Low-noise active mode-locked optoelectronic oscillator based on passive mode-locked laser injection

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***Abstract*—Active mode-locked optoelectronic oscillator (AML-OEO) can generate high-performance microwaves, with flexible frequency tuning capabilities and extremely low phase noise at high frequency offset. In order to improve its phase noise limitation at low frequency, here, we propose a scheme to use a low-noise passively mode-locked laser to inject the actively mode-locked OEO to achieve the noise characteristics transition of the passive optical comb. At the same time, we also introduce a phase-locked loop and use the fiber stretcher feedback to adjust the cavity length of the OEO to achieve fine tuning of the repetition rate. An experiment was set up to electrically inject a fiber mode-locked laser after photoelectric conversion into the AML-OEO, achieving noise synchronization between the passive optical comb and the active optical comb. It reveals the feasibility of the practical application of flexibly tunable low-phase-noise microwave source based on AML-OEO.**

Keywords—AML-OEO, injection, phase noise, tunable

I. Introduction

In recent years, high-purity microwave signals generated by optical oscillators have played a vital role in many scientific fields such as coherent radar [1], and very long baseline interferometry (VLBI) measurement [2]. Application such as microwave photonic radar [3] require that the microwave source be able to cover multiple bands, meaning that the optical oscillator itself must have excellent frequency tuning capabilities. Microwave generators based on optoelectronic oscillators can achieve a wide range of microwave frequency adjustment because the resonant frequency of the OEO depends only on the frequency selection element. When using a programmable filter within the loop, a wide tuning range of 8-18 GHz can be achieved [4]. However, single-frequency OEO oscillators cannot be finely tuned to generate microwave signals of arbitrary frequencies. To solve this problem, the researchers introduced an active mode-locking mechanism in the OEO loop [5] to generate a microwave frequency comb (MFC), which consists of a series of discrete microwave signals with equal frequency spacing and stable coherent phase relationships [6]. The center frequency of the MFC still depends on the frequency selection components of the OEO loop, while the frequency interval between two adjacent groups of microwaves is consistent with the modulation frequency of active mode locking. This allows us to tune the center frequency over a large range, and also to achieve full coverage of any frequency through the microwave sequence with narrow frequency spacing.

The actively mode-locked optoelectronic oscillator (AML-OEO) inherits extremely low phase noise at high frequency offset ot the signal-frequency OEO, aned poor phase noise characteristics at low-frequency offset, resulting in poor long-term stability of the microwave signals. In order to reduce the low frequency part of the phase noise, we proposed a scheme to inject a passive OFC into the active mode-locked optoelectronic oscillator (AML-OEO).

II. Schematic and Experimental Setup

According to the loop model of OEO established by Steve Yao [7] when injecting out-of-loop signals, Fig. 1 shows the schemes that a passive optical comb injects into the AML-OEO. The reference comb can be coupled into the feedback branch directly (optical injection), or be converted into an electrical signal and injected into the feedback port of the loop (electrical injection).

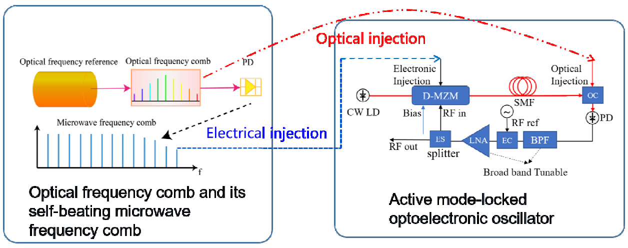

Fig. 1. Schematic diagram of injecting a passively mode-locked laser into an actively mode-locked laser, including electrical injection and optical injection.

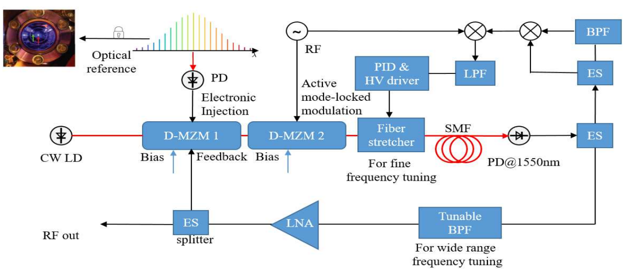

Fig. 2. Experimental setup of the electrical enjection AML-OEO with adjustable cavity length.

In order to verify the effectiveness of the proposed scheme, we carried out experiments on electrical injection using an Er-doped mode-locked fiber laser, which is shown in Fig. 2. The frequency stabled Er: fiber mode-locked laser is used as a high stability microwave source. The low-noise RF comb generated after photoelectric conversion will be divided into two parts. One part is extracted into a single frequency component by a tunable band-pass filter (BPF) to be used as the modulation signal for the AML-OEO, and the others is completely injected into the OEO loop through a Mach-Zehnder modulator (MZM). By measuring the phase noise of the output microwave comb, we can confirm whether the passive optical comb injection will suppress the noise of the active comb, especially the low-frequency part.

When we fine-tune the frequency of the RF source, it will be slightly detuned from the repetition rate of the optical comb. At this time, a phase-locked loop is introduced to phase-detect the two, and the error signal is fed back to the fiber stretcher actuated by piezoelectric ceramics, which changes the fiber cavity length and adjusts the repetition rate. So that the two can be re-matched and enter a new balance.

III. Result and Discussion

We experimentally measure phase noise curves of the passive Er-doped fiber mode-locked laser and the AML-OEO, respectively. In our measurement, the low-noise characteristics of the passive optical comb are synchronized to the active optical comb after injection. The power spectrum density (PSD) of the phase noise reached 85 dBc @ 300 Hz, and -128 dBc @1 MHz. This indicator needs further optimization.

IV. Conclusion

This paper proposed a scheme to inject a passive OFC into the AML-OEO to supress the phase noise of the MFC, especially at the low frequency offest. This scheme makes it possible to generate microwaves with large frequency range, fine frequency adjustment and low phase noise at the same time, which will promote their application in various scientific devices.

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