Simple hybrid digital and analog laser synchronization system

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***Abstract*—A homodyne laser synchronization system with a simple structure is demonstrated for synchronizing a single-frequency laser to a mode-locked laser. The system used a hybrid 'digital + analog' locking mechanism and achieved a frequency fluctuation of less than 2.5 Hz over 24 hours of operation, indicating reliable short and long-term stability.**

***Index Terms*—Hybrid 'digital + analog' locking, Laser synchronization**

I. Introduction

Laser synchronization is a process of locking the wavelength of a free-running laser to a reference laser so that their frequency offset remain constant. This technology finds broad application in multi-wavelength interferometry [1], fiber-optic communication [2], and laser cooling [3]. Laser synchronization mode has direct synchronization and indirect synchronization. Direct laser synchronization usually requires a small wavelength difference between the two lasers, so the photodetector can directly detect the beat frequency signal, and this technique is used in coherent optical communication [4]. However, in applications where a large difference in wavelength between the two lasers is required, such as multi-wavelength interferometry or long-distance time and frequency transfer [5], [6], it is difficult to use a photodetector to get the beat frequency signal directly.

This problem can be solved by indirect synchronization of the lasers, i.e., both lasers are directly synchronized to a reference source simultaneously. Indirect laser synchronization can be achieved by locking the two lasers to different longitudinal modes of the high-stability Fabry-Perot cavity or two high-stability Fabry-Perot cavities [7]–[9], but the technique is complex and costly. Absorption lines can also be used for indirect synchronization of lasers [10], but the absorption properties of the atoms or molecules limit the laser wavelength difference. An optical frequency comb (OFC) is an optical spectrum consisting of equidistant lines with a fixed pulse repetition frequency (f_{rep}). Currently, f_{rep} locking techniques for mode-locked lasers (MLL) are mature and have low complexity relative to high-stability Fabry-Perot cavity synchronization [11]–[13]. An OFC enables synthesis over broad spectral regions, including the near-infrared, the visible domain, and as far as extreme ultraviolet (XUV) [14]. Therefore, using the OFC as an intermediate reference, it is possible to synchronize two lasers with almost any wavelength difference.

The traditional analog-locking system generally utilizes an analog phase-lock loop (PLL), which usually requires complex circuit designs and has a trade-off between bandwidth and accuracy [15]. As a result, achieving both short- and long-term stability through analog locking alone becomes challenging. Digital locking systems have no trade-off like analog locking and maintain robust long-term stability. However, its locking accuracy is limited by the speed and precision of the feedback mechanism [16]. The current hybrid 'digital + analog' system for synchronizing single-frequency laser (SFL) to mode-locked laser (MLL) is structurally complex and has poor short- and long-term stability [17].

This paper presents a hybrid "digital+analog" laser synchronization system for synchronizing a SFL with a f_{rep} locking MLL and between SFLs. The analog control relies on a feedforward configuration based on an acousto-optic modulator (AOM) for locking accuracy. The digital control uses a piezoelectric transducer (PZT) inside the laser as a

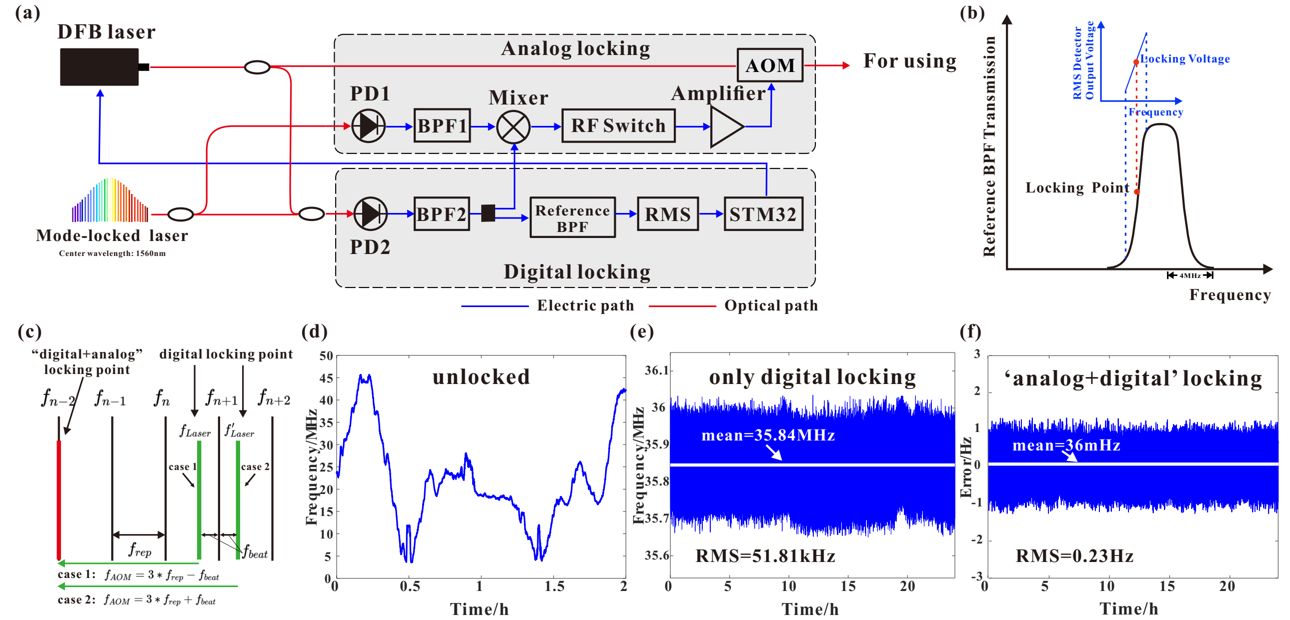

Fig. 1. (a) The schematic of hybrid 'digital + analog' laser frequency synchronization system. BPF: band-pass filter, PD: photodetector, RF Switch: radio frequency switch, AOM: acousto-optic modulator, RMS: root mean square detector, MCU: microcontroller unit. (b) Schematic of the principle of digital locking part. (c) Schematic of the principle of the analog locking part. Black lines: optical modes of MLL; Green lines:SFL frequency after only digital locking; Red line: SFL frequency after 'digital+analog' locking; (d) The laser frequency offset between SFL and MLL in a free-running state for two hours. (e) The laser frequency offset in 24 hours only digital locking. (f) The laser frequency offset variation in 24-hour 'digital + analog' locking.

feedback component for long-term locking. In the digital control part, we propose a narrow-band filter-based digital frequency locking technique, realizing 24 hours of frequency offset locking between an MLL and an SFL with less than 350 kHz of jitter. With the addition of analog control, the system made the peak-to-peak frequency deviation of the frequency offset between an MLL and an SFL less than 2.5 Hz in 24 hours. The proposed hybrid synchronization system possesses excellent long-term and short-term stability with a simple and adaptive design.

II. Experiments and Results

A. Experimental setup

The laser synchronization system is divided into three parts: analog locking and digital locking. The analog locking is an analog feedback system, feeding the error frequency directly to the acousto-optic modulator (AOM) by mixing and filtering, thereby requiring no additional reference. The digital locking is a digital feedback system that employs the electrical intensity locking technique, which exploits the transmittance properties of the filter roll-off band to locking the laser frequency offset to a reference bandpass filter (BPF). The alalog and digital lockings can be operated independently. Turning on only the analog locking enables the system to maintain high locking accuracy, but it is unable to achieve long-term locking due to the small control bandwidth. By activating the digital locking only, the system's long-term operation can be guaranteed, albeit with limited locking accuracy. Simultaneous operation of the alalog and digital lockings allows for the synchronization of SFL and MLL with excellent short and long-term stability. Fig. 1(a) displays the schematic of the homodyne laser synchronization system. The homemade MLL has a repetition frequency (f_{rep}) of 100 MHz and a central wavelength of 1560.2 nm, while the SFL has a center wavelength of 1550.12 nm.

1) Principle of digital locking part: In the digital locking part of Fig. 1(a), the beat frequency (f_{beat}) signal is obtained after photodetector1 (PD2) and BPF2. After the power divider, one branch signal travels to the analog locking part, and another enters into reference BPF. The RMS detector detects signal intensity and converts it to voltage. The combination of a reference BPF and an RMS detector can form a frequency discriminator. STM32 was used to collect the voltage and control the wavelength of the DFB laser. Fig. 1(b) illustrates the principle of electrical intensity locking. The solid black line indicates reference BPF transmission, while the solid blue line shows the RMS detector output voltage. The combination of reference BPF and RMS detector realizes that frequency to voltage. Based on this voltage, the laser frequency offset is locked on a roll-off band of reference BPF. The locking point is set at the maximum slope in the filter roll-off band, achieving high feedback sensitivity. Feedback control of f_{beat} can be implemented based on the variation in output voltage of the RMS detector.

2) Principle of analog locking part: In Fig. 1(a)'s analog control part, PD1 and BPF1 extract the third harmonic of f_{rep}, which mixes with the f_{beat} signal from the digital locking part. The mixer output is divided into two paths, each passing through a BPF with a distinct center frequency. The appropriate path is selected by the radio frequency (RF) switch. Fig. 1(c) illustrates the principle of RF path selection, where the green solid line represents the frequency of the SFL after digital locking only, the red represents the frequency of the SFL after 'digital + analog' locking, and the black line represents the optical modes of the MLL. After digital locking, the variation range of f_{beat} is small, and there are two cases. In case 1, the laser frequency is less than a specific optical mode, and therefore, the selection is $f_{AOM} = 3 * f_{rep} - f_{beat}$. In case 2, the laser frequency is more than a certain optical mode, resulting in the selection of $f_{AOM} = 3 * f_{rep} + f_{beat}$. The selected signal is then amplified and loaded onto AOM (driving frequency is 300 MHz $\pm$ 50 MHz) to achieve homodyne frequency compensation.

B. Results

Fig. 1(d) shows the frequency offset of SFL and MLL over 2 hours without locking. The MLL has a f_{rep} of 100 MHz; theoretically, the offset frequency should be between 0 and 50 MHz. Due to the limited measurement, the detected offset frequency oscillates between 5 MHz and 45 MHz. Fig. 1(e) represents frequency fluctuation of frequency offset is less than 350 kHz and the RMSE is 51.84 kHz over 24 hours with only digital locking. The results show that digital locking based on BPF and RMS detectors has robust long-term stability. Fig. 1(f) illustrates the frequency error between SFL and MLL after 'digital + analog' synchronization. The frequency fluctuation is less than 2.5 Hz and the RMSE is 0.23 Hz in 24 hours, which indicates that the hybrid synchronization system provides reliable short and long-term stability. The system structure is straightforward and easily replicated, allowing MLL-based multi-laser cross-band synchronization in subsequent stages.

III. Conclusion

In this paper, we demonstrate a new laser synchronization system that uses a hybrid 'digital+analog' to lock the wavelength of the SFL to the zero difference of the MLL comb. Its absolute error of locking is less than 2.5 Hz and the RMSE is 0.23 Hz over 24 hours. The relative frequency offset instability can be improved by about 5 6 orders of magnitude compared to the relative frequency offset instability when the SFL is free-running and compared to the relative frequency offset instability when the SFL is free-running. In addition, in the slow-loop feedback, we propose a narrow-band filter-based electrical intensity locking technique, which is simple in structure, low in cost, and fast in feedback. The locking error between SFL and MLL is about 350 kHz within 24 hours of running only slow-loop feedback. This digital-analog hybrid single-branch synchronization system can be applied to lock multiple SFLs with a single MLL to achieve wavelength synchronization between multiple SFLs. The system can also be used for wavelength locking of lasers with large wavelength differences, and synchronization of multiple single-frequency lasers in the full wavelength band can be achieved by expanding the spectrum of the MLL's output. In addition, if the f_{rep} and f_{ceo} of the MLL are locked to make the MLL an OFC, locking the single-frequency lasers to the OFC can also achieve frequency stabilization of multiple lasers. This technique can be applied to quantum precision measurement,precision frequency metrology, and long-distance fiber optic time transfer.

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