Optics Communications 427 (2018) 335–340

Contents lists available at ScienceDirect

Optics Communications

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

Simultaneous time and frequency transfer over 100 km optical fiber based on sub-carrier modulation

Longqiang Yu [a,*], Lin Lu [b,*], Lei Shi [a], Zhiyan Xu [a], Jiahua Wei [a], Chuanxin Wu [b], Yimei Wei [b], Heng Wei [b]

[a] *Information and Navigation College, Air Force Engineering University, Xi'an, Shanxi, 710000, China*
[b] *Communication Engineering College, Army Engineering University of PLA, Nanjing, Jiangsu, 210007, China*

ARTICLE INFO

Keywords:
Time and frequency transfer
Optical fiber
Sub-carrier modulation

ABSTRACT

In this paper a novel scheme is proposed to realize the simultaneous transfer of precise time and frequency signals. By performing sub-carrier modulation to the time signal, the time and frequency signals can be directly transferred in the same optical channel without causing mutual interference. The remote user does not need a slave oscillator to clear up the frequency signal and therefore can maintain a simple structure. We test the scheme in the proof-of-concept experiment, in which the 50 MHz modulated time signal and 400 MHz frequency signal are transferred together over 100 km optical fiber link. Good signal compatibility and system performance is observed in the experimental results.

1. Introduction

Fiber optic time and frequency transfer has drawn considerable interest during the past decade because they are capable of providing accurate and stable access to high-level atomic clocks or realizing ultra-precision time and frequency comparison. Presently, great system performance has been achieved for frequency dissemination both in point-to-point systems [1–6] and point-to-multipoint networks [7–15], which deeply facilitates their applications in scientific projects, such as the well-known Square Kilometer Array (SKA) [16] and Acatama Large Millimeter Wave Array (ALMA) telescope [17]. On the other hand, various fiber optic time synchronization systems were also demonstrated by two-way clock comparison or round-trip transfer [18–21], making the technique more closer to be widely used in navigation, guidance, security, et al. However, still it should be noted that sometimes exclusive time or frequency transfer cannot meet the demand of particular applications, such as the deep space exploration, coherent radar array and communication systems for which both time and frequency synchronization is indispensable. Therefore simultaneous time and frequency transfer is needed for such applications.

One technical issue in simultaneous time and frequency transfer is how to avoid the interference between the time signal (TS) and the frequency signal (FS). Some groups use the wavelength division multiplexing technique to distinguish them in the optical domain [14,22]. The method is straightforward, but in fact it is just the direct combination of two independent systems. Also this will lead to relative phase shift between TS and FS when the transmission delay varies, which may be a problem in applications where mutual calibration of the TS and FS is needed. A better choice is to transfer them by a common optical carrier. In [13], Z. Jiang et al. try to reduce the interference by modulating FS and TS on two individual Mach–Zehnder modulators. Though obvious suppression of the interference is observed in the report, unavoidable interference is still expected because two signals will beat with each other in photon detector, and one may have to use a clear-up oscillator to purify the FS at the remote end. L. Sliwczynski et al. [6,11] design a special structure to combine two signals. They mark the TS by introducing phase change to one of the falling edges of the 10 MHz square signal, so that the FS and TS can be recovered respectively with reference to the rising and the falling edges. The scheme is quite effective, however, a slave oscillator is still indispensable to extract the FS from the rising edges, which also increases the structural and technical complexity of the remote user.

In this manuscript, we present a new solution to simultaneously transfer the TS and FS. The solution is based on sub-carrier modulation in which the base-band TS is shifted to intermediate frequency. It not only realizes the joint transfer of TS and FS in common optical channels, but also eliminates the interference on FS without additional clear-up slave oscillator. Experiment is performed to transfer a 50 MHz modulated TS and a 400 MHz radio frequency (RF) signal. Stabilization

* Corresponding authors.
E-mail addresses: yulq_go@163.com (L. Yu), nj_lulin@163.com (L. Lu).

https://doi.org/10.1016/j.optcom.2018.06.043
Received 29 March 2018; Received in revised form 23 May 2018; Accepted 16 June 2018

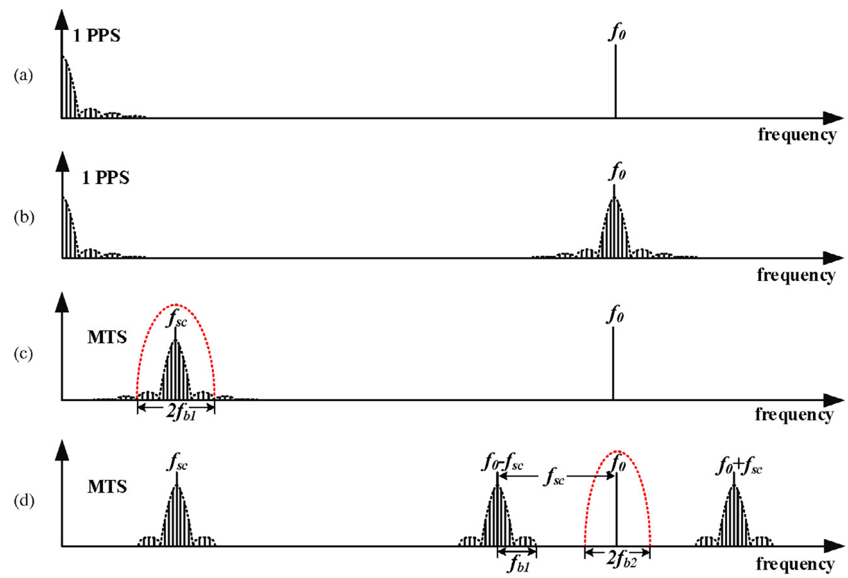

Fig. 1. Sketch of the spectra of (a) 1PPS and RF before modulation, (b) 1PPS and RF after joint transfer, (c) MTS and RF after sub-carrier modulation, (d) MTS and RF after joint transfer.

schemes are also applied to counteract the variation of the transmission delay.

2. Principle

The spectra of TS and FS, as well as their interactions after transfer, are shown in Fig. 1. The TS is usually in form of one pulse per second (1 PPS) and its Fourier spectrum is composed of discrete points with the absolute envelop of a sinc function, while FS is a continuous sinusoidal wave and its spectrum is a single point, denoted by f_0 in Fig. 1(a). Fig. 1(b) shows the spectra when FS and TS are directly combined and transferred together. It is expected that around f_0 there will be dense interfering components whose spectrum is identical to that of the 1 PPS. This is also the case reported in [23], indicating that the FS is interfered by the TS. There are two reasons for the illustrated interference. One is that the TS and FS, when received by the remote user, will mutually beat with each other in photon detector, obeying square law. Moreover, because neither the direct modulation nor external modulation is ideally linear, the TS will be modulated on the FS in the local modulation procedure, known as cross modulation. As the 1 PPS can be regarded as a square wave of 1 Hz, the spacing of its spectrum components is 1 Hz too. Therefore it will be impossible for ordinary electronic filters to clear up the interfering frequencies around f_0. Even if in some schemes the timing signal is in form of pseudo-random code with frequency of several kilohertz [24], it is still too harsh for the filtering. In such case additional clear-up oscillator with locking bandwidth <1 Hz is needed to perform narrow-band filtering to purify the FS.

Here we propose a solution to combine the FS and TS, which can relieve FS from the interference of TS when they are simultaneously transferred in the same transmission channel. To start with, we modulate the TS on an intermediate-frequency sub-carrier, f_{sc}, as is shown in Fig. 1(c). Then when the modulated TS (MTS) is transferred with the FS, the center frequency of the interfering signals will shift from f_0 to $f_0 \pm f_{sc}$. However, since the spectrum of the MTS is similar to that of the TS, the interfering frequency components still exist. So we use a bandpass filter to limit the bandwidth of the MTS within $2f_{b1}$ before it is combined with FS. As a result, the bandwidth of the interfering signal is also limited. Then after the MTS and FS are detected at the remote end, we use another ordinary bandpass filter, whose center frequency and bandwidth is respectively f_0 and $2f_{b2}$, to clear up the side bands. As long as the condition $f_{sc} > f_{b1} + f_{b2}$ is satisfied like the case in Fig. 1(d), all the residual interfering components will remain outside the passband of the filter. Then the FS can be extracted without deterioration.

To stabilize the FS, we make some improvement over the passive hybrid frequencies transfer scheme proposed in our previous research [25], shown in Fig. 2. The FS, $\boldsymbol{V_R} \propto \cos \omega_0 \boldsymbol{t}$, is bidirectionally transferred over the optical fiber, indicated by the blue path. φ is the phase change over single trip. By mixing the round-trip FS, $\boldsymbol{V_R} \propto \cos\left(\omega_0 \boldsymbol{t} + 2\varphi\right)$, with the frequency-tripled local reference, $\boldsymbol{V_T} \propto \cos 3\omega_0 \boldsymbol{t}$, we get the phase-conjugated signal, $\boldsymbol{V_I} \propto \cos\left(2\omega_0 \boldsymbol{t} - 2\varphi\right)$, which could counteract the phase change of the optical fiber. Here instead of directly mixing V_R and V_T, we use the dual-mixer time-difference (DMTD) method to avoid the crosstalk from the second harmonics of V_R, which is also adopted in [26]. An auxiliary frequency, $\boldsymbol{V_A} \propto \cos \omega_{\boldsymbol{A}} \boldsymbol{t}$, is introduced to pre-mix with the two signals. They can do either sum-frequency mixing or beat-frequency mixing. Here we choose the latter. Then the outputs, $\boldsymbol{V_x} \propto \cos\left[\left(\omega_0 - \omega_{\boldsymbol{A}}\right)\boldsymbol{t} + 2\varphi\right]$ and $\boldsymbol{V_y} \propto \cos\left(3\omega_0 - \omega_{\boldsymbol{A}}\right)\boldsymbol{t}$, are mixed again to get the beat signal V_I. It is critical that ω_A should be properly chosen so that no crosstalk will arise in three mixing procedures. The stability of the auxiliary signal is insignificant since its phase terms are canceled eventually. Then after frequency conversion with a coefficient of 0.5m, the phase-conjugated signal $\cos \boldsymbol{m}\left(\omega_0 \boldsymbol{t} - \varphi\right)$ is transferred with the original FS and serves the remote user as a stable frequency standard, illustrated by the red path.

We developed a large-dynamic-range compensation scheme to compensate the true time delay of TS [27]. The scheme runs by resolving the compensation time according to the period of a precise clock into the integral-multiples part and fractional part. Fig. 3 illustrates the compensation procedure. The total compensation time is $1-\tau = nT + \Delta T$, where τ is the single-trip time delay, T the clock period, and ΔT the fractional part after resolution. At the beginning, TS triggers the counter to count the rising edges of the clock. Then it is regenerated when the counting reaches n, amounting to a true time delay of nT. After sub-carrier modulation the MTS is delayed ΔT by an electronic variable delay line (EVDL), accomplishing the whole time compensation.

3. Experimental results

To test the proposed scheme, we simultaneously transfer 50 MHz MTS, 400 MHz and 1 GHz FS over 100 km optical fiber using the same laser diode (LD). The setup of the proof-of-concept experiment is illustrated in Fig. 4 and elaborated below. We first focus on the frequency transfer subsystem, as shown in the left part of the schematic.