

## Optical frequency division

Yuan Yao, Yanyi Jiang\* and Longsheng Ma

State Key Laboratory of Precision Spectroscopy, East China Normal University, China

\*Corresponding author. E-mail: yyjiang@phy.ecnu.edu.cn

Frequency can be measured much more precisely than any other physical quantity, and that therefore, much of precision metrology depends critically on the measurement of frequency and its inverse, time-interval. Optical electro-magnetic waves (or “light”), oscillating more than  $10^{14}$  per second, are at least one thousand times better for precision time/length measurement compared to microwave frequencies near 1 GHz. However, electronics do not respond to such rapid optical oscillations. Thus, optical frequencies cannot be measured directly, instead we must divide them down to the RF (radio frequency) regime for electronic counting. It has been a historical challenge to realize optical frequency division with arbitrary divisors. In the 1970s, the absolute frequency of a methane-stabilized He-Ne laser was measured by dividing its frequency to the RF region with a frequency chain based on many nonlinear frequency conversions. By measuring the laser frequency, the measurement accuracy of the velocity of light was improved by 100 times [1]. However, the frequency chain for optical frequency division was complex and huge in size, and it covered only few specific wavelengths. The accuracy of the frequency chain was only  $10^{-10}$ , limiting its application in precision measurements with high accuracy.

Optical frequency combs, invented in 1999, have revolutionized the art of optical frequency division [2,3]. The spectrum of an optical frequency comb consists of a series of discrete optical frequency lines uniformly spaced by a radio frequency interval. By interfering optical waves with the comb, researchers can link optical-optical and optical-microwave frequencies in a single step. In 2001, the first frequency comparison between a Ca optical clock and a Hg<sup>+</sup> optical clock was made using an optical frequency comb [4]. In 2004, an international frequency comparison among four combs (two different types) from three laboratories verified that optical frequency combs could support optical frequency division with  $10^{-19}$  uncertainty [5], confirming combs can serve as the clockwork for optical atomic clocks with  $10^{-18}$  uncertainty. Fascinating development of optical atomic clocks bloomed in the following fifteen years: both the fractional frequency instability (long term) and uncertainty of optical clocks have reached  $10^{-18}$ , and they are making progress towards  $10^{-19}$ - $10^{-20}$  [6].

In most early work, the noise from combs, RF electronic timebases and other technical noise limit the division uncertainty at the  $10^{-19}$  level. In 2015, most of the noise from combs and RF timebases were reduced by using the transfer oscillator scheme [7] and synchronously

counting relative to a H-maser. With these techniques of noise reduction, the frequency ratio of two independent frequency-stabilized lasers was simultaneously and independently measured with a Ti:sapphire comb and a fiber comb, and the agreement between these frequency ratio measurements was  $3 \times 10^{-21}$  [8]. In 2016, the comb frequency noise was further reduced by employing both the transfer oscillator scheme and a narrow-linewidth, frequency-stabilized comb. Meanwhile, a self-referenced RF timebase divided from one of the laser frequencies was introduced to remove the noise from an additional RF timebase. Along with noise reduction of common optical-path propagation, the uncertainty of optical frequency division was demonstrated to be  $1.4 \times 10^{-21}$  by comparing against the frequency ratio between the fundamental and the second harmonic light [9]. Additional laser linewidth broadening due to optical frequency division is less than 1 mHz.

Due to the unprecedented precision and accuracy provided by optical clocks, eight optical frequency standards have been recommended as ‘secondary representations of the second’, and a roadmap towards the redefinition of the SI second has been proposed [10]. To assure continuity between the present definition and the new definition, frequency comparisons (at least three) between optical clocks and Cs primary clocks (called absolute frequency measurements), should be made with uncertainties below  $3 \times 10^{-16}$ . Moreover, to show the achievable accuracy provided by optical clocks beyond that from the present definition, frequency ratio measurements between optical clocks based on different species or transitions (at least five) with agreement below  $5 \times 10^{-18}$  will be performed. Even after the SI second redefinition, frequency comparisons between optical clocks will be frequently performed to measure the frequency instability, uncertainty and reproducibility of optical clocks. To meet the requirement of the SI second redefinition, accurate optical frequency dividers with multiple channels must be developed for regular frequency measurement and transfer. If optical frequency dividers connect optical clocks with  $1.5 \mu\text{m}$  lasers for signal transmission in optical fiber, together with fiber noise cancellation, an optical clock network will be established for time/frequency dissemination, geodesy and astronomy.

Other applications of optical frequency dividers with multiple channels include test of fundamental physics by measuring the frequency ratios among different optical clocks at different times and locations. Do fundamental constants, such as the fine-structure constant and the proton-to-electron mass ratio, vary with time and space? Measurement of these dimensionless fundamental constants play a special role in tests of the equivalence principle. Moreover, using a multiple-channel optical frequency divider to accurately set the frequency ratios between an optical/RF frequency standard and wavelength-tunable, single-frequency continuous-wave lasers with useful power, coherent laser light can be generated at any desired wavelength over a wide optical region with high precision on demand, making the dreams of optical frequency synthesizers come true. Optical frequency synthesizers are

invaluable for atomic and molecular spectroscopy, optical communications, and coherent light detection. Moreover, they can also divide the frequency of optical clocks to the microwave region to take advantage of the accuracy and low phase noise provided by optical clocks.

Motivated by the above applications, researchers seek to reduce the noise and uncertainty of optical frequency dividers below that of optical clocks by at least one order of magnitude. Although accuracy is very important, to meet practical applications, optical frequency dividers also need to be improved for compact size, continuous long-term operation, and even portability. Ultimately optical frequency dividers will be integrated on a photonic chip [11], similar to chip-scale digital RF frequency dividers. Also, the spectrum covered by optical frequency dividers needs to be extended to ultraviolet and to mid-infrared for wide applications. Looking into future, optical frequency dividers will be widely used in the SI second redefinition and precision measurements, and meanwhile they will be optimized for high accuracy and convenient use.

## FUNDING

This work was supported by the National Natural Science Foundation of China (91636214, 11822402, 11927810, 11804094, 11654004) and the National Key R&D Program of China (2017YFA0304403).

## REFERENCES

1. Evenson KM, Wells JS, Peterson FR, Danielson BL, Day GW, Barger RL and Hall JL. *Phys Rev Lett* 1972; **29**: 1346–1349.
2. Hall JL. *Rev Mod Phys* 2006; **78**: 1279–1295.
3. Hänsch TW. *Rev Mod Phys* 2006; **78**: 1297–1309.
4. Diddams SA, Udem Th, Bergquist JC, Curtis EA, Drullinger RE, Hollberg L, Itano WM, Lee WD, Oates CW, Vogel KR and Wineland DJ. *Science* 2001; **293**: 825–828.
5. Ma LS, Bi Z, Bartels A, Robertsson L, Zucco M, Windeler RS, Wilpers G, Oates C, Hollberg L and Diddams SA. *Science* 2004; **303**: 1843–1845.
6. Ludlow AD, Boyd MM, Ye J, Peik E and Schmidt PO. *Rev Mod Phys* 2015; **87**: 637–701.
7. Telle HR, Lipphardt B and Stenger J. *Appl Phys B* 2002; **74**: 1–6.
8. Johnson LAM, Gill P and Margolis HS. *Metrologia* 2015; **52**: 62–71.
9. Yao Y, Jiang Y, Yu H, Bi Z and Ma L. *Natl Sci Rev* 2016; **3**: 463–469.

10. Riehle F, Gill P, Arias F and Robertsson L. *Metrologia* 2018; **55**: 188–200.

11. Spencer DT, Drake T, Briles TC, Stone J, Sinclair LC, Fredrick C, Li Q, Westly D, Ilic BR, Bluestone A, Volet N, Komljenovic T, Chang L, Lee SH, Oh DY, Suh M-G, Yang KY, Pfeiffer MHP, Kipperberg TJ, Norberg E, Theogarajan L, Vahala K, Newbury NR, Srinivasan K, Bowers JE, Diddams SA and Papp SB. *Nature* 2018; **557**: 81–85.

**Figure caption:**

**Figure 1.** Multiple-channel optical frequency divider based on an optical frequency comb connects optical waves with different frequencies, behaving like gears. It can convert optical frequencies with pre-determined ratios, or measure optical frequency ratios.

