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1 × N hybrid radio frequency photonic splitter based on a dual-polarization dual-parallel Mach Zehnder modulator

Sha Zhu [a,b,c], Ming Li [b,c], Xin Wang [b], Ning Hua Zhu [b,c], Wei Li [a,b,c,*]

[a] State Key Laboratory of Optical Fiber and Cable Manufacture Technology, Strategy Center, YOFC, Wuhan 430073, China
[b] State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, 100083, China
[c] School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing, 100049, China

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ABSTRACT

We report a 1 × N hybrid radio frequency (RF) photonic splitter with arbitrary phase shift and amplitude ratio using a dual-polarization dual-parallel Mach Zehnder modulator (DP-DPMZM). The DP-DPMZM is properly set to generate an orthogonally polarized single-sideband (SSB) modulated optical signal. By controlling a polarization controller (PC) and a polarizer (Pol.) that cascaded behind the modulator, an RF photonic splitter with arbitrary phase and amplitude ratio can be realized. Compared with previous reported works, the proposed RF splitter can be operated in a wide bandwidth since no optical or electrical filters are involved. The proposed scheme is theoretically analyzed and experimentally verified.

1. Introduction

Microwave photonics (MWP) has attracted considerable interests recently through combining radio frequency (RF) engineering and photonic technology to overcome the electronic bottleneck problems. MWP systems cover the advantages of electronics and optics, such as high frequency, large bandwidth, easy tuning, low power consumption, low weight and immunity to electromagnetic interference. Therefore, numerous MWP links have been proposed to generate, transmit, process and detect RF signals [1–6].

In pure electronic domain, RF splitter is a fundamental element which always has fixed number of output ports, fixed amplitude ratio and fixed phase shift [7,8]. It is difficult to change the amplitude ratio and phase shift of an RF splitter. The number of the output ports is also hard to add or drop to accommodate different requirements. This drawback restricts its applications in signal processing and radar systems. Nevertheless, RF photonic splitter, which is constructed in MWP systems, has potential to achieve arbitrary phase shift and amplitude ratio between different outputs in a large bandwidth. The RF photonic splitter can be widely used in RF applications which need a lot of copies of a broadband signal with tunable phase and amplitude, such as multi-tap microwave photonic filters (MPFs) [9–11], complex microwave signal detection in radars [12,13], and analog encryption in RF signal dissemination systems [14]. Some MWP schemes have been reported to realize an RF photonic splitter [15–17]. For example, a 1 × 2 arbitrary RF photonic splitter has been proposed using two different continuous lights [15,16]. However, N laser diodes (LDs) are required to achieve a 1 × N RF photonic splitter which makes the system costly and complicated. The phase shift between the two different RF outputs is adjusted by the bias of a dual-parallel Mach–Zehnder modulator (DPMZM). Thus, the phase shift for each branch of the RF photonic splitter cannot be tuned independently. We have reported a microwave photonic splitter using a polarization modulator (PolM) and an optical bandpass filter (OBPF) [17]. The use of an OBPF limits the operation bandwidth and tunability of the RF photonic splitter.

In this paper, we propose a 1 × N hybrid RF photonic splitter with arbitrary phase shift and amplitude ratio using a single dual-polarization dual-parallel Mach Zehnder modulator (DP-DPMZM). Compared with our previous work [17], no optical or electrical filters are involved in this scheme. Thus, the proposed RF splitter can be operated in a wide bandwidth. An orthogonally polarized single-sideband (SSB) modulated optical signal is generated by properly setting the DP-DPMZM. The RF splitter can be easily expanded to have N branches using a 1 × N optical splitter. By tuning the polarization controller (PC) and polarizer (Pol.) in each branch, the RF splitter can have independently tuned phase shift and amplitude ratio. The possibility of the proposed scheme is theoretically and experimentally verified.

* Corresponding author at: State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, 100083, China.
E-mail address: liwei05@semi.ac.cn (W. Li).

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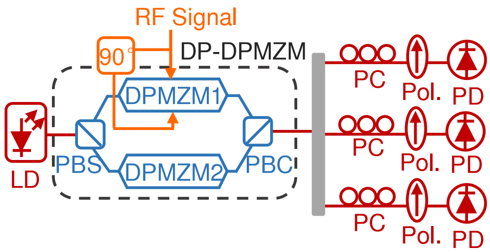

Fig. 1. The schematic of the proposed $1 \times N$ hybrid radio frequency (RF) photonic splitter with arbitrary phase shift and amplitude ratio. LD, laser diode; DP-DPMZM, dual-polarization dual-parallel Mach–Zehnder modulator; DPMZM, dual-parallel Mach–Zehnder modulator; PBS, polarization beam splitter; PBC, polarization beam combiner; 90°, 90° electrical coupler; PC, polarization controller; Pol., polarizer; PD, photodetector.

2. Principle

The structure of the proposed $1 \times N$ hybrid RF photonic splitter with arbitrary phase shift and amplitude ratio is shown in Fig. 1. The key component of the RF photonic splitter is a DP-DPMZM which consists of a polarization beam splitter (PBS), two DPMZMs (DPMZM1 and DPMZM2) at two orthogonal polarization states and a polarization beam combiner (PBC). The major structure of a DPMZM is a parent MZM with two sub-MZMs lying on each of its arms. A linearly polarized optical carrier is fiber-coupled into the DP-DPMZM with an angle of 45° to one principal axis of the PBS. The upper DPMZM1 driven by an RF signal is biased to generate a carrier suppressed single sideband (CS-SSB) modulated signal. Whereas, the lower DPMZM2 is set at maximum transmission point to let a pure optical carrier pass through with maximum optical power. By adjusting PCs in different branches, a $1 \times N$ RF photonic splitter is constructed successfully. Mathematically, when the DPMZM1 is driven by a RF signal, the optical field at the output of DPMZM1 is given by

$$E_x(t) = \frac{1}{8}E_0 e^{j\omega_0 t}[e^{j\beta\cos(\omega_m t)+j\varphi_1} + e^{j\beta\cos(\omega_m t+\pi)}] + [e^{j\beta\sin(\omega_m t)+j\varphi_2} + e^{j\beta\sin(\omega_m t+\pi)}]e^{j\phi_1}, \quad (1)$$

where E_0 and ω_0 are the amplitude and angular frequency of the optical carrier, V and ω_m are the peak-to-peak value and angular frequency of the driven RF signal, β is the RF modulation index of DPMZM1 which is equal to $\pi V/V_\pi$, V_π is the RF switching voltage, $\varphi_1 = \pi V_{DC1}/V_\pi$, $\varphi_2 = \pi V_{DC2}/V_\pi$ and $\phi_1 = \pi V_{DCx}/V_\pi$ where V_{DC1} and V_{DC2} are the direct current (DC) biases of the two sub-MZMs, V_{DCx} is the main DC bias of the DPMZM1. By setting $\varphi_1 = \pi$, $\varphi_2 = \pi$, and $\phi_1 = \pi/2$, under small signal modulation condition, Eq. (1) can be rewritten as

$$E_x(t) = \frac{1}{2}E_0 J_1(\beta) e^{j[(\omega_0+\omega_m)t - \frac{\pi}{2}]}, \quad (2)$$

where $J_1(\beta)$ is the first order Bessel function of the first kind. From Eq. (2) we could see that a CS-SSB modulated signal is generated successfully.

In order to make the pure optical carrier pass through lower DPMZM2 with maximum optical power, the two sub-MZMs and parent MZM of the DPMZM2 are all biased at maximum transmission point. Hence, the optical signal at the output of DPMZM2 is

$$E_y(t) = \frac{1}{2}E_0 e^{j\omega_0 t}. \quad (3)$$

In transmission branch, a PC which consists of a quarter-wave, a half-wave, and a quarter-wave plates is used to adjust the polarization states of the optical signals according to the transfer function of

$$P_{PC} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} e^{j\theta} & 0 \\ 0 & e^{-j\theta} \end{bmatrix}, \quad (4)$$

where α is the rotation angle, θ is the phase difference between the two orthogonal polarized components introduced by the birefringence in a PC [18,19]. A Pol. is cascaded with the PC to project the two orthogonal polarized optical signals onto a linear polarization state. Therefore, the optical field at the output of Pol. is

$$E_{pol.}(t) = \cos\alpha E_x e^{j\theta} + \sin\alpha E_y e^{-j\theta} \quad (5)$$

When the optical signal is detected by a PD for square-law detection, the recovered RF signal is

$$i(t) = E_{pol.}(t) \cdot E_{pol.}(t)^* \propto \sin(2\alpha) J_1(\beta)\cos(\omega_m t - \frac{\pi}{2} + 2\theta). \quad (6)$$

As can be seen from Eq. (6), the amplitude and phase of the recovered RF signal can be tuned independently by adjusting the state of PC. Therefore, if there are N branches in the RF photonic splitter, the amplitude ratio and phase shift for different branches can be tuned independently and arbitrarily. A $1 \times N$ hybrid RF photonic splitter with arbitrary phase shift and amplitude ratio is constructed.

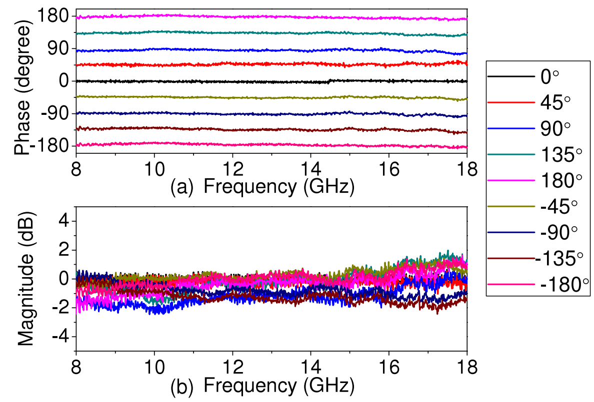

Fig. 2. Measured (a) phase responses and (b) magnitude responses for one port of the RF photonic splitter by adjusting the phase difference θ between the two orthogonal polarization states generated by a PC.

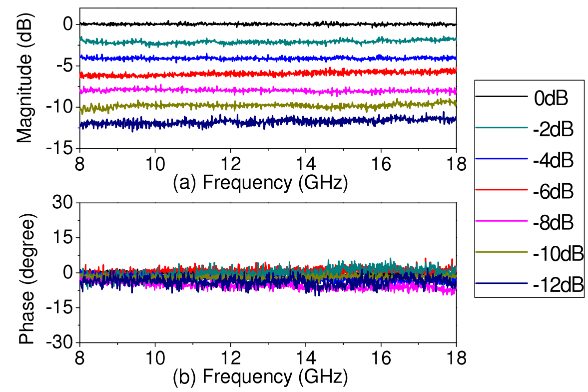

Fig. 3. Measured (a) magnitude response and (b) phase response for one port of the RF photonic splitter by adjusting the rotation angle α of the PC.

3. Experiments and results

A proof-of-concept experiment based on the scheme of Fig. 1 was carried out to verify the feasibility of the proposed RF photonic splitter. A linearly polarized optical carrier centered at 1550 nm was fiber-coupled into a DP-DPMZM with an angle of 45° to one principal axis of the PBS. A vector network analyzer (VNA) generated an RF signal to drive the DPMZM1. By adjusting the DC biases of the DP-DPMZM as describe in Section 2, DPMZM1 worked at CS-SSB modulation state, while DPMZM2 was set to let the pure optical carrier pass through