High resolution frequency shift measurement based on the time domain mode-locked optoelectronic oscillator

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Abstract. A high-resolution frequency shift measurement based on the time domain mode-locked optoelectronic oscillator (TDML-OEO) is proposed and experimentally demonstrated. In the proposed approach, the TDML-OEO is firstly excited and the central frequency is selected by injecting a reference microwave signal through an electrical coupler (EC) and used as the reference frequency measurement comb. Then a named unknown microwave signal with various and lower up to even 1 Hz shift compared to the reference microwave signal is injected into the TDML-OEO loop. Due to such a small frequency difference, the central frequency and nearby sidebands will have spectrum aliasing with the reference signal, which is very difficult to be distinguished by low resolution spectrograph. Benefiting from the comb effect, the small frequency difference is enlarged by fine controlling the loop delay time. The proposed method displays high resolution and accuracy due to the comb effect, which will find potential usage in the Doppler radar system for ultra-slow target detection.

Keywords: frequency measurement, TDML-OEO, Doppler shift, FSR, comb effect.

1. Introduction

Slow targets are arising to be urgent aerial threats. The detection of this kind of target usually uses the Doppler radar to detect the Doppler frequency shift. However, the traditional electrical methods face detecting limitations due to such small echo signals and small Doppler shifts especially at higher frequency regions. The application of microwave photonics in radar systems present great potential in solving the higher frequency, fast speed and anti-electromagnetic interference problems faced by traditional electrical methods [1-2]. Especially, the optoelectronic oscillator (OEO) has attracted much attention in generating high-purity wideband tunable microwave signals attributing to the ultra-low loss optical fiber delay line and finds various applications in radar, sensing, signal processing and communication systems [3-4]. Detection of a weak radio frequency based on the OEO also plays an increasingly important role benefits from the loop oscillation gain [5, 6]. In general, the radar systems based on the OEO have potential usage in small and slow target detection.

There are mainly two kinds of frequency detection systems based on the OEO, which are namely based on the single mode oscillation [7-10] and multimode oscillation OEO [5,11]. The main differences between them are the loop gain and the detection frequency range. The single mode oscillation detection system, contributing to the higher oscillation gain, will demonstrate much more sensitivity frequency detection as the injected frequency is consistent with the OEO oscillation mode. While the frequency measurement based on the multimode OEO can get a large frequency detection range limited by the applied filter and has been discussed to accomplish the unknown signal detection. This system will acquire the open loop gain under the oscillation threshold value [5, 6, 11]. However, both of these frequency detection resolutions are still limited to the resolution of the electrical frequency spectrum, especially for the moving target with ultra-low speed.

Recently, the time domain mode-locked OEO (TDML-OEO) is put forward to generate multimode oscillations and at the same time contributes to the circulate oscillation modulation

[12-16]. Different structures to lower the sidemode suppressions have also been proposed and discussed [17-20]. In the previous work, investigations of the TDML-OEO mainly focus on the generation of the frequency, bandwidth and signal quality of the frequency combs. The investigation of its further usage especially for frequency sensors is still vacant.

In this paper, we proposed and experimentally demonstrated a high-resolution frequency detection method based on a TDML-OEO. A reference frequency signal injection locking technology is adopted in the TDML-OEO to accomplish the central frequency selection. At the same time, a lower radio frequency (RF) signal is injected into the OEO oscillation loop to form the time domain mode locking and used as the frequency measurement comb. Then a named unknown microwave frequency with a much smaller frequency shift is injected and detected when the frequency is matched with one oscillation mode of the OEO loop. This will find potential usage in detecting low slow small targets for Doppler radar.

2. Principle

The schematic of the proposed frequency measurement setup based on the TDML-OEO is shown in Fig. 1. A continuous wave (CW) light wave is sent into a Mach-Zehnder modulator (MZM). The modulated light is delayed by a fixed optical single mode fiber (SMF) and an optical tunable delay line (OTDL) before being detected by a photodetector (PD). The signal is transmitted back to the RF port of the MZM to close the OEO loop after being amplified by electrical amplifiers (EAs) to compensate for the loop loss. A wide electrical bandpass filter (EBPF) is adopted to filter the unwanted spurious frequencies. The injected central frequency selection signal and mode locking lower frequency signal are applied to the OEO loop through electrical couplers (ECs).

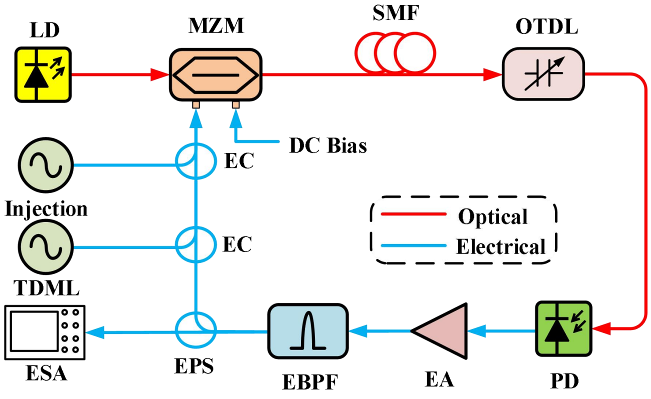

Fig. 1. Schematic of the proposed frequency measurement setup based on the injection locked TDML-OEO.

Mathematically, the time domain mode locking (TDML) can be achieved only as the lower injected signal frequency is synchronized with the round-trip time of the OEO loop. Assuming the round-trip time of the OEO loop is T_0 and the frequency of the mode locking lower frequency signal is f_0. To achieve TDML, the $f_0 = 1/T_0$. Then a reference signal with fixed frequency f_{RF} is injected into the TDML-OEO loop to achieve the central frequency selection. Then we have:

$$f_{RF}{}^{n} = f_{RF} + \frac{n}{T_0} = f_{RF} + nf_0 \tag{1}$$

where n is an integer. Thus, a frequency comb is formed around the reference signal with interval of f_0. Then by inserting a tunable fiber loop with 104 m length, and an unknown signal with frequency of f_x is injected into the loop. To achieve the TDML, the second round-trip loop time of the OEO loop is T_1 and the frequency of the injection signal is f_1, to achieve time domain $f_1 = 1/T_1$.

$$f_x{}^m = f_x + \frac{m}{T_1} = f_x + mf_1 \tag{2}$$

where m is an integer. From formula (1) and (2), we can have

$$f_x{}^m - f_{RF}{}^n = (f_x - f_{RF}) + (mf_1 - nf_0) \tag{3}$$

From formula (3), we can observe that, the frequency difference between the unknown signal and the reference is enlarged by the mode difference. Thus, by employing TDML-OEO comb effect, the frequency detecting resolution gets much more improvement.

3. Results and discussions

An experiment is performed to study the operation of the proposed frequency measurement setup based on the injection-locked TDML-OEO. A distributed feedback (DFB) laser diode (LD, ID Photonics CoBrite DX4) with a maximum output power of 16 dBm is used as the light source. The laser wavelength is set to be 1550.001 nm. An MZM (Eospace AX-0MVS-40-PFA-PFA) with a 3 dB bandwidth of 40 GHz is used in the TDML-OEO loop. A fixed optical fiber with about 100 m in length and an electrically controlled OTDL (General Photonics MDL-002-l-35-56-FC) with an adjustable range of 560 ps are inserted in the oscillation loop to precisely control the delay of the OEO loop. A PD (Finisar HPDV2120R) with a 3 dB bandwidth of 50 GHz and responsivity of 0.65 A/W is adopted to accomplish the demodulation. One low noise amplifier (Ceyear 80230F) and another higher output amplifier (SHF S824 A) with a combined gain of over 50 dB are cascaded to compensate for the loss of electrical signal in the loop. The signal is then fed back to the MZM via an electrical power splitter (EPS) to form a closed loop. The temporal and frequency waveforms of the generated electrical signal are observed by a digital storage oscilloscope (OSC, Keysight DSO-X 93204A) and an electrical signal analyzer (ESA, Keysight N9040B), respectively.

Firstly, the output of free running OEO is measured to roughly calculate the free spectral range (FSR) of the OEO. Fig. 2 (a) shows the spectrum of the generated signal with the central frequency of 10.183 GHz. The main resonant frequency is 10.183 GHz with multiple sidebands due to the adopted wide bandwidth of the electrical filter. The FSR of the OEO is about 1.81 MHz corresponding to a 104-meter fiber delay length. By injecting a signal frequency synchronized with the round-trip time of the OEO loop, Fig. 2 (b) presents the mode-locked frequency spectrum with a span of 90 MHz and a resolution bandwidth (RBW) of 1 kHz. Contributed to the TDML technology, the sidebands of the free running OEO are excited and enlarged to form multimode oscillation at the same time. Then, an external injection signal is inserted into the OEO loop to accomplish the central frequency selection. We can observe that, the sidemode intensity is modulated by the mode competition effect and the sidemode to the main mode ratio is a little depressed caused by the external injecting effect, as shown in Fig. 2 (c). The corresponding temporal waveforms are demonstrated in Fig. 2 (d), 2 (e), 2 (f). The free running OEO is a continuum waveform, while the others are both short time pulses with time intervals of 0.54 us, which is synchronized with the round-trip time of the OEO loop and also the injected TDML signal. Comparing Fig. 2(e), and 2(f), the pulse intensity is both very stable, which indicating a high-quality mode locking state. While the pulse width is broadened by the external effects, which is also consistent with the bandwidth narrow result from the frequency spectra.

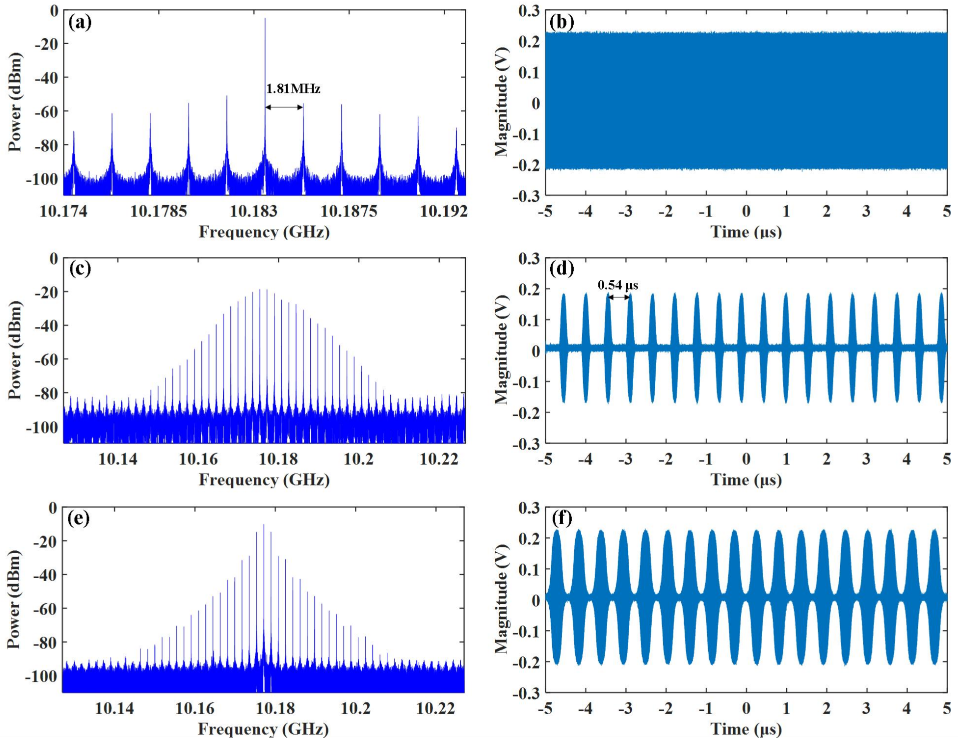

Fig. 2. The frequency spectra of the (a) free running OEO, (b) TDML-OEO and (c) external injection locked TDML-OEO (b); (d), (e) and (f) are the corresponding temporal waveforms, respectively

Since the central frequency is determined by the injected external signal, we inject a reference signal with fixed central frequency and apply the TDML technology to form the multimode microwave frequency measurement comb. Then, an unknown signal with a 1 Hz shift is injected to accomplish the central frequency selection. This frequency shift responds to a moving target with a velocity of 0.015m/s. To enlarge the frequency difference between the unknown signal and the reference signal, a fixed fiber length is added into the OEO loop. To ensure the phase match, an OTDL is also applied. Then the new formed microwave frequency comb will spread around the central unknown frequency. The ultra small frequency difference will be enlarged by the comb effect according to the formula (3). Fig 3 (a) shows the reference comb and the unknown reference comb, which will be amplified with *N* multiple of the FSR difference between the two combs. The insets are the enlarged pictures of the central frequencies and the 15th sidebands. It can be clearly seen that the unknown frequency with a 1 Hz shifter almost coincides with the reference signal at the central frequency area even displayed by a very high RBW (30Hz). While the right inset shows a significant frequency difference benefits from the comb effect. Fig. 3 (b) is the frequency measurement accuracy. The blue dots are the injected unknown frequencies and the measured frequency read from the electrical spectrograph, and the blue line is the simulation results calculated from the formula (3). The red dots are the error between the measured frequencies and the injection frequencies. Limited by the ESA readings, this frequency measure method provides a high resolution of up to 0.01Hz and an accuracy of up to 3Hz.

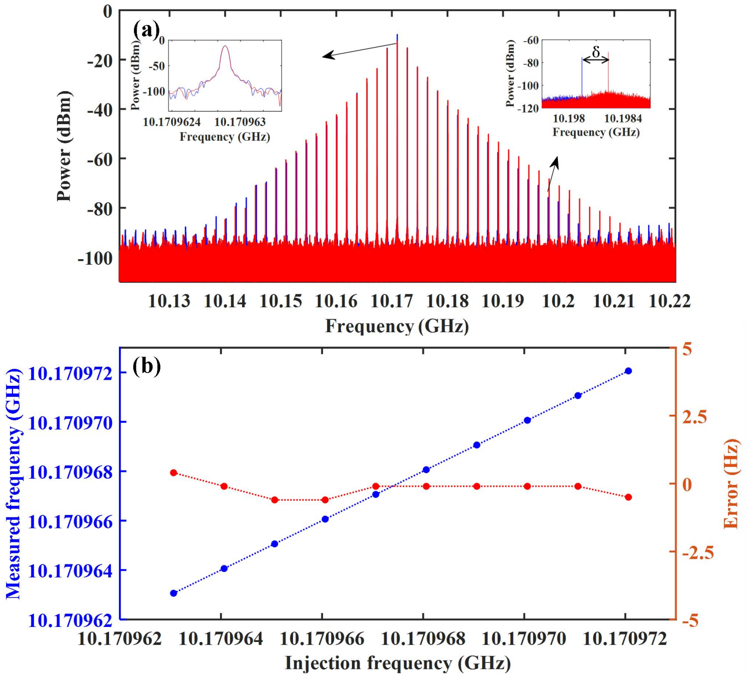

Fig. 3. (a) The reference frequency comb (blue line) and unknown frequency comb (red line) spectra, the enlarges are the spectra of the central frequency (left) and the 15th sideband (right); (b) the measured frequency related to the injection frequency figure (blue) and the calculated errors (red).

4. Conclusion

In conclusion, a high accuracy and resolution frequency shift measurement based on the TDML-OEO system is proposed and experimentally demonstrated. By applying an external injection locking technology in the TDML-OEO structure to select the central frequency and by manipulating the delay difference, an ultra-low frequency up to 1 Hz shift detection with a very high revolution up to 0.01 Hz is achieved. The proposed frequency measurement based on the TDML-OEO shows great application potential in future Doppler radar systems for ultra-small and slow target detection.

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