Simulation of the effect of modulation depth on fiber frequency transfer

Baodong Zhao
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: zhaobaodong@bupt.edu.cn

Hao Gao
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: hao@bupt.edu.cn

Zhuoze Zhao
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: zhaozhuoze@bupt.edu.cn

Yapeng Liu
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: 2023010179@bupt.edu.cn

Song Yu
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: yusong@bupt.edu.cn

Bin Luo
State Key Laboratory of Information Photonics and Optical Communications
Beijing University of Posts and Telecommunications
Beijing 100876, China
Email: luobin@bupt.edu.cn

***Abstract*—Frequency transmission via optical fiber is pivotal in fields such as geodesy and deep space exploration due to its precision and reliability. Among various transmission methods, RF frequency transmission stands out for its simplicity and cost-effectiveness. We've constructed a simulation platform for optical fiber frequency transmission to meticulously assess the impact of varying modulation depths on frequency stability. Our findings reveal that fractional frequency stability is enhanced as modulation depth increases, provided it stays within the linear operational range of the modulator.**

Keywords—frequency transmission, modulation depth

I. Introduction

Frequency transmission via optical fiber holds a significant position in fields such as geodesy, deep space exploration, and navigation due to its inherent advantages such as low attenuation. RF frequency transmission garners considerable attention, often favored for its relatively simple structure and cost efficiency.

In the process of frequency transfer requires the RF signal to be modulated to the optical carrier through a Mach-Zehnder modulator (MZM). The modulated signal travels through a fiber-optic link to the receiver, where it is detected and processed by a photodetector (PD). Enhancing the optical power incident on the PD improves link gain, elevates the signal-to-noise ratio, and results in a higher microwave output power, thus optimizing the system's performance for transmission. However, the optical power entering the PD must not be too high, as excessive optical power may lead to harmonic distortion in the photodetector, reduce its response speed, and potentially cause damage to the PIN diode[1]. In quadrature-biased modulation links, where the optical carrier power, devoid of information, dominates the total power[2], increasing the modulator's modulation depth is seen as an effective approach to enhance the fractional frequency instability of frequency transfer.

In our study, we've developed a fiber stable frequency transmission platform to examine how different modulation depths affect fractional frequency stability. Our results show that, within the linear operating range, an increase in modulation depth correlates with a reduction in fractional frequency stability.

II. Experiment setup

The system structure block diagram is shown in Fig. 1. The 2.4 GHz signal modulated by the MZM is transmitted to the receiver (RX), detected by the remote PD, and transmitted back to the transmitter (TX) through MZM to provide information of phase fluctuation. The 2.4 GHz signal which carries the phase fluctuation and the 7.2 GHz signal tripled by the local 2.4GHz are downconverted to obtain the 4.8 GHz phase conjugate signal. The 4.8 GHz signal is conveyed via a fiber link, where it undergoes phase fluctuation compensation.

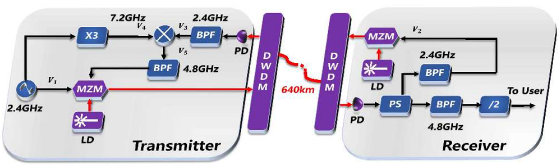

Fig. 1. The structure diagram of system. MZM: Mach-Zehnder modulator; PD: photodetector; LD: laser di-ode; BPF: bandpass filter; PS: power splitter.

The compensation of phase fluctuation caused by fiber link in shown in Fig. 2. The 2.4 GHz signal from the TX can be expressed as:

$$V_1 = \cos(\omega_1 t + \varphi_1), \tag{1}$$

The signal V_2, which is V_1 transmitted to the RX and carries phase fluctuation φ_p over the fiber link, can be represented as:

$$V_2 = \cos(\omega_1 t + \varphi_1 + \varphi_p), \tag{2}$$

V_2 is transmitted back to the TX end through the modulator, and the signal V_3 detected by the PD of the TX end can be represented as

$$V_3 = \cos(\omega_1 t + \varphi_1 + 2\varphi_p), \tag{3}$$

V_3 is mixed with 7.2 GHz V_4 to give a 4.8 GHz pre-compensated signal V_5:

$$V_5 = \cos(2\omega_1 t + 2\varphi_1 - 2\varphi_p), \tag{4}$$

V_5 is transmitted back to RX to compensate for phase fluctuations.

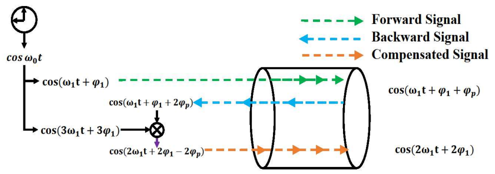

Fig. 2. The structure diagram of link phase fluctuation compensation.

The structure diagram of MZM is shown in Fig. 3. The MZM consists of two upper and lower arms. $V_{up}(rf)$ and $V_{lo}(rf)$ are the RF signal to be modulated. $V_{up}(dc)$ and $V_{lo}(dc)$ are the bias voltage to control the operating point of the MZM. We set $V_{up}(rf)$ and $V_{lo}(rf)$ as signals to be transmitted, $V_{up}(dc)$ is 2.5 V, $V_{lo}(dc)$ is 0 V. The bias voltage of the modulator to 5 V. Thus, the MZM works as quadrature-biased. Modulation depth is usually defined as:

$$m = \frac{\pi V_{rf}}{V_\pi} \tag{5}$$

We change the modulation depth by changing the RF signal power input to MZM.

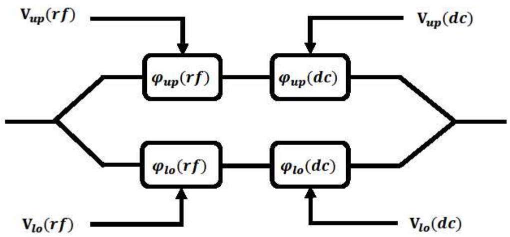

Fig. 3. The structure diagram of MZM.

The simulation software diagram is shown in Fig. 4. The input power of the laser is 10 dBm. To simulate the real environment, we set up a 640 km fiber span with a loss of 0.2 dB/km and a dispersion of 1.7×10^{-5} s/m^2, and every 80 km, we included an 8 km span of fiber with a loss of 0.6 dB/km and a dispersion of 1.7×10^{-4} s/m^2 to compensate for the chromatic dispersion and deployed EDFAs to offset the cumulative link losses.

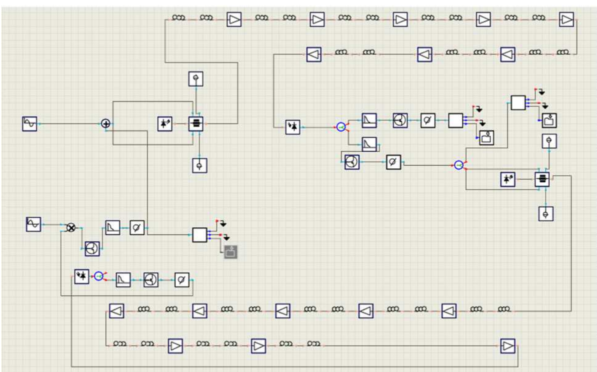

Fig. 4. The structure diagram of simulation system.

After the RX's PD, we implemented a phase detection module to measure the phase difference between the TX and RX, thereby assessing the system's fractional frequency instability. In our simulation, due to the requirement for the signal to traverse the link three times to compensate for the phase fluctuations, we ensure that the signal cycles through the system three times to accurately determine the true phase difference.

By changing the V_{rf} power to MZM, we test the effect of different modulation depths on fractional frequency transfer instability, and the results are shown in Fig. 5. Our research findings demonstrate that within the linear operating range, an increase in modulation depth leads to an improvement in the fractional frequency stability of the system.

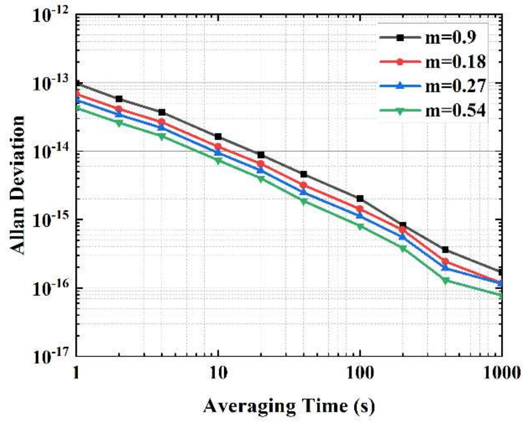

Fig. 5. Allan deviation at different modulation depths.

III. CONCLUSION

In conclusion, our experimental investigation on a fiber frequency stable transmission platform establishes a direct correlation between modulation depth and fractional frequency instability within the linear operational range. The results consistently show that increasing the modulation depth leads to a reduction in fractional frequency stability.

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