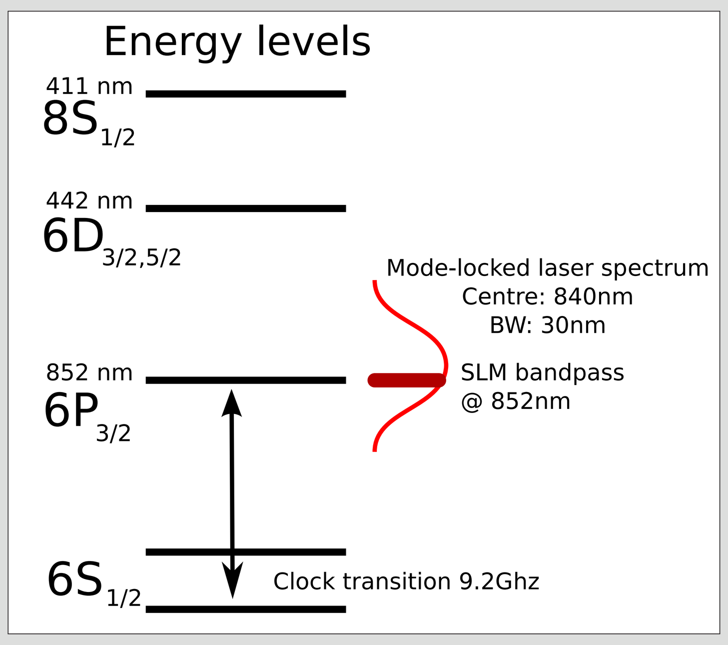
The coherent population trapping clock

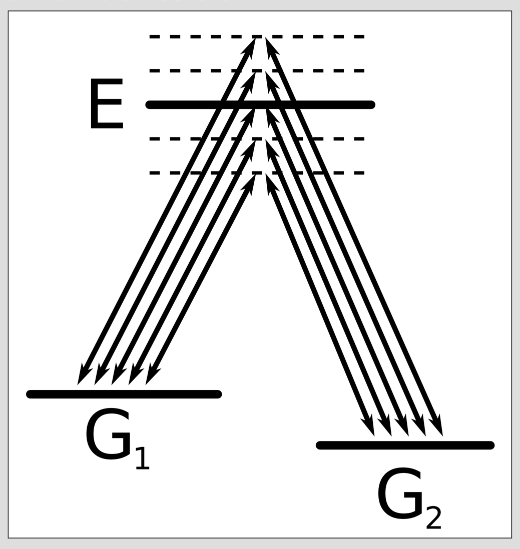
- The microwave frequency standard is cumbersome to link to the optical frequency range
- Coherent population trapping (CPT) or dark resonance is able to produce robust, narrow linewidth transitions, that can bridge the gap between microwave and optical freqencies
- In our scheme we further reduce the linewidth and eliminate light and pressure shifts of previous methods by:
  - Mode-locked laser (short interaction time, high peak intensity)
  - Using cesium (advantageous energy levels)
  - High pressure buffer gas (pressure induced narrowing)
- Potentials
  - Frequency reference over a wide optical bandwith
  - Frequency reference over large distances due to high peak power
  - Compact, robust, all-optical system

Atom-laser interaction

- Cesium atom excited by a mode-locked laser
  - Spectrum is a series of lines separated by the repetition rate: $f_n = n\Delta + \delta$
  - Wide bandwith, can cover a large number of energy levels
- Excited state linewidths are of the order of 700 MHz due to Doppler-broadening



- Simplified picture for CPT with mode-locked laser:

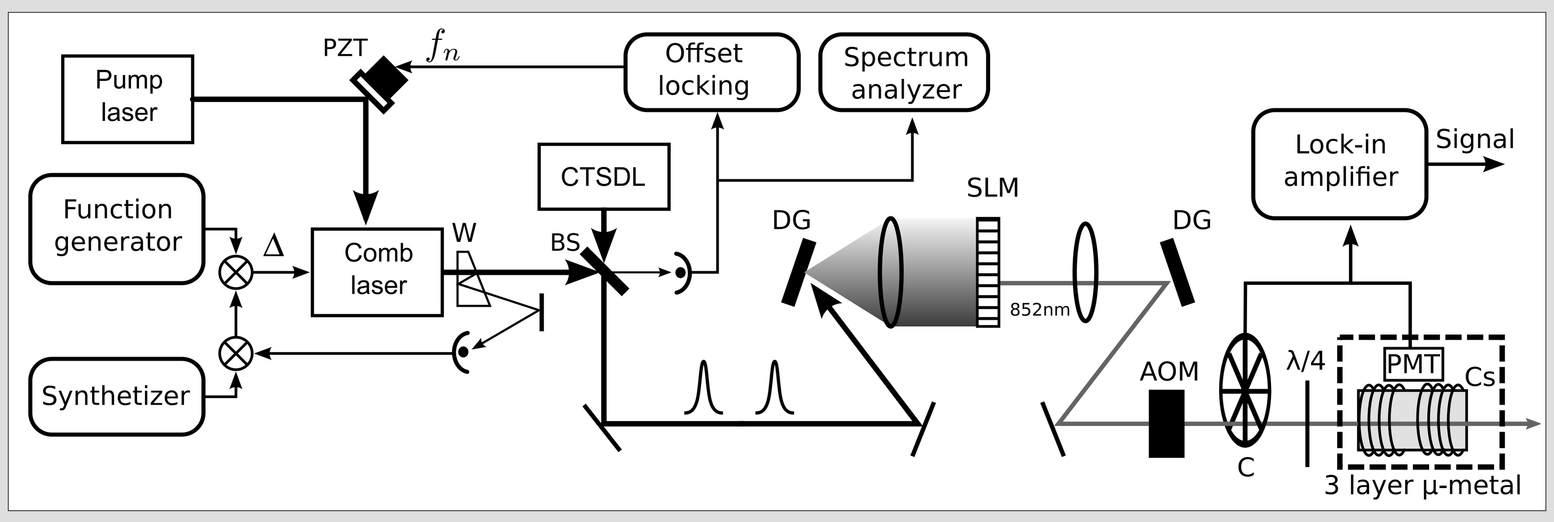


- Coherent population trapping in the hyperfine ground states
- Excited state is on the D2 transition
- Input light is band-pass filtered with spatial light modulator (SLM) to reduce background scatter

  - The mode-locked laser have multiple resonance conditions between the excited state E and the two ground states G_1 and G_2.
  - Interaction is tuned by the repetition rate Δ

Experimental setup

A unique Ti:Sapphire pumped mode-locked laser system allows orthogonal control of repetition rate Δ and offset freqency δ. Details presented in in W-Y Cheng, *et. al.* Appl. Phys. B, 92, 13-18(2008).

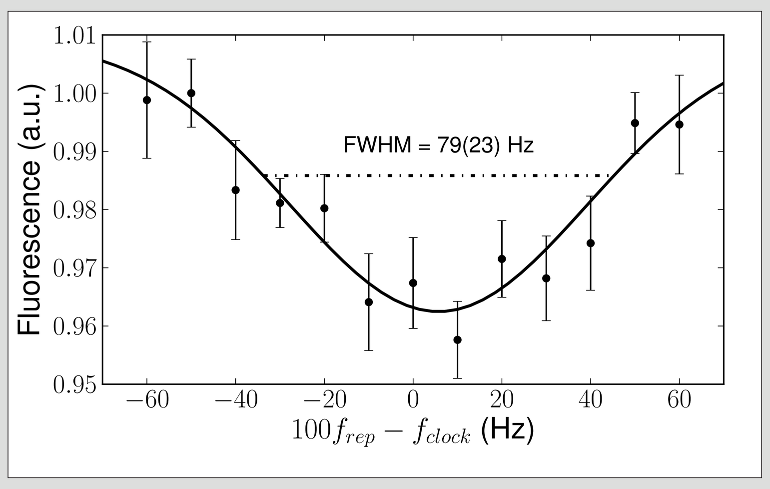


PZT: piezoelectric transducer, W: output wedge, BS: beam splitter, CTSDL: cesium two-photon stabilized diode laser, DG: diffraction grating, SLM: spatial light modulator, AOM: acousto-optic modulator, C: mechanical chopper, PMT: photo-multiplier tube, Cs: cesium cell

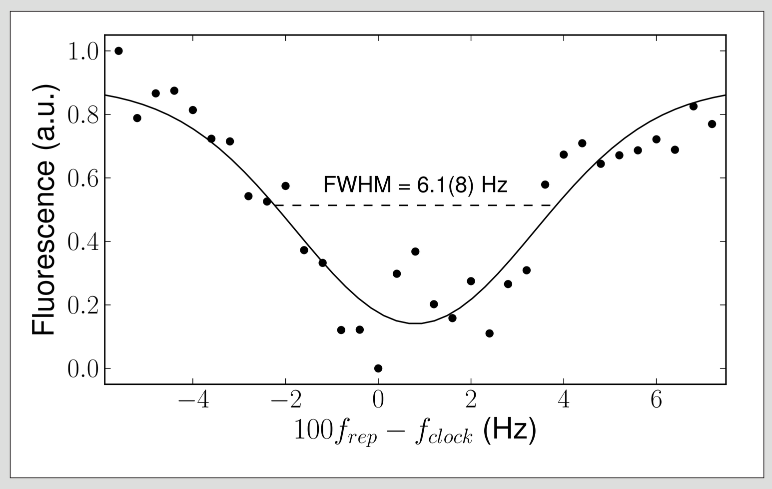
- The repetition rate Δ is near integer fraction of the ground-state splitting (e.g. 1/100 $\approx$ 92 MHz)
- Repetition rate locked to 5th harmonic of synthetizer (with 10 mHz stability)
- Time-base locked to LORAN-C signal
- SLM band pass filter bandwith $\approx$ 0.2 nm ($\approx$ 1 ps pulse length)
- Chopping frequency 500-1000 Hz
- Time-average input intensity 140μW feedback stabilized to $<1\mu$W

Experimental results

Experiments have been done with two different buffer gas cells:



1.5 kPa N_2 + 1.5 kPa *He* buffer

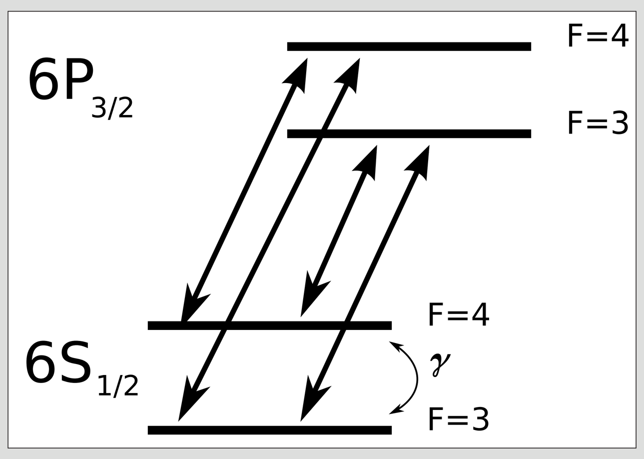


8.7 kPa *Ne* buffer, ≈100°C cell wall

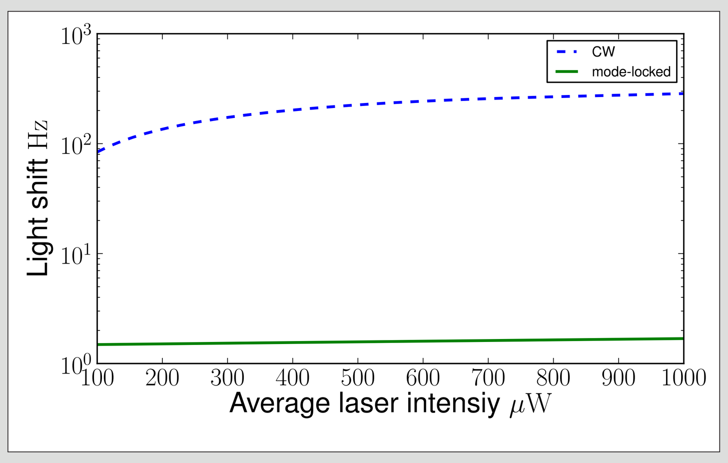
- Higher pressure buffer gas have line-narrowing effect
- Pressure and light shift reduced below the uncertainty of the experiment, lower than predicted from no-buffer gas simulations.
- Current system achieves ≈5% contrast
- Lock-in amplifier time constant of the order of 3 ms, 500 repeats, total measurement time 90 s/point.
- Signal is sensitive to:
  - Residual magnetic fields and field inhomogeneities
  - Cell temperature change (at ≈10°C reduced temperature the signal disappears)
  - Light intensity stability
  - Offset dither > 1kHz

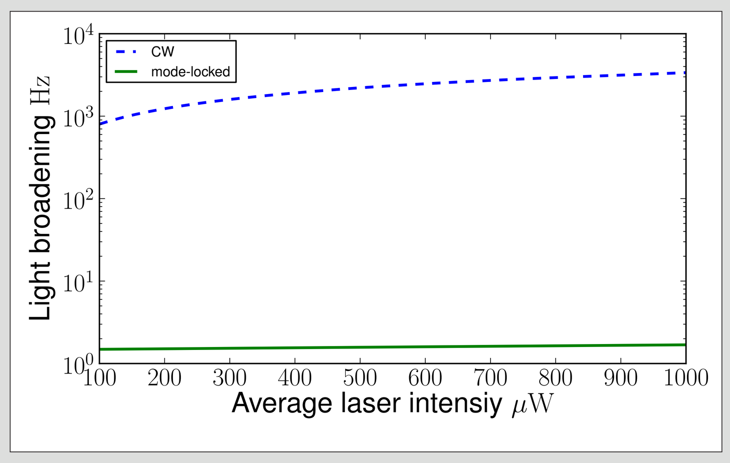
Theoretical considerations

- Simulation uses simplified level structure
  - All Zeeman sublevels included, 32 levels in total
  - Upper state F=2,5 contributions are included in decoherence γ



- Build-up time of the order of 1 ms
- Frequency offset locking is not required, slow centre frequency drift does not affect CPT signal
- Reduced light shift and light broadening compared to CW, with small intensity dependence.

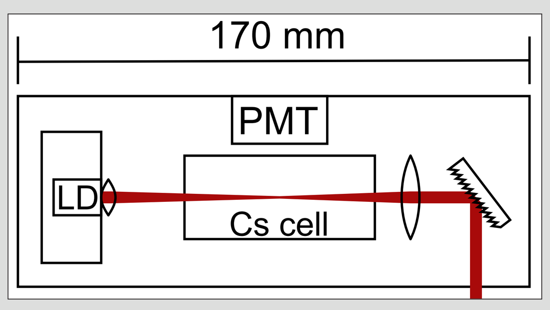




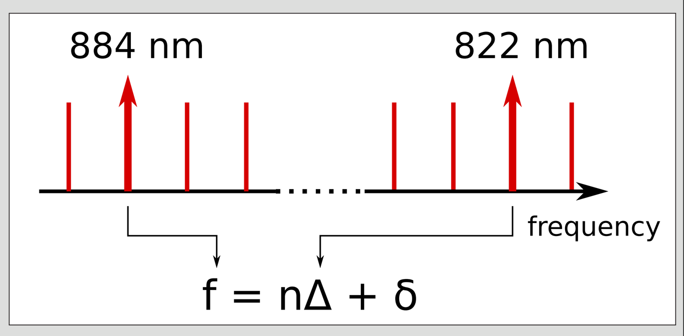
Outlook - the optical vernier

Our group developed compact frequency standards for two differen 2-photon Cs transitions (8S at 822 nm and 6D at 884 nm).

- Extended cavity diode laser with intracavity cesium cell
- Focused beam for ≈ 1000 SNR for 822 nm
- Maximum output power of 30 mW



- Combine this with a frequency comb to get an optical vernier.
  - 822 nm reference locks the repetition rate
  - 884 nm reference lock the absolute frequency
  - CPT transition provides monitoring of the repetition rate, connecting the microwave and optical regime



This scheme removes the need for a highly stable synthetizer, which is an obstacle to a compact and robust design.

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