

# Traceability of laser frequency/wavelength calibration through the frequency comb at Inmetro

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**Abstract:** The acquisition of a femtosecond laser comb by the Optical Metrology Division of Inmetro now allows for carrying out high precision calibrations of optical frequencies for lasers which are used as standards of the length unit with gauge block interferometers. The frequency comb is operated as an optical frequency synthesizer and is presently linked to the time unit by a 10 MHz oscillator which is disciplined by GPS. Laser frequencies are determined with accuracy in the range of few parts in  $10^{12}$ . This measurement method now links the length unit, meter, to the SI-second attending the recommendation by the BIPM.

## 1. Introduction

The current SI definition of the meter adopted in 1983 specifies that the meter is the length of the path traveled by light in vacuum during a time interval of  $1/299\,792\,458$  of a second [1]. This new definition implies that the traceability of the length unit must be linked to the time unit. Following the new trends several National Institutes of Metrology started to use the laser frequency combs, linked to the primary cesium clocks, to maintain the traceability chain in the area of interferometric gauge block calibration.

At the Optical Metrology Division (Diopt) of Inmetro the length scale is maintained using a He-Ne laser stabilized to the  $a_{16}$  component of the iodine R(127) 11-5 hyperfine transition. The use of only one standard restricts the scope of the calibration for He-Ne lasers with a wavelength of 633 nm. In 2011, to broaden the measurement capabilities in this field with the use of new standard lasers operating at different wavelengths a commercial frequency comb synthesizer was acquired. In 2014, the characterization and validation of this new system was analyzed and approved by an international peer reviewer. The next step was constructing the length traceability chain with respect to the time unit. The operation and characterization of the comb frequency system at Inmetro is presented in this article.

## 2. Frequency comb synthesizer

The frequency comb has become a common tool in the area of high-resolution spectroscopy and optical frequency metrology in laboratories around the world [2,3]. The most important property of such system is that the repetition frequency of the femtosecond laser can be locked to an external standard RF frequency source in order to generate an output beam at optical frequencies consisting of millions of equally spaced modes of a monochromatic phase locked coherent radiations with frequencies given by



$$f_{comb} = n \cdot f_r \pm f_0 \quad (1)$$

where  $n$  is an integer,  $f_r$  is the pulse repetition frequency of the femtosecond laser and  $f_0$  is the carrier envelope offset frequency [4,5]. The latter depends critically on the laser power and dispersion properties of the laser cavity but  $f_0$  can also be referenced and locked to the same RF-reference source.

### 2.1 Method of measuring a laser frequency

The optical frequency of a laser can be determined with the frequency comb using a heterodyning technique. A beat signal,  $f_b$ , is generated with a fast photodetector by superimposing the wavefront of the laser beam of frequency  $f_{cw}$  with the wavefront of a comb mode of similar frequency  $f_{comb}$  [6]. This frequency difference is the beat signal ( $f_b$ ) [7] and is being measured with a frequency counter. The repetition frequency  $f_r$  is also measured straightforward through a photodetection of the output pulse train from the laser comb beam. To determine the offset frequency it is necessary that the frequency range of the comb spans a region larger than an optical octave. The offset frequency is determined by a self-referencing technique as proposed by Hansch [8-10].

The frequency of the laser under calibrations can be written:

$$f_{cw} = f_{comb} \pm f_b = n_r f_r \pm f_0 \pm f_b \quad (2)$$

This equation requires knowledge of two RF-frequencies ( $f_r$  and  $f_0$ ) and mode number  $n$  with absolute certainty.  $f_0$  and  $f_r$  must be locked to a reference radio-frequency, which must be generated by frequency standard, traceable to the primary cesium standard [11].

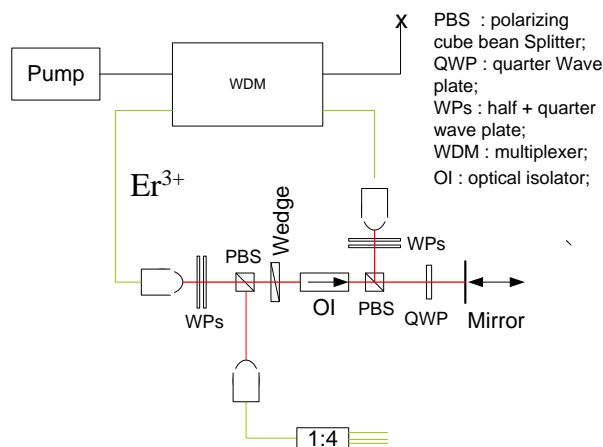
If the laser frequency ( $f_{cw}$ ) is known *a priori* with accuracy higher than half of the repetition frequency, the value of mode number  $n$  is determined by taking the integer part of the ratio given by:

$$n = \frac{f_{cw-apriori}}{f_r} \quad (3)$$

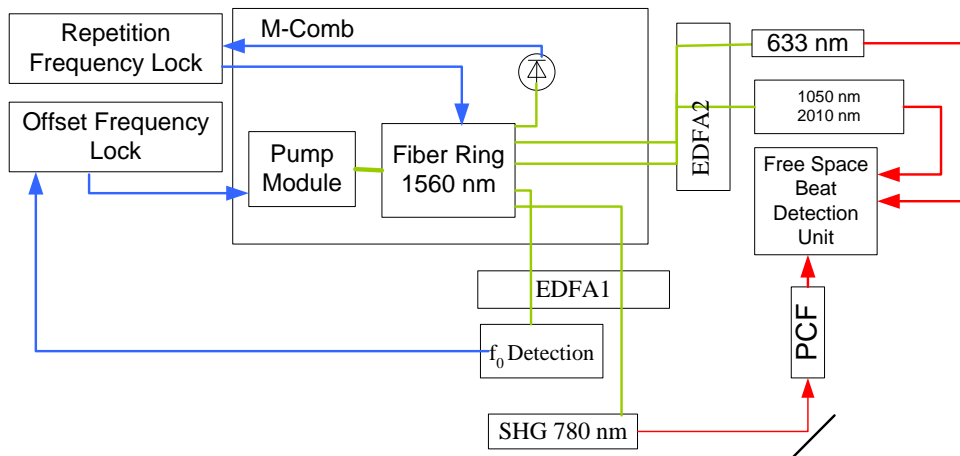
In this case only one measurement is sufficient to determine the absolute laser frequency. The *a priori* information of the laser frequency can be obtained through a previous calibration certificate or through the measurement performed with the aid of a wavemeter [12].

## 2.2 The Frequency Comb

Inmetro's frequency comb is a commercial system based on a diode-pumped erbium doped fiber laser (M-comb), operating at 1560 nm wavelength, described in [13], schematically shown in figure 1. The M-Comb output is divided in four beams that are amplified in two erbium doped fiber amplifier (EDFA1 and EDFA2) units as shown in figure 2. Part of the amplified beam from EDFA1 is sent to a spectral broadening setup for generating the octave-spanning and then fed into a nonlinear interferometer for detection of the offset beat frequency.

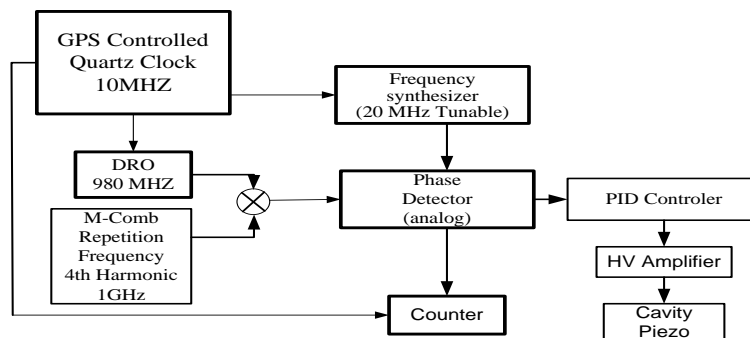


**Figure 1.** M-Comb, the green lines represent the fiber connection and the red lines the free space laser radiation.

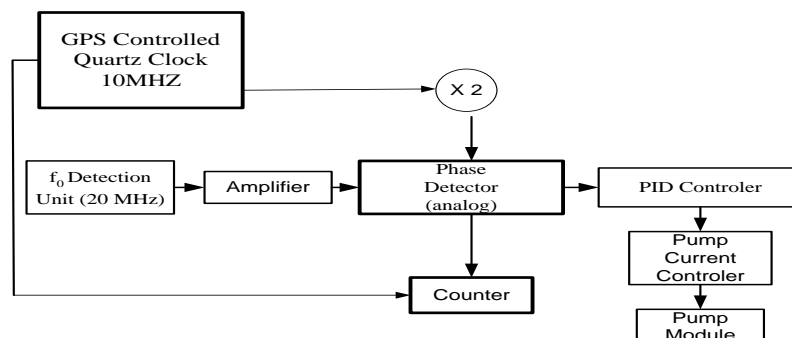


**Figure 2** –FC 1500 setup, the green lines represent the fiber connection, blue lines the electrical/RF connection and the red lines the free space laser radiation.

The repetition frequency and the offset frequency are phase locked by controlling the cavity length and the pump power. A GPS controlled quartz clock calibrated at the National Observatory provides the traceability of the system. This unit provides the 10 MHz reference signal used to phase-lock the repetition frequency, the offset frequency, as well as the time base of the counter and the synthesizer, as shown in figures 3 and 4.



**Figure 3.** Repetition frequency phase lock setup.



**Figure 4.** Offset frequency phase lock setup.

The nominal repetition frequency  $f_r$  of the M-Comb is 250 MHz, but its cavity is provided with elements for coarse and fine tuning about this value and  $f_r$  can be phase locked to a preset precise value linked to a RF-frequency synthesizer. Also the offset frequency  $f_0$  can be tuned and controlled with a phase locked loop.

Part of the amplified beam from ADFA1 is sent to a frequency doubling stage generating a beam at 780 nm which is fed into a photonic crystal fiber in order to broaden the spectrum into the visible region. This beam is used to calibrate lasers with wavelength in the visible region of the spectrum. The EDFA2 is a high power fiber amplifier with internal spectral broadening. Part of the beam from the EDFA2 is filtered for generation of an output radiation at 1266 nm with subsequent frequency doubling stage for 633 nm generation used to calibrate the He-Ne laser.

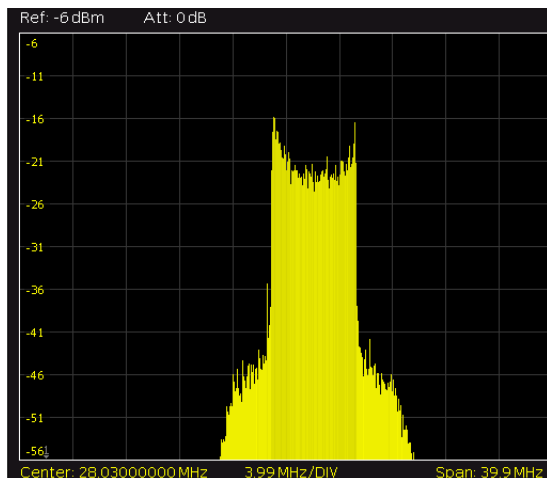
### 3. Measurement and results

We measured the frequency of an  $I_2$  stabilized He-Ne lasers, named PR020, which is the Inmetro's primary standard. The cold finger temperature, the frequency modulation width and the one-way intracavity beam power were kept within the operational conditions required by the BIPM [14].

The reliability of the measurements is directly related to the occurrence of cycle slips in the phase-locked loops (PLL) or if miscounts occur in the measurement of the beat frequency between the comb and the laser under calibration.

To ensure that the offset and repetition frequency phase lock are operating properly, the offset and the repetition frequency signals are split and send to the locking electronics and to the counter. Any cycle slips are easily visible in the recorded counter readings. Any reading that differs by more than 0.002 Hz or 10 Hz from the repetition and offset reference frequency, respectively, is discarded.

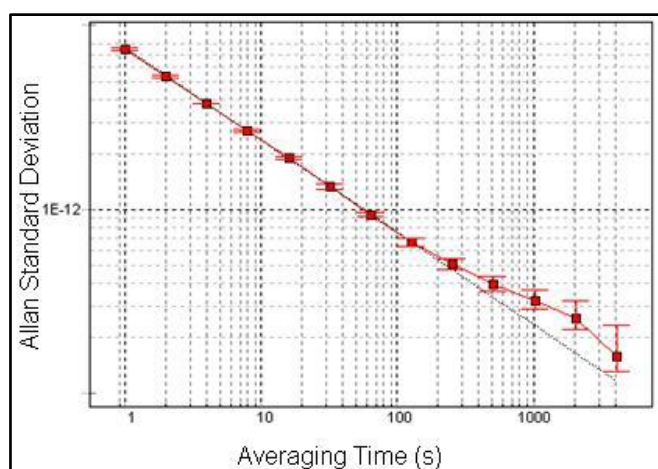
The counting errors can be avoided if the beat signal has a good absolute power and a good signal to noise ratio (SNR). In our system the beat frequency, after detection, is low pass filtered and amplified and then band pass filtered at 30 MHz (filter center: 30 MHz, 3 dB bandwidth 25 MHz – 35 MHz). The signal is then fed to the Counter. Typical beat signal is shown in figure 5.



**Figure 5.** He-Ne (PR020) and comb beat note after filtering and amplification (100 kHz RBW).

Several tests to verify the counter's sensitivity to the signal level as well as to the SNR have been performed. We have changed the absolute signal power and the SNR by changing the polarization of the beam that is coupled into the frequency doubling stage for 633 nm generation in the IDFA2 unit. To evaluate the reliability of this method we compared the standard deviation of the acquired data with the one predicted by the Allan deviation. We conclude that an absolute signal level above  $-25$  dBm and with a SNR higher than 26 dB is appropriate to ensure a reliable measurement.

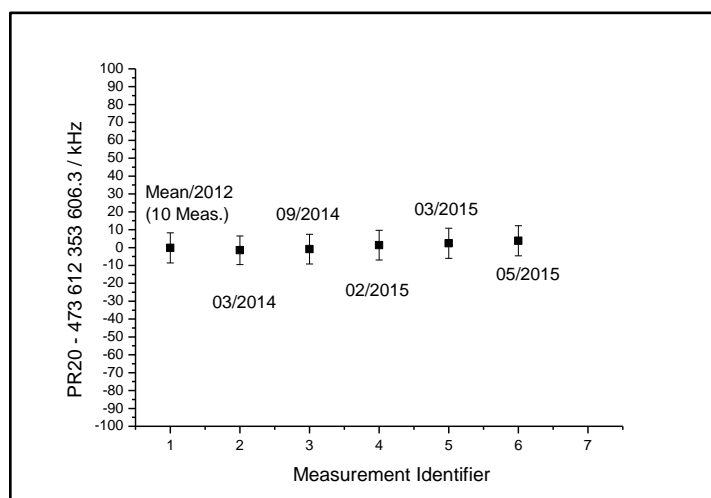
The figure 6 shows the stability of the beat frequency between the He-Ne laser and the comb. These measurements quantify the combined stability of the two systems demonstrating that good accuracy can be achieved for measuring periods larger than 100 s, when the Allan deviation falls below  $10^{-12}$ .



**Figure 6.** Stability of the beat frequency between the He-Ne laser (PR020) and comb.

The uncertainty budget for the calibration is composed by three parts, one from fluctuation of the beat signal, one related to the contribution of stability of quartz clock ( $4 \times 10^{-12}$ ,  $k=1$ ), and one from the uncertainty in the settings of the laser's working parameters.

The figure 7 shows the results of measurements with the Inmetro's comb. The values calculated with (2) were correct to take into account the quartz clock offset from the National Observatory primary time standard.



**Figure 7.** Measurements of the PR020 frequency compared to the CCL K11 value.

#### 4. Conclusion

The frequency comb at Inmetro was successfully put into operation. The absolute frequency measurements of 633 nm standard are in good agreement with the reference value, which ensures the measuring capability of the system and the traceability for length metrology with minimum relative uncertainty of  $4 \times 10^{-12}$  ( $k=1$ ).

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