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Wavelength-Tunable Ultra-Stable Optical Frequency Comb Based on All-Polarization-Maintaining Fiber Laser

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This study details the implementation of a wavelength-tunable ultra-stable optical frequency comb (OFC), which is generated by a passively mode-locked all-polarization-maintaining Erbium (Er)-doped fiber laser based on a non-linear amplifying loop mirror. The center wavelength can be tuned from 950 to 1,080 nm and from 1,650 to 2,080 nm by adjusting the pump's power. Standard deviations of 100 μHz ($\tau = 1$ s) for repetition rate and 330 μHz ($\tau = 1$ s) for carrier-envelop offset frequency were measured in 15 h. The corresponding Allan deviations were 2.4×10^{-17} and 8.2×10^{-17} at 1 s. The repetition rate and carrier-envelop offset frequency of OFC were counted by a $\prod$-type counter from K+K Messtechnik.

Keywords: optical frequency comb, mode-locked Er-doped fiber laser, all-polarization-maintaining fiber, tunable comb, ulta-stable comb

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INTRODUCTION

Optical frequency combs (OFCs) have garnered interest due to their versatility in applications, such as ultra-low noise microwave generation [1–3], high resolution spectroscopy [4, 5], astronomical spectrograph [6, 7], time and frequency transfer and optical clocks [8–10]. For the aforementioned applications, the frequency instability of OFCs is the most important parameters. Beyond that, many other characteristics of OFCs, such as robustness, turn-key operation ability, high power output, high repetition rate and wide wavelength range, must be considerate.

OFCs are dependent on the repetition rate and carrier-envelop offset frequency of femtosecond pulses in microwave clocks. The optical frequency of a comb tooth given by $\nu_n = f_{ceo} + nf_{rep}$, where f_{ceo} is the carrier-envelope offset frequency, f_{rep} is the repetition rate, and n is an integer. Typically, f_{ceo} and f_{rep} refer to radiofrequency (RF). To achieve superior short-term stability systems, OFCs require narrow linewidth lasers phase-locked to a high fineness optical cavity as reference. OFCs may obtain short-term stability from sub-hertz linewidth lasers. Consequently, narrow-linewidth lasers are crucial to superior short-term stability OFCs. There have been significant performance improvements in narrow linewidth lasers in recent years. Cole et al. presented a new optical coating technology based on direct-bonded monocrystalline multilayers to improve mechanical loss and optical quality [11]. Kessler et al. constructed a silicon single-crystal optical cavity, and obtained a sub-40 mHz linewidth laser at 1.5 μm [12]. Matei et al. reported a narrow linewidth laser, stabilized with silicon Fabry-Perot cavity, operated at linewidth as small as 5 mHz at 194 THz [13].

Zhang et al. reported a laser locked to a silicon cavity operating at 4 K with a median linewidth of 17 mHz [14].

The measurements of optical atomic clock transitions often require the comparison of different species of atomic clocks [15, 16]. To operate several kinds of clocks with the same OFC, multi-wavelength systems are required. OFCs based on Erbium (Er)-doped fiber lasers have been proven capable of long-term operation. However, the wavelength-tunable ultra-stable fiber-based combs operating beyond dozens of nanometers have not been proven.

OFCs based on Er-doped fiber lasers are better choice because they are turnkey, robust, and support compact design. Er fiber-based OFCs based on non-linear amplifying loop mirror (NALM) [17–19], semiconductor saturable absorber mirror (SESAM) [20–23], and non-linear polarization rotation (NPR) [24–26] have been proven to be efficient alternatives. However, NPR with a single-mode (SM) fiber design is undesirable because its mode-locking state is easily disrupted by environmental perturbations. All of polarization-maintaining (PM) design is a solution to this problem. Sinclair el al. employed SESAM and NALM-based designs, using PM fibers, to demonstrate a self-referenced OFC based on mode locked Er-doped fiber laser that can operate outside the metrology lab [23]. Feng built a SESAM-based PM fiber OFC, which provided better environmental stability [22]. Kuse et al. reported a fully stabilized all-PM Er fiber-based OFC with a NALM optimized with an additional phase bias [18]. Compared with OFCs based on SESAM mode-locked fiber lasers, OFCs based on NALM have lower intrinsic phase noise and timing jitter. Therefore, tunable low-noise OFC with NALM represents a promising means to realizing both superior short-term stability and PM fiber configuration.

This study demonstrates a wavelength-tunable ultra-stable OFC based on PM Er-doped fiber laser, which is phase-locked to a 1,550-nm sub-hertz linewidth fiber laser. The widely tunable range is due to instantaneous Kerr non-linearity effect of highly non-linear fiber pumped with an Er-doped comb. The center wavelength could be tuned from 950 to 1,080 nm and from 1,650 to 2,080 nm by adjusting the input power of the pump comb. The 1550-nm narrow linewidth fiber laser, with a most probable linewidth of 185 mHz and a frequency instability of 7×10^{-17} at 1–10 s averaging time, was realized by frequency-stabilization with high fineness Fabry-Perot cavity using a standard Pound–Drever–Hall technique [27]. The femtosecond fiber laser oscillator was a 200 MHz Er-doped mode-locked PM fiber laser, based on the NALM mechanism. A stage fiber amplifier, pulse compressor and octave-spanning spectrum in highly non-linear fiber (HNLF) were used in obtaining the f_{ceo} signal. Fully phase stabilization of the comb was obtained by locking f_{rep} and f_{ceo} via standard phase locked loop technique. A long-term stability of 100 μHz ($\tau = 1$ s) for f_{rep}, and 330 μHz ($\tau = 1$ s) for f_{ceo} were measured in 15 h, and the corresponding Allan deviations were 2.4×10^{-17} and 8.2×10^{-17} at 1 s gate-time.

EXPERIMENTAL RESULTS AND DISCUSSION

The complete fiber system shown in **Figure 1** consists of an all-PM Er fiber oscillator (IMRA GmbH) with phase biased NALM

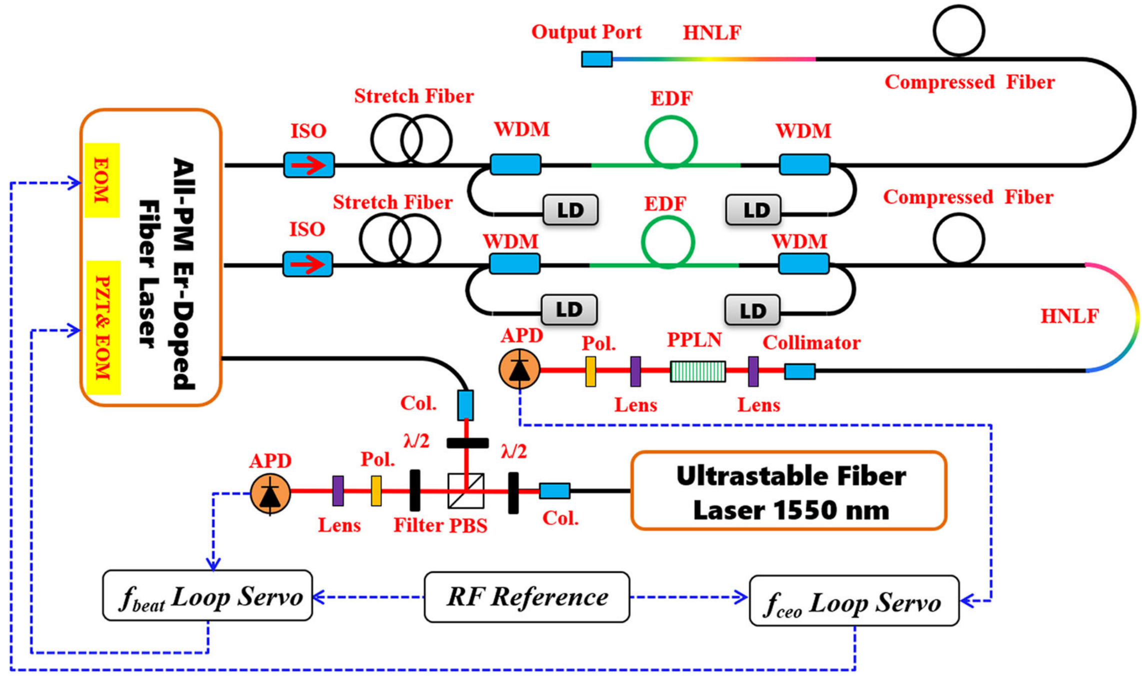

FIGURE 1 | Experimental set-up of wavelength-tunable ultra-stable OFC.

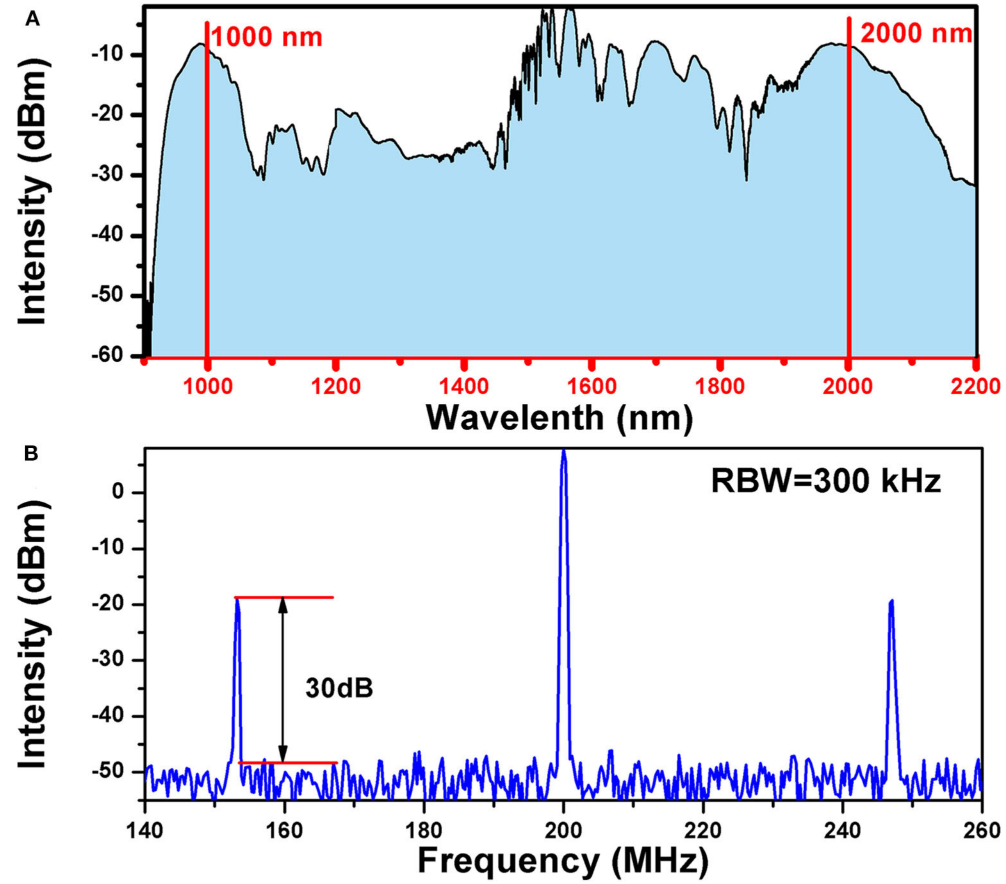

FIGURE 2 | (A) Octave-spanning super-continuum spectrum after the HNLF. **(B)** f_{ceo} heterodyne signal at a 300 kHz resolution bandwidth (RBW).

as an artificial saturable absorber. This oscillator is set to provide pulses of ∼1 ps at a 200 MHz repetition rate, and an average power of 1.5 mW. The output spectra, with a full-width-half-maximum (FWHM), is about 50 nm from the laser cavity.

Referring to **Figure 1**, the black lines represent PM fiber, red lines represent free space ray, and the blue lines represent electrical signal path. OFCs consist of are an electro-optic modulator (EOM), a piezo actuator (PZT), an optical isolator (ISO), a wavelength-division multiplexer (WDM), a laser diode (LD), an erbium doped fiber (EDF), a highly non-linear fiber (HNLF), a periodically-poled lithium niobate crystal (PPLN), a polarizer (Pol.), two photo detectors (APD), and a 1,550-nm sub-hertz linewidth continuous wave laser.

To achieve an octave-spanning spectrum, part of the Er-doped fiber oscillator (∼1.5 mW) was launched into a short pulse Er-doped fiber amplifier (EDFA). The EDFA consisted of 1.5 m of normal dispersion PM Er-doped fiber. EDFA was bidirectionally pumped by 976-nm laser diodes at maximum output power of 750 mW. After amplification, the pulses were compressed using PM1550 fiber, which is anomalously dispersion at the laser wavelength. The compressed pulses, measured by an intensity auto-correlator (Femtochrome, FR-103XL), showed a pulse width of 60 fs (an average output power of ∼285 mW). The 285-mW pulses were then coupled into 30 cm length of HNLF. After non-linear spectral broadening in the HNLF, the optical spectrum spanned more than one octave, from 980 to 2,000 nm, as seen in **Figure 2A**. The standard collinear self-referencing approach was used for detecting the f_{ceo} by doubling the ∼2,000 nm portion of the light and heterodyning it against the ∼1,000 nm end of the comb to generate an RF beat signal. The periodically poled lithium niobate (PPLN) crystal was utilized for doubling light from 2,000 to 1,000 nm. The octave-spanning light and the fundamental light were both filtered at 1,000 nm by an optical band-pass filter with 10 nm bandwidth. An amplified photodetector was then used to obtain f_{ceo} signal. The signal to noise ratio (SNR) of f_{ceo} at a resolution bandwidth (RBW) of 300 kHz was more than 30 dB, as shown in **Figure 2B**. The f_{ceo} signal was then sent to a homemade phase-locked loop to stabilize at an RF reference. This was achieved by controlling a fast electro-optic modulator (EOM) in the laser cavity [28]. To transfer the short-term stability of narrow-linewidth laser to OFC, the OFC was phase-locked to a cavity-stabilized sub-hertz linewidth fiber laser. The 1,550-nm narrow linewidth fiber laser (with a most probable linewidth of 185 mHz and frequency instability of 7.0×10^{-17} at 1–10 s averaging time) was realized by frequency-stabilization to high-finesse Fabry-Perot cavity

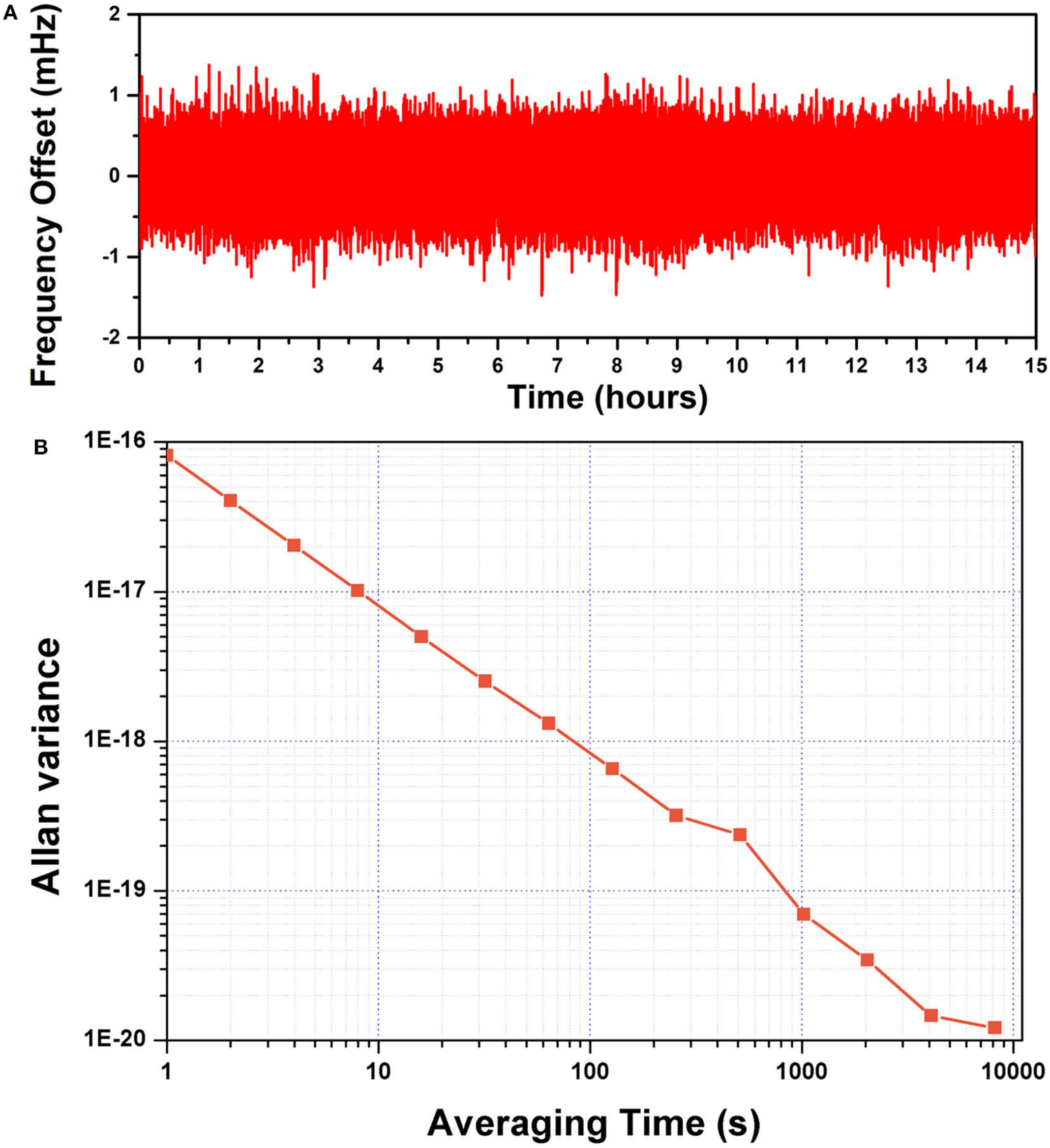

FIGURE 3 | (A) Frequency deviation of f_{ceo} for 15 h and **(B)** Allan deviation of f_{ceo}.

using the Pound-Drever-Hall technique. More information on 1,550-nm sub-hertz linewidth fiber laser can be found in [27].

To make the phase-locked loop robust, a 40 × frequency divider was employed. The long-term stability of f_{ceo} frequency was also demonstrated. **Figure 3A** shows the frequency fluctuation of f_{ceo} recorded over more than 15 h by the frequency counter at 1 s gate-time (FXQE80, K+K Messtechnik). The standard deviation of f_{ceo} was estimated to be about 330 μHz and the frequency fluctuation about 2 mHz. In-loop relative frequency instability of f_{ceo} (normalized with the optical frequency of ∼195 THz) was about 8.2×10^{-17} at 1 s, as shown in **Figure 3B**. The value is below those of the best optical clocks.

The repetition rate of OFC can be stabilized to an RF or optical standard. In order to transfer the stability of the optical reference to the comb and reduce the noise on the comb lines, the fiber oscillator was stabilized relative to a 1,550 nm, sub-hertz linewidth continuous wave laser. Two servo actuators were used to increase the bandwidth of the beat lock; one controlling a slow PZT, and the other a fast EOM inside the fiber oscillator. The PZT had a low bandwidth for removing low-frequency noise and the EOM had a high bandwidth for removing high-frequency noise. **Figure 4A** shows the frequency fluctuation of the beat signal, which was counted with a commercial counter in 1 s gate-time. The beat frequency offset from a 25-MHz reference was recorded over 15 h with an RF frequency counter. The standard deviation of the beat signal was calculated to be 100 μHz. As seen

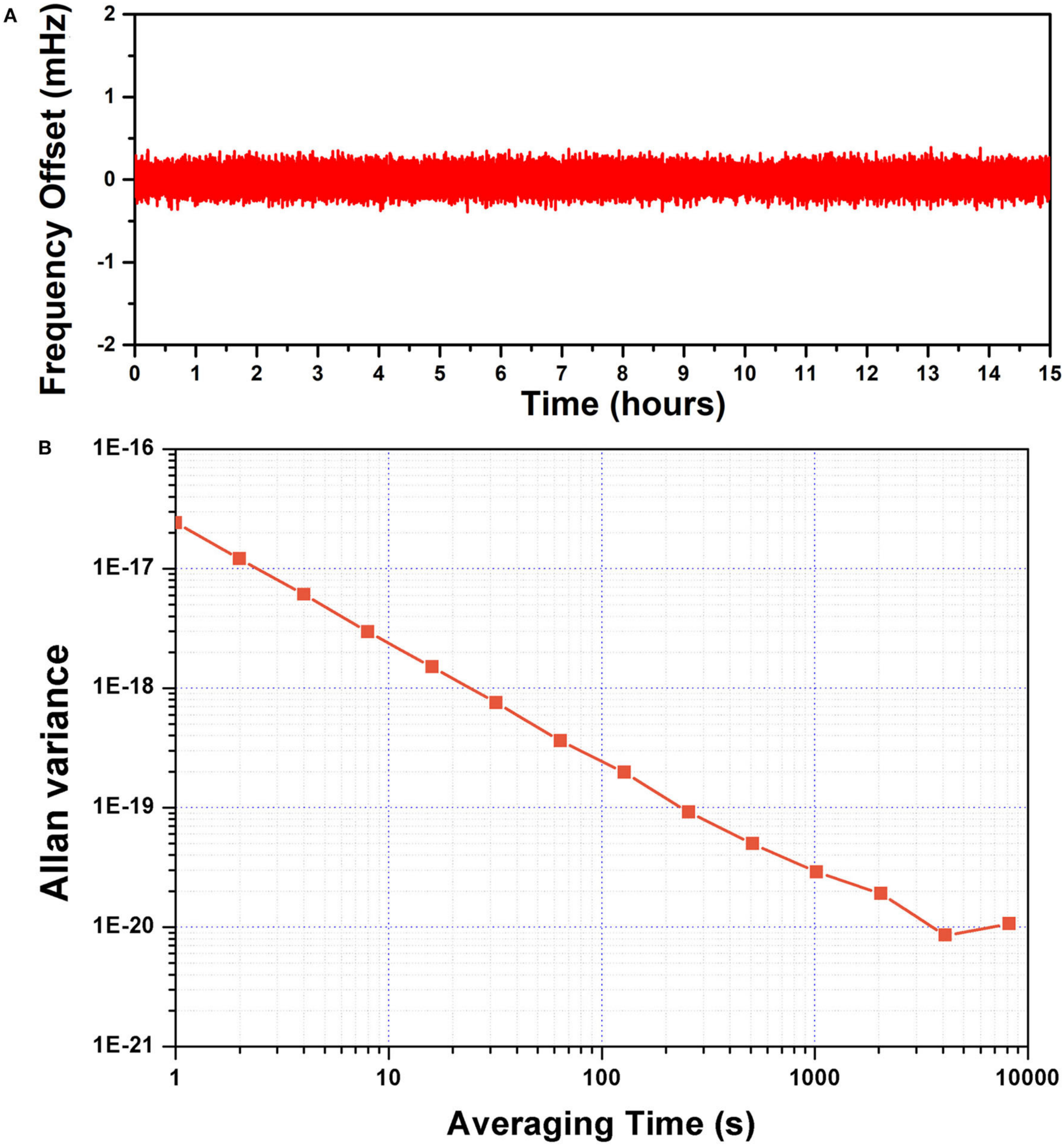

FIGURE 4 | (A) Frequency deviation of f_{beat} for hours; **(B)** the Allan deviation of f_{beat} for 15 h.

in **Figure 4B**, the corresponding Allan deviation of the in-loop optical beat note was 2.4×10^{-17} at 1 s, and scales down with a slope of $1/\tau$, reaching around 1×10^{-20} at 1 h.

To generate the maximum output power at desired wavelength, a short section of HNLF with a larger non-linear coefficient (24 $W^{-1}\cdot km^{-1}$), and shorter zero dispersion wavelength (1,350 nm) were employed. The compact Er fiber amplifier provided a maximum average optical power of 350 mW, with pulse width as short as 60 fs, and a repetition rate of 200 MHz. The output power of the amplifier was varied from 145 to 350 mW in order to change the wavelength. After femtosecond pulse propagating a 10-cm HNLF, the spectrum with blue shifter part and red shifted part were shown in **Figure 5**. This was primarily due to the instantaneous Kerr non-linearity with an intense femtosecond pump. The HNLF output contains a blue-shifted dispersive wave from 950 to 1,080 nm and a red-shifted soliton ranging from 1,650 to 2,080 nm for different average powers in the pump beam.

CONCLUSIONS

In conclusion, a wavelength tunable ultra-stable OFC based on all-polarization-maintaining Er-doped fiber laser for laser

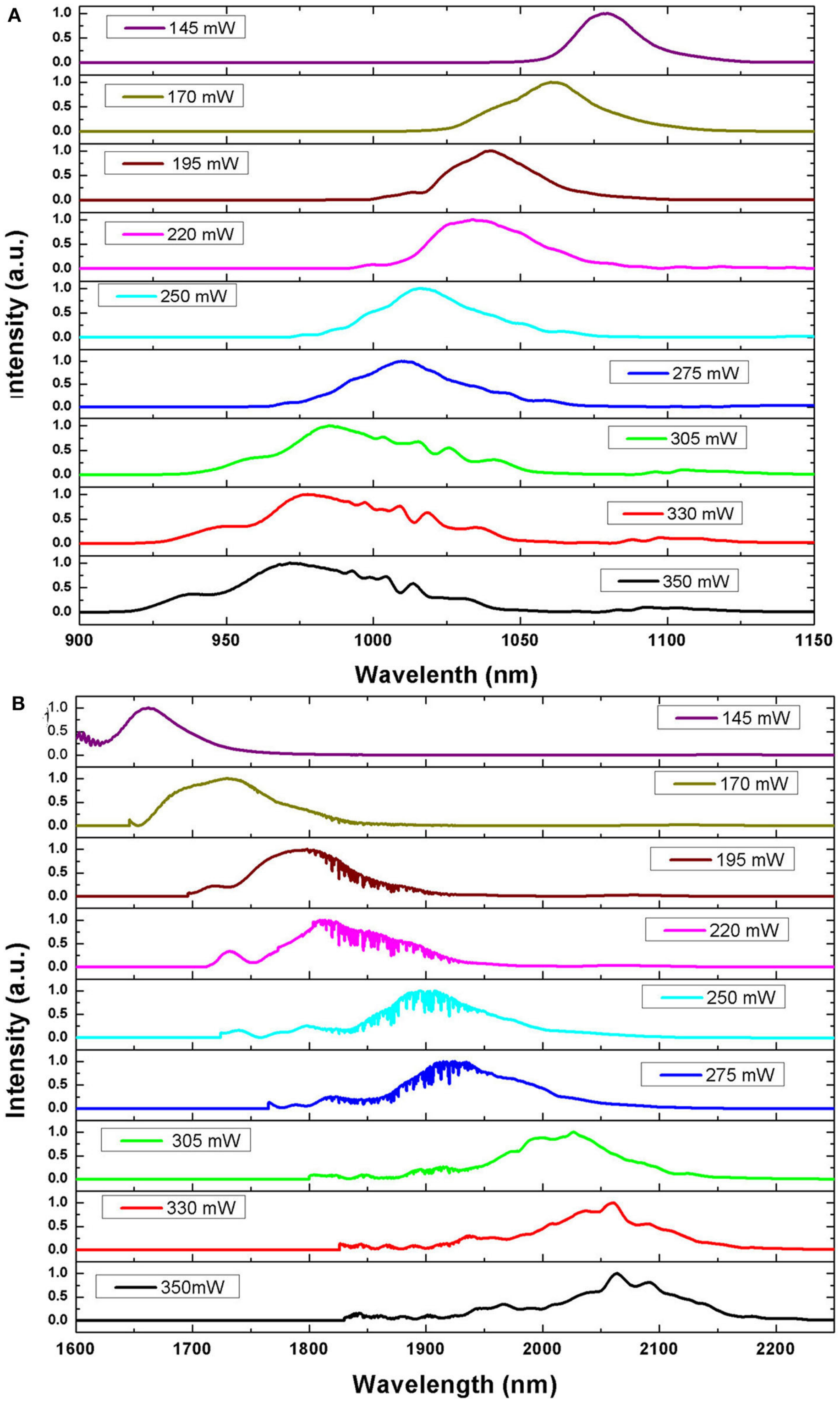

FIGURE 5 | Typical tunable OFC spectrum at different pump power. **(A)** Short wavelength part; **(B)** Long wavelength part.

frequency stabilization and measurement, was developed. The fiber-based frequency comb with a wavelength-tunable configuration can transfer both linewidth and short-term stability. The widely tunable range is attributed to the instantaneous Kerr non-linearity effect of highly non-linear fiber pumped with an Er-doped comb. The center wavelength could be tuned from 950 to 1,080 nm and from 1,650 to 2,080 nm by adjusting the pump's input power. A full phase stabilization of the comb was obtained by locking f_{rep} and f_{ceo} via standard phase-locked loop technique. A long-term stability of 100 μHz ($\tau = 1\ s$) for f_{rep}, and 330 μHz ($\tau = 1\ s$) for f_{ceo} were measured in 15 h, and the corresponding Allan deviations were 2.4×10^{-17} and 8.2×10^{-17} at 1 s. Tunable ultra-stable combs are applicable in optical atomic clocks, comparison of different atomic clock species, measuring the frequency of quantum transitions, low-phase noise frequency synthesis, among others.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

LH and KW conceived the study. XH and PZ are responsible for experiment setting and paper writing. YZ, QL, and HG are mainly engaged in picture editing and related data processing. All authors have made positive contributions to the work.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.