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A flexible millimeter-wave radio-over-fiber system for various transmission bit rate

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A B S T R A C T

In this paper, we propose a flexible scheme to generate millimeter-waves (MMWs) for millimeter-wave radio-over-fiber (MMW-RoF) system. The proposed scheme has two configurations to adapt to various transmission bit rate by slightly rearranging the allocation of the system. The main structure of the system is cascaded $LiNbO_3$ Mach-Zehnder modulators ($LiNbO_3$-MZMs). The first configuration is cost effective method, where we utilize a wavelength division multiplexing de-multiplexer (WDM Demux) and an optical splitter (OS) to generate two unmodulated optical signals and a modulated optical signal. Each unmodulated optical signal and the modulated signal will form an optical single sideband (OSSB) modulation and therefore we simultaneously achieve a Q-band (45 GHz) and a V-band (60 GHz) MMWs in the receiver. The bit-error-ratio (BER) curves show that the power penalties of 45 GHz and 60 GHz are 0.6 dB and 1.1 dB at a BER of 1×10^{-9} with 2.5 Gb/s transmission data rate and 50 km fiber transmission distances. The second configuration can accommodate high bit rate, where few optical devices is rearranged to only generate a 60 GHz MMW with 40 Gb/s 4 quadrature amplitude modulation orthogonal frequency division multiplexing (4-QAM OFDM) signals. The power penalty is 1.1 dB at a BER of 1×10^{-9} with 50 km fiber transmission distances. Therefore, the proposed scheme can flexibly generate either two Q&V-band MMWs (45 GHz and 60 GHz) for the applications of the low data-rate transmission systems or one V-band MMW (60 GHz) for the applications of the high data-rate transmission systems.

1. Introduction

To accommodate the explosive increase of the communication services in the 5G communication systems, attention is turning to millimeter wave (MMW) bands (30–300 GHz) as they can provide abundant spectra and minimize interference with existing wireless services [1]. In the aspect of short distance high speed wireless communication, there have been several standards for V-band 60 GHz MMW, such as IEEE 802.15.3c, IEEE 802.11ad, ECMA387, and so on. As for 45 GHz MMW, it is suitable both for short-distance high-speed wireless communication and long-distance high-speed data communication. For the two communication modes, Chinese researchers have proposed corresponding standard, Q-LINKPAN-S and Q-LINKPAN-L, respectively [2,3]. Besides, IEEE have established new IEEE 802.11aj standard working group for 45 GHz MMW. However, it is too difficult to utilize electrical methods to generate such high-frequency MMWs with super-high speed data streams. Furthermore, MMW signals experience large attenuation in air, rendering them unsuitable for long range transmission [4]. In view of the above-mentioned issues, radio-over-fiber (RoF) technologies are cost-effective and reliable solutions for the generation of MMWs [5–7].

In the generation processes of MMWs, different modulation method has different tolerance to chromatic dispersion (CD) in fibers. Compared with other modulation methods, the optical single sideband (OSSB) modulation has advantages because it can overcome periodical power fading and bit walk-off caused by the CD effect [8–10]. Many methods to implement OSSB modulation have been proposed [11–17]. In [11–14], an OSSB modulation can be directly realized mainly based on a dual-parallel Mach-Zehnder modulator (DP-MZM). However, these systems will constrain the system flexibility, e.g. modulation formats (requiring in-phase quadrature (IQ) mixer for complex modulation formats) and signal bandwidth (limited by the bandwidth of the mixer). Compared with the methods mentioned above, the methods based on external modulators and a WDM Demux/wavelength selective switch (WSS), are simpler [15–17]. In these systems, the optical transmission path is divided into two branches. Although there will be a time delay and polarization variations between the two branches, it is not very difficult to synchronize the path length

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and stabilize the polarization state between the two branches in real transceiver integration process.

Another key issue is how to generate two coherent optical signals simply and cost-effectively. Generally, the cascaded $LiNbO_3$-MZMs are adopted because it is easy to be implemented but there are some undesired harmonics [18]. Actually, a WDM Demux or a WSS can be employed to eliminate them. Two cascaded $LiNbO_3$-MZMs structures have been studied before [19–22]. In [19–20], the first $LiNbO_3$-MZM is biased at the quadrature bias point (QBP) and the second $LiNbO_3$-MZM is biased at the minimum transmission bias point (MITBP). The system needs two local oscillators (LOs) and the frequency of the generated MMW is decided by the sum of the two LO's frequency. Furthermore, the data transmission rate is limited by the bandwidth of the electrical mixer (EM). In [21,22], a frequency sextupling is implemented based on cascaded structure. However, the two systems only focused on the performance of phase noise (PN) without data transmission.

In our proposed cascaded $LiNbO_3$-MZMs scheme, the first $LiNbO_3$-MZM is utilized to implement frequency quadrupling. An optical splitter (OS) is employed to split the optical signals into two branches. At the upper branch, the second $LiNbO_3$-MZM is inserted for frequency octupling, followed by a WDM Demux to split the $\pm 4^{th}$-order unmodulated optical signals into different paths and only make the baseband data modulated on the $+4^{th}$-order optical signal to form an OSSB modulation. At the lower branch, the $+2^{nd}$-order unmodulated optical signal of the first $LiNbO_3$-MZM's output is filtered out by an optical rectangle band pass filter (ORBPF). Finally, the $\pm 4^{th}$-order optical signals of the second $LiNbO_3$-MZM's output and the $+2^{nd}$-order unmodulated optical signal of the first $LiNbO_3$-MZM's output is combined. The proposed system can simultaneously generate two Q&V-band MMWs (a 45 GHz and a 60 GHz MMWs) with a 2.5 Gb/s bit rate and a low-frequency LO (7.5 GHz) simply and cost-effectively in the first configuration. However, the interval of the two MMWs is just 15 GHz, which will affect system performances when super-high speed data are adopted. For the application of advanced modulation high bit rate signals, in the second configuration, the structure of the first configuration is slightly adjusted to eliminate the 45 GHz MMW. Thus, the proposed system can flexibly generate a 60 GHz MMW with 40 Gb/s 4-QAM OFDM signals. Compared with the cascaded structure mentioned before, our proposed cascaded structure can realize MMWs generation flexibly for different transmission bit rate. Besides, the bias point of the two $LiNbO_3$-MZMs is maximum transmission bias point (MATBP), which can simplify their drivers' configurations. Furthermore, the second $LiNbO_3$-MZM can generate a gain about 7.5 dB at the $+4^{th}$-order optical signal of the first $LiNbO_3$-MZM's output, which will improve the performances especially for advanced modulation signals.

The remainder of this paper is organized as follows. Section 2 describes the operation principle of the flexible MMW generation technique. Section 3 shows the simulation setups and discusses the simulation results. Finally, Section 4 concludes the paper.

2. Operation principle of the flexible MMW generation technique

Fig. 1 shows the principle diagram of a $LiNbO_3$-MZM. The continuous wave (CW) emitted from a laser diode (LD), the upper drive and the lower drive of the $LiNbO_3$-MZM can be respectively expressed as:

$$E_{in}(t) = E_c \exp(j\omega_c t) \quad (1)$$

$$V_{up}(t) = V_m \cos(\omega_m t) + V_{bias} \quad (2)$$

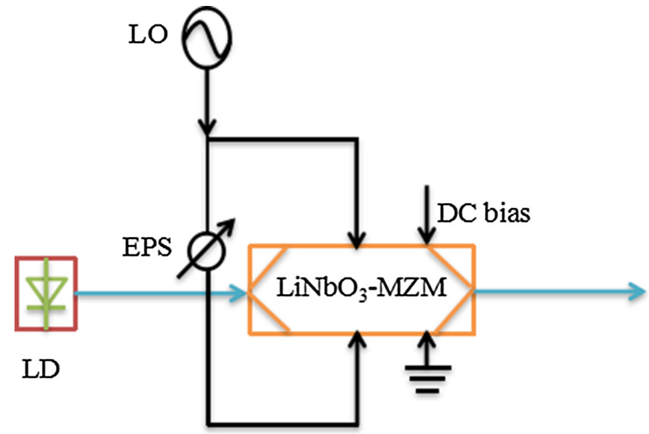

Fig. 1. Principle diagram of $LiNbO_3$ Mach-Zehnder modulator (LD: laser diode; LO: local oscillator; EPS: electrical phase shifter; DC: direct current).

$$V_{down}(t) = V_m \cos(\omega_m t + \theta) \quad (3)$$

where E_c is the amplitude of the CW, $\omega_c = 2\pi f_c$ is the angular frequency of the CW, f_c is the frequency of the CW, V_m is the amplitude of the LO's output, $\omega_m = 2\pi f_m$ is the angular frequency of the LO's output, f_m is the frequency of the LO, θ is the degrees of the electrical phase shifter (EPS). Assuming the extinction ratio (ER) of the $LiNbO_3$-MZM is enough high, the output of the $LiNbO_3$-MZM can be approximately expressed as [23]:

$$\begin{aligned} E_{out}(t) &\approx 0.5E_{in}\{\exp[j\pi V_{up}(t)/V_\pi] + \exp[j\pi V_{down}(t)/V_\pi]\} \\ &= 0.5E_{in}\{\exp[j\eta\pi\cos(\omega_m t) + j\gamma\pi] + exp[j\eta\pi\cos(\omega_m t + \theta)]\} \end{aligned} \quad (4)$$

where $\eta = V_m/V_\pi$ is the normalized amplitude of the LO's output, $\gamma = V_{bias}/V_\pi$ is the normalized bias voltage, V_π is the half-wave voltage, $m = \eta\pi$ is the modulation index of the $LiNbO_3$-MZM, $J_n(m)$ is the nth-order Bessel function of the first kind. When the $LiNbO_3$-MZM is biased at the MATBP ($\theta = \pi$ and $\gamma = 0$), by applying the Jacobi-Anger expansion [24,25], Eq. (4) can be expressed as:

$$E_{out}(t) = 0.5E_c \sum_{n=-\infty}^{n=+\infty} j^n [1 + \exp(jn\pi)] J_n(m) \exp[j(\omega_c + n\omega_m)t] \quad (5)$$

when the m of the $LiNbO_3$-MZM is small, Eq. (5) can be approximately written as:

$$\begin{aligned} E_{out}(t) \approx & -E_c J_2(m)\exp[j(\omega_c - 2\omega_m)t] + E_c J_0(m)\exp(j\omega_c t) \\ & - E_c J_2(m)\exp[j(\omega_c + 2\omega_m)t] \end{aligned} \quad (6)$$

Generally, the cascaded $LiNbO_3$-MZMs can be utilized to generate more coherent optical harmonics. Fig. 2 is the principle diagram of two cascaded $LiNbO_3$-MZMs, used for generation of the coherent optical signals with 8 times the frequency of the LO in

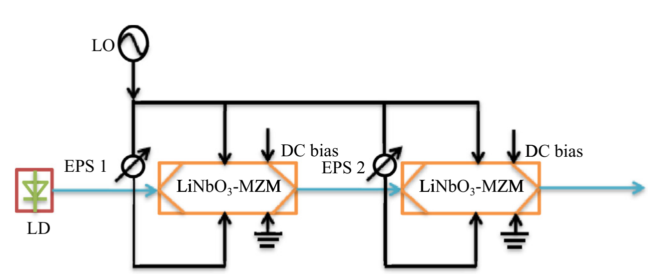

Fig. 2. Principle diagram of two cascaded $LiNbO_3$ Mach-Zehnder modulator (LD: laser diode; LO: local oscillator; EPS: electrical phase shifter; DC: direct current).