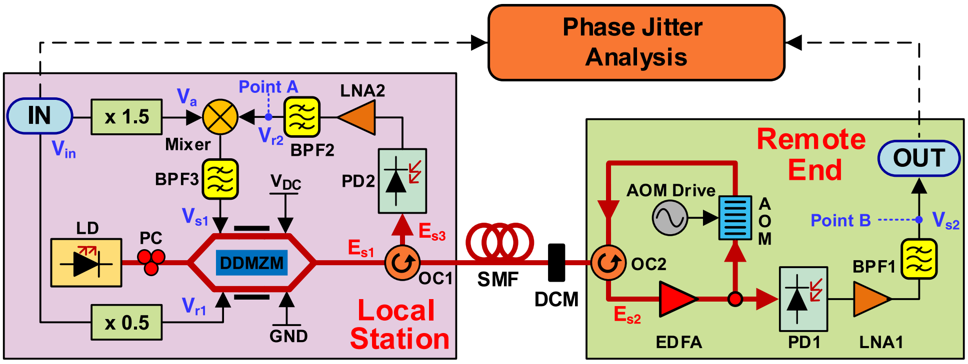
IEEE Photonics Journal
An IEEE Photonics Society Publication

Stable Radio Frequency Transmission of Single Optical Source Over Fiber Based on Passive Phase Compensation

Volume 13, Number 1, February 2021

Chen Hu
Bin Luo
Wenlin Bai
Wei Pan
Lianshan Yan
Xihua Zou



DOI: 10.1109/JPHOT.2021.3054043

Stable Radio Frequency Transmission of Single Optical Source Over Fiber Based on Passive Phase Compensation

Chen Hu, Bin Luo, Wenlin Bai, Wei Pan, Lianshan Yan, and Xihua Zou

Center for Information Photonics & Communications, School of Information Science and Technology, Southwest Jiaotong University, Chengdu 610031, China

DOI:10.1109/JPHOT.2021.3054043

Manuscript received October 7, 2020; revised January 19, 2021; accepted January 20, 2021. Date of publication January 25, 2021; date of current version February 5, 2021. This work was supported in part by National Key Research and Development Program of China under Grant 2019YFB2203204 and in part by National Natural Science Foundation of China under Grant 61922069. Corresponding author: Bin Luo (e-mail: Bluo@home.swjtu.edu.cn).

Abstract: In this paper, we propose a stable radio frequency(RF) transmission scheme for optical link based on Dual drive Mach-Zehnder modulator(DDMZM). By frequency mixing, the phase jitter of the output signal caused by environment variation has been automatically compensated. Different from other passive compensation schemes, the reference signal and the pre-compensation signal are modulated on one optical carrier by a DDMZM, and the crosstalk of two RF signals can be depressed by using dispersion compensation and adjusting the bias voltage of DDMZM, without multiple frequency multiplications and divisions. Meanwhile, the noises induced by Rayleigh scattering can be suppressed by using acousto-optic modulator. Our scheme is featured by single laser diode employed and no extra phase jitter induced by wavelength differences, with the advantages of simple structure and cost-effectiveness. In the experiment, we demonstrate 10 GHz RF signal stability transmission over 50 km single mode fiber, the phase jitter mean square error is 0.82 ps during 10 hours.

Index Terms: Passive phase compensation, radio over fiber, stable phase transmission.

1. Introduction

Highly stable radio frequency (RF) signals are widely used in deep space communication, antenna array [1], [2] and basic physical measurement [3]. Compared with transmission methods of electricity, optical fiber is considered as a ideal alternative for signal transmission due to their advantages of low loss, wide bandwidth and strong anti-interference capability [4], [5]. However, the variations of external environment, such as temperature and stress, will introduce random phase jitter and destroy the stability of system.

Recently, various stable RF optical transmission schemes have been reported [6]–[17] based on the principle of round-trip compensation. In some schemes [6]–[11], the phase information is acquired by the round-trip signal, and the phase jitter is actively eliminated by using feedback control, such as using voltage-controlled oscillators to adjust the phase of the input RF signal [6], [7], using microwave photonic phase shifter based on dual drive Mach-Zehnder modulator(DDMZM) [8] or dual parallel Mach-Zehnder modulator(DPMZM) [9] to control the phase of beat RF signal at

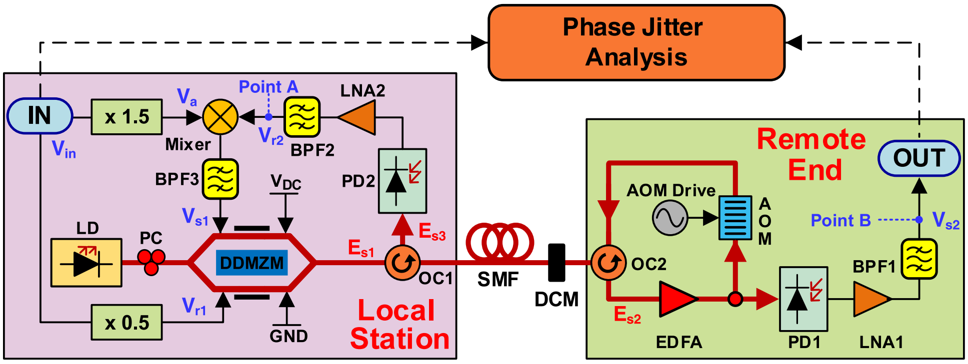


Fig. 1. Schematic diagram of stable RF signal transmission system based on frequency mixing. LD, Laser diode; PC, Polarization controller; DDMZM, Dual drive Mach-Zehnder modulator; OC, Optical circulator; SMF, Single mode fiber; DCM, Dispersion compensation module; EDFA, Erbium-doped fiber amplifier; AOM, Acousto-optic modulator; PD, Photo detector; LNA, Low noise amplifier; BPF, Band-pass filter.

remote, and using wavelength tunable laser to change the time delay of RF signal transmission over fiber [10], [11]. These schemes can greatly reduce the phase jitter, with the advantage of low noise. However, the phase recovery time will be limited to the proportional integral derivative algorithm [12], [13], and the complex feedback control circuits are indispensable. In other compensation schemes, the phase jitter is passively compensated by electric [12]–[16] or microwave photonic [17] frequency mixing based on phase conjugation. However, in order to avoid the interference between reference signal and the pre-compensation signal, the two RF signals are modulated on different lasers [12]–[14], [17] or changed several times by frequency conversion modules [15], [16], which increase the systematic complexity and cost. Furthermore, the leftover phase jitter induced by wavelength difference of lasers will result in degradation of phase compensation performance.

In this paper, we propose a stable RF optical transmission scheme over fiber. The phase drift induced by fiber refractive index variations is compensated automatically based on RF mixing and principle of phase conjugation. Compared with other passive compensation schemes, only one optical carrier is used to transmit the reference and pre-compensation signal simultaneously by DDMZM. In fact, the received signal will contain crosstalk caused by the two RF signals. But the theoretical analysis shows that the intensity of crosstalk is related with the time delay of the two arms of DDMZM under the dispersion effect of the fiber. Fortunately, we find that the crosstalk in two RF signals can be depressed at same time and the power fading due to chromatic dispersion is also avoided in some suitable operation conditions. Therefore, the crosstalk can be effectively depressed by means of controlling the dispersion parameter of optical link and bias voltage of DDMZM, without using different lasers or multiple frequency multiplications and divisions. Thanks to the single laser involved, the leftover phase jitter caused by wavelength difference can be effectively eliminated. In addition, an acousto-optic modulator(AOM) is employed in the remote end to suppress the Rayleigh scattering noises, which can further simplify our system and is conducive to practical application. In the experiment, we successfully achieve 10 GHz RF signal transmission of phase stabilization via 50 km single mode fiber(SMF), and the phase jitter mean square error(RMS) is only 0.82 ps during 10 hours.

2. Principle

The schematic diagram of stable RF signal transmission system is shown in Fig. 1. A narrow line-width laser is employed as the optical carrier, with angular frequency of ω_0 and amplitude of E_0. The input RF signal V_{in} is split into two parts firstly and can be expressed as

$$V_{in}(t) = V_0 \cos(\omega_1 t + \phi_1), \tag{1}$$

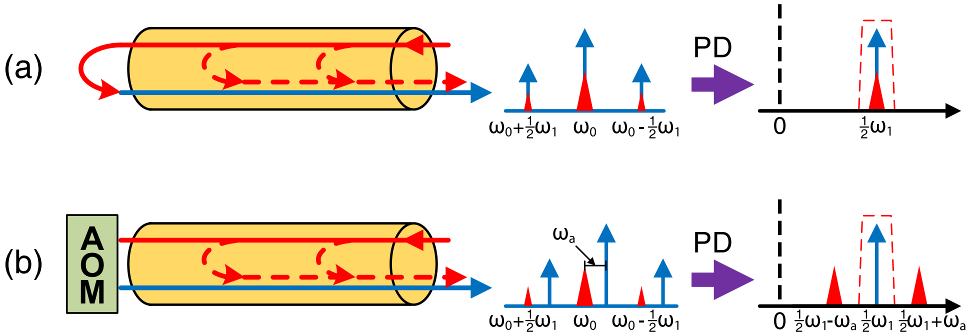


Fig. 2. The principle of depressing the noise caused by Rayleigh scattering (a) without and (b) with AOM.

where V_0, ω_1 and ϕ_1 are the amplitude, angular frequency and phase of V_{in}, respectively.

The two parts of V_{in} are sent to the different frequency conversion modules respectively, and the output signals are recorded as reference signal V_{r1} and assistant signal V_a

$$V_{r1}(t) = V_1 \cos\left(\frac{1}{2}\omega_1 t + \frac{1}{2}\phi_1\right), \tag{2}$$

$$V_a(t) = V_2 \cos\left(\frac{3}{2}\omega_1 t + \frac{3}{2}\phi_1\right), \tag{3}$$

where V_1 and V_2 are the amplitudes of them. Then, V_{r1} is modulated on optical carrier via the lower arm of DDMZM and transmitted to remote over fiber. Here, a dispersion compensation module(DCM) is used to compensate the dispersion parameter of optical link.

In the remote end, the received optical signal is amplified by a erbium-doped fiber amplifier(EDFA) and split into two part by a optical splitter. The one part is transmitted back via the same optical link, where an AOM is used to depress the noise caused by Rayleigh scattering, and its principle is shown as follows.

In Fig. 2, the left side shows optical signal transmission over fiber, the red and blue lines are sending and return optical signals, the dotted lines are back scattering lights. The middle side shows the spectrum of return light, where ω_a is the angular frequency of AOM drive signal, and the blue arrows and red triangles mean the signal and scattering lights, respectively. The right side is the detected RF signal. As can be seen, the frequency of return optical signal is shifted by AOM, so the Rayleigh scattering noises will have frequency differences of $\pm\omega_a$ as RF signal and can be filtered by the band-pass filter(BPF).

In the local station, the return optical signal is detected by a photo detector(PD2) and filtered out by BPF2 to obtain the round-trip RF reference signal V_{r2}. Because the phase shift induced by transmission over fiber is proportional to the frequency of RF signal and the time variation τ is much slower than the round-trip transmission time, the phase shifts of V_{r1} in forward and backward transmission are approximately equal and marked as ϕ_2. Therefore V_{r2} can be defined in the ideal form

$$V_{r2}(t) = V_3 \cos\left(\frac{1}{2}\omega_1 t + \frac{1}{2}\phi_1 + 2\phi_2\right), \tag{4}$$

where V_3 is the amplitude of V_{r2}, $\phi_2 = -\frac{\omega_1}{2}(\beta_1 z + \tau)$, β_1 is the first order Taylor series of the propagation constant β, and z is the length of SMF. By mixing V_a with V_{r2} and passing through BPF3, the obtained pre-compensation signal V_{s1} can be written as

$$V_{s1}(t) = V_4 \cos(\omega_1 t + \phi_1 - 2\phi_2), \tag{5}$$

where V_4 is the amplitude of V_{s1}. Particularly, V_{s1} is modulated on the same optical carrier via the upper arm of DDMZM and transmitted to the remote end via the same optical link, and the output signal V_{s2} can be received at remote after being detected by PD1 and filtered out by BPF1. In addition, the power attenuation of the RF link is compensated by low noise amplifier(LNA).

Because the two RF signal V_{r1} and V_{s1} are modulated on the same optical carrier, the further analysis is required to find the solution to depress the crosstalk between them. At local, the output of DDMZM E_{s1} can be given by

$$E_{s1}(t) = \frac{E_0}{2}\exp(i\omega_0 t)\left\{\exp\left[im_1\cos(\frac{1}{2}\omega_1 t + \frac{1}{2}\phi_1)\right] + \exp\left[im_2\cos(\omega_1 t + \phi_1 - 2\phi_2) + i\theta\right]\right\}, \tag{6}$$

where $m_1 = V_1/V_\pi$, $m_2 = V_4/V_\pi$ are the modulation depths, $\theta = V_{DC}/V_\pi$ is the initial phase difference caused by the time delay of the two arms, V_π is the half-wave voltage of DDMZM. After propagating inside z km SMF, the received signal E_{s2} is

$$E_{s2}(t) \propto E_{s1}(t-\tau)\exp(-i\beta z). \tag{7}$$

Generally, β can be expanded in a Taylor series, and the optical field can be described by the sum of Bessel functions. Therefore,

$$\begin{aligned} E_{s2}(t) \propto \frac{E_0}{2}\exp[i(\omega_0(t-\tau)-\beta_0 z)]\Big\{ & J_0(m_1) + 2J_1(m_1)\exp\left[i\left(\frac{\pi}{2}-\frac{1}{4}\varphi\right)\right]\cos\left(\frac{1}{2}\omega_1 t + \frac{1}{2}\phi_1 + \phi_2\right) \\ & - 2J_2(m_1)\exp(-i\varphi)\cos(\omega_1 t + \phi_1 + 2\phi_2) + J_0(m_2)\exp(i\theta) + 2J_1(m_2)\exp\left[i\left(\frac{\pi}{2}+\theta-\varphi\right)\right] \\ & \cdot\cos(\omega_1 t + \phi_1) - 2J_2(m_2)\exp[i(\theta - 4\varphi)]\cos(2\omega_1 t + 2\phi_1)\Big\}, \end{aligned} \tag{8}$$

where $\varphi = \frac{1}{2}\beta_2\omega_1^2 z$ is a parameter introduced by group velocity dispersion(GVD), β_0 and β_2 are Taylor series of β, and J_0, J_1 and J_2 are Bessel function of the first kind. In addition, the higher order side-bands have been reasonably neglected under small signal modulation.

After being detected by a square-law detector and filtered out by BPF1, the obtained RF signal V_{s2} with frequency of ω_1 will contains two terms, and its expression is

$$\begin{aligned} V_{s2} \propto E_0^2\Big\{ & a_0 J_1(m_2)\sin\left(\varphi - \frac{\theta}{2}\right)\cdot\cos(\omega_1 t + \phi_1) \\ & + \left[\frac{J_1^2(m_1)}{2} - a_0 J_2(m_1)\cos\left(\varphi + \frac{\theta}{2}\right)\right]\cdot\cos(\omega_1 t + \phi_1 + 2\phi_2)\Big\}, \end{aligned} \tag{9}$$

where $a_0 = |J_0(m_1) + J_0(m_2)\exp(i\theta)|$, and the first and second terms are desired signal and crosstalk, respectively. In addition, the beat signals of first and second order side-bands are ignored because they are too weak.

Similarly, the return optical signal E_{s3} in the local station can be given by

$$E_{s3}(t) = E_{s2}(t-\tau)\exp(-i\beta z)\exp[i\omega_a(t-\tau)], \tag{10}$$

and the real round-trip RF signal V'_{r2} with frequency of $\frac{1}{2}\omega_1$ is

$$\begin{aligned} V'_{r2} \propto E_0^2\Big\{ & a_0 J_1(m_1)\sin\left(\frac{\varphi}{2} + \frac{\theta}{2}\right)\cdot\cos\left(\frac{1}{2}\omega_1 t + \frac{\phi_1}{2} + 2\phi_2\right) \\ & + J_1(m_1)J_1(m_2)\cos\left(-\frac{3\varphi}{2} + \theta\right)\cdot\cos\left(\frac{1}{2}\omega_1 t + \frac{\phi_1}{2}\right)\Big\}. \end{aligned} \tag{11}$$

As with V_{s2}, V'_{r2} also consists the two terms of desired signal and crosstalk.

Obviously, the crosstalk has the same frequency but different phase with desired signal, will directly affect the phase stabilization of V_{s2}, and influence the accuracy of phase information

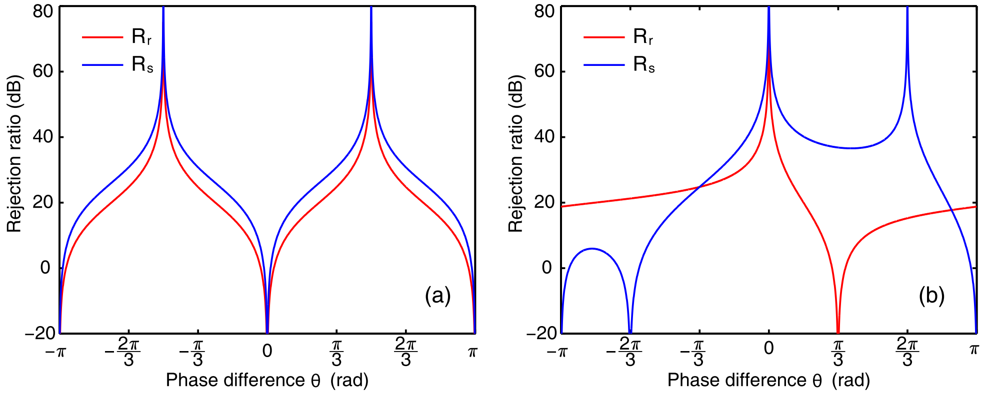


Fig. 3. Evolutions of rejection ratios along θ when the values of φ are (a) 0 and (b) $-\frac{\pi}{3}$.

extracted from V'_{r2}. But it should be of concern that their amplitudes are related to θ and φ. Thus, the crosstalk can be suppressed by adjusting the bias voltage of DDMZM and the dispersion parameter of the optical link. So the point of our scheme is to find the suitable values of θ and φ that the crosstalk in V_{s2} and V'_{r2} can be suppressed at the same time. In addition, φ can be regarded as a constant, because its absolute value is not large (close to $\frac{2\pi}{3}$ when 10 GHz RF signal transmitted over 50 km SMF), and the variation of β_2 induced by temperature is less than ±1% between -40 to 80 ° C according to reference [18].

To facilitate analysis, the intensity ratios of the signal to crosstalk in V'_{r2} and V_{s2} are defined as rejection ratio R_r and R_s, respectively. Their expressions can be obtained from eq.(9) and eq.(11) and shown as

$$R_r = \frac{8(1+\cos\theta)}{m_2^2} \cdot \frac{1-\cos(\varphi+\theta)}{1+\cos(3\varphi-2\theta)}, \tag{12}$$

$$R_s = \frac{8m_2^2}{m_1^4} \cdot \frac{1-\cos(2\varphi-\theta)}{[(2+2\cos\theta)^{-\frac{1}{2}}-\cos(\varphi+\frac{\theta}{2})]^2}. \tag{13}$$

where $J_0(m)$, $J_1(m)$ and $J_2(m)$ are approximated to 1, $\frac{m}{2}$ and $\frac{m^2}{8}$ by using power series under small signal modulation. Mathematically, R_r and R_s can both attain infinity in the cases where θ and φ satisfy the conditions that $\theta = 0,\ \varphi = \pm\frac{1}{3}\pi + 2k\pi\ (k \in Z)$ or $\theta = \pm\frac{1}{2}\pi,\ \varphi = 2k\pi\ (k \in Z)$. Fig. 3 shows the simulation of evolution curves of R_r and R_s along θ when the values of φ are 0 and $-\frac{\pi}{3}$, respectively. As can be seen, the crosstalk in V_{s2} and V'_{r2} can both be effectively depressed by adjusting the bias voltage of DDMZM and the dispersion parameter. Moreover, by substituting this conditions into eq.(9) and eq.(11), we can find the power fading caused by GVD is also avoided. After the negative effects caused by the crosstalk have been depressed, the real round-trip RF signal V'_{r2} is approximate to the ideal signal V_{r2} what we defined previously, and the output signal V_{s2} becomes

$$V_{s2}(t) \propto \cos(\omega_1 t + \phi_1), \tag{14}$$

where the phase drift has been compensated automatically based on principle of phase conjugation, and it has the same phase as the input signal V_{in}.

3. Experiment

A proof-of-concept experiment is carried out based on Fig. 1, shows the 10 Ghz RF signal stable transmission for 50 km SMF. The two different standard microwave sources are used at local and locked by the 10 MHz synchronizing signal, to generate the 5 GHz reference signal V_{r1} and 15 GHz

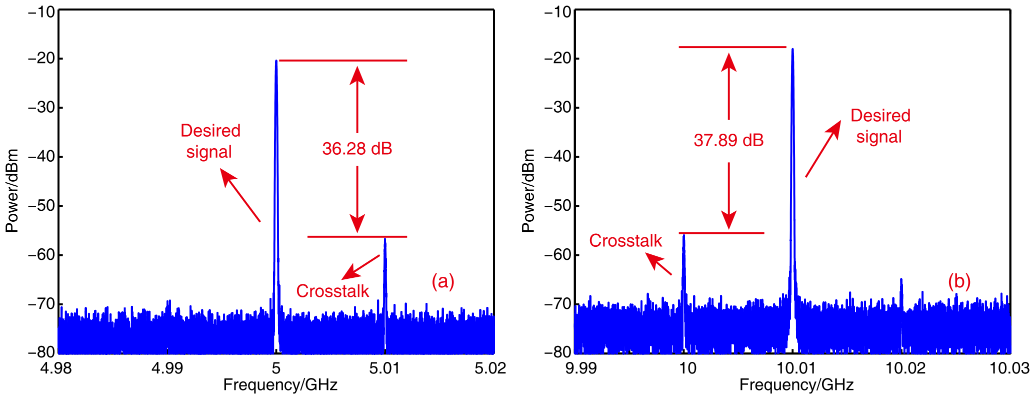


Fig. 4. The Spectrums of (a) round-trip and (b) output signal.

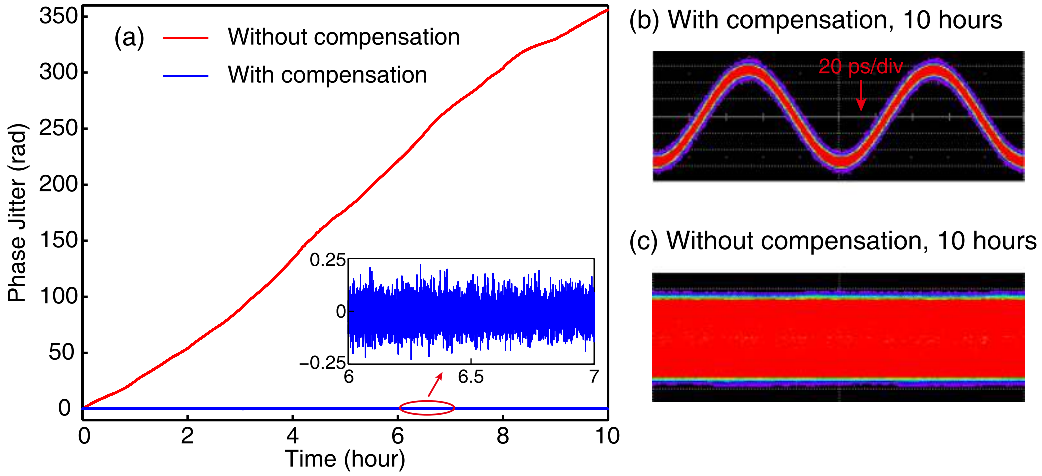


Fig. 5. Measured results of 10 GHz signal via 50 km SMF: (a) phase jitters in the two cases and time-domain waveforms (b) with and (c) without compensation.

assistant signal V_a, as the equivalent replacement for frequency conversions, and the standard 10 GHz signal is obtained from them by frequency mixing. The optical source is provided by a narrow linewidth laser with wavelength of 1550.12 nm. The bandwidth and half-wave voltage of DDMZM are 25 GHz and 5.4 V, and the bias voltage is provided by a stable DC source. The value of φ is controlled to $-\frac{1}{3}\pi$ by a DCM. The frequency of the AOM driver signal is 80 MHz, and the bandwidths of involved PDs and BPFs are 11 GHz and 100 MHz, respectively. Furthermore, the fiber is spooled in lab, and proper electrical and optical amplifiers are used to compensate for the attenuation of transmission link.

Before verifying the phase compensation performance of system, the effect of suppressing crosstalk needs to be confirmed firstly. The frequency of V_a is set to 15.01 GHz temporarily, in order to observe the rejection ratio of desired signal and crosstalk. Next, using a signal analyzer with bandwidth of 13.5 GHz to measure the RF signals at point A and B in Fig. 1 respectively. Then adjusting the output voltage of stable DC source to guarantee the values of R_r and R_s get the maximum at the same time. As shown in Fig. 4, the experimental results are consistent with the previous analysis, the values of R_r and R_s are 36.28 and 37.89 dB, respectively. Finally, the frequency of V_a is reset back to 15 GHz.

To verify its long time compensation performance, the system has run in lab for 10 hours with and without phase compensation, and the results are measured by a real-time sampling oscilloscope with bandwidth of 13 GHz. Fig. 5(a) shows the phase jitters of 10 GHz signal with and without phase compensation, and their time-domain waveforms after 10 hours are shown as Fig. 5(b) and (c), respectively. Obviously, the uncompensated signal has a large phase drift, and its phase jitter RMS is 1803.03 ps (about 113.29 rad) during 10 hours. Whereas, the phase of compensated signal is stable in the process of experiment, and its phase jitter RMS is only 0.82 ps (about 0.05 rad) during 10 hours.

4. Conclusion

In conclusion, we propose a stable RF phase transfer system based on passive compensation, only one optical source and one DDMZM are involved. The key significance of our scheme is that the crosstalk of different RF signals can be effectively depressed by adjusting the bias voltage of DDMZM and dispersion parameter of optical link, without multiple electro-optical conversions and frequency conversions. Meanwhile, the leftover phase jitter caused by wavelength difference has been effectively eliminated. In the experiment, the 10 GHz RF signal is transmitted stably over 50 km SMF, the phase jitter RMS is 0.82 ps during 10 hours.

References

[1] M. Calhoun, S. Huang, and R. L. Tjoelker, “Stable photonic links for frequency and time transfer in the deep-space network and antenna arrays,” *Proc. IEEE*, vol. 95, no. 10, pp. 1931–1946, Oct. 2007.
[2] W.-Q. Wang, “GPS-based time & phase synchronization processing for distributed SAR,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 45, no. 3, pp. 1040–1051, Jul. 2009.
[3] A. Matveev *et al.*, “Precision measurement of the hydrogen 1S-2 S frequency via a 920-km fiber link,” *Phys. Rev. Lett.*, vol. 110, no. 23, Jun. 2013.
[4] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nat. Photon.*, vol. 1, no. 6, pp. 319–330, Jun. 2007.
[5] O. Lopez, A. Haboucha, B. Chanteau, C. Chardonnet, A. Amy-Klein, and G. Santarelli, “Ultra-stable long distance optical frequency distribution using the internet fiber network,” *Opt. Exp.*, vol. 20, no. 21, pp. 23518–23526, Oct. 2012.
[6] S. Wang *et al.*, “Distribution of high-stability 10 GHz local oscillator over 100 km optical fiber with accurate phase-correction system,” *Opt. Lett.*, vol. 39, no. 4, pp. 888–891, Feb. 2014.
[7] D. Wang, T. Jiang, C. Liu, S. Zhou, and S. Yu, “Stable radio frequency dissemination via a 1007 km fiber link based on a high-performance phase lock loop,” *Opt. Exp.*, vol. 26, no. 19, pp. 24479–24486, Sep. 2018.
[8] R. Wu, J. Lin, T. Jiang, C. Liu, and S. Yu, “Stable radio frequency transfer over fiber based on microwave photonic phase shifter,” *Opt. Exp.*, vol. 27, no. 26, pp. 38109–38115, Dec. 2019.
[9] J. Shen, G. Wu, L. Hu, W. Zou, and J. Chen, “Active phase drift cancellation for optic-fiber frequency transfer using a photonic radio-frequency phase shifter,” *Opt. Lett.*, vol. 39, no. 8, pp. 2346–2349, Apr. 2014.
[10] A. Zhang *et al.*, “Phase stabilized downlink transmission for wideband radio frequency signal via optical fiber link,” *Opt. Exp.*, vol. 22, no. 18, pp. 21560–21566, Sep. 2014.
[11] A. Ben-Amram, Y. Stern, Y. London, Y. Antman, and A. Zadok, “Stable closed-loop fiber-optic delay of arbitrary radio-frequency waveforms,” *Opt. Exp.*, vol. 23, no. 22, pp. 28244–28257, Nov. 2015.
[12] W. Li, W. T. Wang, W. H. Sun, W. Y. Wang, and N. H. Zhu, “Stable radio-frequency phase distribution over optical fiber by phase-drift auto-cancellation,” *Opt. Lett.*, vol. 39, no. 15, pp. 4294–4296, Aug. 2014.
[13] F. Yin *et al.*, “Phase-conjugation-based fast RF phase stabilization for fiber delivery,” *Opt. Exp.*, vol. 22, no. 1, pp. 878–884, Jan. 2014.
[14] J. Wei, F. Zhang, Y. Zhou, D. Ben, and S. Pan, “Stable fiber delivery of radio-frequency signal based on passive phase correction,” *Opt. Lett.*, vol. 39, no. 11, pp. 3360–3362, Jun. 2014.
[15] Y. Cui, T. Jiang, S. Yu, R. Wu, and W. Gu, “Passive-compensation-based stable RF phase dissemination for multiaccess trunk fiber link with anti-gvd and anti-backscattering function,” *IEEE Photon. J.*, vol. 9, no. 5, Oct. 2017, Art. no. 7203608.
[16] L. Yu *et al.*, “Stable radio frequency dissemination by simple hybrid frequency modulation scheme,” *Opt. Lett.*, vol. 39, no. 18, pp. 5255–5258, Sep. 15 2014.
[17] X. Guo, X. Wang, Z. Li, and Y. Dong, “Optical parametric mixer-based passive phase correction for stable transfer of millimeter waves,” *Opt. Lett.*, vol. 41, no. 19, pp. 4574–4577, Oct. 2016.
[18] G. Ghosh, M. Endo, and T. Iwasaki, “Temperature-dependent sellmeier coefficients and chromatic dispersions for some optical-fiber classes,” *J. Lightw. Technol.*, vol. 12, no. 8, pp. 1338–1342, Aug. 1994.