A Review of a Frequency Comb at National Observatory

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Abstract. This article presents a review of a Frequency Comb based on an erbium-doped mode-locked laser at a wavelength of 1550 nm, where the self-reference method for identifying the two degrees of freedom, repetition and offset frequencies is explained; detailed how these frequencies are stabilized and how the spectral broadening is performed, generating supercontinuum signals to measure external continuous laser as a motivation for a better understanding of the importance of this equipment in the context of the next redefinition of the second in the optical domain.

1. Introduction

To better understand the Optical Frequency Comb, it is important to know the main discoveries and technological advances that made the construction of this equipment possible. When we mention optical frequencies, we are referring to the laser, a source of coherent light with a frequency in the order of Tera Hertz, covering the spectrum range known as the optical domain, and which fulfills the role of the main component of the Frequency Comb. The laser and fiber optics represent the main technological milestones in the construction of the Frequency Comb. The laser is the main component because it serves as a reference for the measurement of another unknown laser through optical beating (heterodyne measurement). Fiber optics played a role in improving the construction of the laser and therefore in the entire operation of the equipment, making commercial production of the Frequency Comb possible. Both the laser and fiber optics were the result of discoveries and technological advances with origins in the historical context of Quantum Mechanics and which led to the emergence of the Frequency Comb [1] [2] and of large areas of study such as Quantum Optics, Optical Metrology, High-Resolution Optical Spectroscopy and the Processing and Synthesis of Optical Signals. The theoretical foundations of a laser were initially presented by Einstein in the article "On The Quantum Theory of Radiation" from 1916 [3], in addition to appearing in several literatures [4] [5] [6] [7] [8]. The most important improvement in laser technology that helped to conclude the development of the frequency comb was the femtosecond laser[9]. The pioneer in this improvement was Ahmed M. Zewail, that created the Femto Chemistry study area where arised the ultra fast pulses research[10]. Ahmed M. Zewail won the 1999 Nobel Prize in Physics for his development of the Femto-Second Resolution Spectroscopy.The Frequency Comb appears with the function of performing optical measurements of transitions between atomic, ionic and molecular energy levels for the construction of Optical Clocks [11] [12] [13] [14] . Its inventors, John Hall [15] and Theodor Hänsch [16], won half of the 2005 Nobel Prize in Physics for their development of the Frequency Comb. Several applications and improvements of the Frequency Comb still arise, such as the Micro Optical Frequency Combs[17] [18] [19] [20] [21] the Frequency Comb applied to Astronomy (AstroComb) [22] [23] [24], applications of the Comb aimed at High Resolution Spectrometry [25] [26] to the segment of Optical Communications [27] [28], the segment of Dissemination of Synchronism Signals [29] [30] and Optical frequency Metrology [31].

1.1. Optical Domain:

The search for a technology that would allow the measurement of frequencies in the optical domain was a challenge for a long time before the use of the Frequency Comb, for three main reasons:

1 Measurements in the optical domain are performed indirectly using the heterodyne method in which a known laser is beat against an unknown laser and few optical frequencies were known and available;

2 Building an exact and stable laser was still a challenge to be overcome due to the available technologies at the epoch. After this challenge was overcome, the Laser was really improved in stability, portability with the implementation the CW and Mode-Locked Lasers by optical fibers ;

3 The metrological interface between the microwave and optical frequency domains to reference measurements with the Cesium Beam Standard was still challenging, specially when the difference was greater than tens of GigaHertz. This metrological interface became effective only with the use of a Frequency Comb as a metrological bridge between the two domains eletrical (microwave) and optical. While these challenges were not overcome, the Quality factor, (Q), was limited aproximately by 10^8 in the microwave spectrum obtained from the atomic oscillator of the Beam Cesium Standard adopted in 1967, at Measurement and Weight Geral Conference,(CGPM), as a Time and Frequency Standard, where the resonance frequency is 9.192.631.770 Hz based on the transition between hyperfine levels (F=4, mf=0 => F=3, mf=0) of the ground state of Cesium 133. The Q factor is represented by the ratio between the resonant frequency f and the bandwidth Δf of the resonant frequency, according to Equation 1:

$$Q = \frac{f}{\Delta f} \tag{1}$$

At that time, measurements in the optical domain were still inaccurate and unstable, in addition to using a lot of hardware resources. The optical frequency measurement systems were formed by long chains of oscillators, synthesizers and Phase-Locked Loop circuits (PLL), microwave tubes and frequency multiplier crystals connected in cascade to generate known optical frequencies and perform optical beating, (heterodyne measurement), with the unknown frequencies to be measured. With the improvement in the construction of lasers, it was possible to generate different optical frequencies with narrower widths, such as the Continuous-Wave laser, (CW Laser), with a width of thousandths of herts or subHertz, which made it possible to use the laser in heterodyne measurements with quality factors of the order of 10^{14}, enabling the construction of the Frequency Comb and improving the stability of optical clocks, reaching uncertainties in the range of 10^{-18}.

2. Optical Frequency Synthesizer

The Optical Frequency Synthesizer or Frequency Comb is an optical ruler used to measure lasers. Figure 1 presents this analogy where each graduation of a ruler in (1) is aligned with the modes of a laser with locked modes represented partially in the time domain in (2) and in the frequency domain in (3). The laser's representation of locked modes in the frequency domain was the motivation to call the optical synthesizer as a Frequency Comb. Suposing each laser mode similar to each Comb tooth, it would be more intuitive to conclude why the Optical Frequency Synthesizer is called Frequency Comb and one light ruler. The optical synthesizer performs the measurement of a Continuous-Wave external laser, that is, with a single frequency, comparing this laser with the closest mode of the mode-locked laser through an optical beating that results in an intermediate frequency detectable by a photodiode and being possible to measure it in the electrical domain by means of a spectrum analyzer (frequency domain) or an oscilloscope (time domain). It is through this beat between two optical frequencies resulting in an intermediate frequency that the Frequency Comb performs the interface between the optical and electrical domains. Equation 2 presents the relationship between electrical and optical domains first established with the advent of the Optical Frequency Synthesizer or Frequency Comb as below:

$$W = nWr + Wo + Wb \qquad (2)$$

Being W the optical frequency to be measured from the laser, (optical domain),Wr the repetition frequency (electrical domain), Wo the offset frequency, (electrical domain) and Wb it is the beat frequency that is obtained by overlaping the laser beam to be measured and the Frequency Comb beam corresponding to the n mode, on the surface of a fast photodetector. The offset frequency is generated by the difference between the group velocity of the modulating signal and the phase velocity of the carrier frequency, in each cycle of the circulating pulse inside the resonant cavity of the Mode-Locked Laser. This difference increases as the mode also becomes larger and can be seen in figure 2 through ΔΦ e Δ2Φ. Therefore, the Frequency Comb has two degrees of freedom which are the repetition frequencies and the offset frequency and which need to be locked with an Atomic reference. In the case of a first generation comb this reference could be either a Thermal Beam Cesium Standard or a Hydrogen Standard, (MASER). In a second generation of Frequency Comb, this reference could be an Optical Clock or an Cesium Fountain that should have an optical output. In our laboratory there is an additional reference option which is the Brazilian National Atomic Time Scale, UTC(ONRJ)[32]. The Frequency Comb became a reality when it became capable of performing spectral broadening to cover an optical octave, with the aim of self-referencing the fundamental mode n with another mode in a higher octave $2n$. With this challenge overcome, it was possible to calculate the offset of the optical spectrum of the Frequency Comb and perform measurements with very high resolution on the order of Tera Hertz. In this way, the offset Wo is calculated and the interference or beating between optical frequencies Wn and $Wn2$ is performed, which is detected by a photodiode and the optical frequency can be measured through an intermediate frequency by an electrical spectrum analyzer. Below we can visualize the mathematical representation of self-referencing by the doubled fundamental mode equation in 3, the upper octave mode equation in 4 and the subtraction between 3 and 4 in 5 to identify what is the offset frequency Wo.

$$Wn = 2(n.Wr + Wo) \qquad (3)$$

$$Wn2 = (2n.Wr + Wo) \qquad (4)$$

$$Wo \; = Wn \; - Wn2 \qquad (5)$$

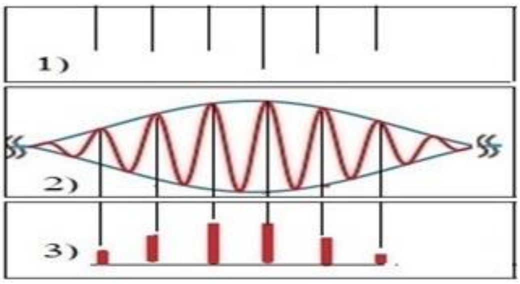

Figure 1. Partial graphical representation of a Frequency Comb. In 1, the analogy of the Frequency Comb with a ruler is represented. In 2, an equidistant coupled-mode laser is represented partially in the time domain and in 3, an equidistant Mode – Locked Laser of a Repeating Frequency is partially represented in the frequency domain as a light ruler as indicated by vertical black lines between 1 and 2. Credit: Primary Time and Frequency Laboratory, National Observatory.

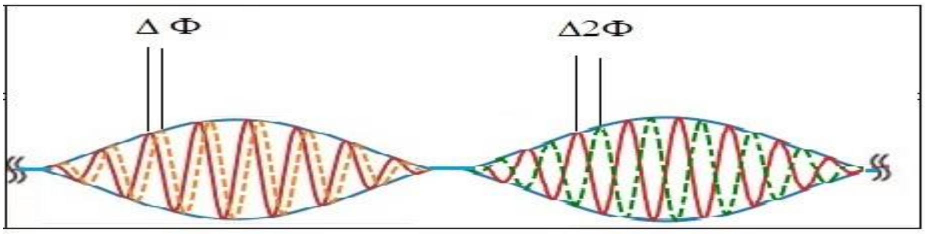

Figure 2. Partial representation of a Mode- Locked Laser focusing on the shift frequency variation (offset) as the laser mode changes with locked modes. Credit: Primary Time and Frequency Laboratory, National Observatory.

3. Operation

A frequency comb as already shown by figures 1 and 2 is formed by a sequence of discrete pulses equidistant in the frequency domain by a frequency that is the repetition frequency. In the time domain it is formed with a mode-locked laser where there is a varying displacement in each mode, called the offset frequency. These two frequencies are the two degrees of freedom present in the operation of the Frequency Comb. These two degrees must be locked or stabilized with respect to the comb's electrical or optical reference. There are some ways to carry out this stabilization according to the way the Comb is constructed, which can be through the mixing of 4 waves in a non-linear way [33] and another that is the most explored in which the two degrees of freedom are stabilized, shown in figures 1 and 2 through self-referencing of the laser in locked modes, represented mathematically by equations 3, 4 and 5. The laser cavity with repetition frequency of 250MHz is finely adjusted by a piezo actuator controled by a feedback loop with a proportional and integral controller synchronized with an atomic reference. The offset frequency is finely adjusted by varying the electric current of the semiconductor lasers used in optical pumping and this feedback loop is also sinchronized with the same atomic reference. Modules that drive both the piezoelectric actuator and the electric current are controlled by conditioned voltage as a result of mixing between two signals of 1GHz and 980MHz. The 1GHZ signal being the fourth harmonic of the repetition frequency of 250MHz value and the 980MHz signal being the output of a quartz oscillator with double phase lock loop,(PLL), and with a synthesizer locked with the 10MHz input signal that is generated by a cesium standard, which is the reference of all Frequency Comb modules. In this way, the command signals of the actuators, once adjusted, will be locked or synchronized with the atomic reference of the all electronic modules operating in the Frequency

Comb[34]. With the Frequency Comb's two degrees of freedom locked or stabilized to the atomic reference, the Frequency Comb is ready to perform external Continuous-Wave Laser,(CW Laser), measurements. This means that the main Laser doped with Erbio at 1550 nm had the output signal doubled to generate the optical octave to carry out the self-referencing in which the offset frequency is identified, measured and stabilized as well as the repetition frequency, as already explained. This higher octave signal represents a 780nm laser that will be spectrally broadened to spectrally span a wide frequency range and allow measurement of a wide range of external lasers. For spectral broadening, photonic crystal optical fibers or microstructured optical fiber are used to generate a supercontinuum optical signal, which provide a non-linear response and therefore broaden the spectrum, but at the cost of providing a non-uniform relationship between intensity and wavelength. In the Primary Laboratory of Time and Frequency, the Frequency Comb has three options of microstructured optical fibers to cover wavelengths up to 1050 nm, in addition to three options of atomic references, being a beam cesium standard, a hydrogen standard or the Brazilian atomic time scale UTC(ONRJ) formed by a set of atomic standards and with traceability by BIPM.

4. Conclusion

I would like to thank ON/MCTI for the financial support to equip this laboratory, perform the upgrade and carry out ongoing maintenance of the frequency comb whose basic operating concepts were introduced with some basic details and several advanced applications cited in this article. With the basic concepts of how a Frequency Comb works presented in this article, the reader will have the theoretical basis to understand the applications mentioned in the introduction as the AstroComb and the MicroComb and the several other applications that will probably arise. In addition, an introductory basis for a better understanding the operation of this optical metrology equipment in the frequency domain was presented, as well as the opportunity for research in Time and Frequency Metrology in the optical domain and future articles proceeding in the context of the future redefinition of the second in the optical domain.

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