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Recent developments in fiber-based optical frequency comb and its applications

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Abstract

Fiber-based optical frequency combs, characterized by compact configuration and outstanding optical properties, have been developed into state-of-the-art precision instruments which are no longer used just for optical frequency metrology, but for a number of applications, including optical clocks, attosecond science, exoplanet searches, medical diagnostics, physicochemical processes control and advanced manufacturing. This short perspective presents some of the milestones and highlights in the evolution of fiber-based optical frequency combs and the technical revolution that are brought by them for a wide range of applications. Along the way, both the challenges and opportunities in the future development of the fiber-based optical frequency comb technology have been described as well.

Keywords: fiber-based mode-locked laser, optical frequency combs, precision measurement

1. Introduction

Since their invention in 1999, optical frequency comb technology based on the frequency stabilization in the output of a mode-locked femtosecond laser has been proved to be a fantastic ‘light gear’ to bridge the large gap between the optical and microwave frequency [1]. On one hand, it opened up new spectral territory to deliver the stability of the microwave hyperfine transition of cesium used to define the SI second to the optical frequency band to perform the laser frequency measurement in a single step, which has removed the need for large and complex ‘frequency chain’ [2, 3]. On the other hand, the optical frequency comb can be used to track an optical frequency quantum transition as the clock oscillator and deriving microwave outputs as well [4, 5]. Nowadays, the fractional stabilities achieved for the strontium optical lattice clock are in the order of $10^{-18}$ [6], which surpasses the accuracy of the Cs fountain clock by more than an order of magnitude [7]. However, it is only by using an optical frequency comb that such optical frequency standard, with by far the highest precision of all physical quantities, can be divided down to microwaves for counting and manipulation in practical use. Precision frequency standards not only promote the measurement of the atomic and molecular energy structure to an unprecedented level, but also provides new techniques for a better understanding and exploration of the universe. Besides the applications in the frequency-conversion field, the optical frequency comb also plays an important role in myriad scientific research and advanced applications, including tests of fundamental laws of nature [8], the precision measurement of fundamental physical constants (fine-structure constant) [9], attosecond pulse generation [10], ultraviolet/visible/infrared spectroscopy [11–13], astronomical spectrograph calibration [14], dimensional metrology, remote sensing, quantum coherent control of atomic and molecular process [15] and low-phase noise microwave source generation [16].

The femtosecond optical frequency comb was traditionally dominated by solid-state lasers like the Ti:sapphire mode-locked laser, typically delivering nJ-level pulses with the duration of about 100 fs or less, at an average power of up to 1 W.
However, such lasers are rarely used in real-life applications outside the research lab environment, owing to their complexity, very poor environmental stability, large size, large power consumption, and reliance on water cooling. More recently the emergence of fiber lasers, based on robust commercial optical fiber technology, have driven a rapid development of the fiber-laser frequency comb technology. Among these techniques, the importance of optical frequency combs based on the erbium-doped fiber mode-locked laser cannot be overstated owing to the operation wavelength near 1.5 μm, which has profound influence on the optical fiber communication technology and has great potential to support future networks of mobile atomic optical clocks [17, 18]. The ytterbium-doped fiber optical frequency comb, offering higher efficiency as well as larger gain bandwidth, is another rapidly rising star and is most likely to replace the Ti:sapphire femtosecond frequency combs. Thanks to the broad spectral coverage and high optical conversion efficiency, the ytterbium-fiber laser frequency comb has been of great importance in the clockwork of optical lattice clocks [19]. Besides, the thulium- and holmium-doped optical frequency combs, operating around 2 μm wavelength, are also very important for many applications in nonlinear optics, medicine and sensing [20, 21].

Actually, there have been some inherent drawbacks in fiber-based femtosecond lasers, such as low pulse energy and large pulse duration. However, along with the progress on ultrafast lasers technique, both the theorem and experiments of the fiber-based lasers have made new breakthroughs. In theory, the modeling of the dissipative soliton mode-locked laser, which allows for higher pulse energy, has been thoroughly studied. And a ytterbium-doped fiber femtosecond lasers with pulse energy above 25 nJ and 150 fs duration has been achieved [22]. The increase in the pulse energy made ultrafast fiber lasers promising candidates for extreme ultraviolet frequency comb generation. In addition, the pulse-width of the fiber-based optical frequency comb at present cannot reach as narrow as the 5 fs of a Ti:sapphire frequency comb [23]. Nevertheless, further nonlinear compression of the pulse duration of fiber lasers has attracted a lot of attention [24, 25] and an experimental 36 fs ytterbium-doped fiber laser has been obtained, which is limited by residual higher-order dispersion [26]. Therefore, we believe that its performance will be continuously improved in future.

In the long run, the fiber-based optical frequency comb, which has merits of small size, high efficiency, low price and remarkably optical properties, will become the inevitable trend in the technological development of optical frequency combs.

2. Principle of optical frequency combs

The fundamental principle of the optical frequency comb is based on mode-locked lasers that emits periodical trains of ultra-short pulses. In the frequency domain, its spectrum is composed by comb-like frequencies and the spacing of the comb modes is given by the repetition rate $f_r$. In fact, successive pulses generated from the mode-locked laser are not generally identical. Due to the dispersion in a real optical fiber cavity, the difference in the group velocity of the pulse and the phase velocity of the carrier wave will introduce a slip of the phase of the electromagnetic carrier wave relative to the pulse envelope from pulse to pulse [27], resulting in a global offset of the comb by the carrier envelope offset frequency $f_{ceo}$. As a result, the absolute frequency of the optical modes can be determined by $f_m = f_{ceo} + m f_r$. The optical frequency of the comb lines is typically on the order of $10^{14}$ Hz, with $f_r$ and $f_{ceo}$ from tens to hundreds of MHz, so the index $m$ is a very large integer ($\sim 10^9$). Therefore, a direct phase-coherent link between optical and microwave domain can be established through precision measurement and control over the $f_r$ and $f_{ceo}$, forming the basis for various frequency comb applications.

3. Overview of fiber-based optical frequency comb techniques

Only if both of the repetition rate and the carrier envelope offset frequency have been precision measured and controlled does the mode-locked laser evolve into an optical frequency comb. As a result, a fully stabilized fiber-based optical frequency comb usually consists of three parts: (1) fiber-based mode-locked laser; (2) octave-spanning supercontinuum generation which forms the basis to implement self-referencing ‘f-to-2f’ technique; (3) the detection and stabilization of the repetition rate and carrier envelope offset frequency.

3.1. Principle for mode-locking in fiber lasers

A mode-locked laser is established by building a fixed phase relationship between all the longitudinal modes in the optical cavity [28]. Mode-locking in a fiber laser can be achieved either by means of an active modulator or a passive saturable absorber. The former is usually achieved with a Mach-Zehnder integrated-optic modulator, or with a semiconductor electroabsorption modulator. The achieved pulse duration is typically in the picosecond range. By comparison, the passive mode-locking scheme is able to provide much shorter pulses, because the saturable absorber with a short recovery time could modulate the cavity loss much faster than any electronic modulator. In fact, such saturable absorbers for passive mode-locking can be either actual absorber devices or structures that induce an effective loss modulation using the Kerr effect of the fiber, including the nonlinear loop mirrors and the nonlinear polarization evolution.

Since the semi-conductor saturable absorption mirrors (SESAMs) have been used with great success for self-starting passive mode-locking of various types of solid-state lasers [29], they have become most common and popular saturable absorbers in commercially available systems [30]. The SESAM device uses a saturable absorber in a form of reflector, thus facilitating its integration into laser cavities as a cavity end mirror. And its main advantage is the possibility to control important parameters such as absorption recovery time, saturation fluence and modulation depth through the design and fabrication process. In the past, researchers have reported
a variety of compact and self-starting SESAM-based fiber mode-locked lasers operating at ~1.5 μm, typically delivering pJ-level pulses with duration of several hundreds of femtoseconds [31]. Through dispersion compensation, 1.3 nJ and 135 fs transform-limited pulses can be obtained [32]. In order to expand the spectral coverage of the fiber laser, SESAMs mode-locks have been subsequently applied to different ytterbium, bismuth and thulium-doped fibers systems for the 1.05 μm, 1.15 μm and 2 μm wavelength regions, respectively [33–37]. Despite considerable improvement occurring in the past years, the SESAMs suffer from a complex and expensive fabrication process and relatively narrowband operation due to its energy bandgap, because each SESAM has to be specifically designed for any given wavelength. Recently, tunable and switchable multi-wavelength SESAMs-based fiber laser have been intensely studied by incorporating inline birefringence elements in the cavity [38, 39], which is important for the next generation wavelength-division-multiplexing (WDM) fiber communication systems and optical fiber sensing network. Besides, researchers also focus on the long-term operation stability of the ultrashort fiber lasers. And the polarizing-maintaining (PM) fibers has been employed in the SESAM-based mode-locked fiber lasers, thereby providing high immunity to external disruption [40].

Nonlinear loop mirrors can be utilized as an artificial saturable absorber to mode lock the fiber laser, namely the figure-eight laser (F8L). Generally, there are two types of nonlinear loop mirror: the nonlinear optical loop mirror (NOLM) [41] and the nonlinear amplifying loop mirror (NALM) [42], where the ultrashort pulses are formed based on the Sagnac interferometer [43]. Light coming from the main resonator has been divided into two intensity-mismatched counter-propagating components through either a coupler with unequal splitting ratio in the NOLM or by the inclusion of an in-line fiber amplifier close to one end in the NALM. These components with differential phase shift would recombine and interfere before re-entering the unidirectional ring cavity, resulting in an intensity-dependent transmission of the optical loop mirror. The figure-eight laser using a NALM as a saturable absorber was first introduced by Duling in 1991, in which 3 mW and transform-limited 2 ps pulses was produced [44]. The most advantage of the F8L is the all-fiber configuration which allows for high average output power up to 100 mW [45]. Further scaling the output power of mode-locked F8Ls up to 1 W has been recently demonstrated [46]. Nowadays, the mode-locked F8Ls have been successfully used to study the noise-like vector pulses [47] and rectangular pulses with wide tunable range in both lasing wavelength and duration [48, 49]. In order to make these lasers more resistant to thermal and mechanical perturbations, all-PM fiber technology has been investigated as well [50, 51]. The pulses with energy as high as 16 nJ and duration of 400 fs have been achieved and the mode-lock state is reliable and long-term stable [52].

Besides the nonlinear loop mirrors, an alternative and widely researched artificial saturable absorber is based on nonlinear polarization rotation (NPR). By controlling the polarization state of the pulse into a fiber via a set of wave-plates, the transmission through a polarizer on the other side of the fiber will be intensity-dependent due to the self- and cross-phase modulation. With proper adjustment of the wave-plates, the wings of the pulse would experience large losses, yet the peak experiences only minimal losses to obtain the mode locking. The first self-starting erbium-doped fiber laser based on the NPR mode-locking mechanism was reported in 1993 and a pulse duration of 1.55 ps was achieved [53]. In the past years, several advances in the performance of NPR-based fiber lasers have been reported, which allows for generation of the shortest pulses in Er- [54–56], Yb- [57], Ho- [58] and Tm-doped fiber lasers [59]. In addition to the pulse duration, the pulse energy is another parameter in which fiber lasers have historically lagged behind solid-state lasers. As a result, the most powerful fiber sources, Yb-doped mode-locked fiber lasers, operating in an all-normal dispersion (ANDi) regime, was demonstrated with 3 nJ pulse energy and 170 fs duration [57]. Recently, in order to further scale up the pulse energy of such lasers, large-mode-area photonic crystal fibers have been employed in an ANDi cavity, and pulse energies up to 140 nJ with 115 fs dechirped pulses have been reached [60]. Despite the simple configuration, NPR mode-locked laser normally suffers from polarization changes which can be introduced by temperature variations. Various modified approaches based on the NPR mode-locking mechanisms in combination with polarization-maintaining fibers have been reported, leading to an environmentally stable laser [61]. However, the pulse energies realized in these schemes are lower and the dechirped pulses are longer.

Since the broadband absorption spectrum of single-wall carbon nanotubes (SWCNTs) in the visible and infrared range has been observed [62], it has gradually become a novel mode-locking device due to the advantages of fast recovery time and low saturation intensity. In 2003, SY Set et al first designed the transmissive and reflective SWCNT saturable absorbers, and demonstrated their applications in the Er:fiber mode-locking lasers [63]. Since then, a number of mode-locked fiber lasers based on the SWCNT saturable absorber have been reported by placing the thin SWCNT film directly into the optical path. In 2005, S Yamashita reported a fiber mode-locked laser by using carbon-nanotube-based saturable absorber and 5.18 GHz repetition rate has been achieved due to the short length of FP cavity [64]. In 2008, AV Tausenev et al has coated a SWCNT film on a fiber end as a mode-locked device so that an all-fiber Er-doped fiber ring laser has been developed [65]. In these schemes, the SWCNT saturable absorbers have been usually prepared as a solution in various solvents (e.g. ethanol or dimethylformamide), and then be deposited on a mirror or fiber connectors through either the spray method or the optical deposition method [66]. Although the SWCNTs are easy to integrate into optical systems, the optically induced thermal damages will hinder the further increase of the pulse energy. Recently, in order to overcome this problem, lateral interaction using an evanescent wave and the guided mode has drawn a lot of attention, which is based on several platforms, including side-polished fibers [67], tapered-fibers [68] and hollow optical fibers [69]. The reduced optical power in the
interaction region favors high-power operation of fiber lasers and an experimental fiber laser with high pulse energy of 34 nJ has been achieved [70].

2D graphene is another promising saturable absorber for passive fiber mode-locked lasers. The energy band of graphene has zero band gap and a linear dispersion relation, which permits wavelength-independent saturable absorption in a range covering the whole infrared spectrum [71]. These properties makes it suitable for both erbium- and ytterbium-doped fiber lasers. Moreover, the advantages of graphene include the controllable absorption characteristics through the number of the layers, ultrafast recovery time, the lower scattering losses, and potentially a higher damage threshold than the SWCNTs. In 2009, Bao et al. first prepared an atomic layer of graphene as a saturable absorber in an erbium-doped fiber laser for the generation of ultrashort soliton pulses with 75 fs pulse width. The authors then fabricated novel graphene-polymer nanocomposites through chemical functionalization, and used it to mode lock an erbium-based fiber laser. Large energy solitons of 3 nJ pulse energy and 700 fs pulse width have been achieved [72]. Afterwards, the preparation methods for the graphene-based mode locking devices through mechanical exfoliation and optical deposition have been widely studied [73, 74]. Currently, researchers devote to increase the damage threshold of the saturable absorption device, and the evanescent wave interaction between the graphene layer and the propagating light has been proposed for high-power operation [75]. An all-fiber dissipative soliton laser with 10.2 nJ pulse energy based on the graphene saturable absorber has been reported with high signal-to-noise ratio [76]. Actually, the fiber lasers based on the graphene saturable absorber are also promising candidate for GHz-repetition rate ultrafast laser sources. Due to their simple and reliable integration into the optical system, the fundamental repetition rate of 7.8 GHz and 9.67 GHz has been achieved in thulium-doped and erbium-ytterbium doped fiber laser [77, 78], which would have wide applications in optical communications and spectral metrology.

3.2. Supercontinuum generation

Nonlinear spectral broadening is the building block for fiber laser frequency combs because the octave-spanning spectrum is not directly available from the fiber laser oscillator. For example, a typical spectrum coverage is 1520 nm ~ 1560 nm and 975 nm ~ 1150 nm for Er- and Yb-doped fiber laser, respectively. As a result, a highly nonlinear fiber (HNLF) or photonic crystal fiber (PCF) must be used for supercontinuum generation. Previous studies have shown that there are four main physical processes that are responsible for the supercontinuum generation, such as self-phase modulation (SPM), stimulated Raman scattering (SRS), self-steepening (SS) [79] and dispersive wave (DW) generation (which is also called non-solitonic radiation) [80]. Generally, the long-wavelength edge spectral broadening can be attributed to Raman scattering self-frequency shift [81], while the short-wavelength edge spectral broadening originates from the dispersive wave generation. Under the combined interaction of all these nonlinear effects, new spectral components are continuously generated and the spectrum of the ultrashort pulse is widened to cover even more than an octave.

For an erbium-doped fiber laser, the HNLF is usually used for the supercontinuum generation. Considering the low average-output-power directly emitted from the laser, an erbium-doped fiber amplifier with combined forward and backward pumping should be included to increase the power launched into the HNLF. JL Peng et al reported an erbium-fiber frequency comb with supercontinuum covering a range of 1050 nm ~ 2100 nm [82]. The total power of the supercontinuum is as high as 160 mW which is enough for the detection and locking of the carrier envelope offset frequency. In order to avoid large peak intensities and amplify the signal linearly, chirped pulse amplification has been always used, in which the pulse is stretched with dispersion before amplification and recompressed afterward to near transform-limited.

Regarding the ytterbium-doped fiber mode-locked lasers, the output pulse train from the oscillator requires to compress through gratings, prisms or holey fiber due to the inherent normal dispersion of conventional fibers around 1 μm [83]. T. Jiang et al reported supercontinuum generation in PCF spanning from 500 to 1600 nm, pumped directly by 500 MHz, 300 mW pulses from the oscillator [84]. Moreover, tapered PCF has been utilized to improve the coupling efficiency and resistance to mechanical drift [85]. The power distribution at both ends of the supercontinuum is high enough to provide sufficient signal-to-noise ratio (SNR) to control \( f_{\text{ceo}} \) over the ‘f-to-2f’ technique. Recently, scientists have focused on reducing the requirements for octave-spanning coherent supercontinuum generation by using novel nonlinear devices. And a number of chip-based supercontinuum generation platforms including periodically poled lithium niobate [86], silica [87], chalcogenide [88] and silicon nitride (Si3N4) [89] have been reported, which have very high nonlinearities and can effectively reduce the pulse energy requirement. Since the silicon-based waveguides in particular provide material compatibility with the established complementary metal-oxide semiconductor fabrication technology, low-cost and large-scale production of the integrated chip-scale devices may be achieved in future.

3.3. Stabilization of an optical frequency comb

To stabilize the optical frequency comb, first of all, it is necessary to obtain the repetition rate \( f_r \) and carrier envelope offset frequency \( f_{\text{ceo}} \). The detection of the repetition rate is relatively simple, which can be obtained with high signal-to-noise ratio by placing a photodiode anywhere along the laser beam. In contrast, the \( f_{\text{ceo}} \) derives from the phase difference between the pulse envelope and the carrier wave, and there hasn’t a direct way to detect this signal from the laser intensity.

Based on an octave-spanning spectrum, the carrier envelope offset frequency is obtained by beating the frequency-doubled comb lines from the low-frequency portion of the spectrum with the fundamental comb lines from the high-frequency portion [90, 91]. As it uses only the output of the
been found to agree within 3 systematic error, two independent fiber frequency comb have achieved through the ’2f-to-3f’ self-referencing interferometer. When only 2/3-octave bandwidth supercontinuum is available, this is an important technique for stabilizing the $f_{\text{ceo}}$ by heterodyning the second harmonic from the high-frequency wing of the spectrum with the third harmonic of the low frequency wing [94].

Self-referencing is not the only approach to acquire the carrier envelope offset frequency given an octave spanning spectrum [95]. The determination of $f_{\text{ceo}}$ can be realized by using an additional cw laser. For instance, assuming that the absolute frequency of the cw laser equals to an integer of the repetition rate and lies close to one comb mode indexed by $k$, the second harmonic of this laser will lie close to another comb line indexed by $2k$ so that a beat note can be obtained between these two signals to give the $f_{\text{ceo}}$ signal as well. However, many nonlinear-optical processes (sum frequency generation and second harmonic generation) and additional cw laser are involved in this scheme, which increases the complexity of the optical system.

With the detection of the repetition rate and carrier envelope offset frequency, both of these frequencies can be locked directly to a single microwave reference (e.g. hyperfine transition of 133Cs) through phase-locked loops (PLL) [96]. Actually, the repetition rate can be stabilized with pump power control of the gain fiber [97], stretching of fibers by a piezoelectric actuator [98], or changing the refractive index of the fiber [99]. As for the carrier envelope offset frequency, the experimental control method is generally achieved through adjusting the pump power in the laser cavity due to the fact that the phase- and group velocity depend differently on the peak intensity of the stored pulse [100]. In 2004, B. Washburn demonstrated the first fully stabilized erbium-doped fiber frequency comb based on an figure-eight oscillator [101]. Shortly afterwards, several other groups independently followed to realize the erbium-fiber optical frequency combs based on ring oscillators [102, 103]. Moreover, in order to investigate the reliability of the developed fiber frequency comb and to inspect the possible systematic error, two independent fiber frequency comb have been found to agree within $3 \times 10^{-16}$ [104] and $6 \times 10^{-16}$ [105]. Even though the Doppler shifts due to the mirror motions caused by thermal expansion set in at this level, no systematic shifts have been found yet.

4. Applications

As a revolutionary breakthrough in the laser technology, fiber-based optical frequency combs have greatly accelerated the development of fundamental science and advanced applications in a broad variety of fields, including optical clocks, direct frequency comb spectroscopy (DFCS), extreme ultraviolet comb generation, calibration of astronomical spectrograph, dimensional metrology and so on.

4.1. Optical-microwave frequency conversion

Frequency standards provide the base unit of time so that the pursuit for more accurate and precise frequency standards and clocks has continued unabated for centuries. At present, the SI definition of time is the radiation emitted from the transition between the two hyperfine levels of the ground state of a cesium 133 atom. Through locking the repetition rate and the carrier envelope offset frequency to a microwave Cs clock, fiber laser frequency comb can serve as a transfer oscillator to accomplish directly traceable measurement of the optical transition frequency of hydrogen [106], strontium [107], ytterbium [108, 109], iodine [110], methane [111] and water [112] with utmost precision. On the other hand, the carrier envelope offset frequency can be stabilized to the repetition rate, which allows for the division of an optical frequency down to the microwave frequency domain or to directly measure optical frequency ratios. In the past decade, ultra-low noise microwave sources have been obtained by stabilizing the fiber laser frequency comb to an ultra-stable optical reference [113, 114]. This technique has also boosted the development of the optical clocks that, by now, have surpassed their predecessors at microwave frequencies in both stability and systematic uncertainty. So fiber-based frequency combs have become important tool to compare the frequency standards from laboratories at different and distant locations since the most precise optical clocks cannot be readily transported for comparison with one another. So far, scientists have made great efforts to link the increasing number of worldwide precision laboratories. In 2012, direct optical frequency transfer over 920 km of telecommunication fiber was reported [115], where the fiber frequency comb was used as optical-microwave converter for frequency transfer and the fractional frequency instability was measured to be $5 \times 10^{-15}$ in 1s integration time. Actually, transfer of a fiber frequency comb over telecommunication fibers can be done and, in this case, both the microwave and the optical frequency references can be simultaneously transmitted [116]. More recently, Chen et al presented precise microwave frequency dissemination of a hydrogen maser-synchronized frequency comb and a fractional frequency instability of $5.28 \times 10^{-16}$ has been obtained [117]. Furthermore, the direct dissemination of the fiber frequency comb has been performed as well and a relative residual frequency instability of $4.9 \times 10^{-17}$ has been achieved [118]. So far, the major limitations of the direct comb transfer are the fiber dispersion and the high pulse intensity-induced nonlinearity. Actually, these difficulties can be overcome by reducing the comb bandwidth.
within standard optical communication band so that the comb transference will become less sensitive to dispersion and the corresponding longer pulses will further significantly reduce its peak power. Another key issue is the phase noise acquired during the fiber transmission, and the traditional compensation technology may involve thermally controlled optical delay line [119]. However, as for much longer fibers (e.g. ~5000 km), the coherent and fully transparent transmission of the fiber laser frequency comb still remains challenging.

Optical frequency comb technology has been extremely important for the development of optical clocks, and a particular transition of these clocks may be chosen to re-define the SI second, which is responsible for improvements in technologies like GPS navigation, wireless communication, length metrology, radio astronomy and tests of general relativity.

4.2. Direct frequency comb spectroscopy

The idea of using mode-locked lasers for high-resolution spectroscopy was first put forward by Hansch in 1970’s. However, this dream was realized 30 years later following the advent of femtosecond optical frequency combs, which at first served as a reference ruler for measurement of the optical transitions of atoms and molecules. In 2004, Jun Ye proposed direct use of an optical frequency comb for spectroscopy, namely direct frequency comb spectroscopy [120]. Considering that there are the hundreds of thousands of comb modes evenly distributed across the optical spectrum of an optical frequency comb, each comb mode acts as independent detection channel so that the DFCS is able to obtain the spectral features across the entire manifold of atomic and molecular transitions with high precision and fast measuring time. Usually, an enhanced cavity is used to increase the interaction length between light and matter and there are several methods to perform high-resolution DFCS. One way is to use spectral dispersion in two spatial dimensions on a 2D array. M Thorpe et al reported the cavity-enhanced DFCS technique through use of a virtually imaged phased array (VIPA) detector as a component in a grating spectrograph, and a spectral resolution of 800 MHz in the spectral coverage from 1.5 to 1.7 μm has been achieved [121]. In order to achieve comb mode resolution, an intermediate filter cavity may be employed. The advantage of this scheme is the short integration time for single image, making it an ideal tool for investigation of transient events. The other way to achieve high resolution spectroscopy is the multi-heterodyne DFCS technique which employs a pair of stabilized fiber-laser frequency combs with slightly different repetition rates Δf. In the time domain, the difference in the repetition rate introduces a continuously and rapidly time-delay variation between pulses from the two lasers, which can be used to perform fast pump-probe spectroscopy, known as asynchronous optical sampling [108]. In the frequency domain, multiple heterodyne beats between the mismatched combs result in a comb in the radio frequency domain with a line spacing of Δf. B Bernhardt et al reported a cavity-enhanced dual-comb spectroscopy technique which used a Fourier transform method to retrieve the spectrum of the C2H2 and NH3 [122]. The experimental spectral resolution was 4.5 GHz, which may be further improved so that individual comb lines are resolved [123]. In this scheme, only a single detector is used and the measuring time is several microseconds, which would further help facilitate the time-resolved spectroscopy of rapidly evolving single event. The main drawback of this method is the need for two fully-stabilized frequency combs, which greatly increase the cost and complexity of the system. So far, the strong vibrational transitions in molecules are located in the mid-infrared spectral region (e.g. 2.5–20 μm) which cannot be covered directly by the fiber-based frequency comb. Currently, such mid-infrared frequency combs have been obtained via nonlinear optical conversion, like the difference-frequency generation (DFG) and optical parametric oscillators (OPO). In spite of the experimental milliwatt-level radiation has been generated spanning from 2.7 to 4.7 μm [124], and 5 to 12 μm [125], respectively, the mid-infrared fiber laser frequency combs are still in early stage to perform mid-infrared spectroscopy. Recently, researchers have successfully explored the DFCS technique for trace gas detection in chemical analysis [126], gas number density sensing [127] and quantum coherent control for modifying and manipulating atomic and molecular systems in the nonlinear spectroscopy like the two-photon absorption [128, 129]. With the ongoing improved performance, the compact fiber laser frequency combs might establish the ground-breaking spectroscopic instruments and promise for wide new applications in medical diagnostics, trace-impurity detection, and characterization of supersonic jets of cold molecules.

4.3. Extreme ultraviolet (XUV) frequency comb generation

Besides the infrared, visible and near ultraviolet spectral regions, many atomic and molecular systems of fundamental interest possess resonance frequencies in the XUV where continuous-wave laser technology is limited, so extending the frequency comb range into the XUV region is highly desirable. By now, the XUV frequency comb has been generally produced through the high harmonic generation (HHG) where very high peak intensity (>1013W/cm2) of the pulse is required to drive the extreme nonlinear process inside the gas target. In 2005, Gohle et al made breakthrough in the intra-cavity HHG in the extreme ultraviolet by using a noble gas jet (Xe) [130]. The key point to acquire the XUV frequency combs is to guarantee the ultrahigh peak intensity at the focus of the intra-cavity. As a result, researchers are now pushing to generate more powerful sources to drive these nonlinear schemes. With the emergence of double-clad fibers and the development of high-power fiber laser technology, the peak intensity of the chirped-pulse amplified Yb:frequency comb is nearly twice the power as in a Ti:sapphire frequency comb. By using such a high-average-power infrared frequency comb, Cingoz et al reported the generation of the 23rd harmonic XUV frequency comb (<40 nm) [131]. Owing to the higher ionization potential of the krypton, an increase of more than an order of magnitude over previous intracavity HHG results has been obtained. In 2014, C. Benko demonstrated
the XUV frequency source with coherence time greater than 1s, which is able to perform sub-hertz spectral resolution [10].

Actually, the technology for XUV frequency comb generation involves a number of challenges. The choice of transparent and XUV-resistant optical materials is fairly limited, and the reflective optical elements should be coated with boron carbide (B4C) to enhance their reflectivity in the XUV. Moreover, even weak surface roughness of the optical components may lead to strong wavefront distortion and scattering losses. So far, only a tiny fraction of the laser power can be converted into the odd harmonics, and the average power of the generated XUV frequency combs are in the order of several tens of microwatt. A recent published study shows that the power of XUV frequency comb can be dramatically improved through optimization of the intracavity design with perfect phase-matching conditions [132]. Therefore, understanding the intracavity ionization dynamics and a suitable intracavity design allow for further scaling of the intensity of the XUV frequency comb. As a powerful tool, XUV frequency combs not only open up new horizons in precision spectroscopy and frequency comb. As a powerful tool, XUV frequency combs not only open up new horizons in precision spectroscopy and manipulation of atoms and molecules, but also provide an ultrahigh time-resolved spectroscopy technique for a deeper insight into the transfer of energy and information in the matter.

4.4. Calibration for the astronomical spectrograph

Measurement of the radial velocity of an astronomical object relative to the observer (on Earth) has been proved to be the most efficient approach for the detection of Earth-like exoplanets, determination of the changing rate of universe’s expansion and many fundamental constants [133]. For example, an extrasolar planet will introduce a changing recoil velocity, which is always rather small, of its star during the orbital period. For an Earth-like planet that orbits a Sun-like star, a velocity change of about 1 cm/s is imposed on the motion of the stars, which corresponds to a Doppler shift of 15 kHz of visible radiation at a frequency of 500 THz. Compared with the Th-Ar lamps, advancing to cm/s radial velocity precisions with the next generation of instruments requires more suitable calibration sources with more lines and fewer dynamic range problems. Nowadays, fiber laser frequency combs have renewed this field due to their perfectly spaced comb modes in very broad bandwidths with uniform strength. In 2008, T Steinmetz demonstrated the first use of a fiber laser frequency comb for the wavelength calibration of an astronomical telescope [134]. In 2012, Wilken et al developed the Yb-doped fiber laser frequency comb with a mode spacing of 18 GHz by using three cascaded FP cavities, and a tiny velocity change of less than 10 cm/s has been observed. However, the finite linewidth of the transmission function of the employed FP cavities is not able to completely suppress the unwanted side modes, resulting in systematic calibration errors. Although linear cavity fiber lasers are ahead in scaling up the repetition rate of femtosecond fiber lasers to multi-gigahertz, the output power is relatively low. So the high-efficiency ytterbium-doped fiber frequency combs have drawn a lot of attentions. Actually, the key issue to make the fiber laser mode locked at GHz-level repetition rate requires high pump power and high-doping gain fiber in a very short laser cavity. Recently, a NPR-based Yb:ferber laser frequency comb with 1 GHz repetition rate and 0.6 nJ pulse energy has been achieved, which may be further developed to a compact source for large-mode spacing frequency combs [135]. So far, even the low-cost, portable rubidium atomic clock provides an adequate precision of ~1 cm s$^{-1}$ ($3 \times 10^{-11}$), the ultimate calibration precision is possibly limited by the signal-to-noise ratio of the detector. The state of the art accuracy in the astronomical spectrograph calibration has been greatly improved due to the development of the fiber frequency comb, getting us closer to the answer of the question for the exoplanet, extra-terrestrial intelligence and the cosmic expansion.

4.5. Laser ranging

Length is a basic physical quantity and its precision measurement is of great significance in both the frontier of fundamental science and advanced technology, such as the test for the Einstein’s general theory of relativity [136], direct imaging of a black hole [137], satellite attitude control and the large-scale manufacturing. Traditional techniques for precision distance measurement are usually based on the laser interferometry [138] and time-of-flight methods [139]. Although subwavelength-resolution can be attained, the interferometric techniques rely on incremental measurement of phase accumulation so the measurement process should not be interrupted and the measurement range is limited within several tens of meters. On the other hand, the time-of-flight techniques provide larger measurement range but the resolution is in the order of several hundreds of micrometers. Owing to a large number of equally spaced frequency components, the optical frequency comb appeared to be a giant leap forward in the field of dimensional metrology. In 2000, Minoshima et al first proposed a high accuracy range finder based on a femtosecond mode-locked laser. By using a series of beat notes between the optical modes, an accuracy of 50 μm in a distance of 240 m was achieved [140]. Subsequently, remarkable progress has been made in this field, and a lot of measurement methods based on fiber laser frequency combs have been extensively studied, such as cross-correlation measurement scheme utilizing the pulse-to-pulse alignment [141], dispersive interferometry [142], multi-heterodyne interferometry [143], time-of-flight method [144] and synthetic-wavelength interferometry [145]. Over recent years, applying the fiber laser frequency comb to accomplish large scale distance metrology has aroused the interest of researchers. In 2009, Coddington put forward a hybrid ranging system which combines the advantages of time-of-flight and interferometric approaches through two coherent fiber-laser frequency combs. The comprehensive measurement precision is better than 5 nm, and through the radiofrequency phase the non-ambiguity range can be extended to 30 km [146]. Recently, Wu reported a multi-heterodyne interferometry by using numerous beat frequencies between a frequency comb and a tunable cw laser,
and the non-ambiguity range can be potentially extended to $10^5$ m by slightly adjusting the comb repetition frequency [147]. As for practical large-scale distance measurements in air, there is still a limitation of measurement accuracy caused by the uncertainty of air refractive index. In order to overcome this problem, two-color heterodyne frequency comb interferometry with self-correction of air refractive index has been proposed, and a measurement stability of $1 \times 10^{-11}$ is attained [148]. With the reduction in price, new versatile measuring principles will continue to spring up, making the fiber laser frequency comb become the next generation benchmark for absolute distance measurement.

5. Summary and outlook

Thanks to the merger of techniques from ultrafast laser, microwave and optical frequency standard and precise laser stabilization, the past decade has seen impressive advances in the development of fiber-based optical frequency combs. As a fantastic ‘light gear’ linking the microwave and optical frequency domain, the fiber laser frequency comb accelerates the research of the optical clock by providing the necessary clockwork and a solution to synchronize such ultra-precise atomic clocks over distance greater than 1000 km. Besides, due to the unique time-frequency characteristics, it has also revolutionized a number of applications including novel spectroscopic techniques, XUV radiation generation and frequency synthesis with ultralow phase noise.

Beyond these ground-based applications, the fiber optical frequency comb has also attracted much attention to extend today’s space missions. For instance, the large-scale laser ranging technique based on the fiber frequency comb is expected to perform the next-generation formation flying space missions, such as DARWIN, XEUS, and LISA [149, 150]. Without the influence of the atmosphere of the earth, the redshift galaxies and exoplanets as well as spectroscopic characterization of their atmospheres can be measured with high precision by using single wide-bandwidth fiber-based optical frequency comb. Although the current progress of the fiber-based optical frequency combs offer sound technological underpinning to these missions, much engineering efforts are highly needed to space-qualify these instruments.

So far, the scientific research for fiber laser frequency combs is under way to access high pulse energy, wider spectral coverage, GHz level repetition rate and ultra-low phase noise. Firstly, high-energy short pulses are useful for direct spectroscopy, bio-imaging and organic material processing. Conventional methods usually increase the cavity length to achieve lower repetition rate and high pulse energy. In such long-fiber cavity, particularly in case of all-normal dispersion cavity, it is hard to compress the pulse duration. To narrow the bandwidth of the intra-cavity spectral filter may weaken the nonlinear effect, which favors the compression of the pulse duration. However, the reduced bandwidth will also lead to longer transform-limited pulse. Secondly, the wavelength of the frequency combs generated directly from the erbium-, ytterbium- and thulium-doped fiber oscillators are centered at 1 $\mu$m, 1.5 $\mu$m and 2 $\mu$m, respectively. And the available spectral coverage of these fiber lasers are not broad enough to meet the requirements for precision spectroscopy. Even though broadband spectral coverage spanning from XUV to mid-IR region can be achieved via nonlinear broadening, the laser source with increased spectral brightness, high spatial and temporal coherence are still highly desired. Thirdly, fiber laser frequency combs with high repetition rate are indeed more desirable for most applications, like astronomical spectrograph calibration, microwave photonics and the low-noise microwave generation. A big challenge for the high repetition rate fiber laser frequency comb is to establish stable pulse generation in such short fiber cavity and reduce the noise of the fiber laser. So the pulse dynamics, the relationship between the dispersion control and noise should be comprehensively studied.

In my opinion, the next few years are crucial for developing fiber laser frequency comb-based instruments to match their capabilities with specific application requirements. For example, a portable optical frequency counter or a direct-frequency-comb spectrometer for medical diagnostics which cannot be provided by simpler conventional techniques. As for the all these applications, the long-term stability, accuracy and repeatability of the entire system are the most important parameters, because all the instruments must be designed for reliable operation over long periods. Additionally, the developed systems should also be compact, integrated and reasonably priced. Indeed, we believe that there will be continued progress in fiber-based optical frequency combs both in their performance and cost reduction, so more and more exciting applications are waiting for us to explore.

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