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A Novel Architecture of Millimeter-Wave Full-Duplex Radio-over-Fiber System with Source-Free BS Based on Polarization Division Multiplexing and Wavelength Division Multiplexing

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Abstract—In this paper, we propose a novel architecture of full-duplex millimeter-wave radio-over-fiber (RoF) system based on polarization division multiplexing (PDM) and wavelength division multiplexing (WDM) technology. In our scheme, the light waves for downlink and uplink transmission are provided by the same laser, which realize the source-free base station (BS) and multi-services transfer for next generation wireless access network. Since the uplink optical carrier is Y-polarized light wave which does not bear the downlink signal, no cross-talk from the downlink contaminates the uplink signal. At the BS, it is detected by a high-speed photoelectric diode (PD) to generate a 15 GHz intermediate frequency (IF) and a 63 GHz radio frequency (RF) signal. This reduces the system complexity and cost. The simulation with 2.5 Gbps NRZ signal transmission exhibits good performance both at 15 GHz (Ku-band) and 63 GHz (V-band).

1. INTRODUCTION

In recent years, with the rapid development of emerging technologies such as HDTV, ultra-high speed browsing, interactive multimedia services, intelligent terminal equipment and artificial intelligence and virtual reality, wireless access network is facing great challenges [1]. In a wireless communication system, with the explosive demand for bandwidth growth, wireless carrier frequency migrates to a higher millimeter-wave band has become an inevitable trend [2, 3]. V-band in the 57–64 GHz range with 7 GHz free license bandwidth has been considered an ideal band for high-capacity data transmission, multi-Gb/s wireless access. However, since the attenuation of the millimeter wave in the atmosphere is quite severe, its coverage is limited by the high air propagation loss. RoF technology has been identified as a potential solution for extending the coverage of wireless communications due to its high capacity, low loss, flexible and mobile nature for fiber optic transmission and wireless transmission [4–6]. In [7], the ROF millimeter-wave distribution network deployed by the wavelength division multiplexing (WDM)-PON architecture greatly improves the flexibility of access and system capacity. Since the two-color optical millimeter-wave signal with one tone can eliminate the RF power fading effect and displacement effect caused by fiber dispersion [8], single-sideband (SSB) optical modulation is considered to be a potential modulation scheme for generating optical millimeter-wave signals [9, 10]. In addition, in order to simplify the base station (BS) of the full-duplex link, the upstream optical carrier is extracted from the downlink optical signal by optical filtering [7, 11–15] to propose and implement a passive BS or a semiconductor optical amplifier (SOA), the downlink information is erased, and the uplink data directly modulated on the downlink optical signal [16].

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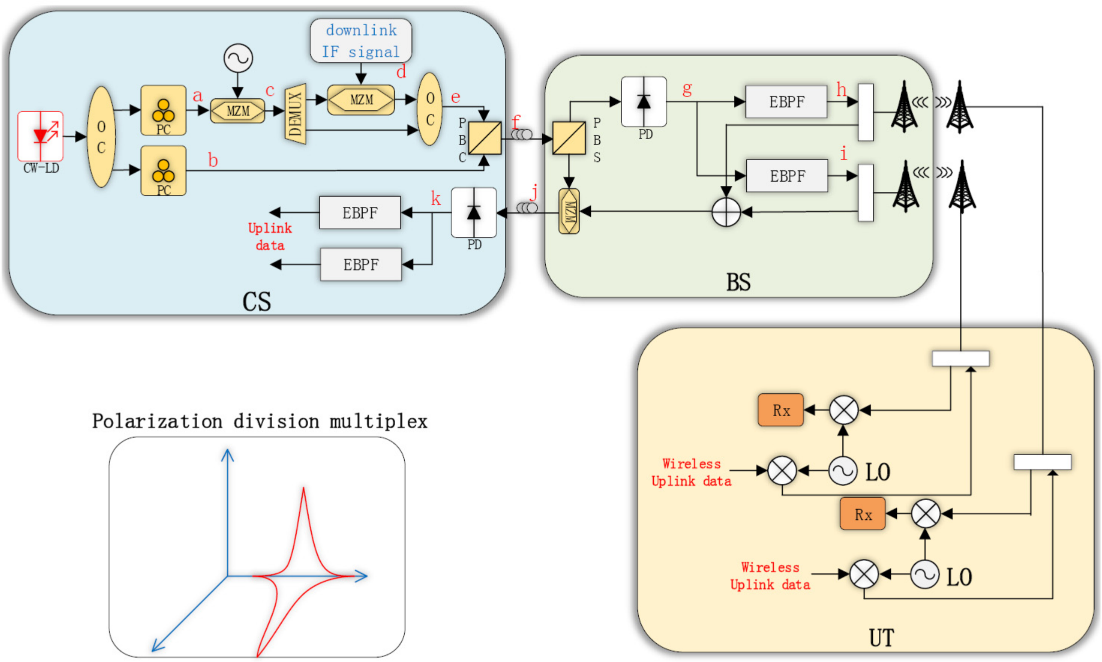
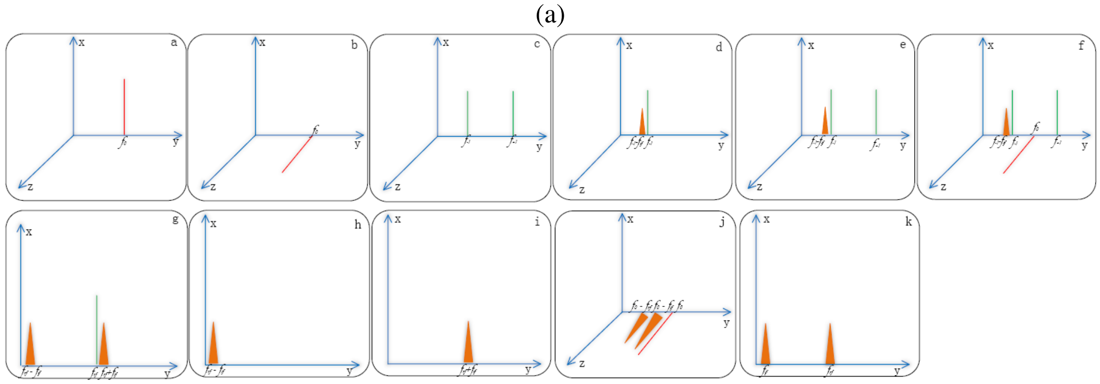
In this paper, we propose a full-duplex scheme based on SSB optical millimeter-wave signals with polarization-multiplexed optical carriers, which makes the passive BS colorless. In the BS, the Y-polarized light carrier is extracted using PBS to carry the uplink signal. Compared with the study in [12, 14], since the optical carrier for the uplink does not carry the downlink signal, the crosstalk from the downlink does not contaminate the uplink signal. At the BS, it is detected by a high-speed photoelectric diode (PD) to generate a 15 GHz intermediate frequency (IF) and a 63 GHz radio frequency (RF) signal. It could provide more flexible wireless access than the research in [17]. Compared with the polarization rotation of 45°, the optical carrier polarization rotates 90° is more easily separated at the BS in the actual system. This reduces the system complexity and cost. The millimeter-wave signal distribution network with a full-duplex link based on WDM-PON can use the same colorless passive BS, which makes the RoF access system simpler and cheaper. The simulation of 63 GHz and 15 GHz with 2.5 Gbps NRZ signal transmission shows that the proposed scheme maintains good performance after 20 km standard single mode fiber (SSMF) transmission.



(a)



(b)

Figure 1. (a) The principle of the proposed full-duplex RoF system based on PDM and WDM technology for multiple services wireless access network; (b) examples of the spectrum evolution of location a–k. MZM, Mach-Zehnder Modulator; OC, optical coupler; PC, polarization control; PBC, Polarization beam combiner; PBS, Polarization beam spliter; EBPF, Electrical band-pass filter.

2. PROPOSED ARCHITECTURE AND OPERATING PRINCIPLE

Figure 1(a) depicts the schematic diagram of the proposed full-duplex RoF system based on PDM and WDM technology. The downlink data optical signal, consisting of three optical tones, is generated by two MZMs based on the optical carrier suppression (OCS) and SSB modulations at the center office (CS), respectively. As shown in Fig. 1(a), the lightwave from the continuous wave laser diode (CW-LD) with the central frequency of $f_c = w_c/2\pi$ can be represented by

$$E_c(t) = E_c \exp(2j\pi f_c t) \tag{1}$$

where E_c and f_c are the amplitude and central frequency of the light wave.

Firstly, the light-wave is divided into two beams by the optical coupler (OC), the X polarized and Y polarized optical carrier are obtained after adjusted by the polarization controller (PC). Fig. 1(b)a and Fig. 1(b)b shows the optical spectrum of X polarized and Y polarized, respectively. The X polarized optical carrier at the frequency of f_c is modulated via a Mach-Zehnder modulator (MZM). The MZM is biased at its optical carrier suppress (OCS) modulation point with the relative DC bias voltage of V_π. Its two arms are driven by the local oscillator (LO) at f_m. Here, all the even-order sidebands are suppressed and the higher-order odd-sidebands are smaller to be neglected. The OCS signal which is given in [18] can be expressed as follow equation:

$$\begin{aligned} E_{ocs}(t) &= \frac{\gamma_1}{2} E_c(t) \left[e^{-j\frac{\pi}{V_\pi} V_{RF} \cos(2\pi f_m t) + j\pi} + e^{j\frac{\pi}{V_\pi} V_{RF} \cos(2\pi f_m t)} \right] \\ &\approx \gamma_1 E_c m_{h1} \left(e^{j[(2\pi f_c + 2\pi f_m)t + \frac{\pi}{2}]} + e^{j[(2\pi f_c - 2\pi f_m)t + \frac{\pi}{2}]} \right) \\ &= B_1 \left(e^{j[(2\pi f_c + 2\pi f_m)t + \frac{\pi}{2}]} + e^{j[(2\pi f_c - 2\pi f_m)t + \frac{\pi}{2}]} \right) \end{aligned} \tag{2}$$

Here, E_c and f_c are the amplitude and central frequency of the light-wave electrical field, respectively. V_{RF} is the amplitude of the LO, and γ_1 and m_{h1} are the insertion loss and modulation index of the first MZM, respectively. And $B_1 = \gamma_1 E_c m_{h1}$. Fig. 1(b)c shows the optical spectrum of the generated OCS optical signal. The generated two tones at $f_c \pm f_m$ serve as the optical mm-wave carrier and are separated by a wavelength division de-multiplexer. As shown in Fig. 1(b)d–e, the passive sideband is modulated by the downlink IF signal, and then combined with the positive sideband together by the wavelength division multiplexer. The IF signal at f_{IF} can be expressed as

$$S_{IF}(t) = V_{IF} A(t) \cos(2\pi f_{IF} t) \tag{3}$$

Here, V_{IF} and $A(t)$ are the amplitude and the instant normalized amplitude of the IF LO and baseband signal, respectively. Then the IF signal is modulated to the lower sideband via the second MZM. Moreover, the relative DC bias voltage between the two arms is set to $V_\pi/2$. So the second MZM is worked in the SSB modulation pattern, the frequency spectrum is shown in Fig. 1(b)d. From Equation (2), Equation (3) and the SSB modulation equation given in [18], we can get the output of the second MZM as follows:

$$\begin{aligned} E_{SSB}(t) &= \frac{\gamma_2 B_1}{2} e^{j[2\pi(f_c - f_{RF})t + \pi/2]} \left[e^{j\frac{\pi}{V_\pi} V_{IF} A(t) \cos(2\pi f_{IF} t) + j\frac{\pi}{2}} + e^{j\frac{\pi}{V_\pi} V_{IF} A(t) \sin(2\pi f_{IF} t)} \right] \\ &\approx \frac{\sqrt{2}\gamma_2 B_1}{2} e^{j[2\pi(f_c - f_{RF})t + \pi/2]} + B_1 \gamma_2 m_{h2} A(t)\, e^{j[2\pi(f_c - f_{RF} - f_{IF})t]} \\ &= B_2 e^{j[2\pi(f_c - f_{RF})t + \pi/2]} + B_3 S_{IF}(t)\, e^{j[2\pi(f_c - f_{RF} - f_{IF})t]} \end{aligned} \tag{4}$$

where $B_2 = \frac{\sqrt{2}\gamma_2 B_1}{2} = \frac{\sqrt{2}\gamma_2 \gamma_1 E_c m_{h1}}{2}$ and $B_3 = \gamma_2 B_1 m_{h2} = \gamma_1 \gamma_2 m_{h1} m_{h2} E_c$, γ_2 and m_{h2} are the insertion loss and modulation index of the second MZM, respectively. We can see that the optical carrier bears the downlink signal at $f_c - f_{RF} - f_{IF}$. After combined with the unmodulated upper sideband at $f_c + f_{RF}$ by optical coupler (OC), the full downlink signal spectrum is shown in Fig. 1(b)e. As given in [18], the full downlink signal can be represented as follows after combined with Equation (2) and Equation (4):

$$E_{full-DL}(t) = B_1 e^{j[2\pi(f_c + f_{RF})t + \pi/2]} + B_2 e^{j[2\pi(f_c - f_{RF})t + \pi/2]} + B_3 S_{IF}(t)\, e^{j[2\pi(f_c - f_{RF} - f_{IF})t]} \tag{5}$$

After combined with the Y polarization optical carrier by an ideal PBC, the optical signal spectrum is shown in Fig. 1(b)f After considered about Equation (1) and Equation (5), it can be expressed as:

$$E_{PBC-DL}(t) = \begin{Bmatrix} E_{full\text{-}DL}(t) \\ E_c(t) \end{Bmatrix} \tag{6}$$

The fiber polarization mode dispersion (PDM) and nonlinear dispersion are not consider here, after being transmitted over standard single-mode fiber (SSMF), the optical signal received by PBS can be expressed as

$$E_{PBS\text{-}DL}(z,t) = \begin{Bmatrix} e^{-\alpha z}\begin{Bmatrix} B_1 e^{j[2\pi(f_c+f_{RF})t-2\pi\beta(f_c+f_{RF})z+\pi/2]} + B_2 e^{j[2\pi(f_c-f_{RF})t-2\pi\beta(f_c-f_{RF})z+\pi/2]} \\ +B_3 S_{IF}(t-\tau)e^{2j\pi\ [(f_c-f_{RF}-f_{IF})t-\beta(f_c-f_{RF}-f_{IF})z]} \end{Bmatrix} \\ e^{-\alpha z} E_c e^{2j\pi f_c(t-\beta z)} \end{Bmatrix} \tag{7}$$

where α and $\beta(w)$ are the attention and propagation constant of the SSMF. z is the fiber length. $\tau = 2\pi\beta'(f_c - f_{RF} - f_{IF})z$ denotes the transmission delay of the tone at $f_c - f_{RF} - f_{IF}$. The output from the PBS is injected into a high-speed photo detector (PD), which is converted to the electrical domain. Based on the heterodyne beating, an IF signal at f_{IF}, a RF signal at $f_{IF} + 2f_{RF}$ and an additional pure RF clock at $2f_{RF}$ are obtained. The spectrum is shown in Fig. 1(b)g, after reference Equation (7) and the heterodyne beating equations which are given in [16], the electrical domain signal be expressed as follows

$$I_{IF\text{-}signal}(t) = 2\mu B_2 B_3 S_{IF}(t-\tau)\cos[2\pi f_{IF}t + 2\pi\beta(f_c - f_{RF})z - 2\pi\beta(f_c - f_{RF} - f_{IF})z] \tag{8}$$

$$I_{RF\text{-}signal}(t) = 2\mu B_1 B_3 S_{IF}(t-\tau)\cos[2\pi(f_{RF} + f_{IF})t + 2\pi\beta(f_c + f_{RF})z - 2\pi\beta(f_c - f_{RF} - f_{IF})z] \tag{9}$$

$$I_{RF}(t) = 2\mu B_1 B_2 \cos[2\pi f_{RF}t + 2\pi\beta(f_c + f_{RF})z - 2\pi\beta(f_c - f_{RF})z] \tag{10}$$

where μ is the sensitivity of the PD.

For an IF wireless access network, an electrical band-pass filter (EBPF) with the central frequency of f_{IF} is used to filter out the IF signal. And the IF signal is shown in Fig. 1(b)h. For mm-wave wireless access network, the RF signal at $2f_{RF} + f_{IF}$ is filter out by the other EBPF with the central frequency of $2f_{RF} + f_{IF}$, and then transmitted to the user terminal by a directional antenna. The RF data signal is shown in Fig. 1(b)i.

For the uplink, the optical carrier at f_c abstracted by the PBS is used to carry wireless uplink data. For wireless, the uplink signal $S_{wireless\text{-}UL}(t)$ is up-converted to a RF signal by mixing with the RF LO at f_{RF2}. The generated uplink RF signal can be expressed as

$$S_{UL}(t) = V'_{RF} S_{wireless\text{-}UL}(t)\cos(2\pi f_{RF2}t) \tag{11}$$

where V'_{RF} is the amplitude of the LO. As shown in Fig. 1(b)j, after transmitted by the antenna, it is added with the IF signal, and then both of them are modulated on the Y polarized optical carrier via an MZM to generate the uplink optical signal. After being transmitted by the SSMF, the uplink optical signal is detected by a square-law PD, as shown in Fig. 1(b)k.

In the proposed full-duplex RoF system, because the uplink optical carrier is provided by the laser diode at the CS, the BS is source free. In addition, the SSB modulation and PDM are used in our system, in which the downlink data is carried by one tone of the downlink optical signal, the fiber chromatic dispersion and laser phase noise and polarization mode dispersion (PMD) have little effect on the transmission performance [7, 9, 18].

3. SIMULATION SETUP AND RESULTS

In order to verify the scheme we proposed above, we build the simulation system without wireless transmission based on the software optisystem 14.2. The simulation architecture is shown in Fig. 2.

For the downlink, the light wave gets from a continuous wave LD with the central frequency of 193.1 THz and linewidth of 0.1 MHz. The MZM with half-wave voltage of 4 V is driven by a 12 GHz LO with a peak-to-peak voltage of 6.124 V. The optical carrier is suppressed completely when the modulation index is 2.405. The output of the MZM is DSB signal with a frequency spacing of 48 GHz. The 15 GHz downlink data is generated by mixing a 15 GHz LO signal with a 2.5 Gbps pseudo random

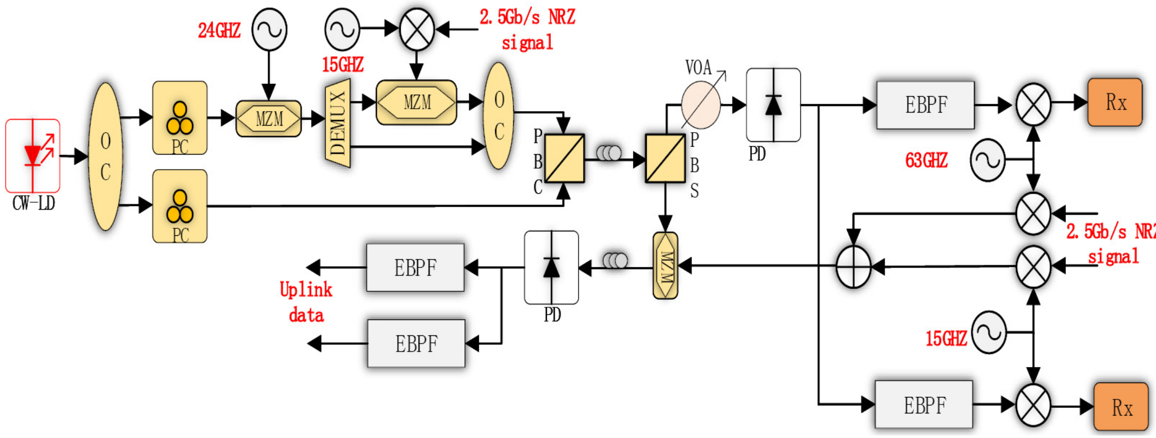


Figure 2. The simulation architecture of Full-duplex RoF system with 2.5 Gb/s NRZ signal transmission for difference frequency band.

binary sequence (PRBS) data which is used to drive MZM. An EDFA with the noise figure of 4.5 dB is used to amplify the orthogonal polarization multiplexing signal to 6 dBm. The adopted fiber in the simulation is SSMF with a chromatic dispersion of 17 ps/nm/km and a power attenuation of 0.2 dB/km at 1550 nm. At the base station, the orthogonal polarization multiplexed signal, which is de-multiplexed by PBS, is directly detected by the high-speed PD after attenuation by a variable optical attenuator. The spectrum of the RF signal is shown in Fig. 3(a), which is coherently demodulated by LOs of 15 GHz and 63 GZH, respectively.

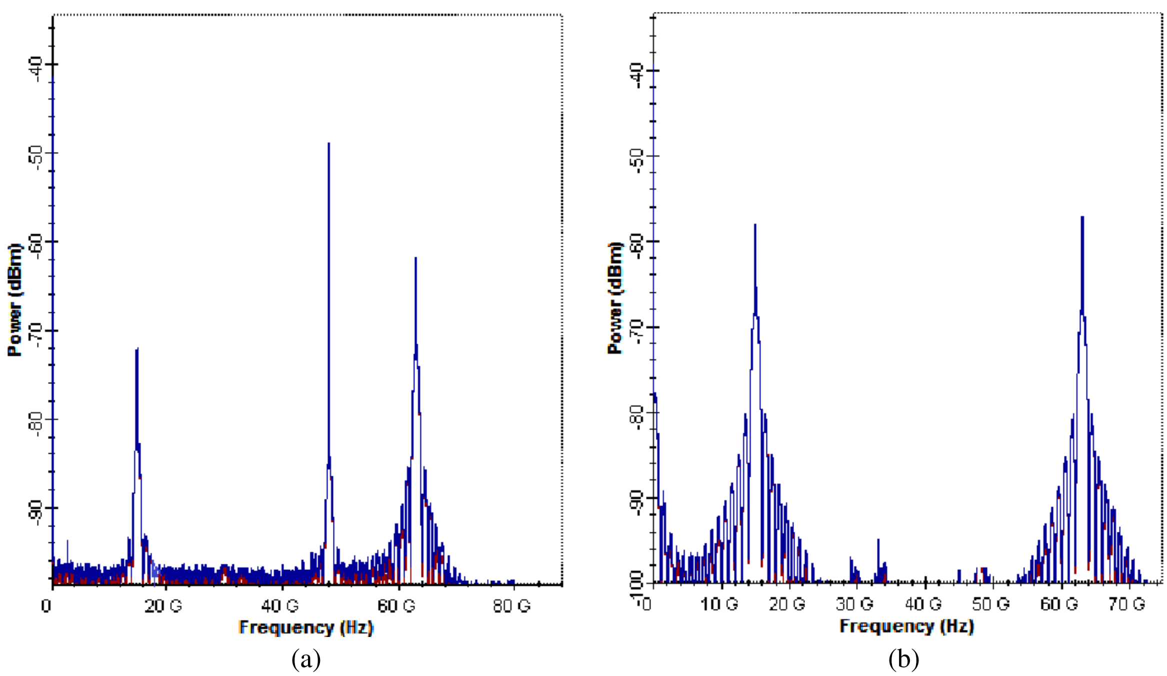
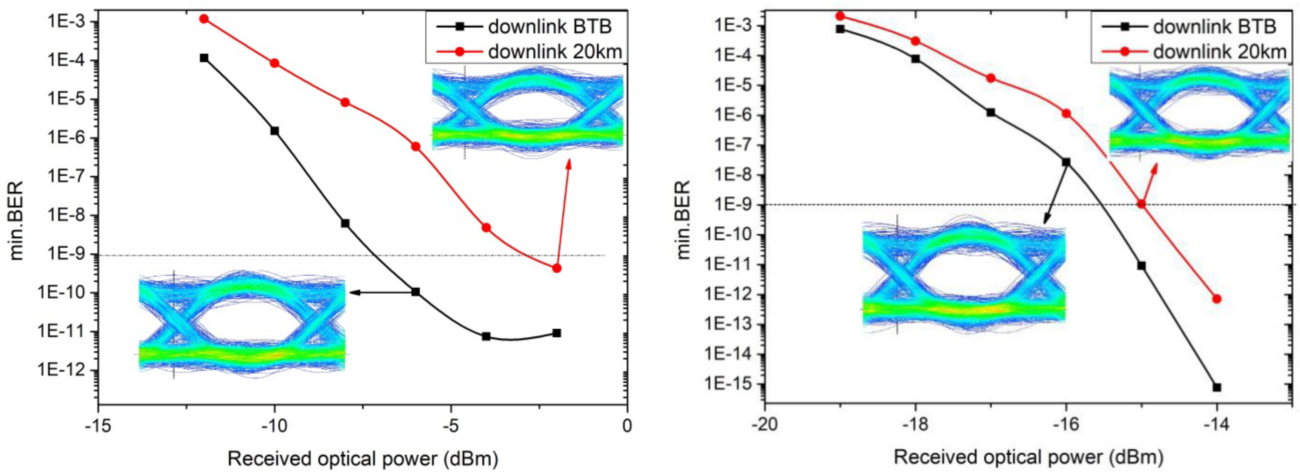


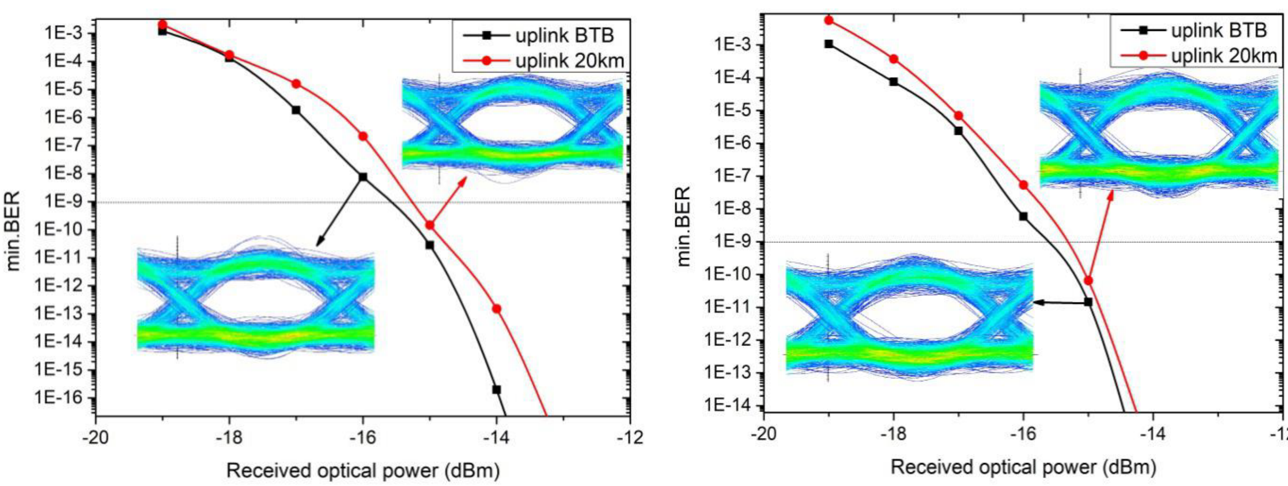
Figure 3. The Spectra of downlink and uplink data after PD. (a) Spectra of downlink data after PD; (b) Spectra of uplink data after PD.

For the uplink, the de-multiplexed Y-polarized signal is divided into two channels for the uplink data by OC. The uplink signal is generated by mixing 2.5 Gbps baseband data with a sine wave source of 63 GHz and 15 GHz respectively. And we can test the uplink performance after demodulated by LO. The spectrum of the uplink RF signal is shown in Fig. 3(b).



(a) (b)

Figure 4. The spectra and measured BER curves for downlink. (a) Measured BER for 15 GHz downlink; (b) Measured BER for 63 GHz downlink.



(a) (b)

Figure 5. The spectra and measured BER curves for downlink. Measured BER for 15 GHz uplink; (b) Measured BER for 63 GHz uplink.

The bit error rate (BER) curves and typical eye diagrams for both BTB and 20 km cases are given to quantify the transmission performance. As shown in Fig. 4(a) and Fig. 4(b), the downlink received sensitivity with the BER of 10^{-9} at the BTB case for 15, 63 GHz are -7 dBm, -15.4 dBm, respectively. According to the dispersion from the SSMF, we can see that there are about 4 dBm power penalty with 10 GHz signal transmission and about 1 dBm with 63 GHz signal transmission for downlink. In Fig. 5(a) and Fig. 5(b), the uplink received sensitivity with the BER of 10^{-9} at the BTB case for 15, 63 GHz are both -15.4 dBm. And the power penalty is about 0.5 dBm for both 10 GHz and 63 GHz signal transmission. The BER can still reach 10^{-9} after transmission 20 km and the eye diagrams are also quite good.

4. CONCLUSION

In this paper, a full-duplex access network architecture with 2.5 Gbps NRZ signal transmission based on PDM and WDM is proposed to provide multi-wireless access services. Compared with other full-duplex architectures, our scheme greatly increases the flexibility of the access network and simplifies the BS. In our proposed system, the uplink carrier at the BS is provided from downlink, and the BS is free from the laser source for uplink wireless access, which significantly reduces the complexity of the BS. The downlink and uplink use the same frequency optical carrier, which greatly alleviate the tension of the optical carrier resources. The BER curves and eye diagrams verify the feasibility of our proposed full-duplex system, which shows that both 15 GZH and 63 GZH wireless transmissions have good performance after 20 km SSMF transmission. The eye diagrams and BER curves of the downlink and uplink obtained by the simulation verify that the proposed full-duplex RoF architecture is a cost-effective solution for the next generation wireless access network.

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