Dead-band-free, high-resolution microwave frequency measurement using a free-running triple-comb fiber laser

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Abstract—Microwave photonic solutions of frequency measurement have advantages in broad frequency coverage, but achieving high-resolution measurement remains a challenge. Those schemes based on optical frequency combs could achieve high-resolution measurement over a broad frequency range. Here a dead-band-free, high-resolution microwave frequency measurement scheme based on undersampling the microwave signal by three pulse sequences generated from a triple-wavelength mode-locked fiber laser is proposed and demonstrated. The triple-wavelength ultrashort pulses generated in one laser cavity have slightly different repetition rates due to chromatic dispersion. This eliminates the needs of multiple mode-locked lasers and frequency control between them and drastically reduces the system complexity. The absolute frequency of the microwave signal can be determined based on three down-converted low-frequency beat notes of the microwave signal with the nearest comb lines without ambiguity. A 10^{-10} relative measurement precision at a sampling speed of 100 Hz is demonstrated from 1 GHz to 20 GHz, and the measurement accuracy remains within 0.3 Hz. Microwave signal with a RF power as low as -75dBm can be measured with a 10Hz precision at 10 GHz by using RF frontend amplifiers. The simple and compact triple-comb fiber laser would enable the development of low-complexity, high-performance microwave characterization instrument.

Index Terms—Mode locked lasers, optical fiber lasers, frequency measurement, optical pulses

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I. INTRODUCTION

Precise determination of the frequency of microwave (MW) signals is of great importance, since such signals covering an increasing broad electromagnetic wave spectrum, from megahertz to even terahertz, have been prevalently used in our information technology infrastructures, such as communications, remote sensing, radar, navigation and many other areas. Electronic solutions for real-time MW signal measurement may be limited by the bandwidth of the acquisition frontend's and are facing challenges in dealing with unknown signals that may reside over an increasingly broad frequency range . Microwave photonic techniques have been investigated as a promising solution for high-frequency microwave signal characterization and processing, due to their potential in broadband operation and immunity to electromagnetic interferences [1-3]. Numerous photonics schemes for MW frequency measurement had been proposed. Frequency-to-power conversion can be realized when the sideband of an optical CW carrier generated by MW modulation is filtered by narrow optical filters [4-6]. Optical mixing method could also map the MW signal frequency to optical power by mixing an optical signal modulated by MW signal and its replica with a given time delay. The mixing process could be realized by two cascaded modulators [7] or nonlinear optical process [8]. Similarly, the power fading of the modulated double-sideband optical signal propagating through a dispersive medium can provide information about the modulation frequency [9-11]. These methods can cover MW frequencies up to several tens of gigahertz, but their measurement resolution is no better than MHz level.

Instead of the schemes based on using CW lasers, optical frequency combs could also be used in MW signal characteristics measurement. When a highly stable periodic pulse train generated by a mode-locked laser, often with a relatively low repetition rate, is modulated by a high-frequency MW signal, the MW signal is undersampled by the short pulse sequence. When detected and filtered by a low-pass filter, a down-converted copy of the MW wave with the same amplitude and phase characteristics is generated [12]. From another point of view, the down-converted signal corresponds to the beat note between the MW signal and the closest neighboring frequency comb line. If two pulse trains with slightly different repetition rates are used to sample the same MW signal, the aliasing caused by the undersampling could be

resolved under certain assumptions, and the absolute frequency of the MW signal can be recovered. Such a scheme had been successfully demonstrated for real-time frequency measurement of continuous-wave THz radiation using dual THz combs, and very high measurement accuracy and precision had been achieved [13]. Similarly, two sets of combs with slightly different comb tooth spacings generated by electro-optic modulation of light from a CW laser have been proposed to down-convert MW signals for characterizations [14-16].

Recently, single-cavity, dual-comb mode-locked fiber lasers have been proposed and demonstrated, which can generate two asynchronous pulse sequences simultaneously by leveraging multiplexing in the dimensions of center wavelength, polarization state, or mode-locking mechanism [17-21]. Among these schemes, dual-wavelength mode-locked laser could generate dual pulsed trains with different center wavelengths by gain tilt tuning [17] or birefringence-induced Lyot filtering effects [19, 21]. Due to the cavity dispersion, the repetition rates of the dual-wavelength pulse trains are slightly different. These kinds of lasers have emerged as an attractive, low-complexity dual-comb laser source, due to the inherent mutual coherence between the dual pulse trains. Besides their application in asynchronous optical sampling and spectroscopy [19], THz frequency measurement with a free-running, dual-wavelength laser had been demonstrated [22].

However, in the current dual-comb frequency measurement schemes, 'dead bands' exist due to ambiguity in determining the relative position between the beat signal and comb teeth [22]. Our preliminary results had shown that using triple-comb instead of dual-comb could eliminate such dead-bands [23]. However, if using two mode-locked lasers are cumbersome, implementation of such a system with three similar but slightly different ultrafast lasers would be prohibitively complicated and impractical for microwave applications. A simple multi-comb laser source would be the key to enable dead-band-free high-resolution MW frequency measurement.

Here, we propose and demonstrate a MW frequency measurement scheme based on a single-cavity, triple-comb mode-locked fiber laser, which overcomes the 'dead band' limitation and achieve gap-less frequency measurement. High-resolution measurement over a frequency range of tens of GHz is realized with a precision of 10^{-10} and sub-Hz accuracy.

II. EXPERIMENTAL SETUP AND PRINCIPLE OF OPERATION

In our experiment demonstration, a triple-wavelength mode-locked fiber laser is used to generate three pulse trains with different repetition rates. The free running, triple-wavelength mode-locked laser in Fig. 1(a) is constructed based on a ring cavity configuration. The relatively simple design consists of a 980-nm pumped laser diode (LD), a 980/1550 nm wavelength-division multiplexer (WDM), 0.45-meter of erbium-doped fiber (Er110), an optical isolator (ISO), a single-wall carbon nanotube (SWNT) saturable absorber, an in-line polarizer (ILP) with two 1-meter-long polarization maintaining fiber (PMF) pigtails at both ends, a fiber output coupler and a fiber-squeezer-based polarization controller (PC). The SWNT saturable absorber is fabricated on an FC/APC ferrule by using the optical deposition method. The

total length of fiber in the cavity is estimated to 6.5m, and the total dispersion is estimated to be ~103fs/nm. Because of the relatively large anomalous dispersion, the laser is expected to operate in the soliton regime. By introducing the ILP with PMF pigtails into the ring fiber laser, birefringence-induced Lyot filtering effects can provide periodic spectral filtering within the gain profile of EDF and could enable simultaneously mode locking at more than one wavelengths, when the intra cavity polarization state is properly adjusted [19, 22]. Based on the width of the EDF gain window around 1550nm and the length of PMF, i.e. the amount of birefringence introduced, it is expected that around three filtered gain windows could be present with relatively equalized peak gains. Therefore, simultaneous triple-wavelength mode-locked ultrashort pulse generation could be realized in such a compact and cost-effective platform. Due to the difference in their center wavelengths and the intra cavity dispersion of the fiber laser, the repetition rates of the triple-wavelength pulses ($f_{rep,i}$, i=1,2,3) would be slightly different, and therefore triple-comb sampling signals could be generated from a single mode-locked fiber laser. As all pulses propagate through the same cavity and share almost the same disturbance and noises, such as temperature fluctuation and pump power RIN noise, it had been demonstrated that good mutual coherence and stable repetition rate difference between the multi-wavelength pulses can be maintained without active feedback control of the laser [19].

Yet, as the laser is operated in a free-running mode, these repetition rates themselves would still drift over time. It is necessary to monitor those repetition rates in real time for high-resolution measurement of the MW frequencies. A scheme similar to our triple-comb MW frequency measurement method is applied. As seen in Fig. 1(b), the output of the laser is split by an optical coupler, and 20% of it is used to for repetition rate monitoring. The pulses are modulated by the reference signal of a known frequency (f_{ref} = 5.985GHz) from a 6 GHz-bandwidth, RF signal generator (Agilent N5162A) through a 10 GHz-bandwidth electro-optic modulator. The modulated triple-comb pulses are detected by a 8.5 MHz-bandwidth photodetector (Thorlabs PDA10CS). As described later, the beat notes between the reference frequency and the triple-comb signals, denoted as f_{beat1_ref}, f_{beat2_ref}, and f_{beat3_ref}, are obtained. f_{ref} is considered to be very accurate and stable, and its ratios to these repetition rates are also known and unchanged as the drifts in the repetition rates are relatively small. Since these repetition rates are already roughly known based on the prior knowledge of the laser source, one can determine the repetition rates with high accuracy in real-time by just monitoring the frequency changes in the down-converted beat notes. These measured repetition rates will be used later in determining the MW frequency.

On the other hand, 80% of the laser output is sent to beat with the MW signal to be measured. Triple-wavelength pulses are simultaneously modulated by the target signal generated by a RF signal generator (CETC AV1487B) with a frequency range of 0.01 GHz to 20 GHz through a 40–GHz-bandwidth electro-optic intensity modulator. Unlikely the repetition rate monitoring setup, the modulated optical pulses from the

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modulator are separated by a dense wavelength division multiplexer (DWDM) and detected by three 150 MHz-bandwidth photodetectors (Thorlabs PDA10CF) respectively. The electrical signals from the photodetectors are further filtered by low-pass filters (Mini-circuits SLP-21.4) before being acquired by analog-digital converters (ADC, NI 5122) at a sampling rate of 50 MHz, higher than twice the maximum of beat frequencies. By using the instantaneous-frequency-calculation algorithm [22], the frequencies of the beat notes f_{beat1}, f_{beat2}, and f_{beat3} can be determined. The repetition rates of the three combs could be determined based on the principle and algorithms given below. In our demonstration, the two RF signal generators and ADC are synchronized by the same 10 MHz clock. This avoids the influence of the absolute precision of the clocks in these instruments on the frequency readings from them, to which our measurement results will be compared in order to determine the performance of our scheme. In future applications, only the reference signal and the ADC are required to be synchronized to a high-quality clock.
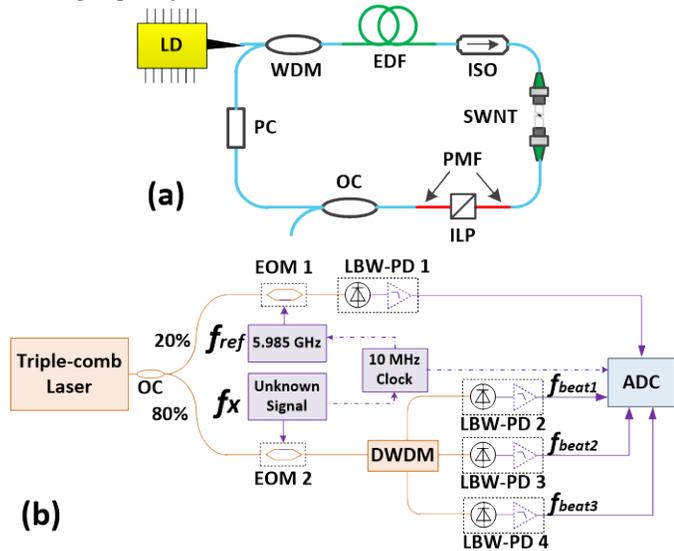
Fig. 1. (a) Configuration of the free-running triple-comb mode-locked laser; (b) Schematic of the experimental setup. OC: optical coupler; EOM: electro-optic intensity modulator; LBW-PD: low-bandwidth photodetector.

The principle of our MW frequency measurement scheme in this article is similar to that of dual-terahertz-comb real-time frequency measurement, but further leverages the down-conversion of high-frequency MW signal through EO modulation as well as the triple-comb sampling pulses. Unlike in the conventional microwave photonic schemes where CW light is modulated by a MW signal, when a sequence of periodic short optical pulses with a repetition rate are used, the MW frequency can be down shifted to a much lower frequency given by its beating with the nearest adjacent frequency component, i.e. comb line, of the pulse sequence [12]. The relationship between the frequency of the MW signal f_x and that of the beat signal f_{beat} is given by

$$f_x = mf_{rep} \pm f_{beat} \qquad (1)$$

where f_{rep} is the repetition rate of the pulse train and m is the mode number of the comb line that beats with the MW signal.

While f_{beat} can be easily measured with high accuracy, m remains to be determined, as well as the choice of the sign in (1), depending on the relatively position between mf_{rep} and f_x.

As shown in Fig. 2, dual-comb-based scheme provides an effective solution to this problem to identify m. With two pulse sequences with slightly different repetition rates, by assuming the lowest beat notes f_{beat1} and f_{beat2} are generated by beating with the comb lines of the same m-th order, the comb mode order m can be determined based on:

$$m = \frac{\left| f_{beat2} \pm f_{beat1} \right|}{f_{rep2} - f_{rep1}} \qquad (2)$$

where f_{rep1} and f_{rep2} are the repetition rate of the dual combs respectively and it is assumed that $f_{rep2} > f_{rep1}$. The sign of f_{beat} and f_{beat1} also is determined by the relative position of f_x, f_{rep1}, and f_{rep2} [22].

However, there are 'dead bands' in dual-comb-based frequency measurement, due to the limitation of the above assumption [22]. When the frequency to be measured falls close to the midpoint of a pair of comb teeth and may beat with comb lines of different mode numbers, (2) becomes no longer applicable to determine m. Therefore, the absolute frequency of the signal can't be determined in these dead bands. Using a third comb to beat with the signal can overcome the mode number ambiguity as illustrated in Fig. 2. It is assumed the repetition rate of the third comb is larger than the previous dual combs, which is $f_{rep3} > f_{rep2} > f_{rep1}$. If only Comb1 and Comb2 are used, the frequency range of A and B (marked grey in the figure) are dead bands because WM signal beats with the m-th order mode of Comb1 but m-1-th order mode of Comb2. On the other hand, if only Comb2 and Comb3 are used, the range C and D are dead bands. However, as these frequency ranges are disjoint, dead-band-free frequency measurement could be realized by selecting a right pair of dual combs among the triple combs. For example, when in the range of A and B, Comb2 and Comb3 can be used to give the correct results
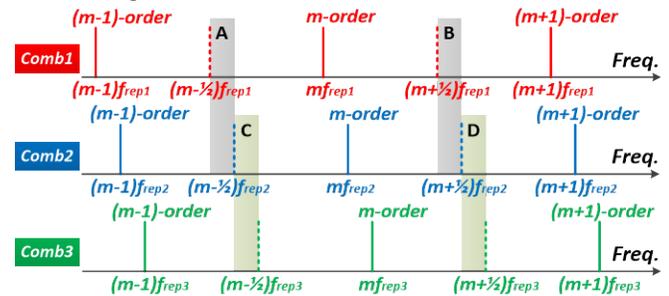
Fig. 2. Illustration of the dead-band issue with dual-comb and triple-comb frequency measurement schemes.

In the dead-band-free frequency measurement based on the triple-comb, different formulas for calculating m are applied to different relative position between f_x, mf_{rep1}, mf_{rep2} and mf_{rep3}. If the WM signal beats with the m-th order of Comb2, which means $(m-1/2)f_{rep2} \leq f_x < (m+1/2)f_{rep2}$, the frequency region can be divided to six disjoint sets of frequency bands, as shown in Fig. 3(a). These bands, namely, band I : $(m-1/2)f_{rep2} \leq f_x < (m-1/2)f_{rep3}$, band II : $(m-1/2)f_{rep3} \leq f_x < mf_{rep1}$;
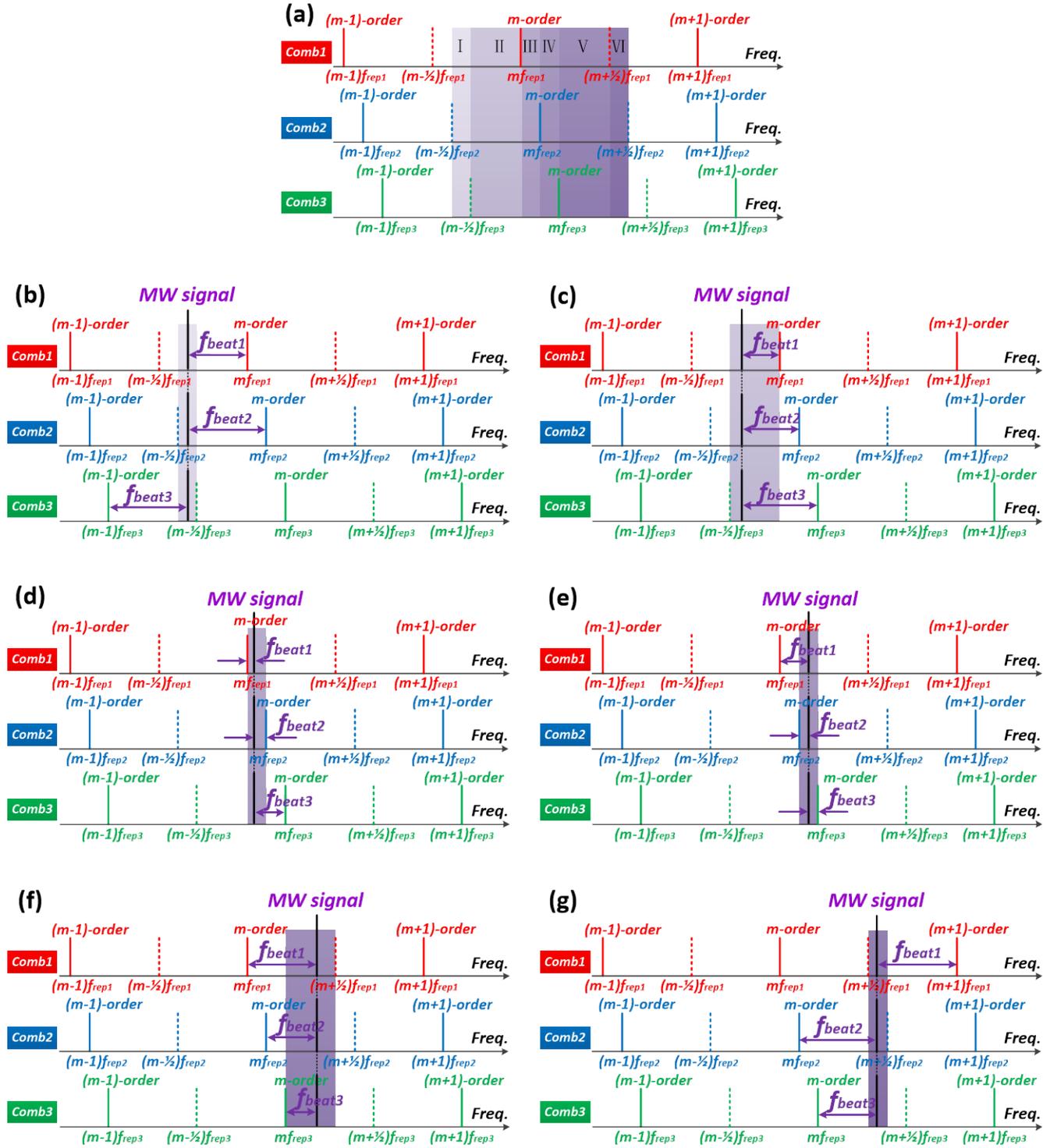
Fig. 3. Schematic of the six bands and their corresponding senarios in triple-comb sampling. (a) six bands; (b) band I; (c) band II; (d) band III; (e) band IV; (f) band V; and (g) band VI.

band III: $mf_{rep1} \leq f_x < mf_{rep2}$; band IV: $mf_{rep2} \leq f_x < mf_{rep3}$; band V: $mf_{rep3} \leq f_x < (m+1/2)f_{rep1}$; and band VI: $(m+1/2)f_{rep1} \leq f_x < (m+1/2)f_{rep2}$, correspond to different combinations of the lowest beating frequencies between the MW signal and the triple-comb, as shown in Fig. 3(b-g).

Once f_{rep1}, f_{rep2}, f_{rep3}, f_{beat1}, f_{beat2}, and f_{beat3} are obtained simultaneously, the frequency band and m can be determined by the following (3) to (8), where the subscript of m indicates

the corresponding frequency band that the MW signal falls into.

$$m_{\mathrm{I}} = \frac{f_{beat2} - f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{f_{rep3} - f_{beat3} - f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{f_{rep3} - f_{beat3} - f_{beat2}}{f_{rep3} - f_{rep2}} \quad (3)$$

$$m_{\mathrm{II}} = \frac{f_{beat2} - f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{f_{beat3} - f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{f_{beat3} - f_{beat2}}{f_{rep3} - f_{rep2}} \quad (4)$$

$$m_{\mathrm{III}} = \frac{f_{beat2} + f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{f_{beat3} + f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{f_{beat3} - f_{beat2}}{f_{rep3} - f_{rep2}} \quad (5)$$

$$m_{\mathrm{IV}} = \frac{-f_{beat2} + f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{f_{beat3} + f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{f_{beat3} + f_{beat2}}{f_{rep3} - f_{rep2}} \quad (6)$$

$$m_{\mathrm{V}} = \frac{-f_{beat2} + f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{-f_{beat3} + f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{-f_{beat3} + f_{beat2}}{f_{rep3} - f_{rep2}} \quad (7)$$

$$m_{\mathrm{VI}} = \frac{-f_{beat2} + f_{rep1} - f_{beat1}}{f_{rep2} - f_{rep1}} = \frac{-f_{beat3} + f_{rep1} - f_{beat1}}{f_{rep3} - f_{rep1}} = \frac{-f_{beat3} + f_{beat2}}{f_{rep3} - f_{rep2}} \quad (8)$$

The frequency of MW signal can then be calculated using:

$$f_x = \begin{cases} m f_{rep2} - f_{beat2} & \text{band I, II, III} \\ m f_{rep2} + f_{beat2} & \text{band IV, V, VI} \end{cases} \quad (9)$$

For any unknown single-frequency signal, the above equations can unequivocally determine its relatively position to the closest neighboring comb lines and identify the mode number and, thus, the absolute frequency of the signal.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

When the fiber laser is pumped above its mode-locking threshold and the polarization state is properly adjusted, three pulse sequences are simultaneously generated with similar peak spectral intensity in the optical spectrum, as shown in Fig. 4. Their spectra are centered at 1549.36 nm, 1555.18 nm, and 1560.85 nm with 3-dB bandwidths of 0.76 nm, 0.71 nm, and 0.98 nm, respectively. The intervals between their central wavelengths are 5.67 nm and 5.82 nm, which are consistent with the birefringence introduced by the PM fiber. The small difference between the two intervals is caused by the non-flat gain profile of the erbium fiber. After filtered by a dense-wavelength-division-multiplexing (DWDM) filter, the spectra of the triple-wavelength pulses are well-separated with no overlap, and are named as Comb3, Comb2, and Comb1, from shorter to longer wavelength (also shown in Fig. 4). Their repetition rates are ~31.8166 MHz with differences of 527 Hz and 610 Hz, respectively, as in Fig. 5. Because of the anomalous dispersion in the cavity, Comb1, which has the lowest repetition rate, has the longest central wavelength.
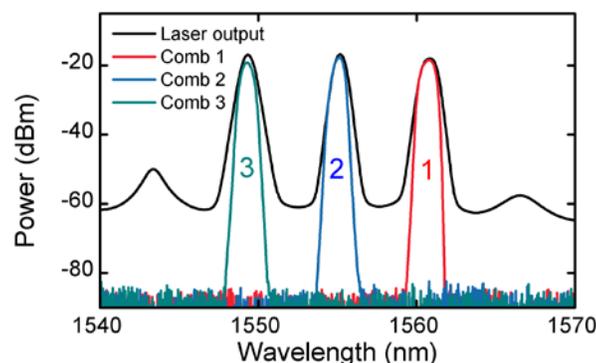
Fig.4. Output optical spectrum of the triple-comb laser and the spectra of the filtered three combs.
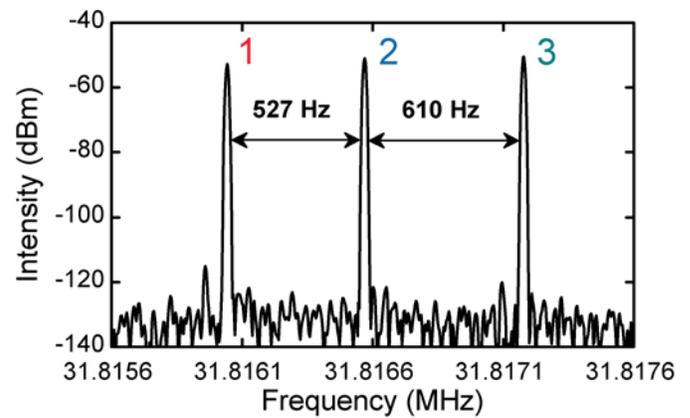
Fig.5. RF spectrum of the triple-comb pulses.

In our current setup, the total output power of the triple-wavelength ultrafast pulse laser is ~300 μW. Due to the insertion loss of the splitter, modulators and filters, the received optical power at LBW-PD1 is ~15 μW and the optical power at LBW-PD 2, 3, 4 is ~7 μW/each. We note that since the high-frequency signal is down converted to rather low beat frequencies and high-gain low-bandwidth photodetectors can be used instead of high-bandwidth ones, μW-level optical power is sufficient for the following high-resolution measurements.

To demonstrate dead-band-free measurement across a broad microwave frequency range, the frequency of the MW signal to be measured is scanned from 1 to 20 GHz, first, with 1 GHz step. The signal power is set to 0 dBm. The data acquiring time for each measurement is 10 ms. As shown in Fig. 6(a), the measured frequency matches the real frequency of the signal in every measurement. To prove the capability of dead-band-free measurement of the proposed triple-comb scheme, around 10GHz, the frequency of the signal is scanned from 10.006055 GHz to 10.006235 GHz over a 180 kHz range with a small frequency step. Within this frequency range, there is a dead band for the conventional dual-comb measurement scheme. Yet, the frequency of the MW signal can still be resolved accurately without any ambiguity, seen in the zoom-in inset of Fig. 6(a).

The measurement accuracy and precision are also evaluated. Accuracy is defined as the difference between the mean of the measurement results and the nominal value, and precision is defined as the standard deviation (SD) of the measured values. As shown in Fig. 6(b), the accuracy is less than 0.3 Hz over the whole frequency range when averaged over 100 continuous measurements, which is much higher compared to other proposed microwave photonic methods [3]. On the other hand, the precision increases roughly linearly with the signal frequency and the relative precision defined as $\sigma(f_x)/f_x$ is $\sim 10^{-10}$. The dependence of the precision value on the frequency can be explained as following: as seen in (9), the error of the measured f_x is given by that of f_{rep} and f_{beat}, and the former is also indirectly related to the error in measuring the beat note frequency in the repetition rate setup measurement. In our current configuration, the relationship can be given as:

$$\sigma(f_x) = \frac{m}{188}\sigma(f_{beat2\_ref}) + \sigma(f_{beat2}) \quad (10)$$

Equation 10 shows that *SD* of the beat frequency measurement contributes to the error in determining the measured frequency, and the measurement *SD* would increase linearly as *m* increases. 188 is the mode number of the most adjacent comb line to the reference frequency (5.985GHz), given the repetition rate is ~31.8166 MHz.
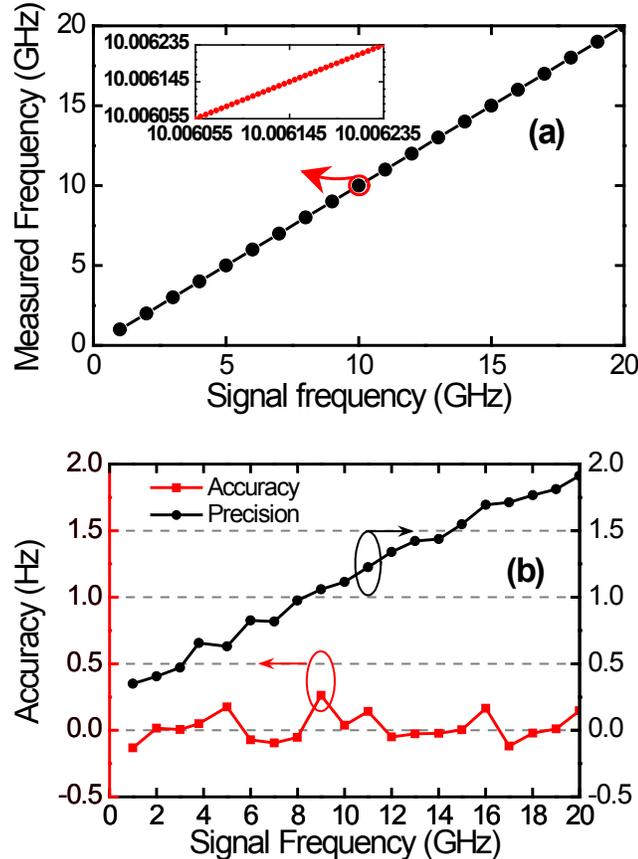
Fig.6. (a) Measured frequency of the MW signal, the inset: dead-band-free measurement demonstration; (b) frequency measurement accuracy and precision.

In order to determine the detection limit of our scheme for weak microwave signal, the measurement precision is evaluated under different RF powers. The frequency of the MW signal is set to 10 GHz and the sampling time remains at 10 ms. When we gradually reduce the input power, after the power drops between -10 dBm, the measurement precision gets significantly worse, because of increased errors in determining the beat frequencies due to the lower signal to noise ratio (SNR), as shown in Fig. 7 (black line). At -25dBm input RF power to the EO modulator, the precision is ~6 Hz. By introducing broadband microwave amplifiers that are widely available for high-speed optical communications, the required RF power can be significantly reduced. When two modulator drivers (one with 32 dB gain @10 GHz and the other with ~21 dB gain) are cascaded and used, the required power to reach the same measurement precision is reduced by ~45 dB. This is slightly lower than the nominal cascaded gain of ~53 dB, likely due to the introduced amplifier noise. With the amplifiers, at -55dBm input power, the precision can be still around 10^{-10} level as shown in Fig. 6(b). Even at the input RF power of -75 dBm, a precision of about 10 Hz for a 10GHz input can still be realized.
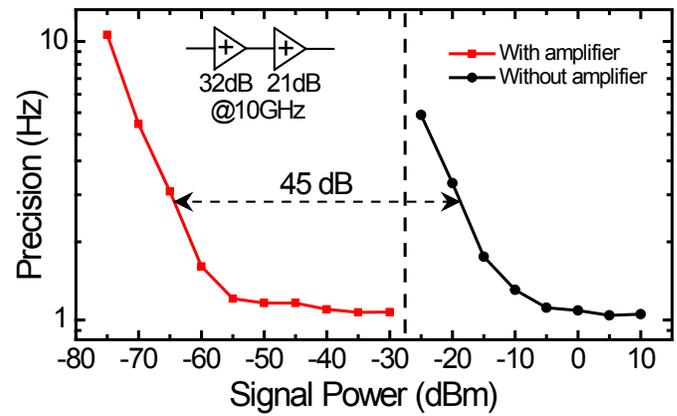
Fig. 7. Frequency precision changes with signal power w/o electrical amplifier.

Finally, for the purpose of fast, real-time frequency measurements, the dependence of measurement precision on the sampling speed is investigated. The MW signal is set to 10 GHz and 0 dBm power. As shown in Fig. 8, at a sampling speed of 25 Hz, the precision can reach less than 0.25Hz. The precision get worse when the sampling time get shorter. This is because errors increase in determining the beat frequencies when the sampling time is decreased. This would lead to reduced measurement precision as well. However, even if the measurement is operated at a fast speed, for example 1 kHz, a precision of about 50 Hz at 10 GHz can still be achieved.
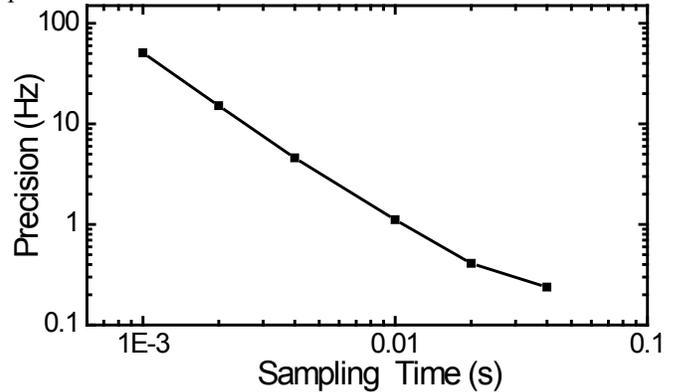
Fig.8. Frequency measurement precision vs. sampling time.

IV. CONCLUSIONS

A triple-comb-assisted high-resolution microwave frequency measurement scheme is demonstrated for the first time using a single simple and cost-effective fiber laser source as well as other fiber-optic components. The frequency of microwave signal between 1 and 20 GHz can be unequivocally determined with a 10^{-10} precision at a sampling speed of 100 Hz at an input power of -55dBm, and the measurement accuracy remains within 0.3 Hz. The precision could be further improved at an increased sampling time. Though limited by the bandwidth of the EO modulators (~40 GHz) and the RF source (20 GHz) used here, our demonstration is limited to the current frequency range. Nevertheless, the modulators with 100 GHz bandwidth or higher and lower driving voltage are already available. Considering the bandwidth of the triple-comb laser pulses and the potential to further tailoring the repetition rates and their differences, it is easy to see that our scheme can readily cover

microwave frequencies to 100 GHz and even beyond.

We note that the multi-wavelength, multi-comb fiber source has negligible complexity increase compared to a traditional mode-locked fiber laser. Compact and portable microwave photonic real-time frequency characterization systems capable of covering a broad microwave range with excellent accuracy could be implemented. One could further expect the emergence of more multi-comb-based microwave photonic schemes enabled by such accessible single-laser-based multi-comb sources.

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