Length Measurement using Frequency Comb and Optical Clock Technology at Inmetro

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Abstract: Inmetro is assembling a frequency comb for measurements of optical frequencies traceable to a Cesium clock and/or an optical clock. This setup will replace meter traceability based on length standards to time standards based.

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OCIS codes: (120.3940) Metrology; (320.7160) Ultrafast technology.

1. Introduction
The International Committee for Weights and Measures (CIPM) recommended national metrology institutes (NMIs) to pursue the optical frequency comb technique to the highest level of accuracy, seeking simplicity when substituting very complex frequency chain techniques. The committee also considers new femtosecond comb techniques very useful to relate the frequency of high stability optical frequency standards (length standards) to the frequency of the practical realization of the SI second, the cesium atomic clock. The comb is very convenient because it can provide traceability to the SI and an optical frequency tunable source as well as measurement technique [1].

The Kaarls report 2007 [2] enumerates some needs for innovative measurement standards and methods, one of them is considered very important for accurate dimensional measurements: the development and application of lasers and interferometry. Additionally, more accurate measurements of time and frequency are needed for improving satellite systems performance, bringing rise to the optical clock technique as a solution to be pursued.

Aware of these recommendations, the Brazilian National Council for Metrology, Standardization and Industrial Quality (CONMETRO) approved in 2008 some strategic directives for Inmetro fully assigns its function as NMI [3]. The aim for optical frequency metrology is the development of the femtosecond laser frequency comb technique in Brazil in order to change the length traceability to a length connected to time traceability. Nowadays, the project is beginning its first stage. The infrastructure to assemble a new laboratory is being constructed and this new lab will be dedicated to pursue the three main applications of frequency combs: measurement technique, frequency source (optical and IR range) and transfer device for traceability issues.

2. Laboratory setup
Inmetro is assembling a frequency comb for measurements of optical frequencies traceable to the microwave frequency of a Cesium clock. This will replace the Brazilian length standard traceability, one of the BIPM recommended Mise en pratique, consisting of an Iodine cell stabilized He-Ne laser whose stability is $10^{-11}$ (1s average) and accuracy is 25 kHz. Efforts have been made in order to change this frequency standard for another one that consists of an Iodine cell stabilized $2\omega$-Nd:YAG laser whose stability is $10^{-13}$ (1s) and accuracy is 5 kHz. This result approaches the laser to the time standard stability, with the advantage of better short term stability. Although cesium fountain atomic clocks can reach $10^{-15}$ stability in 100s average, the Nd:YAG is a good initial approach for this secondary standards competition.

The $2\omega$-YAG was stabilized using saturated absorption in an Iodine cell and 3f detection technique in order to close the loop feedback and it can be used as timekeeping element for an optical clock and the frequency comb is the clockwork mechanism which allowed one to measure the frequency. The first results from the frequency comb under assembling will be presented at the meeting. The metrological characterization of the Nd:YAG laser will be presented in order to evaluate its stability and frequency accuracy.

The frequency comb will be assembled in a 60 m$^2$ laboratory with an airflow hood and a 10 MHz reference frequency provided by a GPS disciplined quartz crystal oscillator, whose stability in (1s) is $10^{-12}$. Another 10 MHz reference frequency will be available when the Cesium atomic clock signal will be transmitted to the whole campus.

The fiber connection between the comb and the cesium clock needs some technical restrictions because better than $10^{-13}$ stability is required.

Three optical tables will be connected in cross configuration and in each arm will be located an equipment. The frequency comb will be located in one arm and in the other arms: $2\omega$-Nd:YAG laser, He-Ne laser and (ECDL)-Blue.
The first two are independently stabilized by iodine cells while the latter is electronically stabilized by the comb signal itself.

The frequency comb is a Menlo Systems fiber based comb design and the company is a spin-off from Max Planck Institute for Quantum Optics and one of its founders is 2005 Nobel prize winner T. Hansch. The rate frequency is referenced to the quartz oscillator and/or cesium atomic clock while the phase offset (carrier envelope offset CEO) is self referenced using the beat frequency of one selected comb frequency and its second harmonic.

3. Traceability Issues

Nowadays, the practical realization of the length unit of SI (International System of units) is obtained by the vacuum wavelength of a He-Ne laser whose frequency is locked to an iodine transition. The dissemination inside the country is reached by the traceability transfer to lamps considered secondary standards. These lamps are used to shine interferometers which calibrate gauge blocks (material artifacts) that can be disseminated mechanically to the industry and commerce in general. The maintenance of the meter is achieved by an ensemble of three lasers whose frequencies are periodically intercompared through heterodyne beat measurements. Each of these lasers has a wavelength of 633 nm (474 THz) which is known with an uncertainty of less than 2.5 parts in $10^{11}$ (12 kHz).

These traceability chain is very useful but since the definition of meter is connected to the second [4], and the realization that the best measurements in science are frequency related due to its measurement being digital by nature [5], this definition allowed one to begin to merge the length standards and time standards as frequency standards and they could be used in equivalence.

The frequency comb implantation will allow the connection of the wavelength standards to time standards (quartz or cesium) and the change in the traceability of length in the country. Inmetro intends to assemble three lasers irradiating in red, green and blue frequencies in order to substitute the lamps (secondary standards) and these lasers will be traceable to the SI unit of time. We will use an iodine stabilized He-Ne laser as red emitter, a $2\omega_-$Nd:YAG also iodine stabilized as green emitter and an extended cavity stabilized blue diode laser. These lasers will shine a Koesters interferometer which is responsible for the long gauge blocks calibration and these material artifacts can disseminate the length unit to the whole country. The small gauge block calibration will be performed by JENA interferometer shined by Cd lamps.

Brazil will give a step forward with this construction and will join the selected group of nations that have this frequency comb traceable to the international atomic time.

A further leap will be the connection of the iodine stabilized Nd:YAG laser as frequency reference to the comb. The stabilized Nd:YAG is the simplest optical atomic clock and has short term stability better than atomic clocks. The cesium atomic clock has some short term instabilities that are usually corrected by adding a maser to the pool of time reference clocks. At Inmetro, we will study the Nd:YAG stability and compare the measurements made with cesium atomic clocks and optical atomic clocks.

4. Acknowledgements

The authors would like to thank Prof. Dr. João A. Jornada and Prof. Dr. Humberto S. Brandi for their efforts to make this project a reality.

References: