

Absolute frequency measurement of wavelength standard at 1542nm: acetylene stabilized DFB laser

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Abstract: The frequency of a wavelength standard at 1542 nm (194 THz) developed in CMI for the telecommunication band C was measured with a fiber femtosecond frequency comb. The measurement was done for three transitions of acetylene $^{13}\text{C}_2\text{H}_2$: P(14), P(15) and P(16). The results agree well with values in the recommendation for Practical realization of the definition of the metre [1] and even better with recent measurements made in NMIJ/AIST [2,3] - the differences are lower than 2 kHz (or 1×10^{-11} rel.) for all three transitions. This agreement is significant considering the fact that the CMI laser uses an extremely simple spectroscopic arrangement and substantially lower saturation power.

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1. Introduction

The Consultative Committee for Length (CCL) of the Metric Convention included lasers stabilized to acetylene $^{13}\text{C}_2\text{H}_2$ into the list of radiations realizing the SI definition of metre in 2001 to provide a primary wavelength standard for the important field of optical telecommunications. The initially adopted relative uncertainty of $5 \cdot 2 \times 10^{-10}$ ($k=1$) [4] was decreased by a factor of ten by CCL 2003 [1], which states the following values for the P(16) ($\nu_1+\nu_3$) transition of acetylene $^{13}\text{C}_2\text{H}_2$:

Frequency	(194 369 569 385 \pm 10) kHz,	$u=5 \times 10^{-11}$ rel. ($k=1$)
Vacuum wavelength	(1 542 383 712, 37 \pm 0,08) fm	
Working parameters	pressure	(1, 3 .. 5,3) Pa,
	modulation (third harmonic locking tech.)	(1, 5 \pm 1) MHz,
	intensity (one-way intracavity beam power)	(25 \pm 13) W/cm ²

In addition to the above mentioned reference transition P(16) at 1542,384 nm the recommendation includes another 29 lines of the P-branch and 24 lines of the R-branch covering the spectral band (1522,33202 to 1551,56014) nm, but the uncertainty associated to these additional transitions remains 20 times larger (200 kHz for $k=1$).

New results with improved uncertainty especially for the other transitions were reported by Onae and Jiang in [2, 3]. The frequency of P(16) was also measured by NRC Canada [5] and NPL UK [6,7], in all cases the second harmonic ~ 771 nm was measured by visible Ti:sapphire combs; the values are summarized in [3].

2. Acetylene stabilized lasers

The wavelength standard according to CCL recommendation was developed in CMI in 2002-2005. During about six months of comparisons of two of such standards it was proven, that the simple spectroscopic arrangement with single path of pump and probe beam through a 50 cm long cell is sufficient to reach the reproducibility far better than a total uncertainty of 20 kHz stated in recommendation. Also it was confirmed that cheap commercially available DFB laser with FWHM linewidth ~ 0.5 MHz can be used for successful locking to sub-doppler acetylene lines of FWHM ~ 1 MHz (for cell pressure of 2 Pa) by the third harmonic locking technique with ~ 1 kHz repeatability and stability [8, 9].

In order to improve the immunity of these lasers to light back-scattered from objects in the output beam (detector, wavemeter or fibre coupler) the arrangement was slightly changed – the scheme used during the comb measurement is shown in Fig. 1.

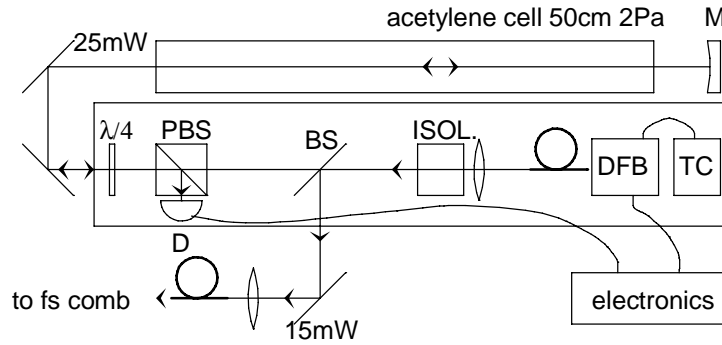


Fig. 1. Schematic of acetylene stabilized laser.

The temperature of the pigtailed distributed feedback laser diode (DFB, JDS Uniphase CQF935/708-19440) is stabilized by a temperature control circuit (TC, Analog Technologies TEC-A1LD), the fibre output (40mW) is collimated by a lens ($f=7.5\text{mm}$). After passing through an optical isolator (ISOL) the beam splits (BS) to output beam coupled into the single mode fiber and to a beam used for sub-doppler spectroscopy. The latter one passes through a polarizing beam splitter (PBS) and is then converted to circular polarization by a quarter wave plate ($\lambda/4$) and serves as a pump beam in the acetylene cell. After passing the cell this beam is reflected back by a mirror (M, $r=1\text{m}$, reflection changes the sense of circular polarization) and passes the cell as a test beam, the wave-plate converts it back to linear polarization (but orthogonal to the original one) and the PBS deflects all the test beam power to the detector.

The laser wavelength is modulated by current modulation. The lock-in detector is set to detect the third harmonic of the modulation frequency. Because of good linearity of current to power dependence of the DFB laser diode in the selected point, no third harmonic signal is detected outside the Doppler broadened spectral lines. Due to a relatively low modulation width $1.7\text{MHz}_{\text{p-p}}$ compared to the Doppler broadened linewidth (FWHM $\sim 500\text{MHz}$) no signal is detected anywhere outside the saturated (sub-doppler) peak (FWHM $\sim 1\text{MHz}$ for 2Pa cell or 1.7MHz for 5Pa cell). With this single path saturation spectroscopy and corresponding low saturation power $3\text{W}/\text{cm}^2$ the sub-doppler line signal for 2Pa 50cm cell is only about 10^{-4} of the total detected power, but the signal to noise ratio is quite good: 36dB at 11Hz resolution bandwidth and remains good ($>34\text{dB}$) even when the power density is decreased below $1\text{W}/\text{cm}^2$.

The main working parameters and the frequency shifts related to their changes are summarized in table 1.

Table 1. Operating parameters and frequency shift coefficients of acetylene-stabilized lasers [8]

	Typical value		Frequency shift coefficient		
Laser power	40	mW			
Beam diameter	1	mm			
Power density inside cell (one way)	3	$\text{W}\cdot\text{cm}^{-2}$	0	± 0.25	$\text{kHz}/(\text{W}\cdot\text{cm}^{-2})$
Modulation frequency	1111	Hz			
Modulation width	1.7	$\text{MHz}_{\text{p-p}}$	0	± 1	kHz/MHz
$^{13}\text{C}_2\text{H}_2$ pressure	2	Pa	-0.3	± 1	kHz/Pa

3. Frequency comb generator

The acetylene standard has been measured against a fiber laser frequency comb generator developed in a collaboration between the Max-Planck-Institute for Quantum Optics (MPQ)

and MenloSystems GmbH (for a more detailed description, see Ref. [10]). The comb generator is based on a polarization-mode-locked femtosecond fiber-ring laser with a repetition rate f_{rep} of 100 MHz. In an EDFA, the laser oscillator output is amplified and subsequently broadened in a highly nonlinear fiber to cover a frequency spectrum of one octave. Using the f - $2f$ technique, the carrier-envelope-offset frequency f_{CEO} of the frequency comb is determined.

For the experiment, approximately 5 mW of radiation have been split off from the fiber oscillator output and have been superimposed with the cw laser radiation in a fiber coupled beat detection unit. Unlike in previous measurement [2, 3, 5, 6], the 1542nm radiation is directly measured – no second harmonic generation is needed. To enhance the S/N ratio, the beat note has been detected free space after a grating.

By phase locking f_{rep} and f_{CEO} to a primary frequency standard, the frequency comb generator allows for phase coherent comparisons between the rf and optical frequency domain. In this experiment, the 8th harmonic of f_{rep} has been phase locked to a HP8662A synthesizer. f_{CEO} has been phase locked to 20 MHz generated by a Marconi 2022C synthesizer.

All relevant frequencies in the experiment have been counted by HP53131A frequency counters, which as well as the synthesizers have been referenced to a primary frequency standard (HP5071A) with relative stability of 5×10^{-12} at 1s.

4. Measurement results

The output radiation of the acetylene stabilized wavelength standard was coupled into a single mode fiber; 5mW to 6mW were coupled.

After proper alignment and polarization matching the signal to noise ratio of the beat between the comb and acetylene stabilized laser reached 30dB (at 400kHz bandwidth) and it was sufficient for reliable counting.

The Fig. 2 shows the stability and reproducibility of the laser locked to transition P(16). To check the repeatability, between the series the laser was re-locked, driving electronics re-calibrated and in the end the polarity of the servo was reversed.

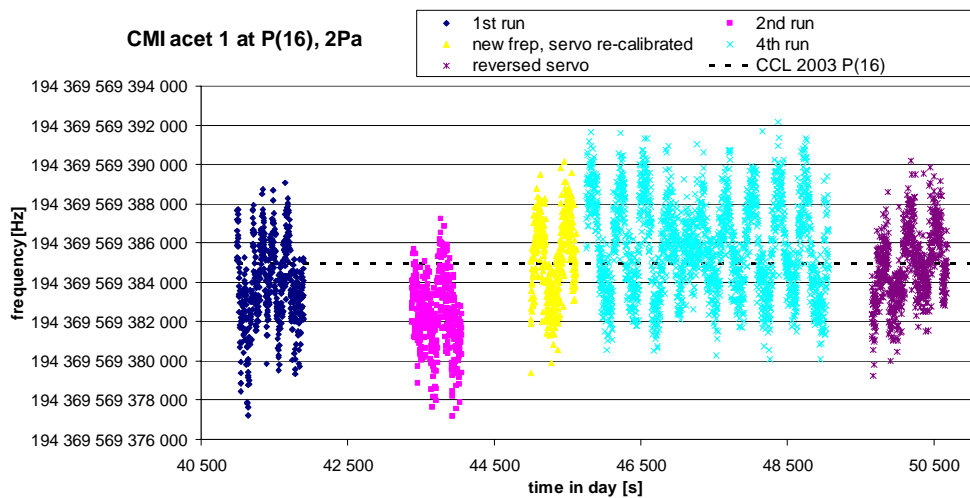


Fig. 2. Stability and repeatability of acetylene-stabilized laser relative to fs comb during nearly three hours of measurement of transition P(16)

The averages of these measurements differ less than 3.5 kHz and the total average lies just 125 Hz below CCL value. The stability 3×10^{-12} rel. for 10s sampling equals to that reported by NMIJ/AIST[3].

The Fig. 2 also shows few kHz oscillations of frequency with a period of about 200s. These oscillations were not present during previous internal comparison of two similar lasers in CMI (see Fig. 3) but were still present in a comparison of two acetylene stabilized lasers after absolute measurement. The cause of this increased fluctuation was not found yet but the comparison of two lasers before and after absolute measurement confirmed that the average frequency remains constant to better than 2kHz.

After about 5000 s of measurements of the P(16) transition frequency, another two transitions were measured, each for over 800 seconds. The results are shown in table 2.

Note: the comb measurement was done with 1-second samples separated by 0.65s dead time, so the squares in the Fig. 3 do not represent strictly the Allan standard deviation, but were calculated as if the samples were 1.65s long without dead time.

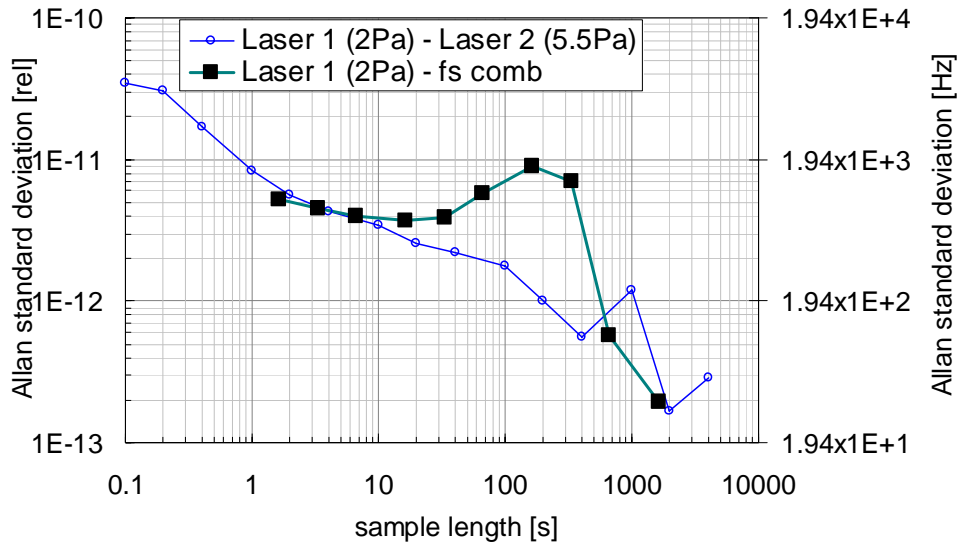


Fig. 3. Stability of acetylene-stabilized laser relative to fs comb (with output fiber, squares) and relative to another acetylene-stabilized laser (without output fiber, circles)

Table 2. The frequencies of three acetylene transitions and comparison to previously published values (in Hz)

$^{13}\text{C}_2\text{H}_2$ transition	Frequency	Uc	This work deviation from			
			NMIJ [2]	NRC[5]	NPL[7]	CCL [1]
P(16) 1542.384nm	194 369 569 384 875	3 000	-125	1 045	-1 525	-125
P(15) 1541.772nm	194 446 632 391 028	3 500	1 028	-252	-1 872	91 028
P(14) 1541.167nm	194 523 020 608 418	3 500	418		-6 182	8 418

It should be noted that the operating conditions, mainly the vapor pressure and saturation power, differ for this and previous measurements [2,5,7]. All data were submitted to 12th meeting of CCL in 2005. The new CCL recommendation similar to [1] will be based on these data corrected to newly assigned standard condition.

5. Conclusion

The absolute frequency of a wavelength standard for optical telecommunications – an acetylene stabilized laser – was measured for three $^{13}\text{C}_2\text{H}_2$ transitions: P(16), P(15) and P(14). The results agree well (mostly to better than 2kHz, 1×10^{-11} in relative) with previous measurements made in NMIJ/AIST, NRC and NPL. It was proven that our very simple design based on DFB lasers and single path saturation spectroscopy is suitable for this wavelength standard.

Acknowledgments

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