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Absolute frequency measurement at 563 THz with the Inmetro´s femtosecond laser comb

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Abstract: The 563 THz frequency of an I_2 stabilized Nd:YAG frequency laser standard has been measured with Inmetro´s femtosecond laser operating as an optical frequency synthesizer. We describe the measurements that have been carried out with the comb system. The results obtained are found to be in excellent agreement with the recommended BIPM values. This allows us to extend our comb based frequency calibration capability into the green range of the optical spectrum.

Keywords: Optical frequency comb, optical frequency measurements, traceability.

1. INTRODUCTION

Currently in Brazil the national primary length standard is a He-Ne laser stabilized to the a_{16} component of the $^{2}I_{127}$ R(127) 11-5 hyperfine transition. The traceability of the primary standard is ensured from participation in CCL-K11 key comparison.

The use of only one standard restricts the calibration scope for stabilized He-Ne lasers with frequency of 473 THz, although interferometer systems also use lasers operating at other frequencies, such as 543 nm and 594 nm, as length standard. To overcome this restriction in 2011 a commercial Frequency Comb Synthesizer was acquired [1]. To validate the comb system calibration capability at 473 THz the frequency of a primary length standard was measured [2].

Over the last two years we have measured the 563 THz frequency of a Nd:YAG laser stabilized to the a_{10} component of the $^{2}I_{127}$ R(56) 32-2 hyperfine transition which was developed at Inmetro’s Optical Metrology Division and was operated in compliance with the recommendations of the practical realization of the definition of the meter (Mise en pratique, in later text referenced as *MeP*) [3]. The results presented in this article are in good agreement with the recommended values, allowing the expansion of the comb based frequency calibration capability to range of the optical spectrum near 563 THz (532 nm).

2. FREQUENCY COMB SYNTHESIZER

Since the late 90's the optical frequency metrology has been experiencing extraordinary growth as a result of the emergence of optical frequency synthesizers (laser comb) based on mode-locked femtosecond lasers. Such equipment has become a common tool in the area of optical frequency metrology in laboratories around the world [4, 5].

The central idea of the frequency synthesizer is that the pulse train generated by a mode-locked femtosecond laser produces, in the frequency domain, a spectrum consisting of an arrangement of discrete and regularly spaced modes, called laser comb [6]. Each comb line has a frequency ($\boldsymbol{f_{comb}}$) that is an integer multiple (**n**) of the repetition frequency ($\boldsymbol{f_r}$) plus or minus an offset frequency ($\boldsymbol{f_0}$) [7-8].

$$\boldsymbol{f_{comb} = n.f_r \pm f_0} \qquad (1)$$

The value of mode number **n** can be obtained through a previous calibration certificate or through the measurement performed with the aid of a wavemeter [9, 10].

The measurement of the laser frequency with a frequency comb is accomplished by observing a beat signal, $\boldsymbol{f_b}$, obtained heterodyning the beam from the laser under calibration with a corresponding mode of the comb [11]. The power of the mixed beam is measured with a fast photodetector and its frequency can be monitored with a counter. The repetition frequency can be measured straightforward through a photodection of the output pulse train from the laser comb beam. The offset frequency is detected via self-referencing technique [12, 13]. The frequency of the laser under calibrations can be written:

$$\boldsymbol{f_{cw} = f_{comb} \pm f_b} \qquad (2)$$

For absolute frequency measurements the frequencies $\boldsymbol{f_0}$ and $\boldsymbol{f_r}$ must be locked to a frequency reference, generated by frequency standard, traceable to the SI-second [14, 15].

2.1 Inmetros´s Frequency Comb

The Inmetro´s frequency comb is a commercial FC 1500 system [1] based on an erbium doped fiber laser (M_{comb}), operating at 1560 nm wavelength, schematically shown in figure 1a. The repetition frequency is detected in this unit.

The M_{Comb} unit output is divided in four beams that are amplified in two erbium doped fiber amplifier (EDFA1, EDFA2) units. Part of the amplified beam from EDFA1 is sent to a spectral broadening setup for generating the octave-spanning and then fed into to a nonlinear interferometer for detection of the offset beat frequency as shown in figure 1b.

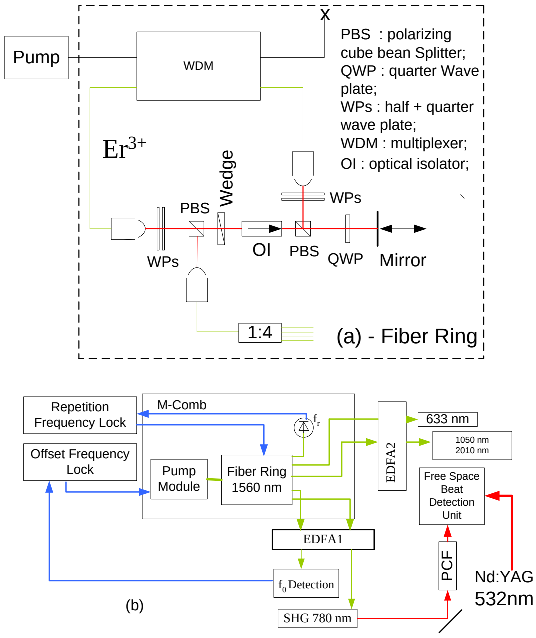

Figure 1 - FC 1500 setup. The green lines represent the fiber connection, blue lines the electrical/RF connection and the red lines the free space laser radiation.

Part of the amplified beam from ADFA1 is sent to a frequency doubling stage for generation of 780 nm wavelength beam which is fed into a photonic crystal fiber for generation of a broadened spectrum used to measure the frequency of the Nd:YAG laser.

3. MEASUREMENT AND RESULTS

3.1 The Nd:YAG frequency standard

The laser radiation of the $^2I_{127}$ stabilized Nd:YAG at 563 THz, developed at Inmetro´s Optical Metrology Division as a national standard for the definition of the metre, has been measured. In the present work the system described in [16] was used. The system was slightly modified in order to be operated in compliance with the recommendations of the *MeP*. The new setup is shown in figure 2.

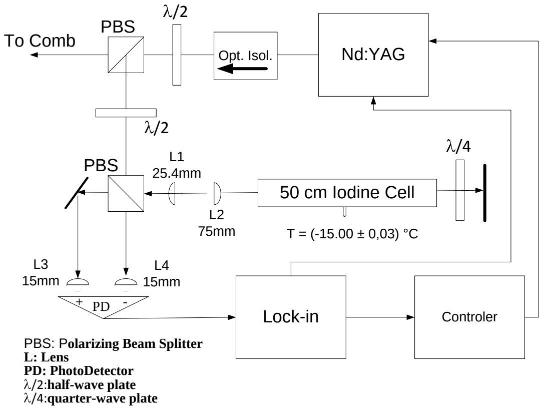

Figure 2 - Schematic diagram of the I_2 stabilized Nd:YAG.

The iodine cell cold finger temperature was set to -15°C. The frequency modulation width was measured with a spectrum analyzer. The figure 3 shows the Nd:YAG beat note and the fit used to calculate the modulation width. The signal shape is due to frequency modulation of the Nd:YAG laser.

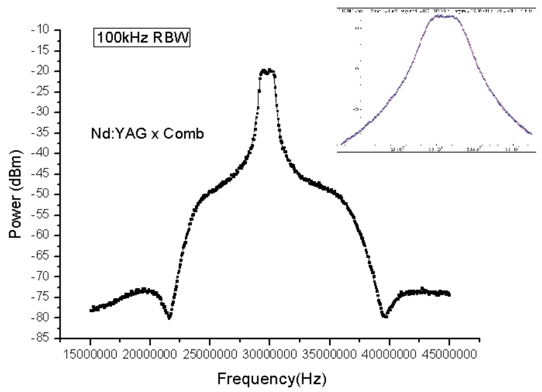

Figure 3 - Nd:YAG and comb beat note after filtering (filter center: 30MHz, 3 dB bandwidth 25 MHz-35 MHz) and amplification.

An absolute signal level above –25 dBm and with a SNR higher than 26 dB is appropriate to ensure a reliable beat signal measurement.

A GPS controlled quartz clock, calibrated at the National Observatory, provides the traceability of the system. This unit provides the 10 MHz reference signal, with a stability of 2.8 x 10^{-12} at 1s, used to phase-lock the repetition frequency, the offset frequency, as well as the time base of the counter and the microwave frequency synthesizer. To ensure that the offset and repetition frequency phase lock are operating properly, any reading that differs more than 0,002 Hz and 10 Hz from the repetition and offset reference frequencies, respectively, is discarded.

The Figure 4 shows the time record of measurements of the Nd:YAG frequency (a_{10} component) compared to the *MeP* value. One second gate time was used in the measurement.

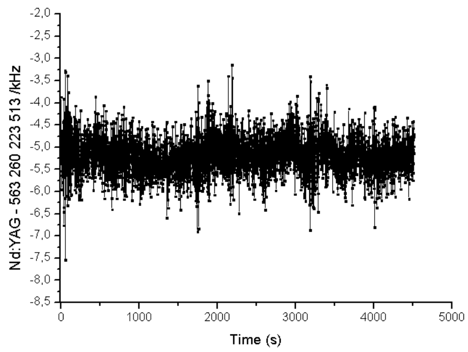

Figure 4 - Time record of measurements of the Nd:YAG frequency compared to the *MeP* value.

The figure 5 shows the Allan standard deviation curve as calculated from the data shown in the previous figure. The observed beat frequency stability of about one part in 10^{12}, in 1 second, is mainly determined by the stability of the quartz clock and enables accurate beat frequency measurements.

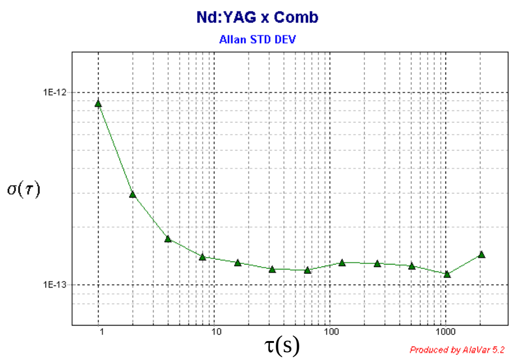

Figure 5 - Relative Allan standard deviation.

The figure 6 shows the measurement results with Inmetro's laser comb over two years. The average frequency of reference component a_{10} at recommended conditions is:

$$f_{a_{10}} = 563\,260\,223\,507.5 \pm 9.7 \quad kHz$$

i.e. 5.5 kHz below the MeP value.

The uncertainties quoted are expanded (k = 2) and correspond to the relative standard uncertainty of 8.9 x 10^{-12} recommended by the *MeP*.

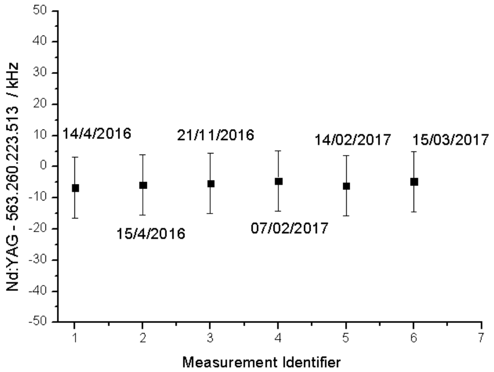

Figure 6 - Measurements of the Nd:YAG frequency compared to the *MeP* value.

4. CONCLUSION

The absolute frequency measurements of 532 nm standard with the Inmetro's laser comb are in good agreement with the reference values, allowing Inmetro to expand the comb based frequency calibration capability to the green range of the optical spectrum. The frequency comb is the reference system to optical frequency measurements and it has direct impact in the Inmetro´s length traceability chain. .

5. REFERENCES

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