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A full-duplex radio-over-fiber link with 12-tupling mm-wave generation and wavelength reuse for upstream signal

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ABSTRACT

A full-duplex radio-over-fiber (RoF) link with a novel scheme to generate 60 GHz mm-waves from a 5 GHz RF signal source is investigated. In the RoF downlink, the required frequency of the RF oscillator is reduced greatly. Since the optical carrier is not modulated by downstream data, part of it is reused to carry upstream data and the upstream data is transmitted to the central station using optical single-sideband modulation. In this way, a single wavelength is used for both downstream and upstream transmissions. Based on this scheme, a full-duplex RoF link is built and its transmission performance is analyzed. Theoretical analysis and numerical simulation show that the downstream signal cannot only eliminate code form distortion caused by time shift of the code edges, but also reduce the influence of the fading effect as the 60 GHz DSB optical mm-wave signal is transmitted along the fiber, and the upstream signal is immune to both fading effect and time shift of the code edges.

1. Introduction

Radio-over-fiber (RoF), the integration of optical and wireless systems, is a promising technique in increasing capacity and mobility as well as decreasing the system costs, while millimeter-wave (mm-wave) is a promising frequency resource for future broadband communication.

Optical mm-wave signal generation is a key technique to realize low cost and high transmission performance in RoF-based optical wireless access networks [1]. Many different approaches have been reported, such as optical heterodyne detection[2], frequency up-conversions using four-wave mixing[3], frequency doubling using optical carrier suppression modulation[4], and frequency quadrupling, sextupling and octupling using the optical frequency multiplication technique [5–7]. In order to simplify RoF system, different methods for wavelength reuse in the base station have been proposed [8].

In this paper, we propose a duplex RoF link with a novel method to generate 60 GHz mm-wave signal at the base station from a 5 GHz RF oscillator. The optical carrier is not modulated by downstream data, and part of it is reused to carry upstream data. In this way, it can utilize the optical power efficiently and reduce the cost of the system. We theoretically analyzed the dispersion performance of the full-duplex link. Finally, we demonstrated the transmission performance of the full-duplex link by simulation.

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2. Principle

The block diagram of the RoF link is shown in Fig. 1. The narrow bandwidth CW lightwave from a laser diode (LD) is expressed as $E_c(t)=E_0\cos\omega_c t$ for simplification. Here $\omega_c=2\pi f_c$ is its angular frequency, and E_0 is the lightwave field amplitude. The lightwave is injected into a cascaded MZM architecture as we have proposed in [9] to generate optical mm-wave with only 4kth-order sidebands. Both of the MZMs are bias at the maximum transmission point. The local oscillator, which is applied to the two MZMs with 90° phase difference, has an angular frequency of $\omega_m=2\pi f_m$, and its amplitude is V_{RF}. In [9], we give an analytical expression of the output signal of the MZM2 as

$$E_1(t)=E_0\sum_{n=-\infty}^{+\infty}\left\{\cos\left(\frac{\pi}{2}n\right)\cos\left(\frac{\pi}{4}n\right)J_n(\sqrt{2}m)\exp\left[j(\omega_c+n\omega_m)t+\frac{\pi}{2}n\right]\right\} \tag{1}$$

where, n is an integer, V_π is the half-wave voltage of the MZM, m is the RF modulation index defined as $m=\pi V_{RF}/V_\pi$, and $J_n(\cdot)$ is the nth-order Bessel function of the first kind. Only 4kth-order sidebands (k is an integer) are generated at the output of MZM2. When V_{RF} is properly set, the amplitudes of sidebands higher than $\pm$4th-order can be ignored. So, the lightwave just includes the carrier and its two 4th-order sidebands. The output can be simplified as

$$E_1(t)\approx E_0J_0(\sqrt{2}m)\cos(\omega_c t)+E_0J_4(\sqrt{2}m)\cos(\omega_c-4\omega_m)t + E_0J_4(\sqrt{2}m)\cos(\omega_c+4\omega_m)t \tag{2}$$

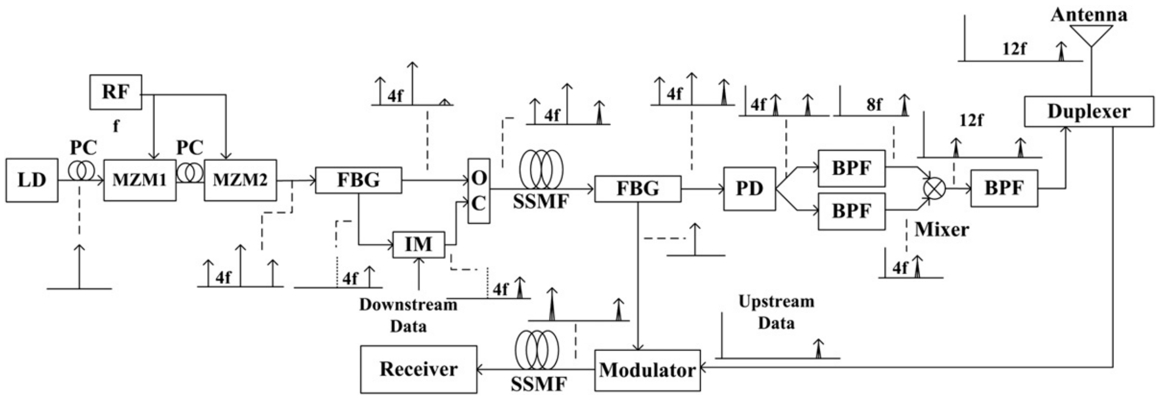

Fig. 1. Principle of a full-duplex RoF system based on frequency 12-tupling and wavelength reuse. LD, LD, laser diode; PC, polarization controller; FBG, fiber Bragg grating; MZM, LiNbO3 Mach–Zehnder modulator; IM, intensity modulator; OC, optical couple; SSMF, standard single-mode fiber; PD, photodiode; BPF, bandpass filter; EDFA, erbium-doped fiber amplifier; EA, electric amplifier.

The downstream data signal represented by 0–1 sequence $s(t)$ is intensity-modulated onto the $+4$th-order sideband. Then it is recombined with the other two un-modulated sidebands by a 3 dB optical coupler. So the optical mm-wave carrying downstream data signals can be expressed as

$$E_2(t)=E_0J_0(\sqrt{2}m)\cos(\omega_c t)+E_0J_4(\sqrt{2}m)\cos(\omega_c-4\omega_m)t+s(t)E_0J_4(\sqrt{2}m)\cos(\omega_c+4\omega_m)t \quad (3)$$

Then the optical mm-wave is distributed over standard single-mode fiber (SSMF) to the base station. Since fiber chromatic dispersion exists in SSMF, the optical carrier and its two sidebands propagate along the SSMF with different velocities. We assume the phase shifts of the carrier, the $+4$th-order sideband, and the -4th-order sideband are ϕ_0, ϕ_{+1}, and ϕ_{-1} respectively, after transmission over an SSMF with the length of L. So the optical mm-wave received at the base station can be expressed as

$$E_3(t)=E_0J_0(\sqrt{2}m)\cos(\omega_c t+\phi_0)+E_0J_4(\sqrt{2}m)\cos[(\omega_c-4\omega_m)t+\phi_{-1}]+s(t+t')E_0J_4(\sqrt{2}m)\cos[(\omega_c+4\omega_m)t+\phi_{+1}] \quad (4)$$

where t' is the time delay caused by fiber chromatic dispersion, and $t'=\phi_{+1}(\omega_c+4\omega_m)^{-1}$.

At the base station, one half of the blank optical carrier is reused as carrier for upstream data signals. Here, we use single-sideband modulation for upstream data signals. The other half of the optical carrier and the two sidebands are sent to the photodiode (PD). The photocurrent in RF band detected by the PD can be expressed as

$$i(t)\propto\mu|E_3(t)|^2=\mu E_0^2[s(t+t')J_4^2(\sqrt{2}m)\cos(8\omega_m t+\phi_{+1}-\phi_{-1})+s(t+t')J_0(\sqrt{2}m)J_4(\sqrt{2}m)\cos(4\omega_m t+\phi_{+1}-\phi_0)+J_0(\sqrt{2}m)J_4(\sqrt{2}m)\cos(4\omega_m t+\phi_0-\phi_{-1})] \quad (5)$$

To generate mm-wave with frequency 12-tupling, two electrical bandpass filters are used to separate the two tunes, and then a mixer is used to multiply the two tunes to generate $12\omega_m$ mm-wave signal.

$$\begin{aligned}i'(t)&\propto\frac{1}{2}\mu^2E_0^4J_0(\sqrt{2}m)J_4^3(\sqrt{2}m)\left[s(t+t')\cos(12\omega_m t+\phi_{+1}+\phi_0-2\phi_{-1})+s(t+t')\cos(12\omega_m t+2\phi_{+1}-\phi_0-\phi_{-1})\right]\\&=\mu^2E_0^4J_0(\sqrt{2}m)J_4^3(\sqrt{2}m)s(t+t')\cos\left(\frac{\phi_{+1}+\phi_{-1}-2\phi_0}{2}\right)\times\cos\left(12\omega_m t+\frac{3}{2}\phi_{+1}-\frac{3}{2}\phi_{-1}\right)\end{aligned} \quad (6)$$

Eq. (6) shows that the signal code $s(t)$ only delays a time shift of t', which only cause all signal code bits have a constant time delay, so the downlink is free from the distortion caused by the time shift of the code edges.

We have

$$\begin{aligned}&\phi_0=\beta(\lambda_c)L\\&\phi_{+1}=\beta(\lambda_c+\Delta\lambda)L=\left[\beta(\lambda_c)+\frac{d\beta}{d\lambda}\bigg|_{\lambda=\lambda_c}\Delta\lambda+\frac{1}{2!}\frac{d^2\beta}{d\lambda^2}\bigg|_{\lambda=\lambda c}(\Delta\lambda)^2\right]L\\&\phi_{-1}=\beta(\lambda_c-\Delta\lambda)L=\left[\beta(\lambda_c)-\frac{d\beta}{d\lambda}\bigg|_{\lambda=\lambda_c}\Delta\lambda+\frac{1}{2!}\frac{d^2\beta}{d\lambda^2}\bigg|_{\lambda=\lambda c}(\Delta\lambda)^2\right]L\\&\frac{d^2\beta}{d\lambda^2}=-\frac{2\pi cD}{\lambda^2},\quad \Delta\lambda=-\frac{c}{f^2}\Delta f\end{aligned} \quad (7)$$

so

$$\frac{\phi_{+1}+\phi_{-1}-2\phi_0}{2}=\frac{1}{2!}\frac{d^2\beta}{d\lambda^2}\bigg|_{\lambda=\lambda c}(\Delta\lambda)^2L=-\frac{\pi D\lambda^2(\Delta f)^2L}{c} \quad (8)$$

where L is the fiber length, λ_c is the central wavelength of the LD, $\Delta\lambda$ and Δf are the wavelength and frequency differences between the carrier and the two 4th-order sidebands, β is the propagation constant, and D is the chromatic dispersion parameter of SSMF.

We assume the power of the generated mm-wave is P, so

$$P\propto\cos^2\left[\frac{\pi D\lambda^2(\Delta f)^2L}{c}\right] \quad (9)$$

If $D=16$ ps/nm/km, $c=2.9979\times10^8$ m/s, $\lambda_c=1552.5$ nm, $\Delta f=20$ GHz, the mm-wave power is zero when $L=9.72(2n+1)$km (n is an integer), and the mm-wave power reach its maximum value when $L=(19.44n)$km (n is an integer). So, the fading period of the downlink 60 GHz mm-wave is 19.4 km. If a 60 GHz DSB optical mm-wave is transmitted along the same fiber, its fading period is 2.16 km by calculation, which is only 1/9 of the fading period of our scheme. From this point, the fading period of the 60 GHz mm-wave generated by our scheme is greatly extended.

In the base station, since the optical carrier is blank, it is reused as the carrier for the upstream data signals. We express the received upstream signal at the base station as

$$i_0(t)=a(t)V'_{RF}\cos(\omega_s t) \quad (10)$$

Then it is single-sideband modulated onto the carrier separated from the downstream signal. The uplink optical signal can be expressed as

$$E_0(t)=\frac{E_0'}{2}\sum_{n=-\infty}^{+\infty}J_n[\delta a(t)]\left[\exp\left(j\frac{n\pi}{2}\right)+\exp\left(j\frac{\pi}{2}\right)\right]\exp(j\omega_c t+jn\omega_s t) \quad (11)$$