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An intensity-modulation direct-detection radio-over-fiber link with a tunable transfer function

Haiyan Ou [a,*], Kun Zhu [b], Chenhui Ye [b], Ying Hu [b]

[a] Institute of Applied Physics, University of Electronic Science and Technology of China, 610054, Chengdu, PR China
[b] Centre for Optical and Electromagnetic Research, Zhejiang University, Hangzhou 310058, PR China

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ABSTRACT

An intensity-modulation direct-detection (IMDD) radio-over-fiber link with a tunable transfer function is presented. It utilizes a bias drift free intensity modulator based on a Sagnac fiber loop interferometer containing an optical phase modulator. By adjusting the polarization controller in the interferometer, the transfer function of the whole system can be tuned. The present method is simple and easy to implement.

1. Introduction

Radio-over-fiber (RoF) technology is one of the most attractive solutions for future high speed broadband wireless communication [1]. In a millimeter-wave (mm-wave) band RoF system, a central station (CS) should distribute different signals to many base stations (BSs) through optical fibers to provide different kinds of services to customers. It also takes the advantages of a standard single-mode fiber (SMF) such as the low loss, high bandwidth, lightweight, compactness, and immunity to electromagnetic interference, etc.

There are many different approaches to transmit mm-wave signals from CS to BSs through optical fibers, among which the intensity-modulation and direct-detection (IMDD) technique is a relatively simple and practical method [2]. In an IMDD link, the mm-signals are intensity modulated on the optical carrier and then transmitted through an optical fiber. At a BS, the mm-wave signals are recovered by direct detection in a photodiode (PD).

However, in a general IMDD system, the fiber chromatic dispersion intrinsically occurring in a standard 1550-nm single-mode fiber is one of the main drawbacks that limits the transmission distance and operation bandwidth [3]. The dispersion results in a carrier to noise (C/N) penalty on the mm-wave signal due to the phase shift of the modulation side bands with respect to the optical carrier. The phase shift depends on the length of the fiber, dispersion parameter, and the modulated RF frequency.

In this paper, we present an IMDD RoF link with a tunable transfer function, which in turn changes the C/N penalty of the mm-wave signal. The tunability of the system is introduced by a bias-free intensity modulator, which is based on an electro-optic phase modulator in a fiber Sagnac interferometer. Experimental results are presented to verify the new concept.

2. Principle

The structure of the Sagnac-loop-based intensity modulator is illustrated in Fig. 1. An optical coupler with 50:50 coupling ratio is used to form the Sagnac fiber loop interferometer. The input light is split equally with half traveling in the clockwise (CW) direction and the other half traveling in the counterclockwise (CCW) direction. In the center of the fiber loop, there is an electro-optical phase modulator, which is a commercially available product made from $LiNbO_3$ crystal. The driving radio frequency (RF) signal is applied to the crystal through the traveling-wave electrodes. Two polarization controllers (PC) are employed: one of them is placed outside the loop at the input to the optical coupler (PC_1), and the other is placed inside the loop at the right-hand side of the optical phase modulator (PC_2). PC_1 is used to adjust the polarization state of the optical wave that travels in the CW direction inside the Sagnac loop to let it align with the phase modulator; PC_2 is used to control the phase difference between the counterpropagating waves. These two PCs work as a nonreciprocal bias unit, which introduces a phase difference between the CW and CCW phase-modulated optical signals.

The output power of the structure is related to the phase difference between the CW light and CCW light as follows [4]

$$P_{out} = \frac{1}{2} P_{in} L_p (1+\sin\Delta\varphi) \quad (1)$$

* Corresponding author. Tel.: +86 28 83202541.
E-mail address: haiyan.ou@gmail.com (H. Ou).

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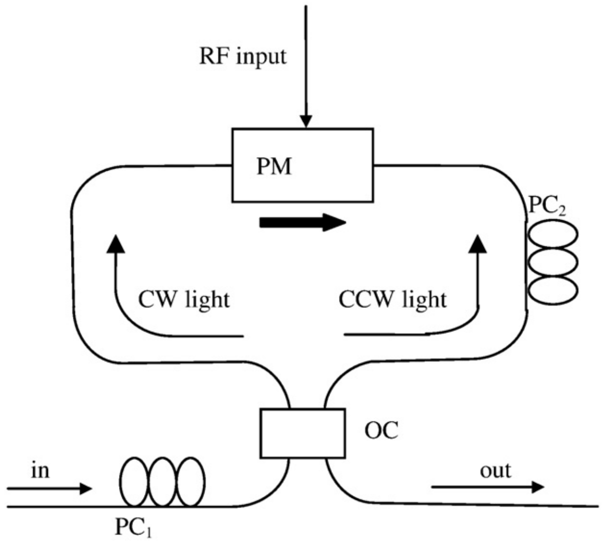

Fig. 1. Structure of the Sagnac-loop-based intensity modulator. OC: optical coupler; PC: polarization controller; and PM: phase modulator. Arrow on the phase modulator indicates the microwave propagation direction.

where P_{in} and P_{out} are the input and output optical powers, L_p is the polarization-introduced optical loss when CW and CCW optical signals recombine and interfere at the coupler output, and $\Delta\varphi$ is the total phase difference between the CW light and CCW light.

Assuming a microwave signal with frequency ω_{RF} and amplitude V_{RF} is applied to the phase modulator, the total phase difference $\Delta\varphi$ is then given by

$$\Delta\varphi = (1-r)\beta\cos\omega_{RF}t + \Phi \tag{2}$$

where $\beta=\pi V_{RF}/V_\pi$ is the modulation index of the phase modulator for the CW signal, Φ is the polarization-related phase difference between the CW light and CCW light, and r is the ratio of backward to forward phase modulation index, which is included because the forward and backward phase modulator frequency responses can be different at high frequency due to velocity mismatch in travelling wave modulator [5]. The modulation index ratio r can be expressed as

$$r = \frac{\sin(\omega_{RF}\tau_x)}{\omega_{RF}\tau_x} \tag{3}$$

where τ_x is the transit time in the phase modulator. One can conclude from Eq. (3) that for a given electro-optical phase modulator, the modulation index of the CW and CCW signals are almost the same when ω_{RF} is small; however, as ω_{RF} grows to high radio frequency, r drops dramatically.

It also needs to mention that modification of the polarization not only changes the phase modulation depth β which depends on the input polarization to the waveguides, but also modifies the state of polarization (SOP) of the CW and CCW waves at recombination in the coupler output. So the output optical power of the Sagnac-loop-based intensity modulator will vary when modifying the PC, which is in accordance to Eqs. (1) and (2). And there is no response if the SOP of the CW and CCW signals is orthogonal.

The principle of this intensity modulator is shown in Fig. 2. From Fig. 2 one can see that, for a given value of Φ and L_p, the output power varies periodically with the frequency of phase modulation, which indicates that an intensity modulator is formed. This structure has the advantages of eliminating the dc bias voltage that is required for traditional electro-optic intensity modulators and exhibiting a high stability without using a feedback bias controller [6].

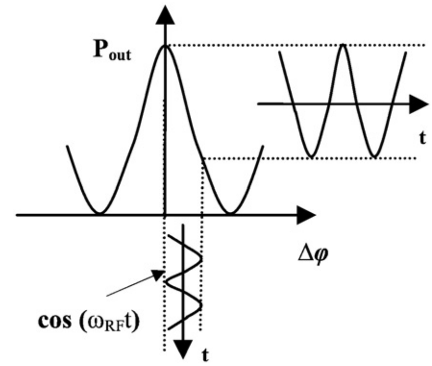

Fig. 2. A diagram showing the relation between the optical power and the total phase difference (given by Eq. (2)) between the CW and CCW signals.

Fig. 3 shows the topology of the IMDD RoF link with the Sagnac-loop-based intensity modulator implemented. The input RF signal is directly applied on the intensity modulator. After transmission through a 50 km single-mode fiber (SMF), the signal is directly recovered by the PD.

After the recombination of the CW light and CCW light, the optical field at the output port of the intensity modulator can be expressed as

$$\begin{aligned} e_t(t) &= \frac{1}{2}e^{j(\omega_0 t + \beta\cos\omega_{RF}t + \Phi)} - \frac{1}{2}e^{j(\omega_0 t + r\beta\cos\omega_{RF}t)} \\ &= \frac{1}{2}[J_0(\beta)-J_0(r\beta)]\cos(\omega_0 t + \Phi_0') \\ &\quad + \frac{1}{2}[J_1(\beta)-J_1(r\beta)]\cos\left[(\omega_0+\omega_{RF})t + \frac{\pi}{2} + \Phi_1'\right] \\ &\quad + \frac{1}{2}[J_1(\beta)-J_1(r\beta)]\cos\left[(\omega_0-\omega_{RF})t - \frac{\pi}{2} + \Phi_{-1}'\right] \end{aligned} \tag{4}$$

where ω_0 is the angular frequency of the optical carrier, $J_n(\beta)$ is the nth-order Bessel function of the first kind, Φ_0', Φ_1', and Φ_{-1}' are polarization-induced phase delays of the optical carrier ω_0, and first order sidebands $\omega_0+\omega_{RF}$, and $\omega_0-\omega_{RF}$, respectively.

After transmission through the SMF, the optical field can be expressed as [7]

$$\begin{aligned} e(t) &= A\cos(\omega_0 t + \Phi_0' + \Phi_0) \\ &\quad + \frac{1}{2}[J_1(\beta)-J_1(r\beta)]\cos\left[(\omega_0+\omega_{RF})t + \frac{\pi}{2} + \Phi_1' + \Phi_1\right] \\ &\quad + \frac{1}{2}[J_1(\beta)-J_1(r\beta)]\cos\left[(\omega_0-\omega_{RF})t - \frac{\pi}{2} + \Phi_{-1}' + \Phi_{-1}\right] \end{aligned} \tag{5}$$

where Φ_0, Φ_1, and Φ_{-1} are the phase delays of the spectral components ω_0, $\omega_0+\omega_{RF}$, and $\omega_0-\omega_{RF}$ induced by the chromatic dispersion of the SMF.

The transfer function (defined as the ratio of the output and input mm-wave powers) of the system can then be approximately expressed as

$$\begin{aligned} H(f) &\propto \cos\left(\frac{\Phi_1 + \Phi_{-1} + \Phi_1' + \Phi_{-1}'}{2} - \left(\Phi_0 + \Phi_0'\right)\right) \\ &= \cos\left(\left(\frac{\Phi_1 + \Phi_{-1}}{2} - \Phi_0\right) + \left(\frac{\Phi_1' + \Phi_{-1}'}{2} - \Phi_0'\right)\right) \end{aligned} \tag{6}$$

It is well known that the phase delay induced by the fiber chromatic dispersion can be given by an expansion in a Taylor