Astronomical Techniques and Instruments, Vol. 1, March 2024, 105–116

Review Open Access

Optical frequency comb technology: from ground to space

Xiaodong Shao[1], Yu Yan[1], Hainian Han[1,2*], Zhiyi Wei[1,2]

[1]*Beijing National Laboratory of Condensed Matter Physics*, *Institute of Physics*, *Chinese Academy of Sciences*, *Beijing* 100190, *China*

[2]*Songshan Lake Materials Laboratory*, *Dongguan* 523808, *China*

*Correspondence: hnhan@iphy.ac.cn

Received: January 25, 2024; Accepted: February 29, 2024; Published Online: March 22, 2024; https://doi.org/10.61977/ati2024016

Citation: Shao, X., D., Yan, Y., Han, H., N., et al. 2024. Optical frequency comb technology: from ground to space. *Astronomical Techniques and Instruments*, **1**(2): 105−116. https://doi.org/10.61977/ati2024016.

Abstract: Optical frequency combs, as powerful tools for precision spectroscopy and research into optical frequency standards, have driven continuous progress and significant breakthroughs in applications such as time-frequency transfer, measurement of fundamental physical constants, and high-precision ranging, achieving a series of milestone results in ground-based environments. With the continuous maturation and evolution of femtosecond lasers and related technologies, optical frequency combs are moving from ground-based applications to astronomical and space-based applications, playing an increasingly important role in atomic clocks, exoplanet observations, gravitational wave measurements, and other areas. This paper, focusing on astronomical and space-based applications, reviews research progress on astronomical frequency combs, optical clock time-frequency networks, gravitational waves, dark matter measurement, dual-comb large-scale absolute ranging, and high-resolution atmospheric spectroscopy. With enhanced performance and their gradual application in the field of space-based research, optical frequency combs will undoubtedly provide more powerful support for astronomical science and cosmic exploration in the future.

Keywords: Optical frequency comb; Astronomical comb; Optical clock-based time and frequency network; Gravitational waves and dark matter; Dual-comb ranging

1. INTRODUCTION

Exploring the mysteries of the universe and searching for extraterrestrial life are important topics in the field of space science. In recent years, with the development of aerospace and space communication technology, several countries have carried out successive crewed spaceflights, lunar exploration, Mars exploration, and other space missions. The rapid development of space science has also provided more possibilities for human societal progress, the exploration of the universe, and the utilization of extraterrestrial resources. At the same time, more advanced precision measurement technologies are being developed in detail for space applications, providing greater possibilities for future deep space exploration and the development of fundamental physics.

Optical frequency combs (OFCs)[1,2] are significant achievements of the 21st century. Their emergence has led to a leap in the development of applications such as optical frequency measurement[3], precision spectroscopy[4], precision distance measurement[5], and optical atomic clocks[6]. After over 20 years of development, the technology and implementation forms of OFCs have gradually diversified, and a variety of parameters make it possible for them to play a role in more complex scenarios. In particular, the application of OFCs in the field of astronomy and space science is attracting increasing attention.

One of the main applications of OFCs in the field of astronomy is in astronomical frequency combs[7,8], with many evenly spaced, frequency-stable "comb teeth". This allows astronomical frequency combs with a repetition rate greater than 10 GHz to calibrate astronomical spectrographs. Theoretically, this can allow radial velocity measurements with a resolution approaching 1 cm/s, which cannot be achieved using iodine absorption cells and thorium-argon lamp spectral lines for calibration. Such high-resolution astronomical spectrographs can not only search for Earth-like exoplanets but also support direct measurement of the acceleration of cosmic expansion[9].

OFCs are among the most crucial components of optical atomic clocks[3], allowing them to achieve an instability of 10^{-18} to date, which is an improvement of two orders of magnitude over the best microwave atomic clocks currently available[10]. As high-precision frequency synthesizers connecting optical frequencies and microwave frequencies, OFCs can convert such high-precision frequency standards to the microwave domain or other optical frequency domains[11]. They can also transmit frequency standards over long distances through time-frequency transfer technology[12], thereby building a complete optical clock network[13]. There is increasing awareness that the establishment of a space-based optical clock network will support many cutting-edge scientific research applications. These applications include intercontinental optical clock comparison[14], redefinition of the SI second[15], geodetic measurement based on optical clocks to detect local gravitational potential and verify general relativity[16], space-based gravitational wave detection[17], and the search for dark matter[18], among others.

In addition, the ground-based applications of OFCs in absolute distance measurement[19] and precision spectroscopy[4] show strong potential for space-based applications. Dual-comb absolute distance measurement has the characteristics of high measurement precision, fast measurement speed, and long measurement range[5] . So it can support the needs of applications such as high-resolution space-based optical remote sensor imaging[20], distributed synthetic aperture radar imaging, high-resolution space-based gravity imaging[21], and gravitational wave detection[22]. Comb spectroscopy, especially dual-comb spectroscopy, exhibits characteristics such as a wide spectral range, fast measurement speed, and high measurement accuracy. It has achieved great success in the field of ground-based spectroscopy[4]. Moreover, space comb spectrometers can be applied to the study of atmospheric composition, structure, motion, and circulation. This can assist in monitoring climate change, understanding atmospheric chemical reactions, and exploring the origin and evolution of planetary atmospheres.

This article will review the main technological advances in space-based applications of OFCs. In Section 2, we introduce the main forms of generation and parameter expansion technology of OFCs. Section 3 focuses on the basic principles and research progress of astronomical combs (astro-combs), and Section 4 introduces the current research progress in space OFCs, along with related applications based on the space clock network and precision measurement of OFCs in space. Finally, we summarize the space-based applications of OFCs and highlight prospective future work.

2. OPTICAL FREQUENCY COMB TECHNOLOGY

OFCs consist of a series of separated "comb teeth", which are longitudinal modes with equal frequency intervals. The interval between comb teeth is equal to the repetition rate of the pulse f_{rep} and the position at which all comb teeth deviate from zero frequency is called the carrier-envelope offset frequency (f_{ceo}). Once the interval and offset are determined, the frequency of the nth comb tooth can be expressed as $f_n = nf_{rep} + f_{ceo}$. The time and frequency domains of the optical frequency comb are illustrated in Fig. 1. The repetition rate f_{rep} and the f_{ceo} will drift or jitter with interference from the environment. By using a phase-locked loop circuit to lock f_{rep} (or a comb tooth f_n) and f_{ceo} to an atomic clock or optical reference, the frequency stability of each comb tooth of the optical frequency comb can achieve the same stability as the atomic clock, enabling various precision measurement applications.

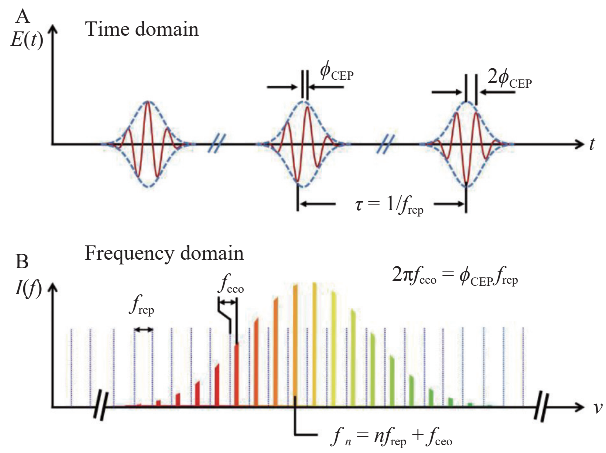

Fig. 1. The time domain and frequency domain of OFCs.

Due to the increasingly widespread application of OFCs, a single type of OFC or related technology cannot meet the needs of all applications. These application requirements have given rise to diversified comb sources and parameter expansion technology, mainly including spectral expansion, power expansion, repetition rate increase technology, and frequency stability technology for OFCs.

2.1. Optical Frequency Comb Generation

At present, OFC sources are mainly generated in one of three ways: mode-locked combs, electro-optic frequency combs, and microcavity frequency combs. These three types of OFCs differ in output parameters with distinct advantages and disadvantages. No single comb or technology can fulfill all applications, necessitating the development of multiple types of combs and associated technologies. Table 1 lists the main parameters of these three different forms of OFCs.

Passive mode-locking technology can achieve femtosecond pulse output, and the earliest OFC was implemented using mode-locked femtosecond lasers[3]. Its key features include a broad spectrum, excellent coherence, and low noise. Mode-locked femtosecond OFCs mainly include solid-state combs and fiber combs. Solid-state OFCs employ solid materials as the gain medium, use continuous laser pumping, and achieve mode-locking with the Kerr lens effect or semiconductor saturable absorber mirror (SESAM), and yield extremely low phase noise. The oscillators can directly output power levels ranging from hundreds of mW to several W, with spectra spanning tens to hundreds of nm. Ti: sapphire oscillators can even out-

Table 1. Types and main parameters of OFCs

	Mode-locked optical frequency combs		Electro-optic frequency combs	Microcavity frequency combs
	Solid-state combs	Fiber combs		
Repetition rate	0.1−10 GHz	0.1−1 GHz	0.1−40 GHz	20 GHz−1 THz
Average power	200 mW−1 W	1mW−100 W	1mW−100 mW	1mW−100 mW
Central wavelength	800 nm in Ti: sapphire; 1 030 nm in Yb: doped crystals	1 040 nm in Yb: fiber; 1 550 nm in Er: fiber	1 030 nm or 1 550 nm	1 550 nm
Oscillator spectrum or spectral bandwidth/nm	500−1 200	<100	10	10

put broadband spectra exceeding one octave. Fiber comb is a mode-locked optical frequency comb with lower cost, higher integration, and better long-term stability. Over the past two decades, combined with technologies such as power expansion, spectral expansion, repetition rate expansion, and frequency stabilization, fiber combs have been used in numerous ground-based application demonstrations.

In terms of space-based applications, only fiber combs have been successfully launched, due to their compact design and superior stability[23,24]. However, the radiation resistance of gain fibers, pump laser diodes, semiconductor saturable absorbers, and other devices is subpar, necessitating a more resilient design[25]. Solid-state combs exhibit superior radiation resistance compared with fiber combs but do not have advantages in space applications that require small size and low power consumption because of their high cost and large size. In recent years, high-repetition diode-pumped Kerr lens mode-locked lasers[26,27] and on-chip Ti: sapphire mode-locked lasers have been reported[28]. Solid-state combs are progressively being developed toward compact size, low power consumption, and integration. Increasing compactness gives improved potential for space-based applications.

The electro-optic frequency comb uses the electro-optic effect to modulate a continuous laser, generating sidebands with equal frequency intervals, forming an OFC[29]. The repetition rate of the electro-optic frequency comb is equivalent to the modulation frequency, enabling it to easily achieve high repetition frequencies ranging from 10 GHz to 40 GHz. This is highly attractive for astronomical comb applications. In 2019, Metcalf et al. reported the world's first electro-optic frequency comb with a repetition rate of 30 GHz, used for radial velocity measurements with the Hobby-Eberly telescope. The resolution can support a radial velocity accuracy of 6 cm/s, and the spectrum covers 700−1 600 nm after nonlinear fiber and waveguide expansion[30]. Using a high repetition rate and easy adjustability, a dual-comb system can be easily created with a large repetition rate difference, which has more advantages in high-speed dual-comb ranging and dual-comb spectroscopy applications. However, if the electro-optic frequency comb aims to achieve a wide band, flat spectrum output, it needs to cascade multiple modulators and increase the drive power, which significantly increases the complexity and power consumption of high-performance systems. In addition, the further away from the central frequency, the greater the noise and instability of the comb teeth, which necessitates additional optical cavities for spectral filtering in wide band applications[31].

The Q (quality) factor is an indicator of the quality of the laser's optical resonance cavity and is a measure of the strength of the oscillation damping. When there is no energy loss, the Q factor diverges to infinity. The microcavity frequency comb is an OFC generated by continuous laser pumping in a high-Q optical microcavity through nonlinear effects. Typical features of the microcavity frequency comb are integration, compact size, and low power consumption, which are essential for space-based combs. Fully on-chip integrated combs are rapidly being developed, and it is anticipated that more practical devices will emerge soon. Mode-locked combs in microcavity combs have been applied in numerous ways, including optical frequency measurement, low-noise microwave generation, laser ranging, astro-comb, and laser communication. However, microcavity frequency combs currently face some challenges. First, due to the high repetition rate and low single-pulse energy, it is challenging to obtain a supercontinuum spectrum of the octave to measure and lock the f_{ceo}. Additionally, an octave-spanning spectrum inside the microcavity can only be obtained at the THz repetition rate, which is out of the range of microwave electronics. Second, the frequency-locking performance of the microcavity frequency comb is significantly inferior to that of the mode-locked comb. For high-precision systems such as optical clocks, further exploration of locking methods and enhancement of locking accuracy are needed[32].

2.2. Optical Frequency Comb Parameter Expansion

The femtosecond laser pulse output directly from the mode-locked oscillator is constrained in terms of spectrum, repetition rate, power, and frequency stability. Therefore, it is necessary to expand the output parameters of the optical frequency comb to cater to complex and diverse application requirements. The expansion of the OFC in terms of spectrum and repetition rate is summarized in Fig. 2, HHG means high-harmonic generation, SHG means second harmonic generation, OPO means ptical parametric oscillator, DFG means difference frequency generator.

Spectral expansion is an important direction in OFC research. The high peak power of ultrafast lasers, cou-

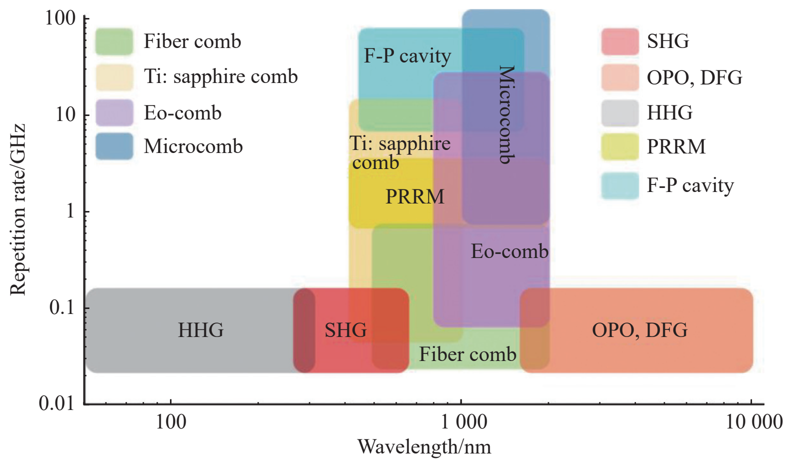

Fig. 2. Optical frequency comb source and its parameter expansion.

pled with optical nonlinear effects, makes frequency conversion possible, thereby evolving the optical frequency comb from the ultraviolet band to the THz band. Many applications require the OFC to measure and lock the f_{ceo}, and the most commonly employed f-2f technology for measuring the f_{ceo} frequency requires an octave range. This can be attained using high nonlinearity coefficient fibers or waveguide materials to expand the spectrum of the optical frequency comb. In addition, different comb spectroscopy applications demand different spectral ranges. The main spectral expansion methods currently include high-order harmonic generation, which can yield ultraviolet to extreme ultraviolet band OFCs[33]; sum frequency generation and second harmonic generation, which can produce visible band OFCs; optical parametric oscillation and difference frequency generation, which can produce OFCs in near-infrared to far-infrared bands; and photoconductive antenna and optical rectification, which can produce THz band OFCs.

Whether using solid-state or fiber amplification, achieving W-level power output is easily attainable, satisfying most comb applications. However, extreme ultraviolet combs, long-distance transmission, and other applications require higher average power OFCs at tens of watts or even hundreds of watts[34]. Fibers have higher heat dissipation efficiency, combined with chirped pulse amplification technology, cladding pumping technology, and coherently combined technology, and can achieve higher power output. In particular, ytterbium-doped fiber has a higher optical-optical conversion efficiency, and can currently achieve the highest average power kW-level femtosecond laser output[35].

The cavity length of the mode-locked OFC oscillator is typically on the order of meters, resulting in a typical repetition rate of 100 MHz to 1 GHz. A higher repetition rate can be achieved by reducing the cavity length. For instance, a Kerr lens mode-locked oscillator with a repetition rate of over 20 GHz has been reported[36]. However, achieving higher or lower repetition rates is challenging due to limitations in cavity length and mode-locking stability. Therefore, technologies that reduce or increase the repetition rate outside the cavity are commonly employed. Lowering the repetition rate is often used in some amplification systems that require higher single-pulse energy. The oscillator repetition rate can be decreased to kHz or even Hz by using electro-optic or acousto-optic switches. Conversely, to increase the repetition rate, Fabry-Perot (F-P) cavity filtering[37]and pulse repetition rate multiplication (PRRM)[38] can be used. F-P cavity filtering can increase the repetition rate to above 10 GHz, while the PRRM can increase the repetition rate to above the GHz range. High repetition rates have many applications in astronomical combs, high-speed dual-comb spectroscopy, and low-noise microwave frequency generation[39]. The measurement speed of dual-comb spectroscopy depends on the repetition rate difference between the two combs. The higher the repetition rate, the higher the allowable repetition rate difference and the faster the measurement speed, while maintaining the spectral range of the measurement constant[40]. In low-noise microwave frequency generation based on OFCs, a higher repetition rate can reduce the saturation effect of the optical band detector and improve the signal-to-noise ratio of the repetition rate high harmonics.

3. ASTRONOMICAL OPTICAL FREQUENCY COMBS

Astronomers typically use spectrometers to measure the Doppler frequency shift of stars, determining information such as the radial velocity of unknown celestial bodies, the composition of the solar atmosphere, and the rate of cosmic expansion. The radial velocity is usually calculated by cross-correlating the measured spectrum with the spectrum template in the solar system barycentric reference frame, and then correcting the instrument drift. A classical system structure is shown in Fig. 3. Consequently, calibrating astronomical spectrometers has become crucial for accurate observation[41]. However, external environmental instability, limited resolution of traditional spectrometers, and narrow coverage of traditional calibration spectra are factors that greatly restrict this research. Research is focusing on OFCs as an ideal stable calibrator for astro-

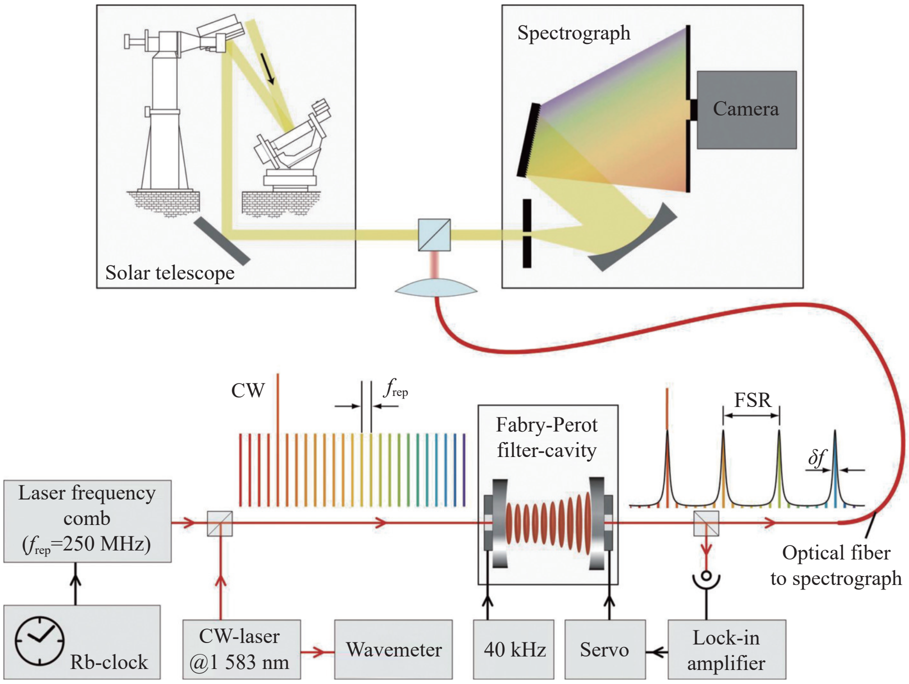

Fig. 3. Schematic diagram of the experimental system of radial velocity measurement using an astro-comb[7].

nomical spectrometers [37,42], with the hope of paving the way for future discoveries.

To calibrate astronomical spectrometers, astro-combs must meet specific requirements in terms of repetition rate, spectrum, and stability. The mode interval of the comb should ideally be 2−3 times the frequency resolution of the spectrometer to achieve the best calibration effect and match the resolution of the spectrometer. This means that the repetition rate of the comb should be at least 10–30 GHz[37]. Simultaneously, to ensure a uniform and comprehensive illumination interval for the spectrometer, a flat spectrum ranging from 350 nm to 800 nm[43] is required. Additionally, due to the varying planetary motion periods causing long observation times, it is crucial to maintain long-term frequency stability for 10 years or more at a stability level of 3×10^{-11} (equivalent to a radial velocity measurement accuracy of 1 cm/s[9,44]). Since 2008, various combs have been developed and deployed for wavelength calibration work in spectrometers[7,30,45,46]. At least 12 telescopes worldwide have used OFCs[43,47] for calibration.

Although the F-P cavity was used for astronomical detection as early as the 1980s[48], it was not until 2007 that Murphy et al. first proposed[37] that OFCs could be used for frequency calibration of astronomical spectrographs. The OFC emits comb-shaped equidistant spectral lines that can be measured against these comb-shaped targets, making it an ideal choice for calibration. By observing the equidistance of the comb modes in the imaging plane of the spectrometer, researchers can calibrate the instrument drift, improving long-term frequency accuracy.

Within a year after this work was proposed, the European Southern Observatory and the Max Planck Institute for Quantum Optics (MPQ) in Germany initiated studies on the feasibility of high-resolution spectrometer astronomical observation system technology based on frequency comb wavelength calibration. Following the feasibility test in the MPQ laboratory, researchers used the comb device for the first time at the Teide Observatory to calibrate the wavelength of the Vacuum Tower Telescope[7], achieving an equivalent Doppler accuracy of about 9 m/s at 1.5 microns, successfully recording a high-precision solar spectrum. At the same time, reports on astro-combs have emerged one after another, including mode-filtering methods[8,44,46], electro-optic modulation methods[30,49,50], and microcavity methods based on the Kerr effect[51,52]. Table 2 summarizes the main astro-combs currently in operation.

In China, Hou et al. developed a 23.75 GHz optical frequency comb in 2015[62], laying the foundation for the precise calibration of high-resolution spectrometers. Because of its high complexity, it is a great challenge to commercialize the mode-locked laser astro-comb system. At present, only Menlo Systems sells such an astro-comb. The 2.16 m astronomical telescope at the Xinglong Observatory is equipped with a high-resolution spectrometer with a resolution of 49 800, developed by a team at Peking University, based on the company's products. The frequency resolution at the wavelength of 532 nm is 11.3 GHz[61], and the actual wavelength calibration radial velocity accuracy is in the region of 30 cm/s.

In addition to the mode-locked optical frequency combs, electro-optic frequency combs have also begun to attract the attention of researchers. In 2015, Yi et al. proposed that a laser frequency comb suitable for astronomical grating spectrometers can be obtained using a method based on electro-optic modulation[49]. This instrument is built using commercially available components that are rela-

Table 2. Currently operational astronomical combs

Astronomical spectrograph	Repetition rate/GHz	Calibration accuracy	Frequency bandwidth/nm
Vacuum Tower Telescope (VTT)[7]	15/18	3 cm/s	1530−1600/ 480−640
High Accuracy Radial velocity Planet Searcher (HARPS/FOCES)[53-56]	18/25	1 cm/s	440−600
Northern hemisphere High Accuracy Radial Velocity Planet Searcher (HARPS-N)[57,58]	16	6 cm/s	500−620
Pathfinder[46]	25	10 m/s	1450−1700
Tillinghast Reflector Echelle Spectrograph (TRES)[59]	51/40	1 m/s	400−420/ 780−880
High Resolution Spectrograph (HRS)[60]	15/25	10 m/s	555−890
Xinglong station of NAOC [61]	30	30 cm/s	560−680
Southern African Large Telescope (SALT)	15	10 m/s	550−890
Habitable Zone Planet Finder (HPF)	30	1 m/s	700−1760
C-SHELL/Keck-II[49]	12	1 m/s	1375−1700
GIANO-B[51]	23.7	25 cm/s	1450−1700
Near-Infrared Spectrometer (NIRSPEC)[52]	22.1	1 m/s	1435−1685

tively simple and reliable. At the same time, a concept verification experiment was carried out at the near-infrared wavelength on the Low-Temperature Step Spectrometer and the Near-Infrared Spectrometer (NIRSPEC) of the NASA Infrared Telescope. The repetition rate of this comb system is 12 GHz, and the calibration accuracy can achieve measurements below 1 m/s. In 2017, Obrzud et al. implemented an electro-optic comb system on the GIANO-B near-infrared step spectrometer of the Galileo National Telescope (TNG) in Spain. This system can achieve a wavelength coverage range of 1400–1800 nm and a repetition rate of 14.5 GHz. One year later, Beha et al. used an electro-optic modulation comb to perform bidirectional frequency conversion between the microwave and optical domains[63]. They achieved the electro-optic generation of a supercontinuum with a bandwidth of 160 THz and realized f-2f self-reference. The mode frequency of the supercontinuum achieves high precision and high stability, paving the way for wide-mode spacing-tunable combs.

In 2019, Serizawa et al. equipped the infrared Doppler instrument operating on the Subaru telescope with an electro-optic frequency comb[64]. The repetition rate of the system is 12.5 GHz, and it can cover the working band from 970 nm to 1750 nm. Observations on 100 nights over three years yielded a long-term wavelength calibration accuracy of 2 m/s. Metcalf et al., of the National Institute of Standards and Technology, built an electro-optic astronomical frequency comb with a 30 GHz frequency interval and a calibration accuracy of under 10 cm/s[30].

The electro-optic astronomical comb system with a wide mode interval (30 GHz and above) currently faces challenges such as the need to add an F-P cavity to address linewidth degradation and calibration errors[50,63]. Additionally, the high pulse repetition rate results in low laser pulse energy, making the generation of broadband spectra with smooth envelopes relatively difficult. Microcavity frequency combs based on dissipative Kerr solitons[65] can also be a unique solution[66-68].

In 2017, Obrzud & Herr demonstrated an effective microcavity frequency comb in a fiber-based F-P microcavity[32]. Combined with supercontinuum generation and micro-photon pulse compression technology, it was shown by the NIRSPEC spectrometer, at the Keck-II telescope, that its frequency interval is 22.1 GHz covering a wavelength range of 1435 nm to 1685 nm. One year later, the same team demonstrated a new type of low-noise microcavity astronomical comb based on this, and for the first time verified the new microcavity comb system on the GIANO-B spectrometer of the TNG telescope in Spain, with a repetition rate of up to 23.5 GHz, with radial velocity measurement reaching an accuracy of 25 cm/s[51]. Almost simultaneously, Suh et al. from the Watson Applied Physics Laboratory also proposed a microcavity comb[52] with frequency interval and wavelength range indicators almost identical to those of the Herr team.

As with the electro-optic frequency comb, the wavelength coverage of the microcavity comb also needs to be further improved. Microcavity combs in the infrared band are relatively easy to create[69], but due to the normal dispersion of the cavity, there are few reports on microcavity frequency combs in the visible wavelength range. However, there have been some attempts to extend the microcavity comb from the near-infrared to visible wavelengths[70-72]. In summary, the microcavity astronomical comb has only been conceptually verified and tested, and is far from being a mature system capable of long-term operation.

4. RESEARCH PROGRESS OF SPACE-BORNE OPTICAL FREQUENCY COMBS

Space conditions, such as microgravity and negligible atmosphere, make it an ideal environment for high-precision optical atomic clocks and astronomical observations. This suggests that space will be one of the main application scenarios for OFCs in the future, and space-based optical combs will be one of the main directions for their continued development.

The design of OFCs for space-based applications presents several technical challenges. Space optical combs must meet the prerequisites of small volume, low power consumption, and low mass, while fulfilling the requirements of their intended applications. To be placed into orbit, they must also withstand the vibration and acceleration of rocket launches. The conditions in space are completely different from the constant temperature and humidity conditions of ground-based laboratories, so space optical combs must be able to operate in space environments and withstand radiation. Mode-locking, parameter optimization, and frequency locking of OFCs also need automatic adjustment capabilities to meet the requirements of uncrewed operations.

To date, there have been three international launches of space optical combs. In 2013, the Korea Institute of Space Technology reported the world's first fiber femtosecond laser oscillator that meets the requirements for use in space[23]. This laser is an erbium-doped fiber laser with SESAM mode-locking, a repetition rate of 25 MHz, and an output power of 14 mW. The laser was first subjected to vibration, vacuum heat testing, and space radiation tests on the ground. The ground tests verified the durability and stability of the laser under extreme environmental conditions such as vibration, temperature, and radiation. In early 2013, the laser was launched into low Earth orbit with a repetition rate locked to the onboard rubidium clock. During its year of in-orbit operation, it was able to maintain stable mode-locked operation, with radiation-induced power attenuation of 8.6%. The success of this test provided an experimental basis for the use of OFCs in space.

In 2016, Menlo Systems used an optical frequency comb to operate an optical clock in space for the first time, completing a precision comparison between the rubidium optical clock and the cesium atomic clock[24]. This experiment opened up the possibility of future space-based precision metrology, including general relativity research, low-noise microwaves for synthetic aperture radar/lidar calibration, and research into precise satellite-to-satellite laser-ranging systems. The structure of the Menlo Systems on-board optical comb is shown in Fig. 4B. The laser uses an all-fiber, all-polarization "Figure-9" cavity mode-locked oscillator as the seed. After amplification, the f-2f module measures the f_{ceo}, and the frequency doubling and beat frequency modules perform the comparison between the atomic clock and the rubidium clock. The optics of the onboard optical comb and the atomic clock are reduced to a module with a volume of 20 liters and a weight of 22 kg and are launched by the TEXUS 51 rocket.

In 2022, China successfully launched the "Dream Sky" experimental cabin, containing the high-precision time-frequency experimental cabinet, carrying a combination of atomic clocks with different characteristics, including OFCs, microwave clocks, cold atomic optical clocks, frequency comparison links, and many other subsystems. The aim is for China to build the world's most precise space-time frequency system[73]. This system will be able to synchronize the time of all parts of major scientific facilities and engineering technical facilities, thereby improving their performance. In the future, it will be able to fill the gap in intercontinental ground-based optical clock comparison technology, potentially helping to redefine the "second" as a unit of time measurement. It is also expected to measure gravitational redshift, detect changes in the fine structure constant, and support high-precision tests of relativity and related theories.

4.1. Space Optical Clock-based Time and Frequency Network

On-board atomic clocks are high-precision instruments that use the frequency of atomic transitions to generate accurate time signals. These signals can be transmitted to the ground via satellites to provide highly accurate navigation and positioning services to ground users. Currently, onboard atomic clocks can provide time accuracy at the nanosecond level, which is important for precise navigation, communications, weather forecasting, and other applications. In satellite navigation systems, the positioning services provided by onboard atomic clocks are of great significance for both military and civilian applications.

The use of on-board optical atomic clocks to replace existing microwave atomic clocks can improve time accuracy by several orders of magnitude. Simultaneously, the space-based optical frequency comb will help with experiments to measure fundamental physical quantities with an accuracy better than 10^{-19}, thanks to an environment low in vibration noise and far from the Earth's gravitational potential. The optical frequency comb will be used in an optical clock system to transmit the frequency standard, thereby establishing a new global time reference. Time and frequency conversion between continents, based on such OFCs, will help to obtain high-precision measurements of the geoid, facilitating research into fundamental physics.

In 2006, the European Space Agency launched the "Space Light Frequency Atomic Clock" project, intending to operate a light lattice clock on the International Space Station around 2023, but that mission has yet to materialize for technical, financial, and other reasons. The Russian Space Agency's Mobile Yb-Ion Optical Clock Prototype plans to test an optical clock in space. The RIKEN Institute in Japan has also developed a high-precision portable optical clock, using strontium, which is expected to carry out further research on space applications. The real space optical clock is the world's first space cold atom optical clock, developed by China and successfully launched to the Tiangong space station as part of the "Dream Sky" experimental cabin on October 31, 2022[73].

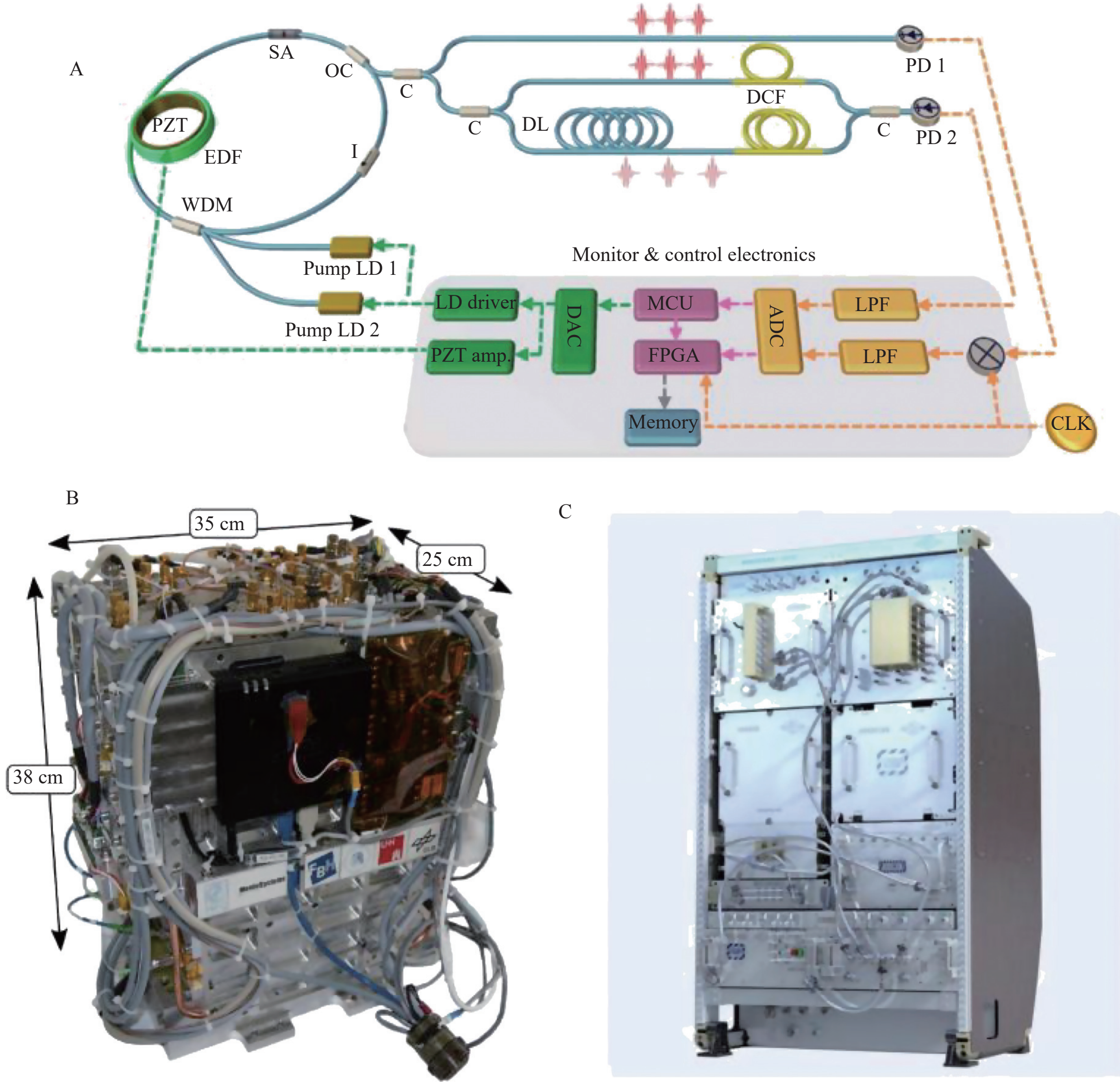

Fig. 4. (A) Schematic of the fiber femtosecond laser oscillator of the Korea Institute of Space Technology. (B) Photograph of the optical frequency comb launched by Menlo Systems. (C) Photograph of the high-precision time-frequency cabinet, part of China's "Dream Sky" experimental cabin.

4.2. Space Gravitational Wave and Dark Matter Detection

Gravitational waves, as the name suggests, are waves of gravitational force. They come from a wide variety of sources, with frequency intervals between 10^{-16} Hz and 10^4 Hz[74], and propagate outward from their source at the speed of light. In 1916, Einstein predicted the existence of gravitational waves on the basis of general relativity, and in 1993, the Nobel Prize in Physics was jointly awarded to Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation". In 2017, Rainer Weiss, Barry C. Barish and Kip S. Thorne were awarded the Nobel Prize "for decisive contributions to the LIGO detector and the observation of gravitational waves". At present, China has three major gravitational wave detection projects in progress, the Tianqin Project[75], the Space Taiji Project[76], and the Ali Project which aims to detect primordial gravitational waves[77].

Generally, ground-based detectors are sensitive to gravitational waves ranging from about tens of hertz to thousands of hertz, while space-based interferometers, based on laser interferometry techniques, are sensitive to gravitational waves at frequencies ranging from tens of millihertz to tens of hertz. The study of gravitational waves offers great potential for investigating the origin, evolution and structure of the universe, searching for black holes and other unknown objects, as well as testing general relativity[78]. It is worth noting, however, that by the time the gravitational waves emitted by a typical dense binary merger system reach the Earth, their amplitude is already less than 10^{-21}, and there may be other sources of noise that affect or even obscure this signal. To study and observe more events, such as mergers of black holes and neutron stars, and the birth of supernovae, and to make the resulting signals clearer, scientists are constantly striving to improve the sensitivity of the detectors. One crucial direction is to eliminate the influence of laser frequency noise and on-board clock noise[79].

Compared with the previously proposed time delay interferometry (TDI)[80]to eliminate noise, in 2015, Tinto et al. proposed a TDI system with an OFC to achieve this[17]. The specific method is that the OFC and the onboard laser are coherently referenced to generate a heterodyne microwave signal, thereby directly eliminating microwave noise. This system can greatly simplify the design of the system, improving the reliability of the space-based gravitational wave interferometer. The team later further verified the reliability of the comb-enhanced gravitational wave detection scheme[81,82], and fully demonstrated that it can meet the requirements of the Laser Interferometer Space Antenna mission.

According to current theories, dark matter is an invisible substance that makes up 85% of the total mass of matter in the universe and participates only in gravitational interactions and not in electromagnetic interactions. Measuring dark matter is crucial to understanding the structure, evolution, and composition of the universe. In 2014, Derevianko & Pospelov proposed that "topological defect dark matter" interacting with the solar system could affect precision clocks in spacecraft networks, such as GPS. The changing time scale of the clock may provide clues to the degree and nature of time division multiplexing. Increasing the accuracy of spacecraft clocks in the Global Navigation Satellite System by three orders of magnitude can correspondingly increase the sensitivity to small deviations caused by dark matter. Only optical clocks based on OFCs can achieve such high accuracy[18].

4.3. Dual-comb Space Ranging and Atmospheric Spectroscopy

In the field of space exploration, absolute distance measurement technology is an important support for high-resolution celestial optical remote sensing imaging technology, distributed synthetic aperture radar imaging, high-resolution space-based gravity imaging technology, space-based gravitational wave detection, and other applications. For example, distributed synthetic aperture radar uses multiple small satellites to form a fleet, providing a large synthetic aperture to enable high-resolution searches for exoplanets, direct imaging of black holes with spaceborne radio telescopes, or accurate measurement of satellite distances in gravitational fields to test general relativity. To create a satellite formation that can operate as a single instrument, it is necessary to perform real-time, high-precision measurement and control of the satellite fleet distance and direction. This requires that the ranging system be able to simultaneously operate with high accuracy, at long range, and in real time.

Based on the time-frequency domain characteristics of OFCs, several absolute distance measurement methods have been developed. These primarily include the scanning repetition rate method, the mode beat frequency method, the dispersion interference method, the wavelength synthesis method, and the dual-comb ranging method. Among these, the dual-comb absolute distance measurement technology, based on asynchronous optical sampling, has become the most widely researched ranging technology in recent decades because of its high measurement accuracy (nm-μm), fast update speed (μs-ms), and scalable non-ambiguity range. Researchers have conducted in-depth studies on the influence of the accuracy of dual-comb ranging, the use of free-running OFCs for ranging, nonlinear optical sampling, dead zone elimination, non-ambiguity range expansion, and other scientific and technical issues. These studies have improved our understanding of dual-comb ranging, simplified the complexity of ranging devices, and enriched the application scenarios of dual-comb absolute distance measurement. The numerous advantages of the dual-comb make it indispensable in space-based applications and, as a result, spaceborne combs and their diverse applications have emerged as the technical pinnacles that aerospace powers strive to master.

Space Heterodyne Spectroscopy technology, based on Michelson interferometers[83], can achieve a series of goals, including atmospheric remote sensing and astronomical detection. Currently, the main satellites used for planetary atmospheric detection at home and abroad mainly include GOSAT[84]launched by Japan in 2009 to monitor global atmospheric carbon monoxide and methane levels; OCO-2[85]launched by NASA in the United States in 2014 to study global climate change; and the carbon monitoring satellites[86] launched by China in 2016. Comb spectroscopy, with its broad spectral coverage, high resolution, high sensitivity, and short data acquisition time, can be miniaturized and integrated into spaceborne detection devices[87], replacing existing laser sources to achieve higher levels of planetary atmospheric analysis and measurement.

5. CONCLUSIONS

OFCs possess significant potential for various applications in astronomical detection and space science, including astronomical spectrometer calibration, constructing space-based optical clock time-frequency networks, measuring gravitational waves and dark matter, large-scale absolute ranging, and precision atmospheric spectroscopy using dual-combs. With the continuing development of aerospace and space exploration, the use of OFCs in space will expand, promoting the further development of astronomical and space science research and applications. At present, whether it is a mode-locked, electro-optic, or microcavity comb, there is a need for compact size, small mass, and low power consumption to meet the requirements of the space environment and the various intended applications. At the same time, new technologies and applications of OFCs need to also be further developed to improve the performance of current systems and reduce system complexity.

ACKNOWLEDGEMENTS

Thanks to the support of the National Natural Science Foundation of China (NSFC) (62305373) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA1502040404, XDB2101040004).

AUTHOR CONTRIBUTIONS

Shao Xiaodong and Yan Yu contributed to the writing and editing the manuscript. Han hainian and Wei Zhiyi revised the manuscript. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

[1] Hansch, T. W. 2006. Nobel Lecture: Passion for precision. *Reviews of Modern Physics*, **78**(4): 1297−1309.

[2] Hall, J. L. 2006. Nobel Lecture: Defining and measuring optical frequencies. *Reviews of Modern Physics*, **78**(4): 1279−1295.

[3] Jones, D. J., Diddams, S. A., Ranka, J. K., et al. 2000. Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. *Science*, **288**(5466): 635−639.

[4] Coddington, I., Newbury, N., Swann, W. 2016. Dual-comb spectroscopy. *Optica*, **3**(4): 414−426.

[5] Coddingtion, I., Swann, W. C., Nenadovic, L., et al. 2009. Rapid and precise absolute distance measurements at long range. *Nature Photonics*, **3**(6): 351−356.

[6] Ludlow, A. D., Boyd, M. M., Ye, J., et al. 2015. Optical atomic clocks. *Reviews of Modern Physics*, **87**(2): 637−701.

[7] Steinmetz, T., Wilken, T., Araujo-Hauck, C., et al. 2008. Laser frequency combs for astronomical observations. *Science*, **321**(5894): 1335−1337.

[8] Li, C. H., Benedick, A. J., Fendel, P., et al. 2008. A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{-1}. *Nature*, **452**(7187): 610−612.

[9] Liske, J., Grazian, A., Vanzella, E., et al. 2008. Cosmic dynamics in the era of Extremely Large Telescopes. *Monthly Notices of the Royal Astronomical Society*, **386**(3): 1192−1218.

[10] Oelker, E., Hutson, R. B., Kennedy, C. J., et al. 2019. Demonstration of 4.8 × 10^{-17} stability at 1 s for two independent optical clocks. *Nature Photonics*, **13**(10): 714−719.

[11] Diddams, S. A., Vahala, K., Udem T. 2020. Optical frequency combs: Coherently uniting the electromagnetic spectrum. *Science*, **369**(6501): eaay3676.

[12] Shen, Q., Guan, J. Y., Ren, J. G., et al. 2022. Free-space dissemination of time and frequency with 10−19 instability over 113 km. *Nature*, **610**(7933): 661−666.

[13] Beloy, K., Bodine, M. I., Bothwell, T., et al. 2021. Frequency ratio measurements at 18-digit accuracy using an optical clock network. *Nature*, **591**(7851): 564−569.

[14] Pizzocaro, M., Sekido, M., Tatefuji, K., et al. 2021. Intercontinental comparison of optical atomic clocks through very long baseline interferometry. *Nature Physics*, **17**(2): 223−227.

[15] Gill, P. 2011. When should we change the definition of the second?. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **369**(1953): 4109−4130.

[16] Ashby, N., Bender, P. L., Hall, J. L., et al. 2009. Measurement of gravitational time delay using drag-free spacecraft and an optical clock. In Proceedings of the International Astronomical Union. 5:414−419.

[17] Tinto, M., Yu, N. 2015. Time-delay interferometry with optical frequency comb. *Physical Review D*, **92**(4): 042002.

[18] Derevianko, A., Pospelov, M. 2014. Hunting for topological dark matter with atomic clocks. *Nature Physics*, **10**(12): 933−936.

[19] Zhu, Z. B., Wu, G. H. 2018. Dual-comb ranging. *Engineering*, **4**(6): 772−778.

[20] Fridlund, C. V. M. 2000. Darwin-the infrared space interferometry mission. *ESA bulletin*, **103**(3): 20−25.

[21] Kroes, R., Montenbruck, O., Bertiger, W., et al. 2005. Precise GRACE baseline determination using GPS. *Gps Solutions*, **9**: 21−31.

[22] Sutton, A., Mckenzie, K., Ware, B., et al. 2010. Laser ranging and communications for LISA. *Optics Express*, **18**(20): 20759−20773.

[23] Lee, J., Lee, K., Jang, Y. S., et al. 2014. Testing of a femtosecond pulse laser in outer space. *Scientific Reports*, **4**(1): 05134.

[24] Lezius, M., Wilken, T., Deutsch, C., et al. 2016. Space-borne frequency comb metrology. *Optica*, **3**(12): 1381−1387.

[25] Buchs, G., Kundermann, S., Portuond-Campa, E., et al. 2015. Radiation hard mode-locked laser suitable as a spaceborne frequency comb. *Optics Express*, **23**(8): 9890−9900.

[26] Lamour, T. P., Ye, F., Mandel, O., et al. 2020. Novel optical frequency comb technology demonstrator for space. In Proceedings of SPIE. 11852: 1185239.

[27] Feng, Y., Lamour, T. P., Ostapenko, H., et al. 2021. Towards a space-qualified Kerr-lens mode-locked laser. *Optics Letters*, **46**(21): 5429−5432.

[28] Wang, Y., Holguín-Lerma, J. A., Vezzoli, M., et al. 2023. Photonic-circuit-integrated titanium: sapphire laser. *Nature Photonics*, **17**(4): 338−345.

[29] Parriaux, A., Hammani, K., Millot, G. 2020. Electro-optic frequency combs. *Advances in Optics and Photonics*, **12**(1): 223−287.

[30] Metcalf, A. J., Anderson, T., Bender, C. F., et al. 2019. Stellar spectroscopy in the near-infrared with a laser frequency comb. *Optica*, **6**(2): 233−239.

[31] Carlson, D. R., Hickstein, D. D., Zhang, W., et al. 2018. Ultrafast electro-optic light with subcycle control. *Science*, **361**(6409): 1358−1362.

[32] Kovach, A., Chen, D. Y., He, J. H., et al. 2020. Emerging material systems for integrated optical Kerr frequency combs. *Advances in Optics and Photonics*, **12**(1): 135−222.

[33] Pupeza, I., Zhang, C., Högner, M., et al. 2021. Extreme-ultraviolet frequency combs for precision metrology and attosecond science. *Nature Photonics*, **15**(3): 175−186.

[34] Shao, X. D., Han, H. N., Wang, H. B., et al. 2023. High

power optical frequency comb with 10−19 frequency instability. *Optics Express*, **31**(20): 32813−32823.
[35] Shestaev, E., Hadrich, S., Walther, N., et al. 2020. Carrier-envelope offset stable, coherently combined ytterbium-doped fiber CPA delivering 1 kW of average power. *Optics Letters*, **45**(23): 6350−6353.
[36] Kimura, S., Tani, S., Kobayashi, Y. 2019. Kerr-lens mode locking above a 20 GHz repetition rate. *Optica*, **6**(5): 532−533.
[37] Murphy, M. T., Udem, T., Holzwarth, R., et al. 2007. High-precision wavelength calibration of astronomical spectrographs with laser frequency combs. *Monthly Notices of the Royal Astronomical Society*, **380**(2): 839−847.
[38] Haboucha, A., Zhang, W., Li, T., et al. 2011. Optical-fiber pulse rate multiplier for ultralow phase-noise signal generation. *Optics Letters*, **36**(18): 3654−3656.
[39] Shao, X. D., Han, H. N., Wei, Z. Y. 2021. Ultra-low noise microwave frequency generation based on optical frequency comb. *Acta Physica Sinica*, **70**(13): 134204−134214. (in Chinese)
[40] Voumard, T., Darvill, J., Wildi, T., et al. 2021. 1 GHz dual-comb spectrometer for fast and broadband measurements. *arXiv:211108599*.
[41] Lovis, C., Mayor, M., Pepe, F., et al. 2006. An extrasolar planetary system with three Neptune-mass planets. *Nature*, **441**(7091): 305−309.
[42] Udem, T., Holzwarth, R., Hansch, T. W. 2002. Optical frequency metrology. *Nature*, **416**(6877): 233−237.
[43] Mccracken, R. A., Charsley, J. M., Reid, D. T. 2017. A decade of astrocombs: recent advances in frequency combs for astronomy. *Optics Express*, **25**(13): 15058−15078.
[44] Braje, D.A., Kirchner, M.S., Osterman, S., et al. 2008. Astronomical spectrograph calibration with broad-spectrum frequency combs. *The European Physical Journal D*, **48**: 57−66.
[45] Li , C. H., Glenday, A. G., Benedick, A. J., et al. 2010. In-situ determination of astro-comb calibrator lines to better than 10 cm s− 1. *Optics Express*, **18**(12): 13239−13249.
[46] Ycas, G. G., Quinlan, F., Diddams, S. A., et al. 2012. Demonstration of on-sky calibration of astronomical spectra using a 25 GHz near-IR laser frequency comb. *Optics Express*, **20**(6): 6631−6643.
[47] Fischer, D. A., Anglada-Escude, G., Arriagada, P., et al. 2016. State of the field: extreme precision radial velocities. *Publications of the Astronomical Society of the Pacific*, **128**(964): 066001.
[48] Campbell, B. 1983. Precision radial velocities. *Publications of the Astronomical Society of the Pacific*, **95**(571): 577.
[49] Yi, X., Vahala, K., Li, J., et al. 2016. Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy. *Nature Communications*, **7**(1): 10436.
[50] Obrzud, E., Rainer, M., Harutyunyan, A., et al. 2018. Broadband near-infrared astronomical spectrometer calibration and on-sky validation with an electro-optic laser frequency comb. *Optics Express*, **26**(26): 34830−34841.
[51] Obrzud, E., Rainer, M., Harutyunyan, A., et al. 2019. A microphotonic astrocomb. *Nature Photonics*, **13**(1): 31−35.
[52] Suh, M. G., Yi, X., Lai, Y. H., et al. 2019. Searching for exoplanets using a microresonator astrocomb. Nature Photonics, 2019, 13(1): 25−30.
[53] Wilken, T., Lo Curto, G., Probst, R. A., et al. 2012. A spectrograph for exoplanet observations calibrated at the centimetre-per-second level. *Nature*, **485**: 611−614.
[54] Wilken, T., Lovis, C., Manescau, A., et al. 2010. High-precision calibration of spectrographs. *Monthly Notices of the Royal Astronomical Society: Letters*, **405**(1): L16−L20.
[55] Cosentino, R., Lovis, C., Pepe, F., et al. 2014. HARPS-N@ TNG, two year harvesting data: performances and results. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy.
[56] Probst, R. A., Curto, G. L., Ávila, G., et al. 2016. Relative stability of two laser frequency combs for routine operation on HARPS and FOCES. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VI.
[57] Glenday, A. G., Li, C. H., Langellier, N., et al. 2015. Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph. *Optica*, **2**(3): 250−254.
[58] Li, C. H., Glenday, A. G., Phillips, D. F., et al. 2012. Green astro-comb for HARPS-N. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy IV.
[59] Phillips, D. F., Glenday, A. G., Li, C. H., et al. 2012. Calibration of an astrophysical spectrograph below 1 m/s using a laser frequency comb. *Optics Express*, **20**(13): 13711−13726.
[60] Mccracken, R. A., Depagne, É., Kuhn, R. B., et al. 2017. Wavelength calibration of a high resolution spectrograph with a partially stabilized 15-GHz astrocomb from 550 to 890 nm. *Optics Express*, **25**(6): 6450−6460.
[61] Ma, Y. X., Zuo, L. J, Meng, F., et al. 2016. A compact 30 GHz spaced astro-comb based on 1 GHz Yb: fiber laser. In Proceedings of 2016 Conference on Lasers and Electro-Optics (CLEO).
[62] Hou, L., Han, H. N., Wang, W., et al. 2015. A 23.75-GHz frequency comb with two low-finesse filtering cavities in series for high resolution spectroscopy. *Chinese Physics B*, **24**(2): 024213.
[63] Beha, K., Cole, D. C., Del'Haye, P., et al. 2017. Electronic synthesis of light. *Optica*, **4**(4): 406−411.
[64] Serizawa, T., Kurokawa, T., Tanaka, Y., et al. 2022. Laser frequency comb system for the InfraRed Doppler spectrograph on the Subaru Telescope. In Proceedings of the Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation.
[65] Herr, T., Brasch, V., Jost, J. D., et al. 2014. Temporal solitons in optical microresonators. *Nature Photonics*, **8**(2): 145−152.
[66] Del’Haye, P., Schliesser, A., Arcizet, O., et al. 2007. Optical frequency comb generation from a monolithic microresonator. *Nature*, **450**(7173): 1214−1217.
[67] Savchenkov, A. A., Matsko, A. B., Ilchenko, V. S., et al. 2008. Tunable optical frequency comb with a crystalline whispering gallery mode resonator. *Physical Review Letters*, **101**(9): 093902.
[68] Kippenberg, T. J., Holzwarth, R., Diddams, S. A., et al. 2011. Microresonator-Based Optical Frequency Combs. *Science*, **332**(6029): 555−559.
[69] Tanabe, T., Fujii, S., Suzuki, R. 2019. Review on microresonator frequency combs. *Japanese journal of applied physics*, **58**: SJ0801.
[70] Lee, S. H., Oh, D. Y., Yang, Q. F., et al. 2017. Towards visible soliton microcomb generation. *Nature Communications*, **8**(1): 1295.

[71] Zhao, Y., Ji, X. C., Kim, B. Y., et al. 2019. Near-visible microresonator-based soliton combs. In Proceedings of the Conference on Lasers and Electro-Optics.
[72] Xue, X. X., Xuan, Y., Liu, Y., et al. 2015. Mode-locked dark pulse Kerr combs in normal-dispersion microresonators. *Nature Photonics*, **9**: 594−600.
[73] Liu. Y., Wang, W. H., He, D. J., et al. 2023. Laser system of cold atom optical clock in China Space Station. *Acta Physica Sinica*, **72**(18): 184202.
[74] Thorne, K. S. 1995. Gravitational waves. *arXiv:gr-qc/9506086.*
[75] Luo, J., Chen, L. S., Duan, H. Z., et al. 2016. TianQin: a space-borne gravitational wave detector. *Classical and Quantum Gravity*, **33**(3): 035010.
[76] Gong, X. F., Lau, Y. K., Xu, S. N., et al. 2015. Descope of the ALIA mission. *Journal of Physics: Conference Series*, **610**: 012011.
[77] Zhang, X. M., Su, M., Li, H., et al. 2016. The origin of the universe and the Ali primordial gravitational waves detection. *Physics*, **45**(5): 320−326.(in Chinese)
[78] Weber, J. 1966. Observation of the thermal fluctuations of a gravitational-wave detector. *Physical Review Letters*, **17**(24): 1228.
[79] Xu, X., Tan, Y. D., Mu, H. L., et al. 2023. Laser Interferometric Multi-Degree-of-Freedom Measurement Technology in Space Gravitational-Wave Detection. *Laser & Optoelectronics Progress*, **60**(3): 0312006.(in Chinese)
[80] Tinto, M., Estabrook, F. B., Armstrong, J. 2002. Time-delay interferometry for LISA. *Physical Review D*, **65**(8): 082003.
[81] Vinckier, Q., Tinto, M., Grudinin, I., et al. 2020. Experimental demonstration of time-delay interferometry with optical frequency comb. *Physical Review D*, **102**(6): 062002.
[82] Yu, N., Grudinin, I., Tinto, M. 2017. Optical frequency comb application in time-delay interferometer. In Proceedings of 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS).
[83] Dohi, T., Suzuki, T. 1971. Attainment of high resolution holographic Fourier transform spectroscopy. *Applied Optics*, **10**(5): 1137−1140.
[84] Yokota, T., Yoshida, Y., Eguchi, N., et al. 2009. Global concentrations of CO_2 and CH_4 retrieved from GOSAT: First preliminary results. *Solar*, **5**: 160−163.
[85] Sun, Y., Frankenberg, C., Wood, J. D., et al. 2017. OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. *Science*, **358**(6360): eaam5747.
[86] Du, S. S., Liu, L. Y., Liu, X. J., et al. 2018. Retrieval of global terrestrial solar-induced chlorophyll fluorescence from TanSat satellite. *Science Bulletin*, **63**(22): 1502−1512.
[87] Coburn, S., Alden, C. B., Wright, R., et al. 2018. Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer. *Optica*, **5**(4): 320−327.