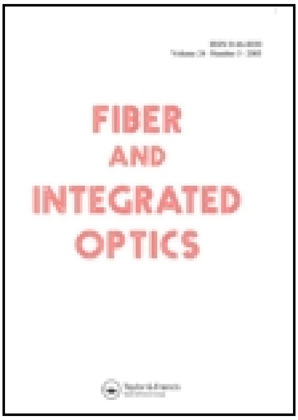

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A Cost-Effective Full-Duplex Radio-over-Fiber System Based on Frequency Octupling and Wavelength Reuse

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A Cost-Effective Full-Duplex Radio-over-Fiber System Based on Frequency Octupling and Wavelength Reuse

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Abstract *The article proposes a novel scheme for full-duplex radio-over-fiber transmissions with frequency-octupling millimeter-wave and wavelength reuse. In this scheme, the base station is simplified greatly as there is no laser, and the uplink millimeter-wave signal is down-converted to a low frequency using a 60-GHz local oscillator, which is optically obtained from the downlink signal. The scheme can utilize optical power efficiently, and thus, a cost-effective radio-over-fiber system is achieved. Transmission performance for both down- and uplink data are theoretically analyzed and investigated by simulation; results show that the performance of the system is not sensitive to fiber dispersion.*

Keywords frequency octupling, optical millimeter wave, radio-over-fiber, uplink down-conversion

1. Introduction

Radio-over-fiber (RoF) systems are attracting attention, as they can provide a promising solution of realizing broadband access for both fixed and mobile users [1–3]. It has been proposed that the unlicensed millimeter-wave (mm-wave) band would be used in future RoF systems and that many base stations (BSs) would be required to cover the service area of a system for the high atmospheric attenuation in this band. As a consequence, to make an mm-wave RoF system practical, both optical mm-wave generation and low-cost BS construction are key technologies [4, 5].

In order to lower the cost of a bi-direction RoF system, many methods for the generation of optical mm-wave signals have been reported [5–9]. Among them, external modulation schemes with a laser and $LiNbO_3$ Mach-Zehnder modulators (MZMs) are the most reliable approaches for high-frequency optical mm-wave generation [10], which can employ different modulation formats and generate beyond 60-GHz mm-wave signals. Different methods have been proposed for bi-directional RoF systems, and many of them sharing a single light source for both downlink and uplink transmissions [4, 11–15].

In this article, a cost-effective full-duplex RoF system supporting 60-GHz frequency up- and down-conversion is proposed based on a novel frequency-octupling mm-wave

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generation scheme. The downlink 60-GHz mm-wave is generated by mixing the modulated lower eighth-order sideband and half of the optical central carrier from a 7.5-GHz radio frequency (RF) local oscillator, and the uplink 55-GHz mm-wave is down-converted to 5 GHz using a 60-GHz local oscillator, which is generated by mixing the other half of the optical central carrier and half of the higher eighth-order sideband. The remained half of the higher eighth-order sideband is reused as the light source to carry the down-converted uplink data signal. In this way, the duplex RoF link can utilize the optical power efficiently and reduce the cost of the system greatly.

The rest of this article is organized as follows. The theoretical model of the RoF system is built in Section 2. Section 3 gives the simulation experiment and analysis of the transmission performance. Finally, some conclusions are drawn in Section 4.

2. Principle

The architecture of the proposed RoF system is schematically shown in Figure 1. It is assumed that the continuous-wave (CW) lightwave applied to the input port from a laser diode (LD) is $E_{in}(t) = E_0 \exp(j\omega_c t)$, where E_0 and ω_c are the amplitude and angular frequency of the lightwave. It is injected into an mm-wave generation module based on two parallel dual-parallel MZMs (DP-MZMs), as proposed in [16] to generate mm-wave signals. The local oscillator is $V_{RF}(t) = V_{RF}\cos(\omega_m t)$, where V_{RF} and ω_m are the amplitude and angular frequency. It is known from [16] that the odd-order sidebands are all suppressed when the four sub-MZMs are all biased at the maximum transmission point. The mathematical expression of the output signal from the mm-wave generation scheme can be represented approximately by

$$E_0(t) = \frac{E_0}{8}\sum_{n=-\infty}^{+\infty}\left\{\begin{array}{l} J_n(m)\exp[j(\omega_c t + n\omega_m t)]\cdot[1+(-1)^n] \\ \quad\cdot[1+\exp(jn\Delta\theta_1)+\exp(jn\Delta\theta_2)+\exp(jn\Delta\theta_3)] \end{array}\right\}, \quad (1)$$

where m is the RF modulation index defined as $m = \pi V_{RF}/V_\pi$, $J_n(\ )$ is the nth-order Bessel function of the first kind, and V_π is the half-wave voltage of the modulators. Note that $\Delta\theta_0 = 0$, $\Delta\theta_1 = \pi/2$, $\Delta\theta_2 = \pi/4$, and $\Delta\theta_3 = -\pi/4$, so only the $8k$th-order sidebands are generated (k is an integer).

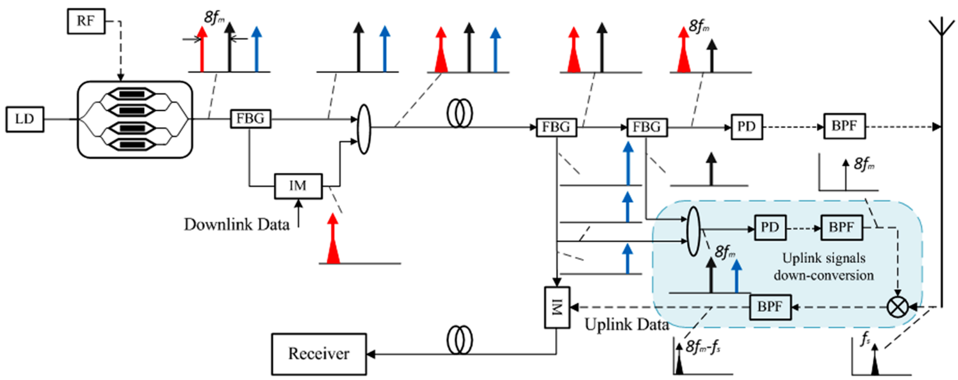


Figure 1. Principle of the full-duplex RoF system based on frequency octupling and wavelength reuse. (color figure available online)

Different from the setting of Section 2.2 in [16], here $J_0(m) \neq 0$ and $m \in (5.520, 8.654)$ (see Figure 2); then only the central carrier and the eighth-order sidebands exist (the 16th-order sidebands are ignored here for their small value). So $E_0(t)$ can be simplified as

$$E_0(t) = E_0\{J_0(m)\exp(j\omega_c t) + J_8(m)\exp[j(\omega_c t + 8\omega_m t)] + J_8(m)\exp[j(\omega_c t - 8\omega_m t)]\}. \tag{2}$$

The downlink binary data signal $S(t)$ is intensity modulated onto the -8th-order sideband, which is then recombined with the un-modulated central carrier and the $+8$th-order sideband by a 3-dB optical coupler. The output optical signals with the data signal can be written as

$$E_1(t) = E_0\{J_0(m)\exp(j\omega_c t) + J_8(m)\exp[j(\omega_c t + 8\omega_m t)] + S(t)J_8(m)\exp[j(\omega_c t - 8\omega_m t)]\}. \tag{3}$$

At the BS, the $+8$th-order sideband is separated from two other frequency components by using a fiber Bragg grating (FBG), and then it is divided into two even parts by a optical splitter—one part of the $+8$th-order sideband is used as a light source to carry the uplink data signal; the other part is coupled with half of the blank optical central carrier to generate a local oscillator for the uplink signal down-conversion. The other half of the optical central carrier and the modulated -8th-order sideband are injected into a high speed photodiode (PD) to generate the downlink modulated mm-wave signal.

In the back-to-back (BTB) case, the frequency octupling mm-wave signal is generated by beating the -8th-order sideband and half of the optical central carrier in a PD. The

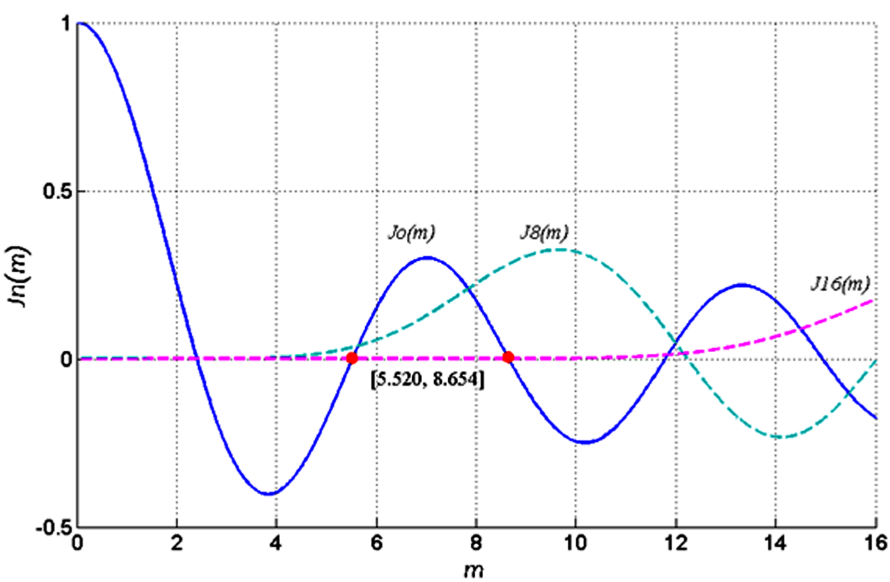


Figure 2. Bessel functions of the first kind. (color figure available online)

downlink optical signal becomes

$$E_2(t) = E_0 \left\{ \frac{1}{2} J_0(m) \exp(j\omega_c t) + S(t) J_8(m) \exp[j(\omega_c t - 8\omega_m t)] \right\}, \tag{4}$$

and its photocurrent can be expressed as

$$\begin{aligned} I(t) &= R \cdot \left\langle |E_2(t)|^2 \right\rangle \\ &= RE_0^2 \left[\frac{1}{4} J_0^2(m) + J_8^2(m) S^2(t) + J_0(m) J_8(m) S(t) \cos(8\omega_m t) \right], \end{aligned} \tag{5}$$

where R is the responsivity of the PD.

When the output optical signals are distributed over fiber to the BS, the optical central carrier and its sidebands propagate at different velocities for the reason of chromatic dispersion. After L-length transmission over the fiber, the generated mm-wave signal becomes

$$\begin{aligned} E_3(t) = E_0 \Big\{ & \frac{1}{2} J_0(m) \exp[j(\omega_c t - \beta(\omega_c) L)] \\ & + S(t-\tau) J_8(m) \cdot \exp[j(\omega_c t - 8\omega_m t - \beta(\omega_c - 8\omega_m) L)] \Big\}, \end{aligned} \tag{6}$$

and its photocurrent is written as

$$\begin{aligned} I(t) = R \cdot \langle |E_3(t)|^2 \rangle = RE_0^2 \Big[& \frac{1}{4} J_0^2(m) + J_8^2(m) S^2(t-\tau) + J_0(m) J_8(m) S(t-\tau) \\ & \cdot \cos(8\omega_m t - \beta(\omega_c) L + \beta(\omega_c - 8\omega_m) L) \Big], \end{aligned} \tag{7}$$

where $\tau = \beta(\omega_c - 8\omega_m)L/(\omega_c - 8\omega_m)$, and $\beta(\omega)$ is the propagation constant of the dispersion fiber. By expanding $\beta(\omega)$ to a Taylor series around the angular frequency of the optical central carrier ω_c, and neglecting the high-order fiber dispersion effect,

$$\beta(\omega_c \pm 8\omega_m) = \beta(\omega_c) \pm 8\omega_m \beta'(\omega_c) + (8\omega_m)^2 \beta''(\omega_c)/2, \tag{8}$$

then the photocurrent can be described by the following expression:

$$\begin{aligned} I(t) \approx RE_0^2 \Big[& \frac{1}{4} J_0^2(m) + J_8^2(m) S^2(t-\tau) + J_0(m) J_8(m) S(t-\tau) \\ & \cdot \cos(8\omega_m t - 8\omega_m \beta'(\omega_c) L + 32\omega_m^2 \beta''(\omega_c) L) \Big]. \end{aligned} \tag{9}$$

After filtering the direct components, the desired mm-wave is written as

$$I(t) = RE_0^2 J_0(m) J_8(m) S(t-\tau) \cdot \cos(8\omega_m t - 8\omega_m \beta'(\omega_c) L + 32\omega_m^2 \beta''(\omega_c) L). \tag{10}$$

It is shown that only a phase shift of the mm-wave is caused by the fiber dispersion, and the data signal $S(t)$ is not influenced except for a delay τ of the fiber. Besides, there is no power fading effect on the generated mm-wave. Hence, the downlink is not only free from the distortion caused by the time shift of the code edges but also immune the fading effect.

In the BS, the 55-GHz mm-wave uplink signal obtained from the antenna is mixed with the generated local oscillator and down-converted to a low frequency that can easily be modulated onto the reserved part of the higher eighth-order sideband. The optical central carrier and its higher eighth-order sideband for the generation of local oscillator after fiber transmission can be written as

$$E_{os}(t) = \frac{1}{2}E_0\{J_0(m)\exp[j(\omega_c t - \beta(\omega_c)L)] + J_8(m)\exp[j(\omega_c t + 8\omega_m t - \beta(\omega_c + 8\omega_m)L)]\}, \tag{11}$$

and its photocurrent can be described as

$$\begin{aligned} I_{os}(t) &= R \cdot \langle |E_{os}(t)|^2 \rangle \\ &= \frac{1}{4}RE_0^2\left\{J_0^2(m) + J_8^2(m) + 2J_0(m)J_8(m) \cdot \cos[8\omega_m t - \beta(\omega_c + 8\omega_m)L + \beta(\omega_c)L]\right\} \\ &\approx \frac{1}{4}RE_0^2\left\{J_0^2(m) + J_8^2(m) + 2J_0(m)J_8(m) \cdot \cos[8\omega_m t - (8\omega_m\beta'(\omega_c) + 32\omega_m^2\beta''(\omega_c))L]\right\}. \end{aligned} \tag{12}$$

After a bandpass filter, the desired local oscillator mm-wave becomes

$$\begin{aligned} I_{os}(t) &= \frac{1}{2}RE_0^2J_0(m)J_8(m) \cdot \cos[8\omega_m t - 8\omega_m\beta'(\omega_c)L - 32\omega_m^2\beta''(\omega_c)L] \\ &= A\cos(8\omega_m t + \varphi), \end{aligned} \tag{13}$$

where $A = RE_0^2J_0(m)J_8(m)/2$, and $\varphi = -(8\omega_m\beta'(\omega_c) + 32\omega_m^2\beta''(\omega_c))L$ is the phase shift induced by the downlink fiber chromatic dispersion. The received uplink signal at the BS can be expressed as

$$i(t) = s(t)V_s\cos(\omega_s t + \theta); \tag{14}$$

here $s(t)$ is the uplink data signal represented by a 0–1 sequence. V_s, ω_s, and θ are the amplitude, angular frequency, and phase of the received uplink signal. Mixing it with the generated local oscillator mm-wave gives

$$\begin{aligned} i(t) &= s(t)V_s\cos(\omega_s t + \theta) \cdot A\cos(8\omega_m t + \varphi) \\ &= \frac{1}{2}As(t)V_s[\cos((8\omega_m + \omega_s)t + \varphi + \theta) + \cos((8\omega_m - \omega_s)t + \varphi - \theta)], \end{aligned} \tag{15}$$

and then the down-converted uplink signal is obtained after a bandpass filter

$$i(t) = \frac{1}{2}As(t)V_s\cos((8\omega_m - \omega_s)t + \varphi - \theta), \tag{16}$$

which is then intensity modulated onto the reserved half of the higher eighth-order sideband of the downlink signal.

3. Simulation Experiment and Results

Figure 3 shows the simulation experimental setup for the proposed bidirectional RoF system based on frequency octupling with wavelength reuse. The simulating spectra at different locations are shown in Figure 4. In the central station (CS), a CW lightwave with a 10-MHz linewidth is generated from an LD, and its emission wavelength is 1,552.5 nm (193.1 THz). The two DP-MZMs are driven by a 7.5-GHz RF local oscillator with voltage amplitude of 7.8 V. The half-wave voltage, extinction ratio, and insertion loss of the MZMs are 3.5 V, 35 dB, and 6 dB, respectively. After the mm-wave generation module, only the optical central carrier and two eighth-order sidebands are generated (other harmonic components are neglected, for they are more than 30 dB lower than the desired components), and the frequency spacing between the eighth-order sideband and the optical central carrier is 60 GHz, shown in Figure 4a. FBG1, with a bandwidth of 10 GHz and a Bragg resonance frequency (BRF) of 193.04 THz, is used to reflectively separate the lower eighth-order sideband from the other frequency components. The separated lower eighth-order sideband is then intensity modulated with a 2.5-Gb/s baseband signal, which is represented by the pseudo-random bit sequence with a length of $2^7 - 1$. The standard single-mode fiber (SMF) with a dispersion of 16 ps/(nm·km) and attenuation of 0.2 dB/km is used in the system, and an erbium-doped fiber amplifier (EDFA) is employed to compensate the downlink fiber attenuation. At the BS, the higher eighth-order sideband and half of the optical central carrier are separated from the received optical signals by FBG2 and FBG3, with a BRF of 193.16 THz and 193.1 THz, respectively. A 60-GHz electric mm-wave is generated by beating the lower eighth-order sideband and the remaining half of the optical central carrier in the PD. For simplicity, the generated 60-GHz mm-wave is directly amplified, with direct current components filtered and then demodulated for performance analysis.

A 60-GHz local oscillator mm-wave is generated by beating half of the optical central carrier and the separated part of the higher eighth-order sideband, as in Figure 4e. The other part of the higher eighth-order sideband is then intensity modulated with the down-converted 5-GHz uplink signal. Another EDFA is used to compensate the uplink fiber attenuation at the CS.

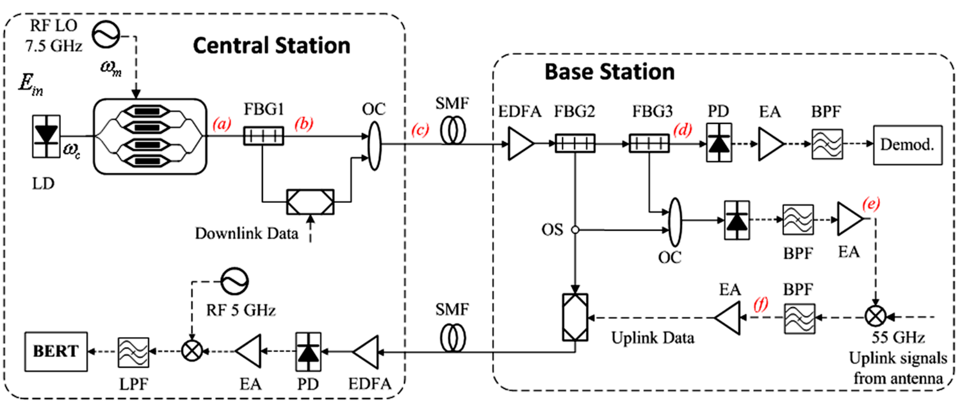


Figure 3. Setup for the proposed full-duplex RoF system (RF LO, RF local oscillator; OC, optical coupler; EA, electrical amplifier; BPF, bandpass filter; OS, optical splitter; BERT, bit-error-rate tester). (color figure available online)

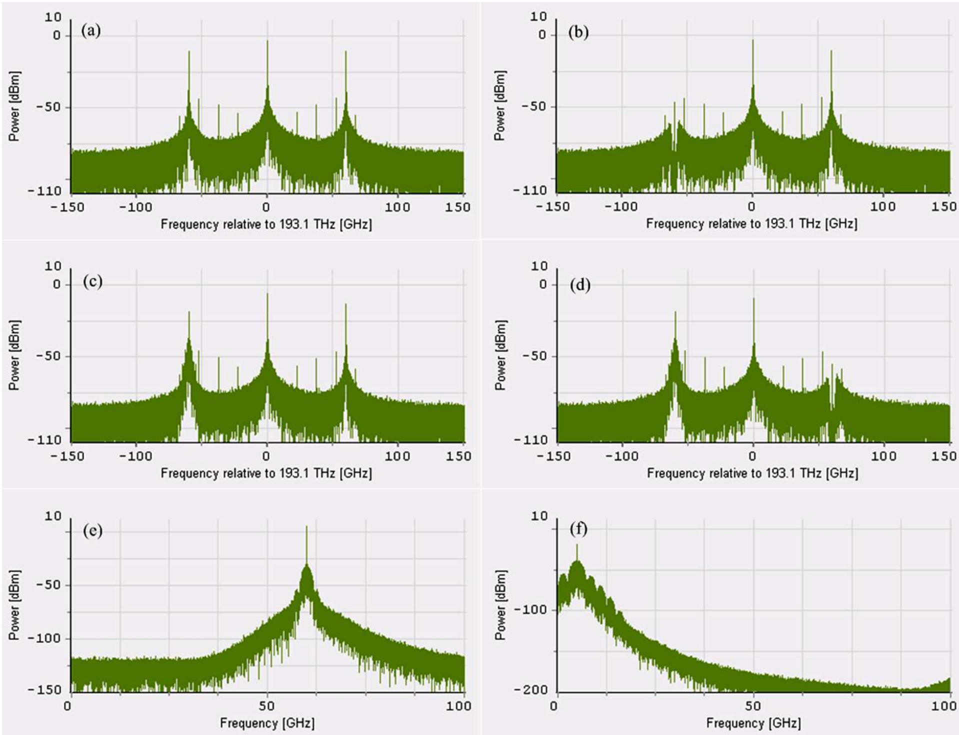
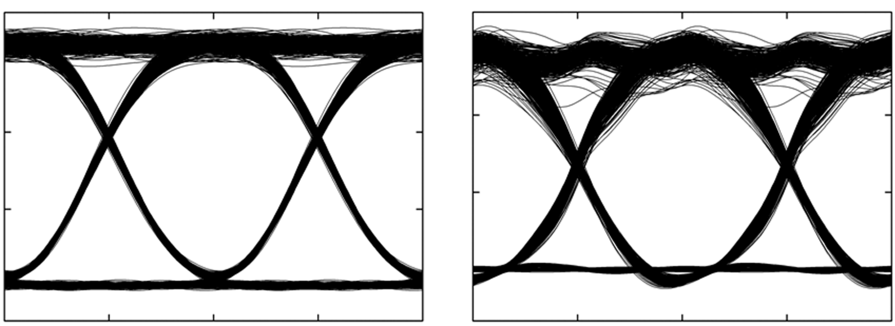


Figure 4. Simulating spectra at different locations corresponding to (a), (b), (c), (d), (e), and (f) located in Figure 3. (color figure available online)

Figure 5 shows the measured eye diagrams of the demodulated downlink and uplink data after transmission over a 20-km SMF.

Figure 6 shows the bit-error rate (BER) performance versus the received optical power for both down- and uplink signals. One can see that after transmission over 20 km, the power penalty caused by fiber chromatic dispersion for both downlink and uplink data are about 0.1 dB and 1.1 dB at a BER of 10^{-9}, respectively.



(a) (b)

Figure 5. Measured eye diagrams after 20-km SMF transmission: (a) downlink data and (b) uplink data.

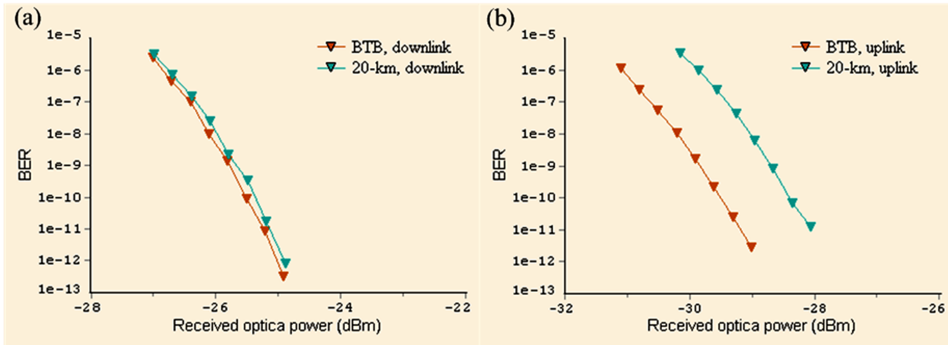


Figure 6. BER curves versus received optical power for: (a) downlink and (b) uplink. (color figure available online)

4. Conclusion

This article has proposed a cost-effective full-duplex RoF link based on a novel mm-wave generation scheme and wavelength reuse. The downlink 60-GHz mm-wave signal is generated by the frequency octupling of a 7.5-GHz local oscillator, and the 55-GHz uplink mm-wave signal is down-converted to 5 GHz using a 60-GHz local oscillator generated by wavelength reuse of the downlink signal. The proposed scheme can greatly reduce the bandwidth requirements of the microwave components and modulators in the CS and simplify the BS significantly. Since half of the higher eighth-order sideband can be reused to carry uplink data at the BS, it can effectively utilize optical power and reduce the cost of the system. Theoretical analysis and simulation experiments show that both downlink and uplink signals are insensitive to fiber dispersion. After transmission over 20 km, the power penalties are about 0.1 dB and 1.1 dB for down- and uplink transmission, respectively.

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