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A full-duplex multiband access radio-over-fiber link with frequency multiplying millimeter-wave generation and wavelength reuse for upstream signal

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ABSTRACT

A full-duplex radio-over-fiber (RoF) link providing multiband wireless accesses including 20 GHz, 40 GHz and 60 GHz millimeter (mm)-wave signal using a 10 GHz RF signal source is proposed. According to our theoretical analysis and simulation of the transmission performance of the signal along the single mode fiber, the code form distortion caused by the sideband walk-off effect due to the fiber chromatic dispersion can be eliminated, and the degradation caused by the fading effect on the down-stream signal is removed by adjusting the relative phase shift between the two sidebands. The upstream signal carried by the optical carrier abstracted from the downlink signal is also immune to the code outline distortion. The numerical simulation results show that the 20 km full-duplex RoF link with our generated optical mm-wave signal maintains good performance.

1. Introduction

Millimeter-wave band provides a promising frequency spectrum source for future broadband wireless access [1], but the large transmission loss in the air and metal waveguide limits its distribution coverage and the cell size of wireless communication system. RoF, the integration of optical and wireless technologies, is a promising technique to resolve the problems and therefore provides a way to increase capacity and coverage as well as to reduce the system costs.

In RoF-based wireless access networks, optical mm-wave signal generation is a key technique to realize low cost and high transmission performance [4]. Several techniques to generate the optical mm-wave have been reported [5–8], including direct modulation of laser diode (LD) [5], heterodyne technique with optical phase locking [6] with electrical subharmonic injection [7], and external modulation [8]. Of all the techniques, optical external modulation is believed to be a good option to generate the optical mm-wave signal with high spectral purity. High frequency mm-wave usually can be generated by high-order optical sidebands beating frequency with low frequency devices [9–11]. In [9], two cascaded Mach–Zehnder modulators (MZM) are used to generating 3rd-order sidebands for frequency sextupling. Four modulators are distributed as rectangle configuration to produce the two 4th-order sidebands as the frequency-octupling optical mm-wave signal [10]. Moreover, 6th-order sidebands and 9th-order sidebands for generating 12-tupling and 18-tupling frequency mm-wave via three parallel modulators are reported [11]. These schemes are complex and two or more MZMs are used for producing the optical mm-wave, which not only raises the cost, but also the generated optical mm-wave signal suffers from more degradation caused by the fiber dispersion as it is transmitted along the fiber.

In this paper, we have purposed a new full-duplex RoF link with only one MZM to generate the frequency doubling DSB optical mm-wave at the central station, the frequency doubling, quadrupling and sextupling mm-wave signal can be obtained at the base station. Since only the positive 2nd-order sideband is used to carry the downlink signal, the code form distortion is eliminated. On the other hand, a phase shift is induced on the negative 2nd-order sideband via an optical phase shifter. By adjusting the relative phase shift between the two sidebands via the phase shifter, the degradation of the received signal caused by the fading effect can be avoided. In the uplink, part of the optical carrier of the downlink mm-wave signal is abstracted and is reused to bear the upstream data. This scheme can not only reduces the system cost, but also provides a good convenience of access. To verify our proposed scheme, a full duplex RoF link providing 20 GHz, 40 GHz, and 60 GHz multiband wireless access is built based on the simulation platform, and the simulation

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results show the degradation of the code form distortion and amplitude fading for both the downlink and uplink signal is eliminated.

This paper is organized as follows: In Section 2, the full duplex RoF link providing multiband wireless access is described and its principle as well as the transmission performance of the signal is analyzed in detail. In Section 3, a full duplex RoF link is built to verify our theoretical analysis results based on the simulation. Finally, a conclusion is given in Section 4.

2. Principle

The principle diagram of the proposed full-duplex RoF is shown in Fig. 1. A narrow linewidth lightwave from a CW LD can be expressed as $E_0(t)=E_0\exp(j\omega_c t)$. Here E_0 and ω_c are the electrical field amplitude and angular frequency, respectively. The lightwave is injected into the first Mach–Zehnder modulator (MZM1), which is biased at maximum transmission point to suppress the odd-order sidebands and to enhance the even-order sidebands. A RF local oscillator with angular frequency of ω_m and amplitude voltage of $V_{RF}=1$ V. is applied to the MZM1 with 180° phase shift between the two arms. The lightwave field output from MZM1 can be expressed as

$$
\begin{aligned}
E_{out1}(t) &= \frac{E_0 e^{j\omega_c t}}{10^{inloss/20}}\left[\frac{1}{2}e^{j\pi(\cos(\omega_m t+\pi)/V_{\pi RF})}+\frac{1}{2}e^{j\pi(\cos(\omega_m t)/V_{\pi RF})}\right] \\
&= \frac{1}{2}\frac{E_0 e^{j\omega_c t}}{10^{inloss/20}}\left[\sum_{n=-\infty}^{n=\infty}(-1)^n J_n(m) j^n e^{jn\omega_m t}+\sum_{n=-\infty}^{n=\infty} J_n(m) j^n e^{jn\omega_m t}\right] \\
&\approx \frac{E_0 e^{j\omega_c t}}{10^{inloss/20}}\left[J_0(m)-J_2(m)e^{j2\omega_m t}-J_{-2}(m)e^{-j2\omega_m t}\right]
\end{aligned}
\tag{1}
$$

here, *inloss* denotes the insertion loss, V_π is the half-wave voltage of the MZM, m is the RF modulation index defined as $m=\pi V_{RF}/V_\pi=\pi/V_\pi$, and $J_n(\ )$ is the nth-order Bessel function of the first kind, n is an integer. When the RF modulation index is set a proper value, the 2nd-order sidebands have considerable amplitude, whereas the forth and the other higher-order are small enough to be neglected. So the output of MZM1 mainly consists of the optical carrier and $\pm$2nd-order sidebands with the DSB spectrum profile.

Then the positive 2nd-order sideband is abstracted and intensity modulated by the downstream unipolar binary data signal $S(t)$ via another MZM (MZM2). The output of the MZM2 becomes

$$
E_{out2}(t)=\frac{E_{in}(t)}{10^{inloss/20}}\left[\frac{1}{2}e^{(j\pi(V_2(t)/V_\pi)+j\pi(V_{b2}/V_\pi))}+\frac{1}{2}e^{(j\pi(V_1(t)/V_\pi)+j\pi(V_{b1}/V_\pi))}\right]
\tag{2}
$$

here $E_{in}=-E_0J_2(m)\exp[j(\omega_c+2\omega_m)t]/10^{inloss/20}$, $V_2(t)=V_2S(t)$, $V_1(t)=V_1S(t)$, $V_{b1}=V_b$, $V_{b2}=V_b+V_\pi$, $V_2=-V_1$. We assume that $V_2=V_\pi/2$, $V_b=V_\pi/2$, so the output lightwave becomes

$$
\begin{aligned}
E_{out3}(t) &= \frac{E_0}{10^{inloss/10}}e^{j(\omega_c+2\omega_m)t}J_2(m)\sin\left[\frac{\pi}{2}S(t)\right] \\
&= \frac{E_0}{10^{inloss/20}}J_2(m)e^{j(\omega_c+2\omega_m)t}A(t)
\end{aligned}
\tag{3}
$$

here we assume $A(t)=\sin[\pi S(t)/2]/10^{inloss/20}$ to simplify the equation. Whereas an optical phase shifter is used to introduce a phase shift of $\Delta\varphi$ on the negative 2nd-order sideband to eliminate the degradation of the fading effect by shifting the fading null points. Then the three tones are recombined after aligning their polarizations by polarization controllers and the data-bearing optical mm-wave signal with the DSB spectrum can be expressed as

$$
E_{out4}(t)=\frac{E_0}{10^{inloss/20}}\left[J_0(m)e^{j\omega_c t}-J_{-2}(m)e^{j[(\omega_c-2\omega_m)t+\Delta\varphi]}+J_2(m)A(t)e^{j(\omega_c+2\omega_m)t}\right]
\tag{4}
$$

Since the three tones of the DSB optical mm-wave signal are separated, processed and recombined in the CS, they experiment different phase and polarization rotation and thus their coherence is degraded. Although we can improve the coherence by shortening the three optical paths in the same circumstance or by utilizing a narrower-linewidth laser, the coherence degradation during this processing is inevitable. If the integrated component for separation, processing and recombination of the lightwaves to generate the DSB optical mm-wave signal is used, the coherence of the three light carriers can be improved greatly. So, the generator of the DSB optical mm-wave signal implemented with integrated components based on PLC (planar lightwave circuit) has great potential in the future.

As the DSB optical mm-wave signals is transmitted along the fiber, the fiber chromatic dispersion causes the three tones of the DSB optical mm-wave to go forward at different velocities. If we assume the fiber propagation constant is $\beta(\omega)$ and the fiber attenuation coefficient is κ, after z-length of fiber transmission, the DSB optical mm-wave signal becomes

$$
\begin{aligned}
E_{out5}(z,t) &= \frac{E_0}{10^{inloss/20}}e^{-\kappa z/2}\left[J_0(m)e^{j[\omega_c t-\beta(\omega_c)z]}-J_{-2}(m)e^{j[(\omega_c-2\omega_m)t-\beta(\omega_c-2\omega_m)z+\Delta\varphi]}\right. \\
&\quad \left.+J_2(m)A(t-t')e^{j[(\omega_c+2\omega_m)t-\beta(\omega_c+2\omega_m)z]}\right]
\end{aligned}
\tag{5}
$$

where $t'=\beta(\omega_c+2\omega_m)z/(\omega_c+2\omega_m)$ is the time delay of the signal carried by the 2th-order sideband caused by fiber chromatic dispersion.

Since the optical carrier is much larger than the sidebands, a fiber Bragg grating (FBG) with the central frequency at ω_c and bandwidth smaller than $4\omega_m$ is used to abstract the optical carrier of the uplink at the base station. In the real system, the FBG is sensitive to the environment. If the narrower bandwidth FBG is used, the drift of the FBG central frequency will fluctuate the power of the reflected optical carrier greatly especially as the

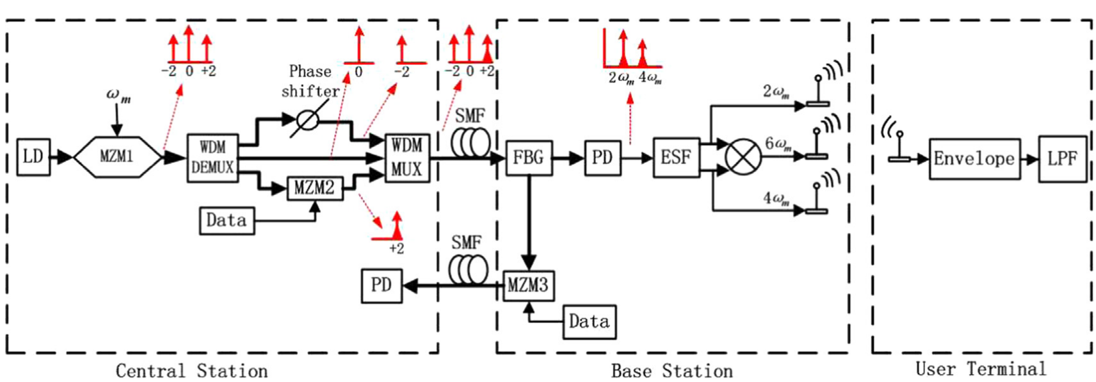

Fig. 1. Principle of a full-duplex RoF system based on multiband wireless accesses and wavelength reuse. LD, laser diode; ω_m, the angular frequency of the radio frequency; MZM, $LiNbO_3$ Mach–Zehnder modulator; SMF, single mode fiber; FBG, fiber Bragg grating; PD, photodiode; ESF, electrical band splitting filter; LPF, low pass filter.

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