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Microwave photonic link with improved phase noise using a balanced detection scheme

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ABSTRACT

A microwave photonic link (MPL) with improved phase noise performance using a dual output Mach–Zehnder modulator (DP-MZM) and balanced detection is proposed and experimentally demonstrated. The fundamental concept of the approach is based on the two complementary outputs of DP-MZM and the destructive combination of the photocurrent in balanced photodetector (BPD). Theoretical analysis is performed to numerical evaluate the additive phase noise performance and shows a good agreement with the experiment. Experimental results are presented for 4 GHz, 8 GHz and 12 GHz transmission link and an 11 dB improvement of phase noise performance at 10 MHz offset is achieved compared to the conventional intensity-modulation and direct-detection (IMDD) MPL.

1. Introduction

Microwave photonic link (MPL) is an essential technique in the support of phased-array radars, fiber-optic signal processors and sensors, and in a variety of other applications such as analog video transmission, frequency-domain reflectometry and large-scale high-precision remote synchronization [1–3]. In these applications, an optically modulated radio frequency signal is typically used as a carrier to transmit signals from central station to remote antenna units. However, in RF photonic links the generated radio frequency carrier can be easily corrupted in the process of transmission. Especially for applications as time and frequency dissemination, the phase noise becomes one of the most important characteristic of the signal [4]. Phase noise is commonly recognized as random variations of the phase that adds to an existing signal. It may cause the broadening of the signal spectrum, thus usually represent the spectral purity of the microwave or radio frequency signal [5]. As the range of applications growing and the frequency increasing, the requirement for higher performance in terms of stability and sensitivity of RF carrier become more stringent. In some scenario, introducing even small noise into carrier may lead to dramatic damage in their spectral purity. Therefore, characterizing and improving the phase noise performance of optically generated radio frequency carrier in the transmission process is crucial for practical applications [6]. The fiber link induced phase noise effects on the transmission of signal has been studied widely for coherent fiber optic communications [7,8], where the laser phase noise presents a strong impairment. Besides, the additive noise of optical components, such as laser and photo-detector, can also cause serious degradation in phase stability. Additive phase noise is a key parameter for accurately characterizing the phase noise contributed by the optical component in a system. Paper [9] and [10] have studied the performance of the additive phase noise induced by analog optical link and show that the relative intensity noise (RIN) is observed as dominate contribute to the phase noise of optical system in most case. While much research has been carried out to address this problem, methods to suppress the RF photonic introduced phase noise to the desirable level have become a major concern.

On the other hand, balanced detection is widely used in optical communication system and famous for its powerful ability to common mode noise suppression. Considerable researches have been carried out to improve the system performance by using balanced detection [11–15]. *In* [11], *Ackerman et al. minimize noise figure (NF) of MPL by reducing the optical source noise with balanced detection method, realizing ultra-low NF of* 13.5 *dB near* 900 *MHz and yielding* 10 *dB improvements in the NFs at the higher microwave frequency bands*. A balanced receiver allows reducing the RIN level by at least 20 dB over a bandwidth of 18 GHz, which results in significantly increase of receiver sensitivity in coherent optical system [12]. In [13], balanced detection is used in a coupled

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optoelectronic oscillator to improve the phase noise performance. A balanced photonic receiver is demonstrated to suppress even-order nonlinearities by subtracting the two branches of signal current in the differential photo detection process [14,15]. Due to the inherent nature of BPD, the link gain can be increased by double the signal current in the differential detection process, while the common-mode noise will be canceled at the same time. One would then expect large improvements in phase noise by using a balanced detection scheme.

In this paper, a simple approach employing a DP-MZM and balanced detection with phase noise improvement is proposed. The proposed system is based on destructive combination of two complementary outputs of a DP-MZM. The intrinsic nature of the proposed scheme leads to an enhancement of link gain and suppression of common mode noise at the same time. *The theoretical analysis focusses on revealing underlying causes of phase noise, taking both the original RF signal source and additive intrinsic phase noise of a typical fiber-optic transmission link into concern*. The analysis provides an insight into how optical device noise contributes to the overall microwave signal phase noise and shows good agreement with the experiment. In Section III, Experiment is carried out to validate the theory and the phase noise performance achieved is compared to the traditional IMDD optical link.

2. Theoretical analysis

The theory of the proposed RF photonic link with the improvement of phase noise is illustrated in Fig. 1. The continuous light wave from a distributed feedback laser diode (DFB-LD) is first coupled into a DP-MZM. The optical carrier is modulated by a RF signal through the DP-MZM which is biased at its quadrature point. The two optically modulated signals at the two output of the DP-MZM (Path 1 and Path 2) are then transmitted to the BPD at the receiver end after adjusting the power and phase difference between the two paths via the optical attenuator (OATT) and tunable delay line (TDL). These two optically modulated RF signals, carrying the same individual intensities, is then recovered and subtracted via the BPD. In such RF photonic link, the output RF signal is maximized by the mixing of the two individual optical field intensities and the common-mode noise could be suppressed by the differential detection process. To analysis the phase noise improvement of the DP-MZM and balanced detection link, the photocurrent of both DP-MZM with balanced-receiver scheme and typical IMDD scheme are presented, as a comparison to highlight the theory of phase noise improvement in the modulation and detection process.

2.1. Signal analysis based on DP-MZM and balanced detection

Theoretically, the electrical field of optical carrier from a distributed feedback laser diode (DFB-LD) can be written as:

$$E_{in}(t)=E_0\,\mathrm{exp}j\left(\omega_0 t+\varnothing_0(t)\right) \quad (1)$$

where E_0 is the amplitude of the optical power, ω_0 is the wavelength of the optical source and $\varnothing_0(t)$ is the time-dependent phase fluctuations of the signal, which is referred to as laser phase noise. The RF signal in terms of power, frequency and phase can be represented as:

$$V_{RF}(t)=V_{RF}\,\exp\left\{\mathrm{j}\left(\omega_{RF}t+\varnothing_{RF}(t)\right)\right\} \quad (2)$$

where V_{RF} and ω_{RF} is the electric field of the voltage amplitude and angular frequency of the electrical drive signal and $\varnothing_{RF}(t)$ represents the phase noise of electrical drive signal. Therefore, the electrical fields of the modulated optical signal at the output of two bridges of the DP-MZM are given by:

$$\begin{aligned}E_{MZM1}(t)=&\frac{\sqrt{2}}{2}E_0 e^{j(\omega_0 t+\varnothing_0(t))}\Big[J_0(\beta)\\&+2\sum_{k=1}^{\infty}(-1)^k J_{2k}(\beta)\cos 2k\left(\omega_{RF}t+\varnothing_{RF}(t)\right)\\&-2\sum_{k=1}^{\infty}(-1)^k J_{2k-1}(\beta)\cos\left[(2k-1)\left(\omega_{RF}t+\varnothing_{RF}(t)\right)\right]\Big]\end{aligned} \quad (3)$$

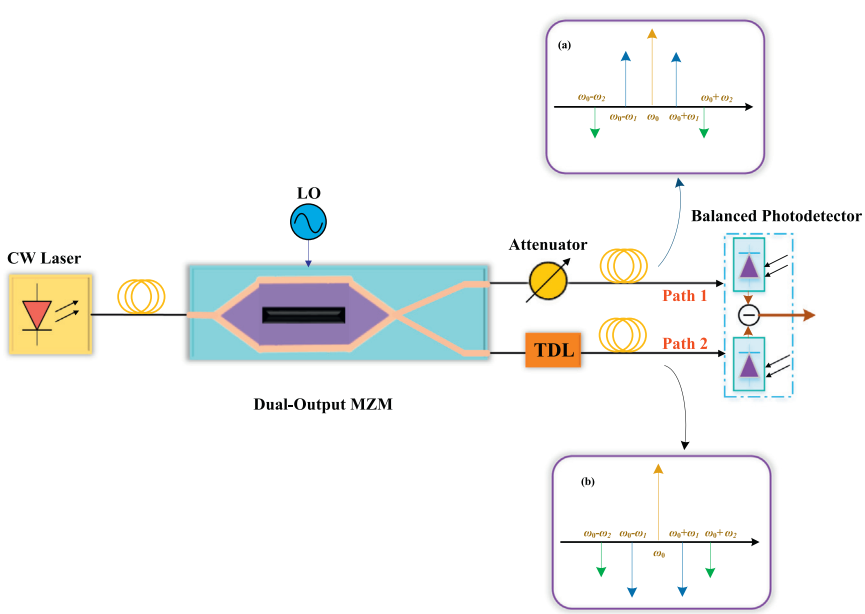

Fig. 1. Schematic diagram of the proposed RF photonic link with the improvement of phase noise.