Optical Single Sideband Modulation With Tunable Optical Carrier-to-Sideband Ratio

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***Abstract*— A novel approach to realize optical single sideband (OSSB) modulation with tunable optical carrier-to-sideband ratio (OCSR) is proposed and demonstrated based on cascaded polarization modulators (PolMs). In the proposed scheme, OSSB polarization modulation is first obtained by driving two cascaded PolMs with two RF signals that are 90° out of phase. Then, by placing a polarizer after the PolMs, an OSSB-modulated signal with a tunable OCSR is obtained by adjusting the polarization direction of the polarizer. An experiment is carried out. An OSSB signal with a tunable OCSR from −26 to 46 dB is achieved. The operation bandwidth covers the frequency range of 5–35 GHz.**

***Index Terms*— Microwave photonics, single sideband modulation, polarization modulation.**

I. Introduction

RADIO over fiber (ROF) technology has attracted much attentions in which the microwave signal is carried on an optical wave that is transmitted through low-loss and large bandwidth optical fibers [1], [2]. Among the many commonly-used modulation schemes for ROF systems, such as optical double sideband (DSB) modulation, optical carrier suppressed (OCS) modulation and optical single sideband (OSSB) modulation [3]–[5], OSSB is the most promising modulation scheme because it is free of fiber dispersion induced power fading [5] and has a high spectral efficiency. Extensive efforts have been devoted to implementing the OSSB modulation. One typical approach is based on DSB modulation and optical filtering. In this method, a DSB modulated signal is first generated by an electro-optic modulator. Then, a fiber Bragg grating (FBG) [5] or a stimulated Brillouin scattering (SBS) [6] based notch filter is followed to remove one sideband of the DSB signal. OSSB modulation is thus obtained. The main limitation of this approach is the use of the wavelength dependent device, i.e., the optical filter. If a wideband optical filter is used, it is difficult to eliminate one first-order sideband without affecting the optical carrier and the other sideband, and if a narrow-bandwidth optical filter is applied, the OSSB modulation can only realized in a small frequency range. OSSB modulation can also be achieved using electro-optic modulators without any wavelength-dependent optical filter. A dual-electrode Mach–Zehnder modulator (MZM) [7], a dual-parallel MZM [8] or an MZM cascaded with a phase modulator [9], which are driven by two orthogonal RF signals, have been demonstrated to realize the OSSB modulation. The key advantage of these systems is the wavelength independent operation, which leads to a large operation bandwidth and a good wavelength tunability. However, for most of the previously reported schemes with or without an optical filter, the optical carrier-to-sideband ratio (OCSR) of the OSSB modulation can not be tuned. Recently, OSSB modulation with tunable OCSR is found to have many applications in ROF and microwave photonic signal processing systems [10], [11], e.g., by optimizing the OCSR, the transmission performance of an ROF system can be significantly improved. Up to now, several schemes have been proposed to realize the OCSR-tunable OSSB modulation [10]–[12], such as using an OSSB with carrier modulation followed by a notch filter [10], [12] or using a dual-parallel MZM [11]. Those systems are simple since only one modulator is employed, but the use of the optical filter would make the system wavelength dependent, and the high requirement of complex DC bias controlling may increase the complexity of the systems.

In this letter, we report a novel approach to implement the OSSB modulation with tunable OCSR based on two cascaded polarization modulators (PolMs). Since no wavelength dependent devices are used, broadband OSSB polarization modulation is implemented over 5–35 GHz with a sideband suppression ratio of 30 dB. The obtained OSSB polarization modulation signal is a combination of two orthogonally polarized OSSB signal with unequal phase differences between the optical carrier and sideband along the two polarization directions [13]. With a polarizer to combine the two orthogonal OSSB signals, a single-polarization OSSB modulation signal is obtained. By controlling the polarization direction of the polarizer, the OCSR of the OSSB signal can be continuously tuned from −26 to 46 dB.

II. Principle

Fig. 1 shows the schematic diagram of the proposed OSSB modulation system, which consists of a laser diode (LD), two PolMs, two polarization controllers (PCs), and a polarizer.

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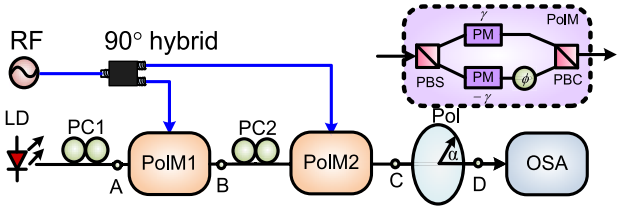

Fig. 1. The schematic diagram of the proposed OSSB modulation system.

The PolM equals to two parallel phase modulators (PMs) with complementary phase modulation indices connected by a polarization beam splitter (PBS) and a polarization beam combiner (PBC), as shown in the inset of Fig. 1. When a linearly polarized lightwave is incident into the first PolM (PolM1) with its polarization direction oriented at 45° to one principal axis of the PolM, two orthogonally polarized DSB signals are generated with complementary phase modulations. Supposing the expression of the input lightwave is $E_{\mathrm{o}} = \exp(j\omega t)$, and that of the RF drive signal is $\cos\omega_{\mathrm{m}}t$, where ω and ω_{m} are the angular frequencies of the optical carrier and the RF signal, respectively, the output signal from PolM1 can be expressed as

$$E_B = \begin{bmatrix} E_{Bx} \\ E_{By} \end{bmatrix} = \begin{bmatrix} J_1(\gamma)\exp j\left(\omega t - \omega_m t + \frac{\pi}{2}\right) + J_0(\gamma)\exp(j\omega t) \\ +J_1(\gamma)\exp j\left(\omega t + \omega_m t + \frac{\pi}{2}\right) \\ J_1(\gamma)\exp j\left(\omega t - \omega_m t\right) + J_0(\gamma)\exp\left(j\omega t + \frac{\pi}{2}\right) \\ +J_1(\gamma)\exp j\left(\omega t + \omega_m t\right) \end{bmatrix} \quad (1)$$

where γ is the phase modulation index of the PolM and J_n is the nth-order Bessel function of the first kind. Eq. (1) is the expanded expression based on Jacobi–Anger expansions where small signal modulation is assumed so that higher orders ($\geq$2) are ignored.

The generated DSB signal is then coupled into the second PolM (PolM2) through a PC (PC2) which rotates the polarization state of the DSB signal by 45 degree. The phase difference between the two principal axes of PolM2 is set as $\pi/2$ by applying a DC bias or controlling the PC (PC2) placed before PolM2. The output signal from PolM2 becomes

$$E_C = \begin{bmatrix} E_{Cx} \\ E_{Cy} \end{bmatrix} = \begin{bmatrix} 2J_1(\gamma)J_0(\gamma)\exp j\left(\omega t - \omega_m t + \frac{\pi}{4}\right) \\ +J_0^2(\gamma)\exp j\left(\omega t + \frac{\pi}{4}\right) \\ 2J_1(\gamma)J_0(\gamma)\exp j\left(\omega t - \omega_m t + \frac{\pi}{4}\right) \\ +J_0^2(\gamma)\exp j\left(\omega t + \frac{5\pi}{4}\right) \end{bmatrix} \quad (2)$$

As can be seen from (2), OSSB modulation is implemented in each polarization direction since only the optical carrier and the -1^{st}-order sideband are remained. Then, a polarizer is connected to PolM2 with its polarization direction aligned to have an angle of $\alpha$to the principal axis of PolM2. The output optical signal is

$$E_D \propto (\cos\alpha + \sin\alpha)J_1(\gamma)J_0(\gamma)\exp j\left(\omega t - \omega_m t + \frac{\pi}{4}\right) + (\cos\alpha - \sin\alpha)J_0^2(\gamma)\exp j\left(\omega t + \frac{\pi}{4}\right) \quad (3)$$

Eq. (3) is a single-polarization OSSB-modulated signal. The OCSR (the power ratio between the optical carrier and the -1^{st}-order sideband) is

$$OCSR = \frac{|J_0(\gamma)|^2(\cos\alpha - \sin\alpha)^2}{|J_1(\gamma)|^2(\cos\alpha + \sin\alpha)^2} \quad (4)$$

As can be seen from (4), the OCSR is related to the phase modulation index of the PolM and the polarization direction of the polarizer. For a given γ, the OCSR can be tuned by adjusting the polarization direction of the polarizer. A detailed illustration of the optical spectra at different locations of the system is shown in Fig. 2, where the phase properties of both TE and TM modes are displayed.

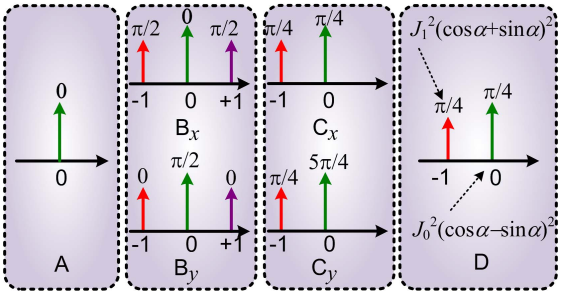

Fig. 2. Illustration of the optical spectra at different locations (A, B (B_x, B_y), C(C_x, C_y), D) in the system.

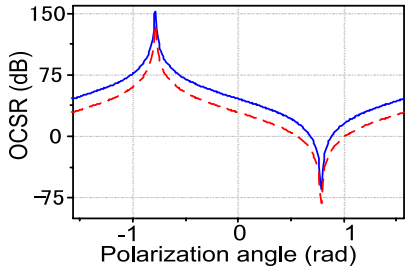

Fig. 3. The relationship between the OCSR and the polarization angle α of the polarizer while fixing γ at 0.4488 (dashed) and 0.2006 (solid).

Fig. 3 shows the simulated OCSR as a function of the polarization angle $\alpha$of the polarizer at different phase modulation indices. When the phase modulation index is 0.4488, the OCSR can be theoretically changed from −75 to 135 dB; while for a phase modulation index of 0.2006, the OCSR can be varied from −70 to 150 dB.

III. Experiment Results and Discussion

An experiment based on the setup shown in Fig. 1 is carried out. A laser diode (Agilent, N7714A) is employed to produce a lightwave at 1552.160 nm which is incident into the two cascaded PolMs (Versawave Inc.). The PolMs have a 3-dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. An RF signal from a microwave signal generator (Agilent, 8267D) with a power of 13 dBm is split into two paths by a broadband electrical 90° hybrid. The obtained two RF signals are applied to the two RF ports of the two PolMs, respectively. Then, another PC and a PBS are connected to PolM2, which work jointly as a polarizer. By tuning the PC, OSSB modulation with a tunable OCSR is obtained. The optical spectra are observed by an optical spectrum analyzer (OSA, AQ6370A) with a resolution of 0.02nm.

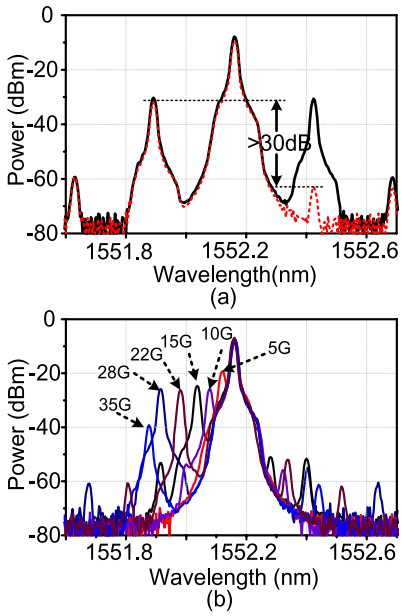

Fig. 4. (a) The optical spectra of the generated signals after PolM2 (point C); (b) the tunable optical spectra of the OSSB modulated signals with the frequency of the drive signal varied from 5 to 35 GHz.

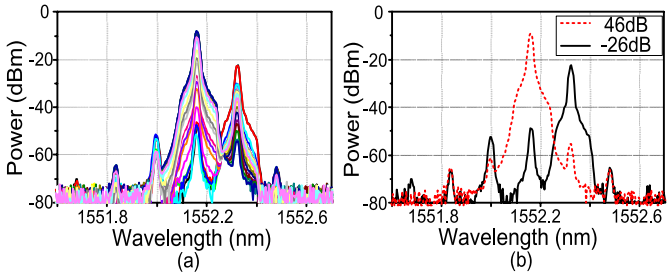

Fig. 5. (a) The optical spectra of the OSSB signals with tunable OCSR, (b) with the largest OCSR of 46 dB and with the smallest OCSR of −26 dB.

Fig. 4(a) shows the optical spectra measured after PolM2 (point C). An OSSB signal is obtained. The amplitude of the $+1^{st}$-order sideband is suppressed by 30 dB as compared with that of the -1^{st}-order sideband. To confirm the large operation bandwidth, the frequency of the RF signal is tuned from 5 to 35 GHz. For all cases, OSSB modulated signals are obtained, as shown in Fig. 4(b). The uneven suppression ratios are mainly due to the uneven output power of the vector signal generator, whose maximum output power at high frequencies is only ∼3 dBm. Besides, it should be noted that the OSSB polarization modulation can also be achieved when the frequency of the drive signal is 1.8–5 GHz as the operation bandwidth is only limited by the bandwidth of the 90 degree hybrid (1.8–36.5 GHz) but it can not be observed in the OSA due to the limited resolution (0.02 nm).

When a polarizer is followed by PolM2, an OSSB signal with a controllable OCSR can be obtained. Fig. 5(a) shows the optical spectra of the OSSB signals with different OCSRs, obtained simply by adjusting the polarization direction of the polarizer when the frequency of the RF signal is 20 GHz. In Fig. 5(a), the OCSR can be continuously tuned in the range from −26 dB to 46 dB. Fig. 5(b) shows the detailed optical spectra corresponding to the OCSRs of −26 dB and 46 dB. As no frequency dependent devices are used, OSSB modulation with a tunable OCSR will be obtained when RF signal with other frequencies are applied. Therefore, large operation bandwidth can be obtained.

IV. Conclusion

In conclusion, a novel approach to implement OSSB modulation with a tunable OCSR was proposed and demonstrated based on two cascaded PolMs. In the experiment, an OSSB signal with a tunable OCSR from −26 dB to 46 dB was obtained simply by adjusting the polarization direction of the polarizer. The proposed scheme features large OCSR adjusting range, wavelength independent operation and broad bandwidth, which may find applications in ROF and photonic microwave signal processing systems.

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