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Full-duplex radio over fiber link with colorless source-free base station based on single sideband optical mm-wave signal with polarization rotated optical carrier

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ABSTRACT

A full-duplex radio-over fiber (RoF) link scheme based on single sideband (SSB) optical millimeter (mm)-wave signal with polarization-rotated optical carrier is proposed to realize the source-free colorless base station (BS), in which a polarization beam splitter (PBS) is used to abstract part of the optical carrier for conveying the uplink data. Since the optical carrier for the uplink does not bear the downlink signal, no cross-talk from the downlink contaminates the uplink signal. The simulation results demonstrate that both down- and up-links maintain good performance. The mm-wave signal distribution network based on the proposed full duplex fiber link scheme can use the uniform source-free colorless BSs, which makes the access system very simpler.

1. Introduction

With the explosive growth of the bandwidth requirement of the wireless communication, the radio carrier frequency of the wireless system is moving toward to the millimeter (mm)-wave band with higher frequency [1,2]. Radio-over-fiber (RoF) techniques in mm-wave band are widely investigated for providing multi gigabit-per-second wireless access with wider service coverage and possible integration with future passive optical network (PON) to overcome its large transmission loss in both air and metal waveguide [3–6]. The mm-wave signal distribution network based on RoF technique could be deployed over the wavelength division multiplexing (WDM)-PON architecture with dramatic increase of the capacity and access flexibility [7]. Since the dual-tone optical mm-wave with one tone bearing the signal can eliminate both RF power fading effect and bit-walk effect caused by fiber chromatic dispersion [8], single sideband (SSB) optical modulation is regarded as a potential modulation scheme to generate the optical mm-wave signal. Moreover, to simplify the base station (BS) of the full duplex link, source-free BS is proposed and implemented by abstracting the uplink optical carrier from the downlink optical signal via optical filtering [7,9–13], or directly modulating the uplink data on the downlink optical signal [14] while the downlink information is erased based on the saturation effect of semiconductor optical amplifier (SOA) [15]. However, optical filtering scheme usually requires wavelength selective devices, such as optical filter [10], fiber Bragg grating (FBG) [11], Mach–Zehnder interference (MZI) [13] or interleaver (IL) [14], which makes the BS sensitive to the wavelength. Although the SOA can make the BS source-free and colorless, there will be serious crosstalk from the vestigial downlink signal if it cannot be erased by the saturation effect of SOA completely [15]. Based on the polarization multiplexing technology, the full-duplex link for the ultra wideband (UWB) signal can be realized colorlessly with the source-free BS [16]. In [17], a phase modulator (PM) and a polarization beam splitter (PBS) are used to achieve a colorless full-duplex RoF link with double sideband (DSB) with optical carrier suppression (DSBCS) modulation, while this scheme suffers greatly from the fiber chromatic dispersion due to the bit-walk effect especially for the higher frequency mm-wave signal with the bit rate over gigabit per second [8].

In this paper, we propose a full-duplex RoF link scheme based on an SSB optical mm-wave signal with polarization-rotated optical carrier, which makes the source-free BS colorless. In the BS, a PBS is used to abstract part of the optical carrier to carry the uplink signal. Since the optical carrier for the uplink does not carry the downlink signal, no cross-talk from the downlink contaminates the uplink signal. The simulation results demonstrate that both down- and uplinks maintain good performance. The mm-wave signal distribution network with the proposed full duplex link based on WDM-PON can use the same colorless source-free BS, which makes the RoF access system simpler and cheaper.

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The paper is organized as follows: the principle of the proposed full-duplex is described in Section 2; and then a simulation platform is setup in Section 3 with the deep analysis on the simulation results. At last, a conclusion is drawn in the Section 4.

2. Principle of the hybrid wired/wireless full-duplex access link

Fig. 1 shows the principle diagram of the proposed full-duplex RoF link for the broadband wireless access. In the central station (CS), the lightwave emitted from the narrow-linewidth laser diode (LD) at the frequency of f_o is modulated via a Mach–Zehnder modulator (MZM) by the mm-wave clock with the frequency at f_m in optical carrier suppression pattern. The generated co-polarized two tones at $f_o \pm f_m$ serve as the optical mm-wave carrier and are separated by an interleaver (IL). One tone is modulated by the downlink baseband signal $S_D(t)$, while the state of polarization of the other tone is rotated by a polarization controller (PC) to keep an angle of 45° between the two tones after they are recombined together by a 3 dB optical coupler (OC). So the dual-tone optical mm-wave signal with polarization-rotated optical carrier can be expressed in Jones matrix as

$$\begin{aligned}\vec{E}(t) &= \vec{E}_{-1}e^{j2\pi(f_o-f_m)t} + \alpha\vec{E}_{+1}S_D(t)e^{j2\pi(f_o+f_m)t} \\ &= \begin{pmatrix} \frac{\sqrt{2}}{2}E_{-1}e^{j2\pi(f_o-f_m)t} + \alpha E_{+1}S_D(t)e^{j2\pi(f_o+f_m)t} \\ \frac{\sqrt{2}}{2}E_{-1}e^{j2\pi(f_o-f_m)t} \end{pmatrix}\end{aligned} \tag{1}$$

Here, the equation was obtained considering small-signal modulation, α accounts for the insertion loss introduced by the second MZM and then α is lower than 1, and the polarization angle between the two tones $< \underset{-1}{\vec{E}}, \underset{+1}{\vec{E}} >$ is 45° after polarization rotation. Then, the polarized optical mm-wave signal is injected into the fiber downlink and is transmitted to the BS. Due to the polarization mode dispersion, the two tones are rotated randomly in the real system. Since the polarization variations during the downstream optical transmission will have impact on the performance of the downlink, a polarization stabilizer is used in the BS to stabilize the state of polarization of the downlink optical mm-wave signal [18,19]. After that, a polarization beam splitter is used to separate it as the optical mm-wave signal and the uplink optical carrier. The former consists of two co-polarized tones: the signal at $f_o + f_m$ and part of the optical carrier at $f_o - f_m$, and can be expressed as

$$E_{mm\text{-}wave}(t) = \frac{\sqrt{2}}{2}E_{-1}e^{j2\pi(f_o-f_m)t} + \alpha E_{+1}S_D(t)e^{j2\pi(f_o+f_m)t}, \tag{2}$$

which is then converted to the electrical mm-wave signal by the photodiode (PD). The photocurrent becomes

$$\begin{aligned}I(t) &= \mu|E_{mm\text{-}wave}(t)|^2 \\ &= \tfrac{1}{2}\mu|E_{-1}|^2 + e^{j2\pi(f_o-f_m)t} + \mu\alpha^2|E_{+1}|^2S_D^2(t) + \sqrt{2}\mu\alpha\mathrm{Re}\{E_{-1}^*E_{+1}S_D(t)e^{j4\pi f_m t}\}\end{aligned} \tag{3}$$

Here μ is the sensitivity of the PD. Then, the desired mm-wave signal at $4f_m$ is abstracted by an electrical bandpass filter with the central frequency at $2f_m$ and bandwidth bigger than the bandwidth of the signal $S_D(t)$. Since the optical mm-wave signal has two tones with one carrying the signal, the degradation caused by the power fading effect and bit-walk effect due to the fiber chromatic dispersion is eliminated [8], and so the theoretical expressions were derived considering an optical back-to-back configuration and then chromatic dispersion phase shift is not present in the expressions of the electric field for simplification. The other part of the optical carrier at f_o–f_m output from the other port of the PBS is expressed as,

$$E_{OLO}(t) = \frac{\sqrt{2}}{2}E_{-1}e^{j2\pi(f_o-f_m)t} \tag{4}$$

and then it can be modulated by the uplink optical mm-wave signal received by the antenna, or the baseband signal, $S_U(t)$, which is demodulated from the uplink mm-wave signal by envelope detection or coherent detection. In the simulation below, the baseband signal with envelope detection is used. Since only the optical carrier is abstracted for bearing the uplink signal perfectly, the crosstalk from the downlink can be avoided theoretically.

In the proposed full-duplex link scheme, because the uplink optical carrier is abstracted from the downlink signal, the BS is free from the optical source. In addition, the optical carrier is abstracted by PBS without wavelength sensitive device, so the BS is implemented colorlessly. Moreover, since part of the optical power is abstracted from the optical carrier of the original dual-tone optical mm-wave signal, its optical carrier to sideband ratio (CSR) is reduced, which improves the detector sensitivity of the optical mm-wave signal and saturation optical power of the PD. In the scheme, the power of the optical carrier is equally divided to the downlink optical mm-wave signal and the uplink optical carrier by keeping a polarization angle of 45° between the two tones. In fact, we can also vary their relative power by adjusting the polarization angle between the two tones in the CS to balance the performance between the down- and uplinks. These advantages make the mm-wave distribution network based on the proposed RoF technique more compatible to WDM-PON with colorless source-free BSs.

3. Simulation setup and results

To verify the proposed scheme of the full-duplex RoF link, a simulation system without wireless part is built, as shown in Fig. 2. The lightwave from the continuous wave LD at 193.1THz with the linewidth of 50 MHz and white noise of −34dBm/0.01 nm, shown in the inset (a) of Fig. 2, is modulated by the 30 GHz mm-wave local oscillator (LO) via a Mach–Zehnder modulator (MZM) biasing at transmission null point in push–pull pattern. The output

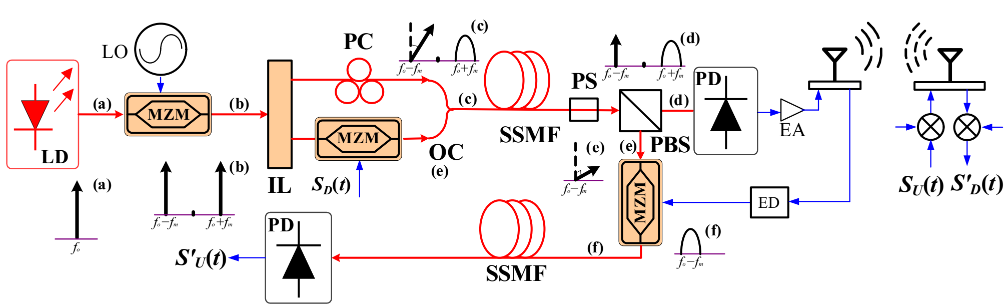

Fig. 1. The principle of the proposed full-duplex RoF link for the broadband mm-wave wireless access with source-free colorless base station. LD: laser diode; MZM, Mach–Zehnder modulator; LO: local oscillator; IL: interleaver; PC: polarization controller; OC: optical coupler; SSMF: standard single mode fiber; PS: polarization stabilizer; PBS: polarization beam splitter; PD: photodiode; EA: electrical amplifier; ED: envelope detection.