Optics Communications 427 (2018) 1–5

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optical frequency standard of continuous wave for fiber communication based on optical comb

Ruiyuan Liu [a], Ye Li [a], Cheng Qian [a], Dawei Li [a,b], Jianxiao Leng [a], Jianye Zhao [a,*]

[a] Department of Electronics, Peking University, Beijing 100871, China
[b] Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD, 21205, United States

ARTICLE INFO

Keywords:
Lasers
Fiber
Laser stabilization
Interferometry

ABSTRACT

An approach is reported to acquire an optical frequency standard based on precise frequency locking between optical frequency comb and continuous wave. A stabilized erbium-fiber-based frequency comb is created by locking to the two-photon absorption resonance of rubidium atoms. An Erbium-doped distributed-feedback narrow linewidth lasers is presented with an actively stabilized all fiber Mach–Zehnder interferometer. With this structure, many lines of the optical frequency comb can make a contribution to the error signal. The signal-to-noise ratio (SNR) is enhanced compared to traditional way which utilizes only one comb line. An acousto-optic modulator (AOM) is used to compensate the noise in fiber which is induced by environment. The relative frequency offset instability is 2×10^{-13} at 1 s and 6×10^{-15} at 1000 s. This stabilized system can be wisely used in optical communication at 1550 nm. The main advantage of this structure is the ability for long distance frequency transmission. Without dispersion, the stability and the robustness of the transmission is greater than the scheme only with the frequency comb. We transferred the signals along 10km optical fiber link with it. The relative frequency stability loss of the frequency signal is 1.1×10^{-15} at 1 s and reaches 7.6×10^{-19} at 1000 s.

1. Introduction

Due to the precise optical frequency of the comb lines and the steady radio frequency spacing between modes, the optical frequency comb bridge the gap between optical frequencies and radio frequencies [1,2]. Because of the bridge, optical clocks working in optical regime can be the references of radio frequencies. A comb with high accuracy and stability must be stabilized to an external frequency reference [3]. With the excellent phase-locking technique, long-term stabilization of optical combs can be achieved [2]. The magneto-optical trapping of Sr can be acquired with the laser system which achieved the phase-locking between the optical frequency comb and an extended cavity diode laser [4]. The clock transition of Yb^{171} atoms confined in an optical lattice can be observed by transferring the laser linewidth of a master laser to a comb mode [5]. These researchers choose a high-finesse optical cavity as the required reference, which can provide great short-term stability rather than long-term stability and accuracy [6]. And the structure with optical cavity cannot be applied to every wavelength. The atomic energy level transition of rubidium is often considered as the reference to optical frequency standard for the good transition spectral lines width. The transition frequency at 778 nm is also near to the half-wavelength of 1550 nm which is applied to the fiber communication. Therefore it can provide stable and accurate frequency reference for optical wavelength division multiplexing and frequency transfer. This makes the application of optical clocks become possible and research of optical clock have practical significance [7,8].

In the system of optical and radio frequencies link, frequency locking between optical frequency comb and CW laser plays a decisive role. It is the key requirement in many fields such as precise microwave generation [1], photonics-based radar, molecule spectroscopy, distance measurement [9–12]. It plays an important role in absolute frequency metrology of molecular vibration spectra, optical frequency dissemination via fiber [13–15]. With the precise locking, accurate optical frequency standards can be obtained, and RF signal with lower phase noise can be acquired from optical clock [16–21].

The key point of any stabilized locking system is to obtain accurate error signal. The quality of error signal between a frequency comb and a CW laser determines the accuracy of the locking system. Traditionally, the error signal of optical frequency comb and CW laser is directly measured by a heterodyne interferometer. The error signal is the frequency difference between CW laser and one line of the comb. The comb consists of thousands of lines and the power of one line is very

* Corresponding author.
E-mail address: zhaojianye@pku.edu.cn (J. Zhao).

https://doi.org/10.1016/j.optcom.2018.05.083
Received 12 March 2018; Received in revised form 23 May 2018; Accepted 27 May 2018

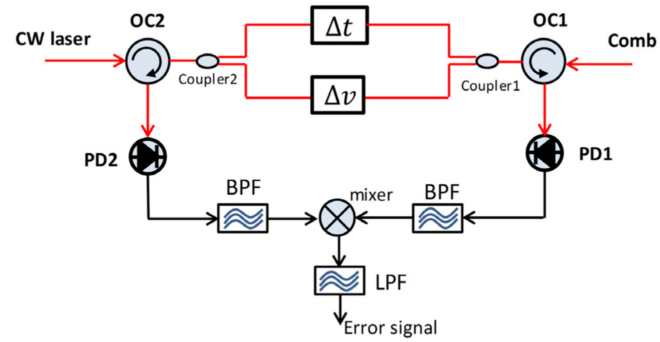

Fig. 1. Basic heterodyne scheme. OC: fiber optical circulator. PD: photodetector. BPF: band-pass filter. LPF: low-pass filter.

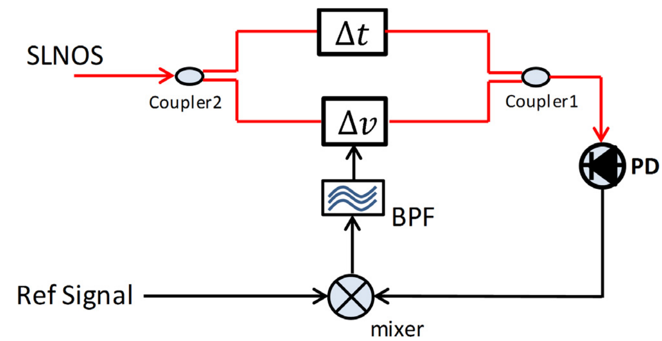

Fig. 2. Basic fiber noise compensation schematic. SLNOS: stable low noise optical source. PD: photodetector. Ref Signal: reference signal.

low. Thus, it is difficult to obtain an error signal with high signal-to-noise ratio (SNR). With the traditional method, a comb with high power is generally required. To enhance the power of the fiber comb, the utilization of optical amplification is inevitable. Therefore, the whole system becomes complex and heavy. And the noise induced by optical amplification will deteriorate the accuracy of the error signal. In our letter, many lines of the optical frequency comb were contributed to the error signal to acquire enhanced signal-to-noise ratio without the complex, fragile, and expensive system.

2. Experimental principle and setup

A free-space Mach–Zehnder transfer interferometer is presented in Ref. [22]. Robust frequency locking between a frequency comb and an ECDL (extended-cavity diode laser) is achieved by the interferometer. Due to mode-matching drifts of the free-space setup, there is some loss in long-term frequency stability. In this letter, an all-fiber locking scheme is proposed to suppress the mode-matching drifts in the free-space setup. In this scheme, longer path length difference of 10 km is utilized to increase the frequency discriminator slope. Phase noise induced by environment is compensated by AOM (acousto-optic modulator) to obtain a more precise locking system. An experiment has been demonstrated with this structure to establish a frequency lock between a 1550 nm distributed feedback laser (DFB) and an Er-doped fiber optical frequency comb.

The basic heterodyne scheme is illustrated in Fig. 1. Path length difference of MZI is L meter. One arm is a fixed time delay line with Δt delay, where Δt equals nL/c. In the other arm, beams are given an optical frequency shift of Δv. We adjust the length L to make sure the interferometer delay nL/c to be an integer multiple of the inverse repetition rate of optical comb. Optical comb and CW laser launch into the MZI at the different ends and propagation through the interferometer in the opposite direction. These two beams are separated at the each end of the interferometer by fiber optical circulator and detected by two photodetectors respectively. The output signals of photodetectors can be processed by a band pass filter, can be expressed as

$$E_{cw} = A_{cw} e^{-j(2\pi v_{cw} nL/c - 2\pi \Delta v t)} \quad (1)$$

$$E_{\rm comb} = \sum A_i e^{-j(2\pi v_i nL/c - 2\pi \Delta v t)} \quad (2)$$

In Eq. (2), i indicates the ith line of comb. Here we assume that the comb has only three lines. Thus Eq. (2) can be expressed as

$$E_{comb} = A_2 e^{-j(2\pi v_2 nL/c - 2\pi \Delta v t)} \left(a_1 e^{j(2\pi f_{rep} nL/c)} + 1 + a_3 e^{-j(2\pi f_{rep} nL/c)} \right) \quad (3)$$

If the amplitude of the 1st comb line equal to the 3rd comb lines, Eq. (3) can be expressed as

$$E_{comb} = A_2 e^{-j(2\pi v_2 nL/c - 2\pi \Delta v t)} \left(2a_1 + 1\right) \quad (4)$$

The two filtered signals from photodetectors mix together and pass through a low pass filter. The output signal, from Eqs. (1) and (4), can be expressed as

$$E_{error} = A_{CW} A_2 (2a_1 + 1) e^{-j\frac{2\pi nL}{c}(v_{cw} - v_2)} \quad (5)$$

Compared with directly heterodyning between comb's line and laser, the amplitude of error signal is increased by $\left(2a_1 + 1\right)$ times. In this way, the MZI converts the frequency difference between CW laser and optical comb to phase error signal in radio frequency domain. All lines of the comb contribute to the error signal. For comb containing multiple lines, if the spectrum is symmetric about the center line, the same transformation as in Eq. (4) can be used to achieve the corresponding result. Typically, the spectrum near the center wavelength of the comb is relatively flat and symmetrical about the center. This part of the spectrum can be selected by a narrow bandwidth optical filter. Utilizing the filtered spectrum can approximately satisfy the requirement of the scheme.

Environmental variations such as thermal drift and vibration will affect the length and refractive index of fiber. As can be seen in Eq. (5), this will affect the phase of the error signal and reduce the accuracy of frequency-difference detection between CW laser and optical comb. To improve the accuracy of the locking system, the phase error caused by fiber noise must be compensated.

In order to overcome this problem, a method for eliminating fiber noise is induced in Fig. 2. A frequency stabilized CW laser and an optical comb propagates through the interferometer. A photodetector at the optical fiber coupler's output port is utilized to detect the beat signal. The detected radio signal is processed by a band-pass filter centered at Δv. The phase of the signal is modulated by $\theta_{\rm laser} + \theta_{MZI} + \theta_{osc}$, where $\theta_{\rm laser}$ is the frequency noise of the CW laser or optical comb, θ_{MZI} is the fiber noise in the interferometer and θ_{osc} is the phase of local oscillator. $\theta_{\rm laser}$ equals to $2\pi v nL/c$, which can be seen in Eq. (1). For a stable low noise optical source and a MZI with small path length difference, $\theta_{\rm laser}$ changes very little. For example, a laser with 1 kHz linewidth and a MZI with 100 m path length difference can cause the $\theta_{\rm laser}$ change of ~3 m rad. The changes can be ignored. The environment-induced fiber noise will change θ_{MZI} and cause phase fluctuations. The detected radio signal is mixed with a reference signal (Rohde & Schwarz SMA100B). with frequency of Δv. After low pass filter, the phase fluctuation can be obtained. This fluctuation of phase is used to adjust the phase of local oscillator. Hence, the active compensation phase θ_{osc} is changed according to the fluctuation of θ_{MZI}. Thereby, the phase of the signal from photodetector is kept constant. The compensation of the environment-induced fiber noise is therefore realized.

The continue wave laser utilized in the experiment is a narrow linewidth laser (KOHERAS ADJUSTIK). Its linewidth is less than 10 Hz by using an efficient frequency noise reduction method [23]. Then it is modulated by an external AOM (AOM1). After the AOM1, the frequency shifted laser is fed into the interferometer from the left end. It propagates