Paper

Long-term Absolute Wavelength Stability of Acetylene-stabilized Reference Laser at 1533 nm

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Abstract—The second harmonic generation process in Periodically Poled Lithium Niobate (PPLN) has been applied in order to measure frequency of reference laser locked to acetylene absorption peak $^{12}C_2H_2$ (P13) (1533 nm) against optical frequency synthesizer. The measurement results have been compared to the results obtained using different techniques for the same reference laser during the past 10 years in other laboratories.

Keywords*—*laser, optical comb generator, optical frequency standard, second harmonic generation.

1. Introduction

Accurate optical frequency standards are important tool in various technological domains. This is most important in high accuracy distance measurement, spectroscopy, and recently in development of fiber optic telecommunications.

A new definition of meter directly related to speed of light in vacuum and time has been proposed. It was possible due to progress in building more accurate atomic time and optical frequency standards. During last decades, a lot of research has been done in the area of spectroscopy of reference materials, which can be used as a reference for optical frequency standards. There are several practical realizations of optical frequency standards and they were summarized by BIPM [1]. In most cases the optical frequency standards in visible and near infrared regions are built as He-Ne (543 nm, 633 nm) lasers locked to absorption lines of iodine, or DFB laser diodes locked to rubidium two-photon transition (778 nm).

The rapid development of Dense Wavelength Division Multiplexing (DWDM) fiber optic networks stimulates research on optical frequency standards in wavelengths range around 1550 nm. The best candidates to meet the increasing demand on these standards seem isotopomers of acetylene $^{12}C_2H_2$ and $^{13}C_2H_2$ which cover wavelength range of 1520–1550 nm. The measurement accuracy at the level of 10^{-9}–10^{-10} of optical frequencies of absorption lines has been achieved in case of molecular absorption cells [2], [3]. The lasers stabilized to acetylene $^{13}C_2H_2$ have been put by Consultative Committee for Length (CCL) of the Metric Convention in 2001 into the list of radiation sources, which realize the definition of SI meter. Especially, the P(16) 1542.384 nm absorption peak has been chosen as most accurate. A lot of specific solutions have been proposed over the years of development up to compact fiber-based solutions [4]–[8].

The commercially available stabilized lasers offer wavelength accuracy of ±0.0001 nm in wavelength domain. In such systems, the dithering of output signal can be observed due to the electronic way of wavelength locking which usually is better than ±0.05 pm (±6 MHz), while the linewidth of DFB laser diodes used in optical frequency standards is not broader than 1 MHz.

The development of optical frequency standards stimulates progress in wavelength/optical frequency measurement methods and measurement equipment. In practice, the interferometric setups, beating of laser signals, and femtosecond laser comb generators are used [9]–[12]. Especially the latter ones [12] facilitate measurement of optical frequencies at highest accuracies. At the beginning, the optical comb generators were driven by Ti:Sapphire femtosecond lasers and did not cover 1550 nm wavelength region. The next generation combs based on Er-doped mode-locked fiber lasers, apart from reducing cost of such system and its complexity, gave the possibility of direct optical frequency measurements in 1550 nm wavelength region without the need of second harmonic generation (SHG). Nevertheless only few laboratories offer measurement of optical frequency against comb generators in full wavelength range.

The authors motivations was to measure frequency of their reference laser against optical frequency comb generator and then compare measurement results with results obtained earlier using different methods.

The application of SHG technique in case of frequency measurement of laser emitting light in 1550 nm region against optical frequency comb generator was reported in [13]. In conducted experiment, in contrast to the cited work we did not use “lab developed” technology but commercially available comb generator which is installed in Central Office of Measures (Warsaw, Poland). The tested laser was also delivered by commercial company and its parameters were not as good as the best of its kind. Thus, we were particularly interested in the behavior of the device parameters over relatively long period.

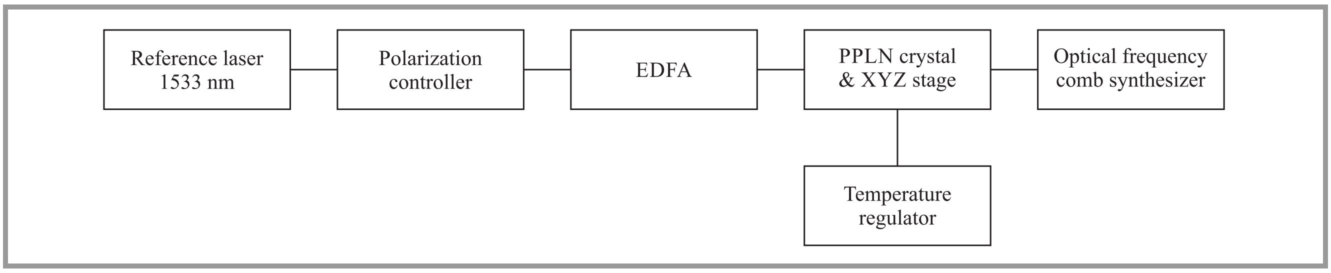

Fig. 1. Schematic block diagram of the measurement setup.

2. Measurement Setup

In Fig. 1 the schematic block diagram of a measurement setup is presented. The general idea of the setup was to measure second harmonic of light emitted from the reference laser.

The object of the measurement was a reference laser locked to acetylene reference $^{12}C_2H_2$ (P13) line (195580979.3711 MHz ±10 kHz, 1532.8307 nm), which might operate in three wavelength stabilization modes: “left”, “right” and “center”. Which mean that the laser wavelength may be stabilized to the left or right slope of the absorption peak or to the highest point of the absorption peak, respectively. The manufacturer stated the laser frequency in center mode as 195.58097 THz (1532.8304 nm ± 0.0003 nm), which is slightly different from the reference wavelength of $^{12}C_2H_2$ (P13) line. On the other side of the setup the optical frequency comb synthesizer FC8004 made by Menlosystems driven with Ti:Sapphire femtosecond laser was used. It has been designed to measure frequencies of optical signals in visible and near infrared regions, i.e., in the wavelength range 532–1074 nm. It is usually used for realizing definition of meter and calibration of the stabilized metrological lasers.

In order to measure 1533 nm reference laser we decided to use second harmonic generation (SHG) technique using Periodically Poled Lithium Niobate (PPLN) crystal to get 766.4 nm signal, which is in the measurement range of the optical frequency comb synthesizer. Similar solution has been reported in case of 1542 nm laser stabilized to P(16) absorption line of $^{13}C_2H_2$ [13].

In our case the maximum output power of the reference laser was only 0.5 mW, which is too low to achieve effective frequency conversion in PPLN crystal. Its efficiency is only 0.5%. As a solution for low power problem, an Erbium Doped Fiber Amplifier (EDFA) was applied. Furthermore, the optical frequency synthesizer can measure optical signals only with power greater than 100 μW. Taking this limitation into account as well as losses caused by reflections and light launching into the optical fibers the maximum output power of EDFA has to be greater than 23 dBm.

The frequency conversion is possible only when the phase matching condition of pump signal and second harmonic signal is fulfilled. This condition strongly depends on polarization of input signal and temperature of PPLN crystal. For that reason the polarization controller and dedicated thermally controlled oven has been used (Fig. 1).

The maximum conversion efficiency can be achieved when the focusing conditions of optical beam fulfils the Boyd and Kleinman requirement: $L/b = 2.84$, where L is the crystal length and b is the confocal parameter. Our optical setup was close to this condition. The PPLN crystal was relatively long (i.e. 40 mm) with input aperture 0.5×0.5 mm. This implicated precise optomechanical setup elements in order to properly focus and adjust the laser beam. Our setup delivers 0.5 mW of converted power, which is enough to be measured with optical comb (frequency synthesizer).

In Figs. 2 and 3 a photo and block diagram of setup of the optical frequency synthesizer are shown, respectively.

Fig. 2. Photo of optical frequency synthesizer.

The main advantage of the comb synthesizer is an efficient technique of locking of the f_r repetition frequency and f_o offset frequency. Both parameters are synchronized with cesium clock and subsequently phase locked by controlling the cavity length and the pump power. An example of spectrum of the optical frequency synthesizer is shown in Fig. 4.

The f_0 frequency is defined according to following formula:

$$2f_n - f_{2n} = 2(f_o + nf_r) - (f_o - 2nf_r) = f_o \,, \qquad (1)$$

where: f_n – frequency of the synthesizer n-mode, f_{2n} – frequency of the synthesizer 2n-mode, f_o – offset frequency, n – integer number, f_r – repetition rate.

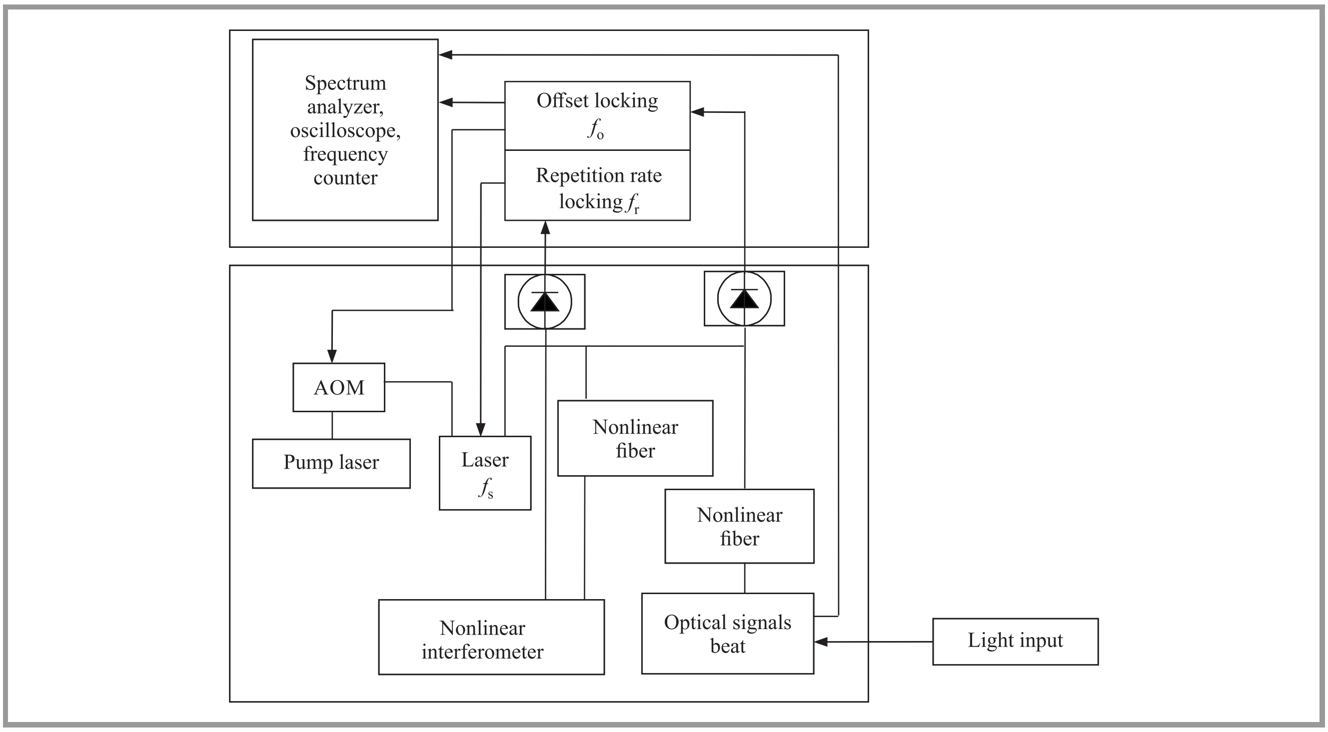

Fig. 3. Block diagram of the optical frequency synthesizer.

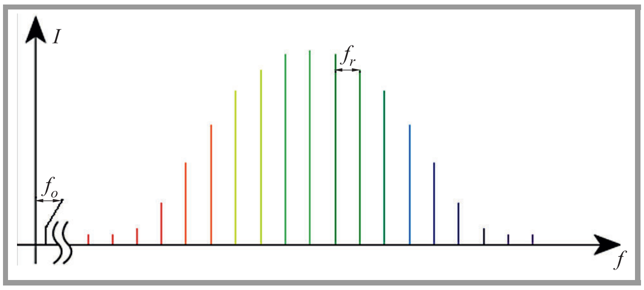

Fig. 4. Frequency synthesizer spectrum example. (See color pictures online at www.nit.eu/publications/journal-jtit)

The reference frequency signal from the cesium clock allows achieving a relative uncertainty at the level of 10^{-13}.

3. Results

The raw measurement results in frequency and wavelength domains of the reference laser after frequency doubling recorded during almost 2.5 h session are presented in Fig. 5. The corresponding Allan deviation is plotted in Fig. 6. The tested laser was operating in the ”left” mode which, as mentioned earlier, means that it was stabilized on the left slope of the absorption peak. In this mode the smallest frequency dithering is observed, and it is smaller than in case of stabilization to the highest point of the absorption peak.

The mean value of frequency and wavelength of the stabilized laser for all operating modes obtained during this experiment (year 2016) as well as the measurement results of the same laser obtained from other laboratories over the past ten years are presented in Table 1.

Over mentioned decade three different measurement methods have been applied in order to verify the laser's frequency stability, namely: imposition of signals from our laser with higher accuracy laser, interferometric method, and method presented here based on optical frequency comb synthesizer.

In 2006 the method of imposition of signals from our laser with higher accuracy laser locked to the same absorption line of acetylene $^{12}C_2H_2$ and measurement of beat signal has been applied. The uncertainty of mean frequency measurement results was ±2.8 MHz for "center" and "right" laser operating mode and ±2.0 MHz for "left" laser operating mode.

In 2011 and 2014 the laser has been compared with primary wavelength standard 1542 nm – acetylene $^{13}C_2H_2$ stabilized laser using interferometric method – absorption line P(16). The uncertainty of mean frequency measurement results in 2011 were ±1.3, ±7.3, and ±8.9 MHz for "centre", "left", and "right" operation modes, respectively. Similarly, the uncertainty of mean frequency measurement results in 2014 were ±3.5, ±8.4, and ±8.4 MHz for "centre", "left", and "right" mode of operation, respectively.

Finally, in 2016 the measurement results, which are the subject of this work, have been obtained. The relative expanded uncertainty of the mean frequency measurement results were $U_w = \pm 3.5$ MHz for all operating modes of the tested laser.

The reported expanded uncertainties in all cases were stated as the standard uncertainties multiplied by the coverage factor $k = 2$, which corresponds to a coverage probability of approximately 95%.

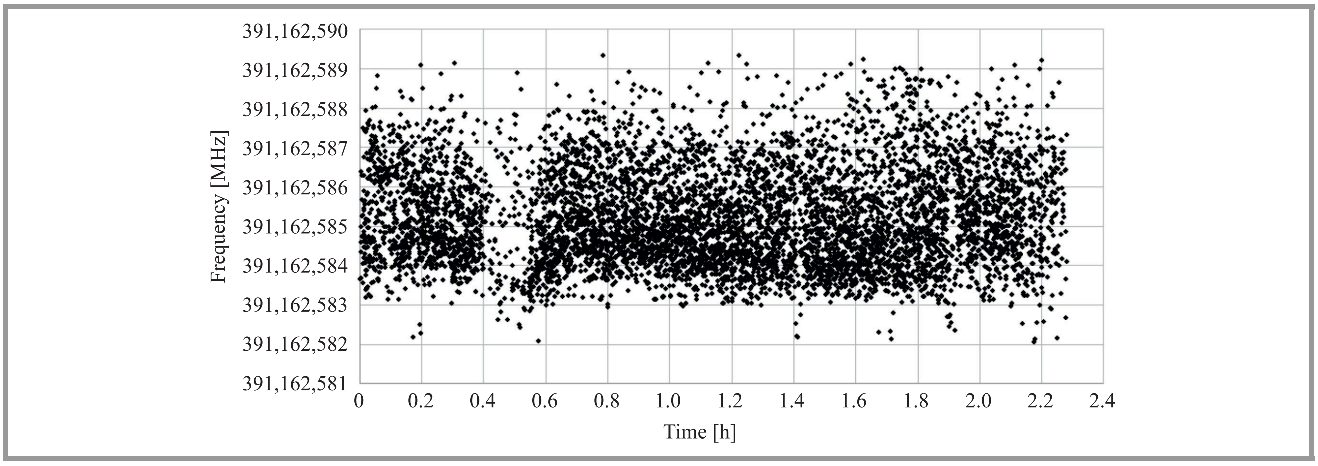

Fig. 5. Frequency of stabilized laser (operating in the "left" mode).

Table 1
Summary of calibration results

Laser stabilization mode	Unit	Year of measurement			
		2006	2011	2014	2016
Left	λ [nm]	1532.827839	1532.827880	1532.827921	1532.827880
	f [MHz]	195,581,297.8	195,581,292.5	195,581,287.4	195,581,292.6
Right	λ [nm]	1532.832912	1532.832856	1532.832829	1532.832867
	f [MHz]	195,580,650.5	195,580,657.7	195,580,661.0	195,580,656.2
Center	λ [nm]	1532.830387	1532.830390	1532.830410	1532.830378
	f [MHz]	195,580,972.6	195,580,972.2	195,580,969.8	195,580,973.8

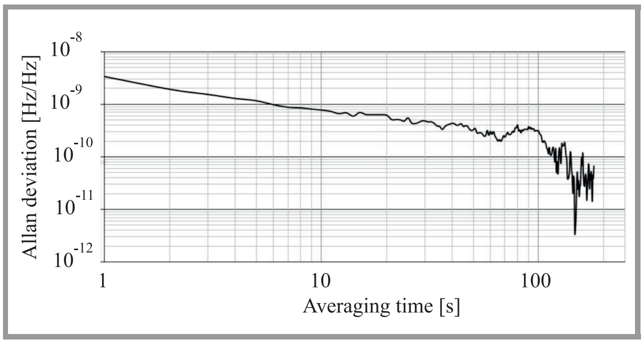

Fig. 6. Allan deviation of frequency measurement of stabilized laser (operating in the "left" mode).

The environmental conditions of the measurements were well controlled in all cases in the range 23.0 ±0.4°C in 2006, 20.0 ±1.0°C in 2011 and 2014, and 23.0 ±0.5°C in 2016. Influence of the temperature on absorption peak has been investigated previously [3] and is relatively small and less than ±100 Hz.

It has to be noticed that the reported dominant uncertainty component was a result of laser modulation, which caused frequency excursions as large as 10 MHz in the worst cases.

The results summarized in this paper can be treated in the sense of interlaboratory comparison. All three methods were applied by highest-level laboratories, which offer uncertainties as good as ±10 kHz. So, in order to investigate accuracy of the methods or its application in particular laboratories the better comparison object is needed.

4. Conclusions

The frequency of a laser locked to the absorption line (P13) of acetylene $^{12}C_2H_2$ against optical frequency comb synthesizer was evaluated. Namely, the signal from the stabilized laser has been amplified, its frequency doubled using second harmonic generation process in PPLN, and finally its stability compared against the frequency generated by the comb synthesizer

Conducted experiments showed that the wavelength accuracy of the stabilized laser is better than ±0.0003 nm (ca. ±38 MHz), which complies with the parameters stated by its manufacturer. Judging upon available literature we can state that the main advantages of the measuring method involving optical frequency comb synthesizer are the direct reference to atomic frequency standards (high accuracy) and wide range of the measurable wavelengths (high flexibility).

Moreover, the differences in results obtained from all the laboratories for the past 10 years are within uncertainty ranges, which also indirectly confirms the validity of used

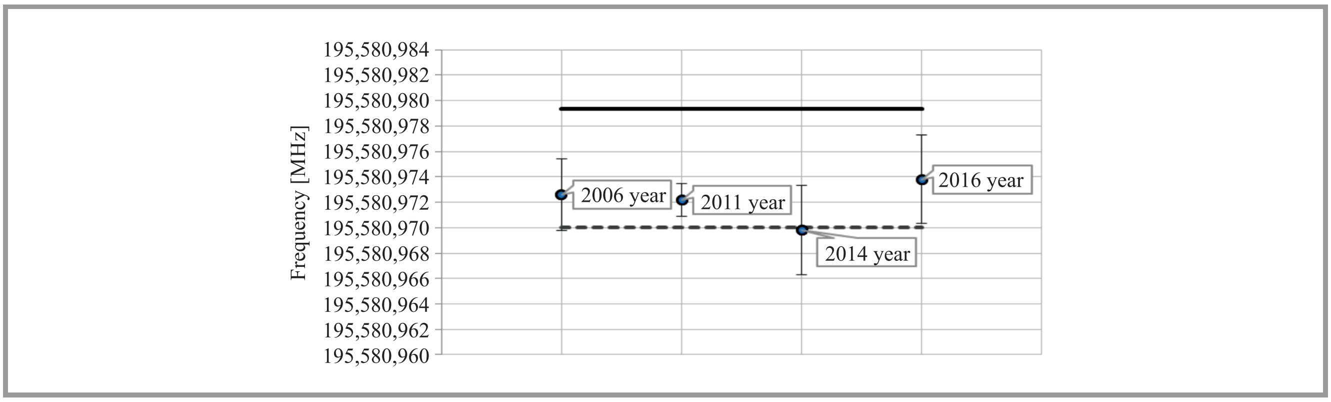

Fig. 7. Comparison of measurement results of laser wavelength ("center" mode), solid line represents reference frequency 195,580,979.3711 MHz of absorption line of P(13) $^{12}C_2H_2$, dashed line represents declared by manufacturer frequency of measured laser 195.58097 THz.

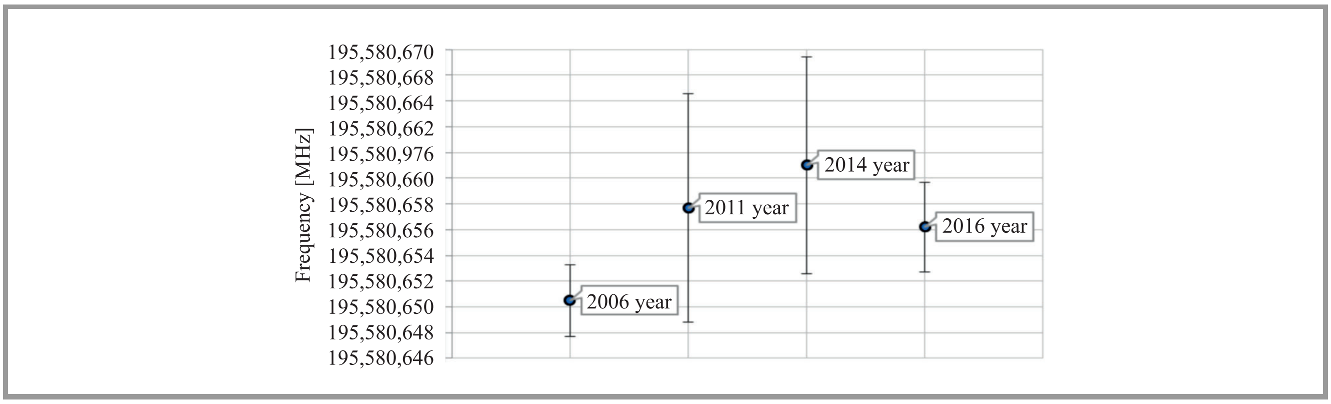

Fig. 8. Comparison of measurement results of laser wavelength ("right" mode).

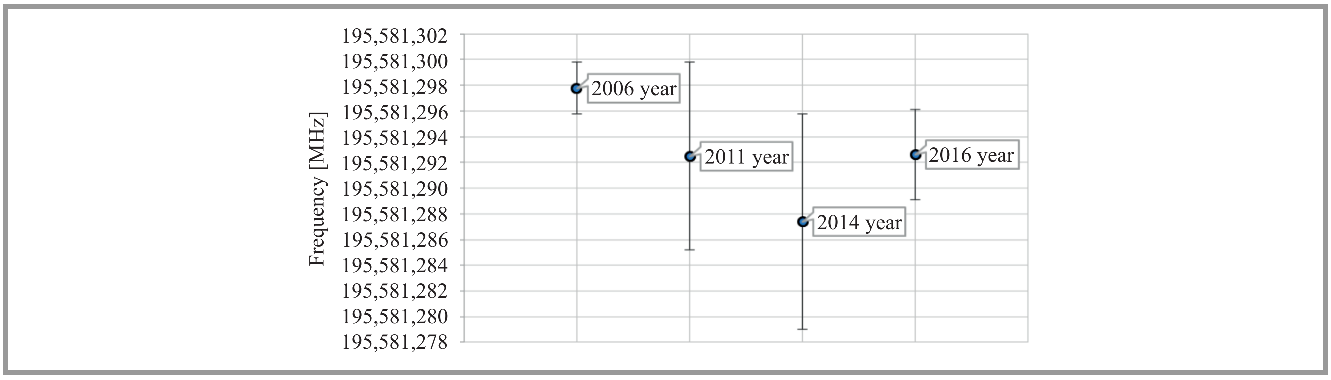

Fig. 9. Comparison of measurement results of laser wavelength ("left" mode).

approach and methods. In general, the influence of pressure or temperature on operation of a stabilized laser with absorption cells has been investigated by many laboratories, but in relatively short periods of time. Nevertheless, according to our knowledge, the long term stability of such lasers, which is an important issue in case of using it as a wavelength standard for calibration of measurement equipment, has not been presented in such a long timescale. The outcomes broaden the information on aging effects of the device and might allow the user to prolong the recalibration period.

References

[1] T. J. Quinn, "Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2001)", *Metrologia*, vol. 40, no. 2, pp. 103–133, 2003 (doi: 10.1088/0026-1394/40/2/316).

[2] K. Nakagawa, M. de Labachelerie, Y. Awaji, and M. Kourogi, "Accurate optical frequency atlas of the 1.5 μm bands of acetylene", *J. Opt. Soc. of America B*, vol. 13, no. 12, pp. 2708–2714, 1996 (doi: 10.1364/JOSAB.13.002708).

[3] W. C. Swann and S. L. Gilbert, "Pressure-induced shift and broadening of 1510-1540 nm acetylene wavelength calibration lines", *J. Opt. Soc. of America B*, vol. 17, no. 7, pp. 1263–1270, 2000.

[4] S. Sudo *et al.*, "Frequency-stabilized DFB laser module using 1,53159 μm absorption line of C2H2", *IEEE Photon. Technol. Lett.*, vol. 1, no. 10, pp. 281–284, 1989 (doi: 10.1109/68.43345).

[5] M. Labachelerie, K. Nakagawa, Y. Awaji, and M. Ohtsu, "High-frequency-stability laser at 1.5 μm using Doppler-free molecular lines", *Opt. Lett.*, vol. 20, no. 6, pp. 572–574, 1995.

[6] V. Ahtee, M. Merimaa, and K. Nyholm, "Fiber-based acetylene stabilized laser", *IEEE Trans. on Instrumen. Measur.*, vol. 58, no. 4, pp. 1211–1216, 2009 (doi: 10.1109/TIM.2008.2008476).

[7] C. S. Edwards *et al.*, "Development and evaluation of compact acetylene frequency standards", in *Proc. Conf. on Precision Electromag. Measur. CPEM 2012*, Washington , USA, 2012, pp. 610–611 (doi: 10.1109/CPEM.2012.6251077).

[8] J. Seppä, M. Merimaa, A. Manninen, M. Triches, J. Hald, and A. Lassila, "Interference cancellation for hollow-core fiber reference cells", *IEEE Trans. on Instrument. & Measur.*, vol. 64, no. 6, pp. 1595–1599, 2015 (doi: 10.1109/TIM.2015.2408800).

[9] P. Balling, M. Fischer, P. Kubina, and R. Holzwarth, "Absolute frequency measurement of wavelength standard at 1542 nm: acetylene stabilized DFB laser", *Optics Express*, vol. 13, no. 23, pp. 9196–9201, 2005 (doi: 10.1364/OPEX.13.009196).

[10] J. L. Hall and S. A. Lee, "Interferometric real-time display of cw dye laser wavelength with sub-Doppler accuracy", *Appl. Phys. Lett.*, vol. 29, no. 6, pp. 367–369, 1976 (doi: 10.1063/1.89089).

[11] C. S. Edwards, G. P. Barwood, H. S. Margolis, P. Gill, and W. R. C. Rowley, "High-precision frequency measurements of the v1 + v3 combination band of $^{12}C_2H_2$ in the 1.5 μm region", *J. of Molecular Spectr.*, vol. 234, no. 1, pp. 143–148, 2005 (doi: 10.1016/j.jms.2005.08.014).

[12] T. Udem, R. Holzwarth, and T. Hänsch, "Optical frequency metrology", *Nature*, vol. 416, pp. 233–237, 2002 (doi: 10.1038/416233a).

[13] F.-L. Hong *et al.*, "Absolute frequency measurement of an acetylene-stabilized laser at 1542 nm", *Optics Lett.*, vol. 28, no. 23, pp. 2324–2326, 2003 (doi: 10.1364/OL.28.002324).

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