

Review

Recent Advances, Applications, and Perspectives in Erbium-Doped Fiber Combs

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Abstract: Optical frequency combs have emerged as a new generation of metrological tools, driving advancements in various fields such as free-space two-way time–frequency transfer, low-noise microwave source generation, and gas molecule detection. Among them, fiber combs based on erbium-doped fiber mode-locked lasers have garnered significant attention due to their numerous advantages, including low noise, high system integration, and cost-effectiveness. In this review, we discuss recent developments in erbium-doped fiber combs and analyze the advantages and disadvantages of constructing fiber combs utilizing different erbium-doped mode-locked fiber lasers. First, we provide a brief introduction to the basic principles of optical frequency combs. Then, we explore erbium-doped fiber combs implemented utilizing various mode-locking techniques, such as nonlinear polarization rotation (NPR), real saturable absorber (SA), and nonlinear amplifying loop mirror (NALM). Finally, we present an outlook on the future perspectives of erbium-doped fiber combs.

Keywords: erbium-doped fiber; optical frequency combs; mode-locked lasers



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1. Introduction

In recent years, optical frequency combs have tremendously progressed from a complex desktop system to a compact chip-level device [1–3]. Many advantages of optical frequency combs have promoted the development of different technical fields that include optical two-way time–frequency transfer [4–6], high-precision laser ranging [7–12], atomic clock networks [13–15], absolute frequency measurement [16–18], wavelength calibration of astronomical spectrographs [19,20], and low-noise microwave generation [21–25]. With the rapid development of these fields, compact and robust optical frequency combs are quite urgent for use in the outdoor environment, even in outer space. Although chip-level optical frequency combs using microresonators have huge potential in the future, they need to solve some pressing problems including low photonic integration, laser propagation loss, and low power efficiency [26]. Currently, optical frequency combs based on fiber lasers offer a relatively ideal choice in many areas of research.

According to the classification based on the gain medium, mode-locked fiber lasers can be categorized into Er-doped mode-locked fiber lasers [27–33], Yb-doped mode-locked fiber lasers [34–38], Tm-doped mode-locked fiber lasers [39–42], and so on. Among them, Er-doped mode-locked fiber lasers have gained considerable attention from researchers for several reasons. These include operation in the 1.5 μm communication wavelength band, mature device fabrication processes, compact structure, and low cost. The locking principles of erbium-doped fiber lasers mainly include real SA mode-locking [43,44], NPR

mode-locking [28,34], NALM mode-locking [29,30], and hybrid mode-locking [45–48]. In addition, the real SA mainly includes semiconductor-saturable absorber mirrors (SESAMs) and carbon nanotubes (CNs). These mode-locked fiber lasers can all serve as coherent light sources for erbium-doped fiber combs. After years of development, significant progress has been made in the implementation of Er-doped fiber combs based on these mode-locking principles. Meanwhile, Er-doped fiber combs have also promoted progress in many fields [7,17,49].

In this review, our main focus is the research progress of Er-doped fiber combs. Firstly, we provide a brief introduction to the principles of femtosecond optical frequency combs in Section 2. Then, we elaborate on the main methods used to create erbium-doped fiber combs in Section 3. Subsequently, we discuss the typical applications and results based on erbium-doped fiber combs in Section 4. Finally, we summarize and provide an outlook for erbium-doped fiber combs in Section 5.

2. Principle of Optical Frequency Combs

As shown in Figure 1a, a mode-locked laser-based femtosecond optical frequency comb outputs a series of pulse trains in the time domain, with adjacent pulses having a common time interval T_r . When the pulse is transmitted in the laser cavity, the existence of intracavity dispersion causes the propagation speed of different wavelengths within the pulse envelope to be different, resulting in a phase difference $\Delta\varphi_{ceo}$ between the pulse carrier and the envelope in the time domain [50]. As shown in Figure 1b, the mode-locked laser exhibits a series of frequency comb teeth in the frequency domain, with the frequency difference between adjacent teeth being the repetition rate f_r [50]. Therefore, the frequency of each comb tooth can be represented as $f_N = N \cdot f_r + f_{ceo}$, where N is the longitudinal mode number of the laser. f_{ceo} and f_r are the two degrees of freedom of the femtosecond optical frequency comb, but there is a clear difference in their effect on the comb teeth. The f_{ceo} signal is the overall offset that affects the position of the comb teeth, while the f_r signal affects the frequency spacing of the comb teeth. Therefore, locking f_{ceo} and f_r is the key to creating the optical frequency comb. The f_r signal is able to be directly obtained through a photodetector. When locking the frequency of the f_r signal, the error signal of the f_r signal is typically used to regulate a piezoelectric ceramic actuator (PZT) or an electro-optic modulator (EOM) inside the laser through a phase-locked loop for adjusting the optical cavity length. Furthermore, the f_{ceo} signal generally needs to be detected using the self-referencing f -to- $2f$ [51] or $2f$ -to- $3f$ [52,53] interferometer techniques. When locking the frequency of the f_{ceo} signal, the error signal of f_{ceo} is generally able to adjust the pump source or an EOM through a phase-locked loop for regulating the dispersion of the mode-locked laser. In addition, the noise measurement and control of the comb system are also quite important [54,55].

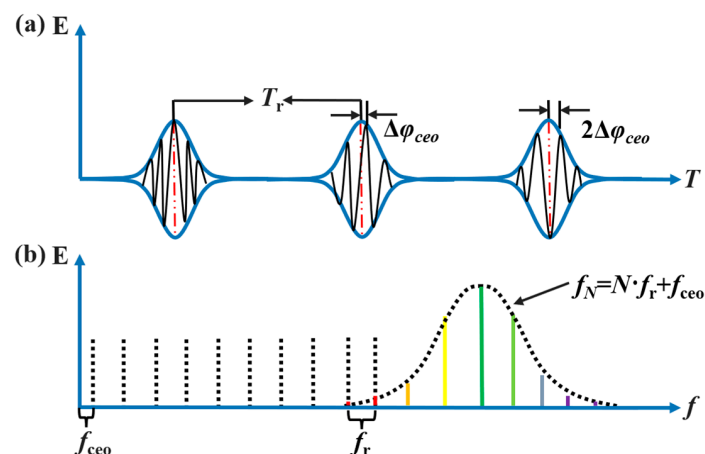


Figure 1. The idea of frequency comb. (a) Pulses in the time domain; (b) Character of the comb teeth in the frequency domain.

3. Optical Frequency Combs Based on Er:fiber Mode-Locked Lasers

Multiple techniques exist for achieving an erbium-doped fiber laser, including NPR, real SA, NALM, and hybrid mode-locking. Due to the complex structure of hybrid mode-locked lasers [46], we mainly introduce the Er:fiber comb composed of the previous three mode-locking principles in this section.

3.1. NPR-Based Er:fiber Optical Frequency Comb

NPR-based fiber lasers utilize a polarization controller (PC) and an isolator (ISO) within the laser cavity for flexible and precise control and manipulation of pulse characteristics. The PC controls the polarization of pulse light, affecting the pulse characteristics upon propagating back to the starting point of the fiber and enabling precise control over the initial phase and shape. The ISO prevents interference from reflected light in the laser cavity and introduces loss to allow only specific polarization states to pass through. By combining the self-phase modulation and fiber birefringence and optimizing the parameters of the PC, the pulses can be tailored to pass through the ISO with minimal loss, enabling NPR fiber lasers to achieve stable, efficient, and low-noise operation [56,57].

In 2004, Adler et al. demonstrated an NPR fiber comb with a repetition rate f_r of 100 MHz and achieved two parallel Er-doped fiber amplifiers (EDFA). One EDFA was used for f_{ceo} detection, and the other EDFA was used to achieve nonlinear frequency conversion. However, a noncollinear $f-2f$ interferometer was employed for f_{ceo} detection in the NPR fiber comb, resulting in a highly complex optical system [58]. In 2006, Masaaki et al. used a simple NPR Er:fiber laser as a coherent light source, combined with pulse amplification, spectral broadening, and a compact collinear $f-2f$ interferometer to detect f_{ceo} signal with signal-to-noise ratio (SNR) of over 45 dB with a resolution bandwidth (RBW) of 100 kHz [59]. To achieve greater frequency stability of the fiber comb, the NPR fiber comb needs to be locked to an optical reference source. In 2010, Nakajima et al. developed an NPR Er:fiber comb that was locked to an ultra-stable optical reference source. For fast responses and precise control of the repetition rate f_r , an EOM with a high servo bandwidth was inserted into the laser cavity. Meanwhile, the relative frequency stability between the two fiber combs was shown, which was 3.7×10^{-16} for a 1 s averaging time [60]. In 2015, Yan et al. inserted an EOM into an NPR Er-doped fiber laser with a repetition rate of 232 MHz. And the optical beat signal f_{beat} between the comb tooth and the ultra-stable optical reference source was locked by the feedback of a PZT and an EOM. The f_{ceo} signal was stabilized by regulating the pump power of mode-locked lasers. The in-loop frequency stability was also discussed, which was better than 1×10^{-16} and 1×10^{-20} in 1 s and 10^4 s averaging times, respectively [61]. In 2017, in order to increase the feedback bandwidth for locking the f_{ceo} , Zhang et al. developed a NPR-based Er:fiber laser and a special design of EOM was placed in the fiber laser. By adjusting the parameters of the EOM, the polarization state in the NPR fiber laser was changed so that the frequency of the f_{ceo} signal could be adjusted in a wide range. In addition, the locking bandwidth of f_{ceo} was about 1.8 MHz. According to the test results, after the f_{ceo} was stabilized, the Allan deviations were better than 2×10^{-17} in a 1 s averaging time [62]. In addition to locking the f_{ceo} signal by adjusting the pump power and the EOM, locking the f_{ceo} signal can also be performed by adjusting an electric polarization controller (EPC). In 2021, Liu et al. implemented a compact, intelligent NPR-based Er:fiber laser using a highly integrated fiber device and an EPC. The EPC was used to achieve intelligent mode-locking, and the f_{ceo} signal was also locked by regulating the parameters of the EPC [63].

However, the operating state of NPR-based Er:fiber lasers with non-PM structures is susceptible to strain, temperature, or humidity. Hence, it is important to weaken the impact of environmental factors on NPR-based Er:fiber combs. In 2021, Xie et al. implemented a polarization-maintaining Er-doped fiber laser combining the NPR mode-locking principle, serving as a coherent light source to achieve a self-reference optical frequency comb, and the f_r and f_{ceo} were simultaneously locked for more than 10 h [64], as shown in Figure 2.

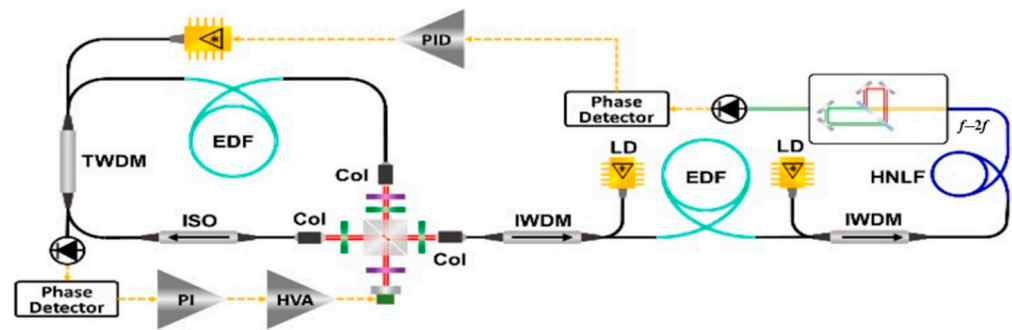


Figure 2. All polarization-maintaining NPR-based Er:fiber combs. Reproduced with permission [64]. Copyright 2021 authors, published by ELSEVIER Publishing.

3.2. Real SA-Based Er:fiber Optical Frequency Comb

The real SA device plays a very important role in self-starting mode-locked fiber lasers. Its long recovery time allows for easy saturation of the absorber with initial growing pulses during continuous-wave operation, enabling simple self-starting. By injecting a continuous-wave light source, the initial light pulses are absorbed by the SA without forming mode-locked oscillation. As time progresses, the absorption capability of the SA decreases, and the light pulses begin to accumulate inside the cavity. Once the energy reaches a certain level, the SA is fully saturated, and the light pulses start to form mode-locked oscillation. This self-starting mechanism simplifies laser operation and improves stability [65–67].

In 2013, Coddington et al. designed a linear cavity polarization-maintained Er-doped fiber laser with a repetition rate of 200 MHz using a micro-optic containing a SESAM and achieved the phase locking of the f_{ceo} signal, but the repetition rate f_r was free running [68]. In 2017, for the first time, Togashi et al. developed a fiber comb system using an all-polarization-maintaining Er-doped mode-locked laser embedded with a single-wall CN. The f_r and f_{ceo} signals were simultaneously stabilized by feedback from the EOM and by adjusting the pump power of the fiber cavity, respectively. The linewidths of the f_r and f_{ceo} signals were reduced to less than 1 Hz, which was limited due to the resolution of the spectrum analyzer [69]. In 2018, Schwyer et al. designed a polarization-maintaining fiber comb using the SESAM Er-doped fiber laser. The mode-locked fiber laser, based on SESAM, incorporated an integrated waveguide EOM. This EOM served to synchronize the comb with the HeNe transfer laser. Additionally, during the long-term operation of the SESAM fiber comb, there was no reliance on the PZT for locking f_r , thereby preventing any degradation in fiber performance caused by mechanical expansion [70]. To enhance the environmental adaptability and expand the application scenarios of optical frequency comb technology, it is necessary to achieve a compact optical comb system. In 2020, Cai et al. designed a highly integrated Er:fiber comb system. A coherent source in the form of a SESAM fiber laser was employed, enabling pulse amplification and spectral extension within an all-fiber structure. f_{ceo} detection was achieved through a fiber-coupled miniature f -to- $2f$ interferometer. This design greatly simplified the optical frequency comb system and enhanced its environmental adaptability [71]. The same year, Zhu et al. developed a self-referenced Er:fiber comb system with a repetition rate of 101 MHz, and the residual phase noise of f_{ceo} was 713 mrad from 1 Hz to 3 MHz [72], as shown in Figure 3. In addition, in order to address the issues of optical and thermal damage in SESAM, in 2015, Jang et al. controlled the pump power to reduce the optical damage, utilized a copper-silicon-layered heat sink to solve the thermal damage, and conducted a stability test on the laser for a duration of 7 days [73].

f_{ceo} and f_{beat} signals were 86.1 mrad and 21.8 mrad, respectively [86]. In 2022, as shown in Figure 4, Zhang et al. demonstrated an all-polarization-maintaining comb system by using an NALM-based Er-doped fiber laser with a repetition rate of 200 MHz. After the f_{ceo} and f_{beat} signals were locked, the frequency instability of the f_{ceo} and f_{beat} signals was 7.5×10^{-18} and 8.5×10^{-18} , respectively, in a 1 s averaging time. At the same time, the four different wavelengths were generated by the method of nonlinear frequency conversion, which can facilitate the frequency comparison between different optical clocks [87].

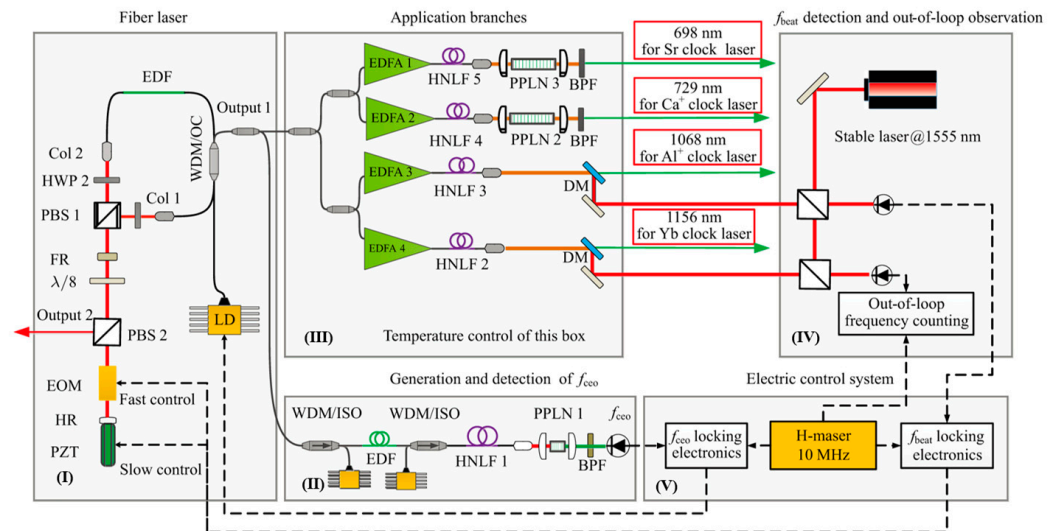


Figure 4. The multi-branch NALM-based Er:fiber comb system was used to compare the frequency stability between different optical lattice clocks. (I) The mode-locked laser. (II) Generation of the f_{ceo} . (III) Generation of 698 nm, 729 nm, 1068 nm, and 1156 nm. (IV) Generation of the optical beat signals. (V) Locking f_{ceo} and f_{beat} . Reproduced with permission [87]. Copyright 2022 authors, published by IOP Publishing.

However, compared with an NPR-based fiber laser [88,89] and a SESAM-based laser [44,90], the repetition rate of the NALM-based laser cavity has difficulty reaching above GHz due to the limitation of the mode-locking principle. To solve this problem, researchers have proposed different research schemes. In 2011, Jiang et al. achieved multiplication of the repetition rate of fiber laser from 250 MHz to 10 GHz outside the laser cavity with two methods, which were Fabry–Perot cavity filtering and unbalanced Mach–Zehnder (MZ) fiber interferometer [91]. On the contrary. In 2023, Cao et al. adopted a method to achieve a repetition rate of GHz in a laser cavity. An optical cavity was nested in an Erbium-doped fiber laser based on NALM to achieve a repetition rate of 907 MHz, and the SNR of f_{ceo} was only about 30dB at a RBW of 10 kHz [92], as shown in Figure 5.

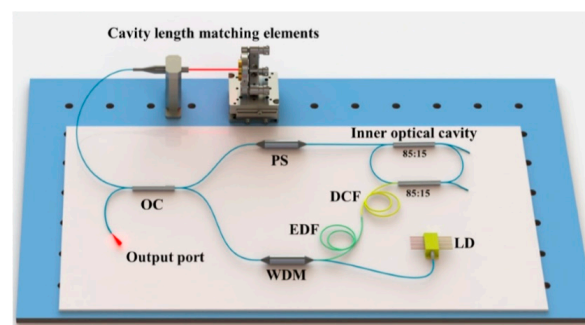


Figure 5. The NALM-based Er-doped fiber laser with a repetition rate of 907 MHz. Reproduced with permission [92]. Copyright 2023 authors, published by Wiley-VCH GmbH Publishing.

In addition, in order to apply optical frequency combs in space environments, researchers have conducted relevant studies on NALM fiber combs. In 2015 and 2016, Lezius et al. reported a compact and robust Er: fiber frequency comb system that was less than 20 l in size and weighed about 20 kg. The comb was installed on a sounding rocket and successfully locked in a microgravity environment, with the entire flight time lasting 360 s [93]. In 2021, Benjamin et al. achieved a great reduction in size, mass, and power consumption of the Er: fiber comb system compared to the work of Lezius et al. They developed a compact dual-comb system that could operate in a vacuum environment. The system was even placed on a sounding rocket for verification [94].

4. Applications

The compact structure and cost-effective of the fiber combs based on Er: fiber lasers have made them a popular choice across various fields. This technology has been utilized in a range of applications, such as free-space time–frequency transfer, low-noise microwave generation, and gas molecule detection. These applications leverage the unique properties of Er: fiber combs.

4.1. Free-Space Time–Frequency Transfer

Free-space time–frequency transmission is an important application field of Er: fiber combs. In 2013, Giorgetta et al. locked two Er: fiber combs to the same optical reference source, which were used as a local comb and transmission comb, respectively. In the 2 km free-space path, a time deviation of about 1 fs was achieved and the system deviation was better than 4×10^{-19} [4]. In 2016, Deschênes et al. demonstrated the comparison and time synchronization of two optical time scales at different locations using three Er: fiber combs. The time synchronization accuracy reached the femtosecond level across a turbulent 4 km free-space path [95]. In 2016, Sinclair et al. also achieved time synchronization between different sites using optical two-way time–frequency transfer based on three Er: fiber combs; even in the presence of strong turbulence across a 12 km free space in urban airspace, the time synchronization accuracy could still reach the femtosecond level [96], as shown in Figure 6. In 2019, Bergeron et al. used a reflector on an aircraft to establish a free-space path between two sites and validated the effect of Doppler shifts on optical two-way time–frequency transfer. The maximum speed of the reflector on the aircraft was 24 m/s. The study results indicated that even with Doppler shifts at the level of 10^{-7} , the frequencies between the sites remained consistent, with the accuracy reaching the level of 10^{-18} [97]. In 2021, Shen et al. established an optical two-way time–frequency transfer link in a 16 km free space using two Er: fiber combs. The research results showed that the instability of the transmission link was approximately 4×10^{-18} at 3000 s. Furthermore, through theoretical analysis, they concluded that a geostationary orbit was the optimal choice for establishing long-distance optical two-way time–frequency transfer [98]. In 2022, Shen et al. achieved optical two-way time–frequency transfer in more than a hundred-kilometer free-space link for the first time using two Er: fiber combs. Despite the loss of the transfer link being as high as 89 dB, they achieved a relative instability of 4×10^{-19} at 10^4 s [99]. In 2023, Caldwell et al. demonstrated two-way time–frequency transfer based on optical frequency combs over a 300 km free-space link, and the link loss supported 102 dB. Meanwhile, different sites were synchronized to 320 attosecond [100].

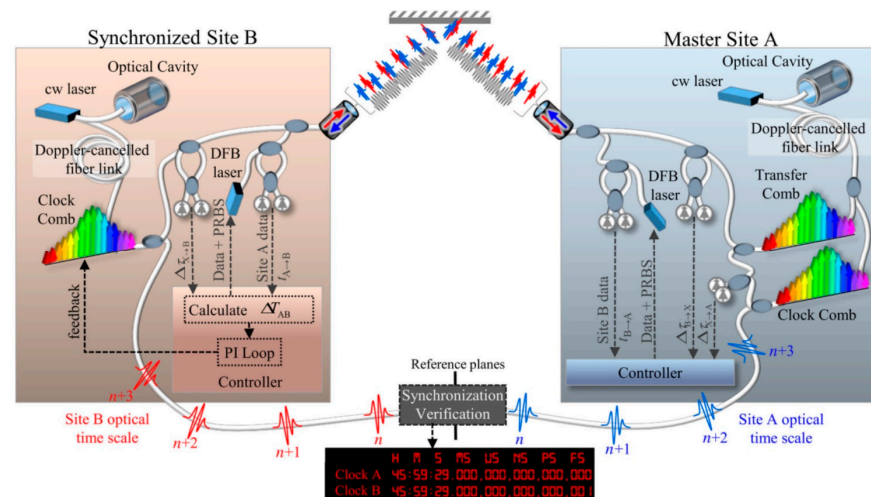


Figure 6. The schematic diagram of time–frequency transfer. Reproduced with permission [96]. Copyright 2016 authors, published by American Physical Society Publishing.

4.2. Low-Noise Microwave Generation

The advanced capability of the Er:fiber comb system was demonstrated by generating low-noise microwave signals. In 2009, Millo et al. reported that the Er-doped fiber comb was stabilized to an optical reference source, which generated a microwave signal of 9.2 GHz. The microwave signal was compared with the cryogenic sapphire oscillator, and the frequency stability was better than 3×10^{-14} at a 1s averaging time [21]. In 2011, Quinlan et al. demonstrated an Er-doped fiber comb system with a repetition rate of 200 MHz, which was locked to an ultra-stable optical reference source. The fiber comb system produced a low-noise 10 GHz signal accompanied by phase noise of less than -100 dBc/Hz at a 1Hz offset [101]. The performance of low-noise microwaves can be also evaluated by a photonic delay line [102,103]. Subsequently, in 2014, Quinlan et al. studied the effect of pulse interleaving on low-noise microwave sources using Er:fiber combs and optimized the photodetector, ultimately achieving an extremely low-phase-noise 10 GHz microwave signal [104]. In 2016, Xie et al. utilized a stable frequency laser as the reference source for an Er:fiber comb and combined it with optical repetition rate multiplication technology to achieve a 12 GHz signal with a frequency stability better than 6.5×10^{-16} at a 1 s averaging time [24]. In 2018, Yan et al. achieved the transfer of frequency stability from an ultra-stable laser to a microwave frequency of approximately 9.2 GHz using an all-polarization-maintaining comb. The frequency stability of the 9.2 GHz signal reached the order of 10^{-15} [105], as shown in Figure 7. In addition, frequency comb-based microwave generation can be extended to THz sources [106,107].

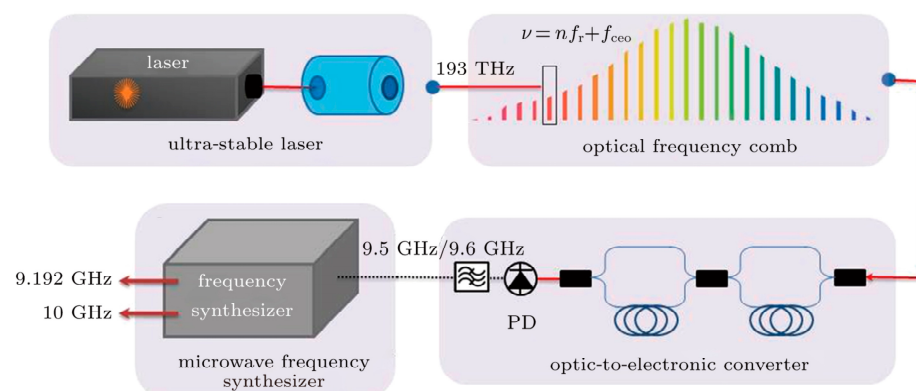


Figure 7. A schematic diagram of low-noise microwave generation. Reproduced with permission [105]. Copyright 2018 authors, published by IOP Publishing.

4.3. Gas Molecule Detection

Dual-comb spectroscopy consists of two optical frequency combs, namely the signal comb and the reference comb, which have slightly different repetition rates. The signal comb is used to probe gas molecules. Then, the two combs interfere with each other to form an interference pattern. By analyzing the interference pattern, the spectral information of the gas molecules can be obtained [108,109].

At present, dual-comb spectroscopy, which consists of Er: fiber combs, has promoted the development of gas molecule detection. In 2015, Okubo et al. conducted dual-comb spectroscopy research using two Er: fiber combs with a repetition rate difference of 7.6 Hz, sub-Hz linewidth, and a spectral range covering 1.0 to 1.9 μm . They measured the five vibration-rotation bands of C_2H_2 , CH_4 , and H_2O [108], as shown in Figure 8. In 2017, Cossel et al. presented a dual-comb spectroscopy detection system with a spectral range of 1.57–1.66 μm . Additionally, a reflector was installed on the flying platform. By employing this dual-comb spectroscopy system, CO_2 , CH_4 , and H_2O could be measured along a 2 km round-trip path [109]. At the same time, Yang et al. developed the detection of acetylene using a dual-comb spectrometer with a flexible and tunable repetition rate and obtained the absorption features of C_2H_2 molecules in the 1.5 μm region [110]. In 2018, Chen et al. utilized a feed-forward acousto-optic frequency-shifting technique to stabilize the f_{ceo} , achieving a coherent time of nearly 2000 s in the dual-comb spectrometer. No phase correction was required for detecting C_2H_2 and CH_4 [111]. In 2021, Herman et al. utilized a dual-comb spectrometer placed in a livestock farm to measure the concentrations of gas molecules, including CH_4 , NH_3 , CO_2 , and H_2O [112].

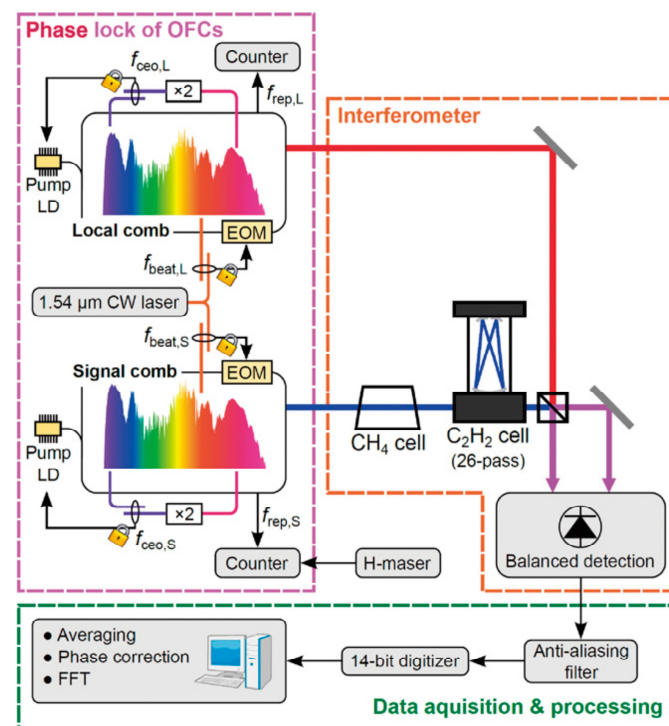


Figure 8. Dual-comb for gas molecule detection. Reproduced with permission [108]. Copyright 2015 authors, published by IOP Publishing.

5. Conclusions and Perspectives

Er: fiber frequency combs have attracted the attention of researchers due to their low noise, compact structure, and low cost. Currently, NPR-based Er: fiber mode-locked lasers, real SA-based Er: fiber mode-locked lasers, and NALM-based Er: fiber mode-locked lasers have been implemented as core light sources for optical frequency combs.

These three types of Er: fiber lasers have their own advantages and disadvantages, as shown in Table 1. The NPR fiber laser has the advantages of simple structure, low noise, and easy implementation, but the NPR fiber laser is usually non-polarization-maintaining due to the limitations of the mode-locking principle. Hence, the state of NPR-based fiber lasers is easily affected by external environmental factors, including temperature, vibration, humidity, and so on. SESAM-based fiber lasers have the advantages of low mode-locking thresholds, all-polarization-maintaining structures, and repetition rates of up to several GHz, as well as good environmental adaptability, but the absorption material carries the risk of optical-induced damage. The advantage of NALM-based fiber lasers is that they can achieve an all-polarization-maintaining structure, have no risk of photo-induced damage, and can be operated long term. Therefore, NALM-based mode-locked fiber lasers are a better choice for creating Er-doped fiber combs. Currently, NALM-based Er: fiber optical frequency combs have been used in various applications such as free-space two-way time-frequency transfer, low-noise microwave source generation, gas molecule detection, and so on.

Table 1. The advantages and disadvantages of three mode-locked fiber lasers.

Type	Advantages	Disadvantages
NPR laser	simple structure, low noise, and easy implementation	non-polarization-maintaining structure
Real SA laser	low mode-locking threshold, all-polarization-maintaining structure, repetition rate of up to several GHz, and good environmental adaptability	the risk of optical-induced damage
NALM laser	all-polarization-maintaining structure, have no risk of photo-induced damage, and can have long-term operation	low frequency rate

However, further research work is needed to apply NALM-based Er: fiber combs to space-to-earth time-frequency transfer, astronomical exploration, and laser ranging. Firstly, while NALM-based Er: fiber combs have been tested on sounding rockets, the flight duration of rockets is relatively short. Meanwhile, the harsh satellite environment presents more challenges for fiber comb systems. Therefore, developing NALM-based Er: fiber optical frequency combs that can achieve long-term operation stably in a space environment is urgent. Secondly, the NALM-based fiber laser has difficulty achieving a repetition rate of GHz or even tens of GHz due to the limitation of the mode-locking principle. This limitation restricts the application of NALM-based erbium-doped fiber combs in astronomical exploration. Although researchers attempted to implement NALM-based lasers with a repetition rate of approximately GHz using a nested optical cavity, the generated offset frequency f_{ceo} only had an SNR of 30 dB in the RBW of 10 kHz. Furthermore, the long-term stability of the laser still needed further testing [91]. Therefore, creating NALM-based Er-doped fiber combs with a repetition rate of GHz remains a challenge. Thirdly, frequency comb-based laser ranging has been researched using different methods, which include the measurement of cross-correlation, balanced optical cross-correlation, dispersive interferometry, and time-of-flight [113–116]. However, the non-dead-zone measurable with a laser range ambiguity is still a challenge. In addition, NALM-based Er-doped fiber combs combined with the stimulated Brillouin scattering effect can achieve an ultra-narrow linewidth single-frequency laser [117–122], with potential applications in long-range laser coherent ranging. Finally, expanding the spectrum of erbium-doped fiber optical combs to the ultraviolet region, visible region, terahertz region, and mid-infrared region is the key to promoting the application of optical frequency combs [123–125]. For

example, in 2021, Lesko et al. demonstrated a comb system achieving a six-octave spectrum from 350 nm to 22,500 nm [123].

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