Frequency combs and frequency dissemination for scientific and industrial applications

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Optical frequency combs enable us to count oscillations of visible light with unprecedented precision. The invention that formed a basis for the patented frequency comb technology was described as “the biggest advance in precision electromagnetic measurements since people began to measure laser frequencies in the seventies…” It is closely associated with the Nobel Prize in Physics awarded in 2005. Theodor W. Hänsch and John L. Hall received the most prestigious scientific award for their contributions to the development of laser-based precision spectroscopy.

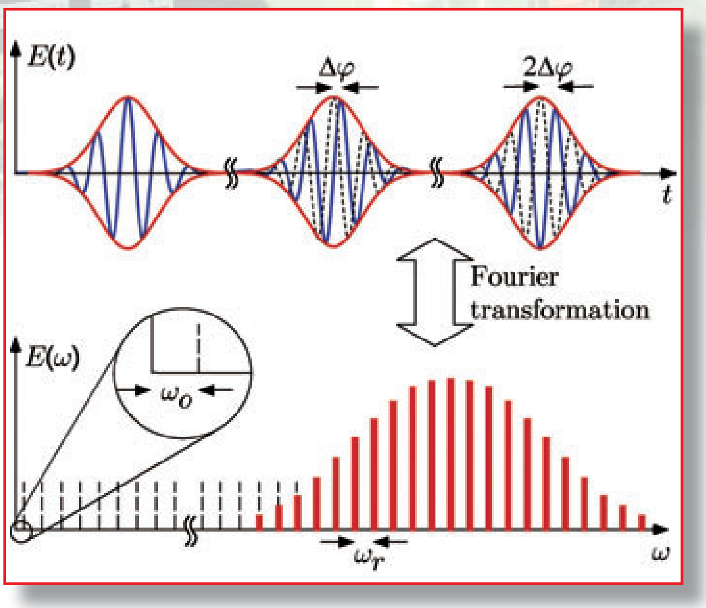

***Figure 1**: A train of ultra-short pulses depicted in time- and frequency space. As the pulse envelope propagates with the group velocity, the carrier moves with the phase velocity, thus the relative phase between the pulse envelope and the carrier wave increases from pulse to pulse by an angle of $\Delta\varphi$. The resulting spectrum of the Fourier Transformation of such a periodical envelope is presented below. It consist of periodic modes with a separation equal to the pulse repetition frequency ω_r and a frequency offset ω_0, which prevents the comb from being comprised of exact harmonics of ω_r*

Professor Theodor W. Hänsch, director of the Max-Planck-Institute for Quantum Optics in Garching near Munich, and his co-workers have pioneered much of the frequency comb technology. In 2001 Michael Mei and Ronald Holzwarth, together with their mentor Hänsch, founded Menlo Systems GmbH to commercialise frequency comb technology and make it available to a broader spectrum of applications. Based on their experience in fundamental research and taking advantage of fibre laser technology, they rapidly developed a successful product: the fibre laser based optical frequency synthesiser. The resulting fibre laser systems – actually the by-products – are finding their way to numerous scientific and industrial applications.

1 Optical frequency combs

The optical frequency comb revolutionised precision spectroscopy. It replaced the conventional way of determining laser wavelengths with interferometry, allowing measurement of optical frequencies with several orders of magnitude higher precision [1-3].

Radiofrequencies can be accurately counted and compared to each other with electronic counters. Furthermore, a wide range of frequency references is commercially available for this frequency range, ranging from simple quartz oscillators up to precision caesium atomic clocks. To obtain highly accurate results it is necessary to measure the frequency of light rather than its wavelength, given that time can be measured more precisely than any other physical quantity, and counting the number of cycles in a second is as accurate as the clock that is used to determine the duration of the second. That is the reason why we try to trace back the definition of other physical quantities to time or frequency. As the meter is defined by the length of the path travelled by light during a given time interval and the speed of light c_0, the conversion between frequency and wavelength can be done without deterioration in the accuracy. The fundamental unit of length measurements, the wavelength λ is defined through the frequency of an electromagnetic signal f as $\lambda = c_0/f$. In practice length is measured using interferometers.

The achievable precision of frequency and length measurements is limited by the precision of frequency standards on which these measurements are based. In measuring optical frequencies with the highest possible precision, there is thus a need for appropriate standards. These frequencies, however, are so high that for a long time it was not possible to count them directly. For instance, the 532 nm wavelength of the green light corresponds to a frequency of 564 THz (1 THz = 10^{12} Hz). The highest electronic frequencies are more than four orders of magnitude smaller; too slow to serve as counter for direct frequency measurement. With the development of the femtosecond frequency synthesiser, it became possible to extend the high accuracy of radio-frequency measurements into the domain of rapid optical oscillations.

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[1] This topic was awarded the 3rd prize of the Berthold Leibinger Innovationspreis 2006

Originally published in German in Photonik 5/2006

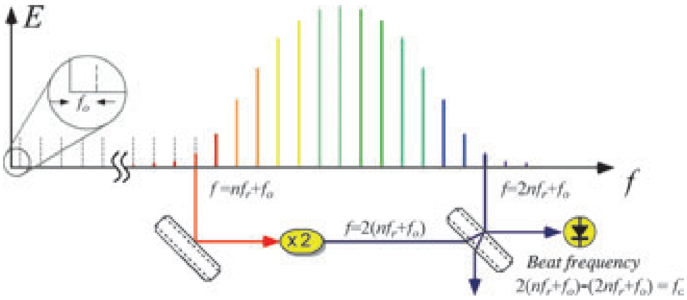

***Figure 2**: A schematic picture of the spectrum of an optical frequency synthesiser. Its white light comprises hundreds of thousands of equidistant narrow spectral lines, whose separation is determined by the pulse repetition rate* $\mathbf{f_r}$*. The absolute frequency of the* n^{th} *comb line is given by* $\mathbf{f_n = n\,f_r + f_0}$*, where* $\mathbf{f_0}$ *originates from the continuous phase shift of the carrier wave. In order to measure* $\mathbf{f_0}$*, the comb lines at the red end of the spectrum are frequency doubled and overlapped with the corresponding blue comb lines on a photodetector, which measures the originating beat signal at* $\mathbf{f_0}$

The frequency spectrum of a mode-locked laser is mathematically obtained by a Fourier transformation of the train of identical pulses in the time domain (**figure 1**). It comprises discrete optical modes spaced precisely by the pulse repetition rate. In the spectral range covered by the laser pulse these modes serve as kind of ruler in the frequency domain. However, this comb of modes is not comprised of exact harmonics of the pulse repetition frequency; they are shifted by an offset originating in the dispersion in the laser resonator. The pulse envelope propagates with the group velocity, while the carrier wave travels with its phase velocity, resulting in a continuous shift of the carrier with respect to the pulse envelope after each round trip. This continuous phase shift corresponds to a shift of the frequency comb; the so-called carrier envelope offset (CEO) frequency. Therefore, in order to determine the absolute optical frequencies of the comb lines, both the pulse repetition frequency and the CEO frequency have to be determined and stabilised.

The procedure for determining the CEO frequency was developed by the Hänsch Group at MPQ. A schematic of the measurement method is shown in **figure 2**. The CEO frequency and the pulse repetition rate are stabilised to an external reference frequency through a feedback loop. Consequently, the single modes of the frequency comb are known with the same precision. Such systems were initially based on mode-locked titan:sapphire (Ti:Sa) lasers (**figure 3**).

2 Fibre combs

For precise long-term measurements and further for the development of optical frequency standards, frequency combs capable of operating for days or even for weeks are crucial. This requirement cannot be easily fulfilled with Ti:Sa laser, mainly because of the frequency doubled vanadate pump lasers used in these systems. The pump laser emits in the green spectral range at 532 nm with an output power of 5-10 W output power, and its lifetime spans some thousands hours – afterwards costly and time consuming maintenance must follow.

In view of this problem, a novel frequency comb based on the erbium-doped fibre laser was developed. The design is very compact, robust and cost-effective due to use of integrated components developed for the telecommunication industry. A noteworthy fact is that laser diodes with an expected lifetime of several decades are available as pump sources. Because of the reliability, the maintenance-free operation and low energy consumption frequency combs based on fibre technology are especially suitable for long-term metrology measurements and optical standards.

3 Applications

High precision frequency measurements bring about time and length measurements with comparable preci-

***Figure 3**:*
Frequency synthesiser based on a Ti:Sapphire laser

Originally published in German in Photonik 5/2006

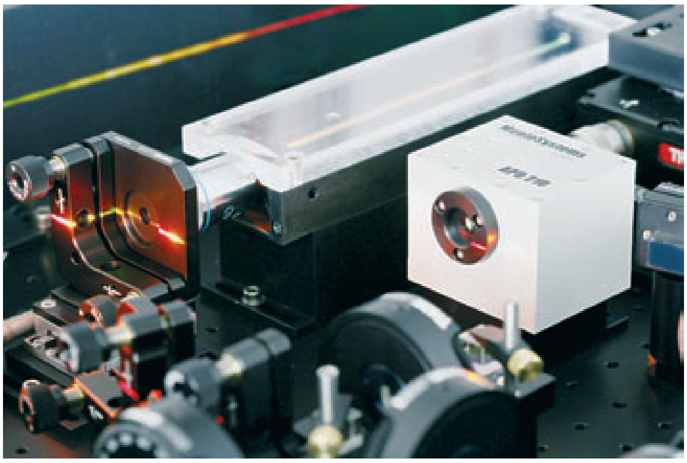

Figure 4: *Part of the optical set-up*

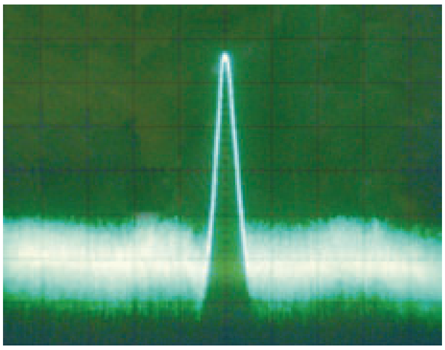

***Figure 5**: Beat signal in the radiofrequency range*

sion. At the moment one cannot see an end to the potential applications. In the following we mention the most common applications at present: length and time standards.

The Austrian Federal Office of Metrology and Surveying – BEV in Vienna was the first customer to purchase an optical frequency comb (**figure 4**). Prior to this invention, the meter bars (so-called gauge blocks) serving as length standards were measured in Vienna with a red helium-neon laser stabilised to a molecular transition. Once every year this reference laser was transported to Paris and compared to the lasers from other European and international standard institutes to make sure that one meter is exactly as long in Vienna as in Braunschweig, Paris or London. These regular comparisons became superfluous with the introduction of frequency combs. A more economic and precise approach can be now followed by local calibrations of the length standard lasers with a cesium atom clock or via GPS. This innovative measuring instrument established a common base for the length standard that can be used for calibration measurements with the highest precision up to date.

From the application of the optical counter in high resolution spectroscopy [4] evolved the possibility to realise the first all-optical clock [5,6]. An optical clock consists, like any other clock, of an oscillator, e.g. the pendulum, and a counter that keeps track of the periodic movement of the clockwork. Trapped single ions came into consideration as clockwork for an optical clock, as originally proposed by H. Dehmelt in 1982 [7]. The counter of such a clock bore the greatest challenge till now, as it must be able to count optical oscillations of hundreds of terahertz. With frequency combs it became possible to correlate phase coherently the optical frequencies to the easily countable radio frequencies (**figure 5**). The precision of the novel optical clocks is estimated to achieve 10^{-18}. This precision value is at least three orders of magnitude better than of the currently most precise caesium atomic clocks [8]. As the achievable precision of satellite navigation and positioning is determined by the exactness of time measurement these compact light counters can improve the positioning accuracy. In fundamental research the time variation of fundamental contacts are investigated with their help.

4 Optical frequency dissemination

With the continuing development of more precise and stable optical frequency standards it becomes increasingly important to establish precise transfer methods in order to compare the standards with each other. Several research groups are therefore currently working on the adaptation and characterisation of optical networks for broadcasting optical frequencies: for example optical and radio frequency standards located in JILA Laboratory (University of Colorado) and National Institute of Standards and Technology (NIST) laboratories have been connected through a 3.5-km optical fibre link and simultaneously measured in both laboratories. Upon implementation of active noise cancellation, the instability of the transfer process exhibited an instability of 3×10^{-15} [9]. At the National Metrology Institute of Japan methods for time and frequency transfer and dissemination using optical fibre network are also being discussed [10]. In France an ultra-stable reference signal of 100 MHz was transferred over a telecom fibre network and various methods for the noise reduction were investigated [11].

Within the framework of a cooperation with Menlo Systems, at MPQ an optical fibre network was built for the dissemination of a particular optical frequency of 269 THz (corresponding to a wavelength of 1120 nm) [12]. This transmitted frequency is used at MPQ for two different experiments on laser cooling. For both experiments only one laser and one stabilisation unit are necessary owing to the highly precise dissemination method. The required frequency stability is realised by the control of a frequency comb. This stabilisation method can be adapted to any arbitrary application that needs a stable laser. The laser wavelength is insignificant, as long as it lies within the broad spectral range of the frequency comb.

Figure 6 shows the schematic of the frequency dissemination system. A continuous-wave laser delivers the optical frequency to be distributed. In order to provide sufficient power for the experiments, the output of the laser is increased using an optical amplifier. Part of the light is used to generate a beat frequency between the laser and the frequency comb, this being used for control of the laser. The frequency comb itself is stabilised to a caesium clock and at the same time its CEO frequency and its repetition rate are both regulated through a phase control loop. The larger part of the amplifier output is transferred though a fibre to the other laboratories. These fibre connections are about 100 m long.

For applications demanding highest precision is has to be considered that temperature fluctuations in the laboratory can

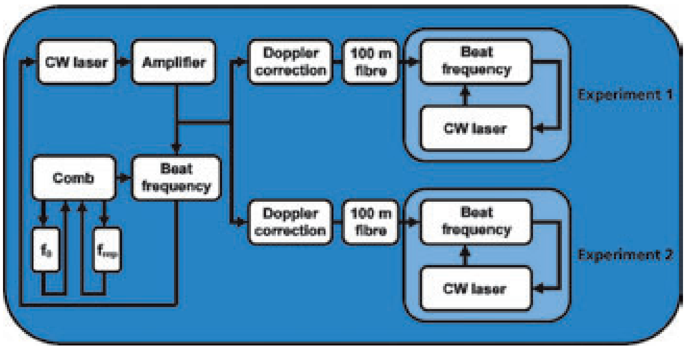

***Figure 6**: Diagram of the frequency dissemination system*

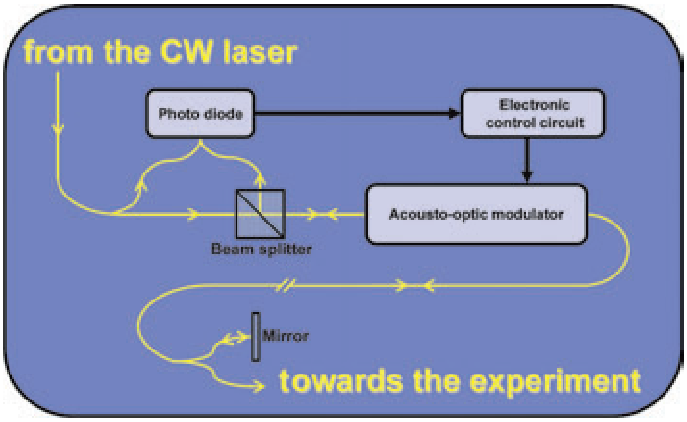

Figure 7: *Schematic of the "Doppler correction" set-up for the compensation of thermally induced frequency fluctuations*

lead to changes in the refractive index and length of the fibre, resulting in a frequency shift of the light and consequently in a degradation of the signal precision. At a fibre length of 70 m and hourly temperature variation of 1 °C a frequency shift of 3 Hz occurs. This frequency shift can be corrected using an acousto-optic modulator (**figure 7**) enabling 10^{-16} and higher precision after transfer through the fiber.

Frequency dissemination represents a novel service: providing unit length from an optical outlet.

The fibre-based frequency comb enables uninterrupted operation of the dissemination system, so the experiments can be continuously supplied with light of the required wavelength. Once the system is installed it runs independently and maintenance free.

Acknowledgements

The award of the Berthold Leibinger Innovation Prize to the authors Dr. Michael Mei and Dr. Ronald Holzwarth would not have been possible without the support of the highly motivated colleagues at Menlo Systems GmbH in the last 5 years. We see this award as an acknowledgment of their outstanding work. The same is true for our colleagues at MPQ. We thank expressly Dr. Thomas Udem and naturally our mentor Prof. Theodor W. Hänsch.

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Originally published in German in Photonik 5/2006