Dissipative solitons, Cherenkov radiation and atomic clock accuracy

Precision optical frequency comb formed in a photonics chip is the future of metrology outside of laboratory environment

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The idea of frequency comb seems relatively simple yet significant technical efforts are required for its generation with high accuracy and stability needed for metrology applications. Frequency standards, synchronisation of atomic clocks, measurements of fundamental constants, modern astronomy and digital telecommunications rely on these devices. No wonder that half of the Nobel Prize for Physics in 2005 was awarded to Hall and Hänsch "for laser based precision spectroscopy including the optical frequency comb technique" [1].

The ideal frequency comb would be a set of discrete equidistant frequency components separated by Δf (Fig.1a). The value of Δf is normally in a microwave range in order to allow measuring and control of the comb "teeth" separation electronically. However, stabilisation of Δf is not sufficient for applicantions. The position of each element of the comb must be fixed for the absolute measurements of optical frequency [2]. This can be done relating any two distant components of the comb by means of nonlinear optics. The simplest way of synchronisation is generation of optical second harmonic $2f_0$ that can be matched with one of the higher frequency teeth of the comb while the fundamental frequency f_0 being synchronised to another lower frequency (Fig.1a). This technique requires the width of the comb to be at least one octave wide. The example of the comb shown in red colour in Fig.1a shows insufficient width. Other nonlinear-optical effects may allow this range to be smaller [3]. Thus, having a nearly octave wide comb is necessary for its 'self-referencing' [2]. The difficulty is that the width of the frequency combs produced by real devices is usually finite and may be narrower than needed (see Fig.1b). Finding a way for creating the wide-band comb spectra is a challenge that has been addressed in the recent work by Brasc et al. [4].

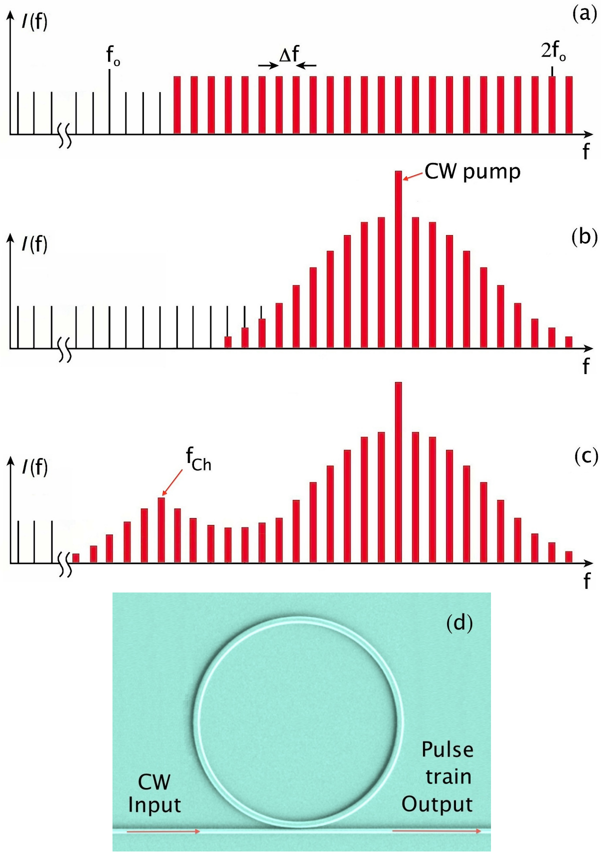

FIG. 1: *(a) An "ideal" rectangular frequency comb where I(f) is intensity of spectral components. (b) Bell-shaped finite width frequency comb resulted from the dissipative soliton circulation in the ring. (c) Fully coherent frequency comb extended due to Cherenkov radiation. (d) Schematics of the micro-ring Kerr-resonator.*

A common way of producing a frequency comb is based on pulses circulating in an optical cavity such as an optical fiber loop coupled to an output fiber which extracts a small part of the pulse energy at each round trip thus forming a train of equidistant identical pulses. The energy loss at the coupler must be compensated by an external pump. The latter is provided either by an amplification of the pulse within the loop or by a continuous wave (CW) on fixed frequency entering the loop through the same coupler. In the former case the device is known as "passively mode-locked laser" while in the latter case it is a "parametric oscillator". Due to the Kerr nonlinearity, the pulse circulating within the cavity can take the form of a soliton with the duration much shorter than the period of circulation. The frequency of circulation is the same as Δf while the duration of the pulse is inversely proportional to the width of the generated spectrum (red comb in Fig.1b). The spectrum usually contains thousands of discrete components, which are assumed but not shown explicitly in Fig.1.

In recent years, the frequency comb devices became significantly smaller as they are fabricated on a chip [5]. Instead of using massive optical tables and long optical fibers, the frequency comb can now be produced in about a 100 micron size ring resonator made on a silicone substrate (Fig.1d). These devices are tiny, solid and mechanically robust. As the pumping laser can also be manufactured on the same chip, the whole set is potentially an integrated optics device.

Stability of the soliton in the loop is crucial for the accuracy of the frequency comb. Optical solitons predicted by Hasegawa and Tappert [6] are pulses of electromagnetic radiation that keep constant shape due to the balance between nonlinearity and dispersion. They have been found experimentally in a fiber by Mollenauer et al in 1980 [7]. In a lossless medium such as optical fiber, solitons can propagate kilometers without changing their shape. Dissipative solitons circulating in a loop are different. They require a continuous energy supply from the pump. Energy gained by the pulse in each round trip is dissipated through the coupler thus keeping balance between its consumption and disposal. Due to this extra balance, the soliton becomes rock-solid as its amplitude and shape are both fixed [8]. The use of dissipative solitons in micro resonators significantly improves the characteristics of the frequency comb [9].

Is there a room for a breakthrough? An international team of scientists from Switzerland and Russia significantly improved this seemingly perfect device [4]. They have found that additional loss by solitons in the form of Cherenkov radiation can extend the frequency comb to a wider frequency range. Such radiation is emitted in presence of the third-order dispersion (TOD) in a specially engineered micro-ring. The frequency of Cherenkov radiation f_{Ch} is defined by the total dispersion [10] and can be placed at a distance from the central frequency of the soliton (see Fig.1c). Radiation circulation in the ring adds comb components around it. However, the major question for accurate spectroscopy is whether this additional part of the comb is coherent with the rest of it. The ingenuity of the work [4] is in providing the positive answer to this question. All comb components are indeed coherent and the total spectrum is wider than the one produced solely by the soliton. Remarkably, the duration of soliton in this device is nearly record low - only 6 optical cycles which makes the comb spectrum sufficiently wide already. Using the Cherenkov radiation allowed the researchers to reach the 2/3 of an octave which is fully coherent and self-referenced. The spectrum from 150 THz to 225 THz obtained by Brasch et al technically is an exceptional achievement. The relative accuracy reached in this device is stunning 3×10^{-15}.

Losses are usually detrimental for the accuracy of oscillations including those in the atomic clocks. Cherenkov radiation due to the third-order dispersion initially thought to be destructive for solitons now occurs to be a beneficial effect. Its coherence to the primary optical field has been found also in the so-called Fermi-Pasta-Ulam recurrence effect in optical fibers [11]. In fact, the losses caused by the TOD can be reversible and irreversible [11]. The magic of the micro-ring resonator engineered in [4] is in the radiation that stays coherent with the frequency comb extending it considerably at the red side of the spectrum.

Frequency combs have a myriad of applications [1, 12]. To mention a few, they are used for synchronisation of atomic clocks, providing us with accurate time. High precision spectroscopy and precise GPS technology are two other applications that we cannot live without today. Now, intensive research efforts brought us the chip based frequency comb device that is ready for the use beyond the laboratory environment.

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