Photonic Generation of Equivalent Single Sideband Vector Signals for RoF Systems

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***Abstract*— A novel approach for generating RF vector signals with equivalent single sideband (SSB) modulation based on a dual-polarization quadrature phase-shift keying (DP-QPSK) modulator is proposed and experimentally demonstrated. One QPSK modulator in the DP-QPSK modulator is driven by a single-frequency RF signal. By properly setting its biases, a SSB carrier suppressed (SSB-CS) signal is generated. The other QPSK modulator in the DP-QPSK modulator is modulated by I/Q data streams, resulting in a baseband vector signal carried by the optical carrier. A polarizer is placed after the DP-QPSK modulator to combine the two signals with orthogonal polarization, leading to the generation of an equivalent SSB signal, which is free from the dispersion-induced power fading effect. By adjusting the angle of the polarizer, the carrier-to-sideband ratio can also be flexible tuned to maximize the transmission performance. The proposed system is verified by an experiment. The generation of a 1.25-GBd vector signal with QPSK modulation format at 10.5 GHz and the transmission of the signal over 25-km single-mode fiber are evaluated. An error-free transmission is achieved at a received optical power of −12 dBm and the power penalty is <1 dB. The proposed approach features all-optical and compact configuration.**

***Index Terms*— Microwave photonics, optical single sideband modulation, vector signal generation, radio-over-fiber system.**

I. Introduction

As a promising candidate in future broadband wireless communications, radio over fiber (RoF) technology, which can effectively integrate optical and wireless systems, has been intensively investigated for the last few years. With the merits provided by fiber-optic links, RoF has advantages of high bandwidth, high mobility, and low propagation loss [1]. When conveying the RF signal to the optical domain, optical double-sideband (DSB) modulation signals are typically generated. Nevertheless, the chromatic dispersion of optical fiber induces a power penalty effect on the detected RF signal. To minimize this fading effect, single sideband (SSB) modulation is preferred. The SSB modulation can be obtained by using a dual-electrode Mach-Zehnder modulator (DEMZM) [2], employing the stimulated Brillouin scattering (SBS) effect [3], filtering out one of the sidebands [4], or utilizing a sideband injection-locked (SIL) semiconductor laser [5]. However, the DEMZM suffers from a low level of receiver sensitivity originating from a large difference in the power of the strong optical carrier and the weak sideband [6], and the SSB modulation caused by SBS effect has a complicated system configuration. The limitation of the other two methods is the use of wavelength dependent devices.

On the other hand, since the wireless spectrum is a scarce and expensive resource, the introduction of vector signal modulation into RoF systems can improve spectral efficiency and increase wireless transmission rate. However, the RF vector signals are conventionally generated in the electrical domain which has imperfect features such as limited bandwidth, nonlinearity and large conversion loss [7]. Due to advantages such as higher frequency and broader bandwidth operation of RF signals enabled by modern photonics, RF vector signals can also be generated directly in the optical domain [4], [7]–[9]. In [4], the 90° phase shift between I and Q branches is implemented in the optical domain. Nevertheless, the baseband I/Q data streams still need to be up-converted in the electronic domain in advance. In [7], I/Q data streams are directly applied to a QPSK modulator and up-converted to RF in the optical domain. To implement SSB modulation, however, an optical filter is required to remove one sideband in this scheme. In [8], two coherent optical carriers are generated by a Mach-Zehnder modulator and separated by an arrayed waveguide grating. One optical carrier is directed to a QPSK modulator to generate a baseband vector signal and recombined with the other unmodulated optical carrier, leading to the generation of an equivalent SSB signal. The main drawback of the scheme is the two optical carriers are physically separated, which can cause phase fluctuations due to environmental disturbance. The two optical carriers can also be provided by two lasers [9]. Since the two carriers are incoherent, the phase noise of the generated RF signal is very large, which has to be corrected by digital signal processing (DSP) algorithm. As the efficiency of algorithm depends on the phase noise of the RF signal, the

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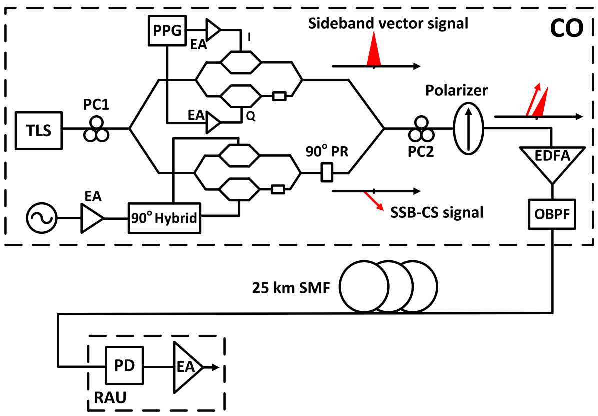

Fig. 1. Experimental setup. TLS, tunable laser source; PC, polarization controller; DP-QPSK modulator, dual polarization quadrature phase-shifting modulator; PR, polarization rotator; PPG, pulse pattern generator; EDFA, erbium-doped fiber amplifier; OBPF, optical band pass filter, EA, electrical amplifier; PD, photodetector; CO, central office; RAU, remote antenna unit.

linewidth of the two lasers is expected to be as narrow as possible.

In this letter, a novel all-optical scheme for the generation of vector signals with equivalent SSB modulation is proposed based on an integrated dual-polarization quadrature phase-shift keying (DP-QPSK) modulator which is initially used in coherent optic communication systems [10]. The DP-QPSK modulator consists of two QPSK modulators which are polarization division multiplexed. In our proposed scheme, one QPSK modulator is driven by I/Q data streams and configured to generate a baseband vector signal carried by the optical carrier. The other QPSK modulator is driven by a single-frequency RF signal and configured to generate a single sideband carrier suppressed (SSB-CS) signal. A polarizer is placed after the DP-QPSK to combine the two signals with orthogonal polarization. After the polarizer, the SSB-CS signal serves as the new optical carrier while the baseband vector signal servers as the sideband, leading the generation of an equivalent SSB signal. By adjusting the angle of the polarizer, the optical carrier-to-sideband ratio (CSR) can be flexibly tuned to maximize the transmission performance [6]. In the experiment, a 1.25 Gbaud QPSK signal at 10.5 GHz is generated. An error-free transmission over 25 km single-mode fiber (SMF) is achieved at a received optical power of −12 dBm. In our proposed approach, the generation of baseband vector signal and up-conversion to RF band are both implemented in the optical domain, which can overcome the electronic bottleneck problem.

II. Principle

Fig. 1 illustrates the schematic diagram of the proposed SSB vector signal generation and transmission system. A lightwave from a tunable laser source (TLS) is sent to a DP-QPSK modulator via a polarization controller (PC1). In the proposed scheme, the lower QPSK modulator in the DP-QPSK modulator is modulated by a single-frequency RF signal. The QPSK modulator consists of two sub-MZMs which are embedded in a parent MZM. Sub-MZM1 and sub-MZM2 are driven by RF signals which have the same frequency and 90° phase difference. V_1, V_2 and V_3 denote the three biases applied to sub-MZM1, sub-MZM2 and the parent MZM, respectively. When sub-MZMs operate at chirp-free configuration, the optical signal at the output of the lower QPSK modulator can be expressed as [11]

$$\begin{aligned} E_x &= E_1 + e^{j\frac{V_3}{V_\pi}\pi} E_2 \\ &= A_x \cos\left[\frac{\pi}{2V_\pi}(V_{\mathrm{rf1}}(t)+V_1)\right] e^{j\frac{V_1}{2V_\pi}\pi} e^{j\omega_0 t} \\ &\quad + e^{j\frac{V_3}{V_\pi}\pi} A_x \cos\left[\frac{\pi}{2V_\pi}(V_{\mathrm{rf2}}(t)+V_2)\right] e^{j\frac{V_2}{2V_\pi}\pi} e^{j\omega_0 t}, \end{aligned} \tag{1}$$

where E_1 and E_2 are the optical signals at output of sub-MZM1 and sub-MZM2, respectively, ω_0 is the angular frequency of the optical carrier, A_x is the amplitude, V_π is the half-wave voltage, $V_{\mathrm{rf1}}(t)$ and $V_{\mathrm{rf2}}(t)$ are the RF signals applied to the sub-MZMs which can be written as $V_{\mathrm{rf1}}(t) = V_m \sin(\omega_m t)$ and $V_{\mathrm{rf2}}(t) = V_m \cos(\omega_m t)$, where ω_m and V_m are the angular frequency and the amplitude of the RF signal, respectively. To generate a SSB-CS signal, the sub-MZMs are biased at minimum point, i.e. $V_1 = V_2 = V_\pi$ and the parent MZM is biased at quadrature point, i.e. $V_3 = -V_\pi/2$, then the optical signal can be expressed as

$$\begin{aligned} E_x &= A_x \cos\left[\frac{\pi}{2V_\pi} V_m \sin(\omega_m t) + \frac{\pi}{2}\right] e^{j\frac{\pi}{2}} e^{j\omega_0 t} \\ &\quad + e^{-j\frac{\pi}{2}} A_x \cos\left[\frac{\pi}{2V_\pi} V_m \cos(\omega_m t) + \frac{\pi}{2}\right] e^{j\frac{\pi}{2}} e^{j\omega_0 t}. \end{aligned} \tag{2}$$

We denote $\gamma = \pi V_m/2V_\pi$ as the modulation index and expand (2) based on Jacobi-Anger identity, then (2) can written as

$$\begin{aligned} E_x &= -A_x \sin\left[\gamma \sin(\omega_m t)\right] j e^{j\omega_0 t} \\ &\quad - A_x \sin\left[\gamma \cos(\omega_m t)\right] j e^{j\omega_0 t} \\ &\approx -2A_x J_1(\gamma) e^{j(\omega_0+\omega_m)t}. \end{aligned} \tag{3}$$

As can be seen from (3), it is a SSB-CS signal where only +1 order sideband is left and the optical carrier is suppressed [12].

On the other hand, the upper QPSK modulator in the DP-QPSK modulator is used to generate a baseband vector signal. In this case, the sub-MZMs in the QPSK modulator are configured as inphase and quadrature branches modulated by two binary data sequences I(t) and Q(t), then the vector signal can be expressed as

$$E_y(t) = A_y[I(t) + jQ(t)]e^{j\omega_0 t}, \tag{4}$$

where A_y is the amplitude of the optical field. A polarizer with its polarization direction adjusted by PC2 to have an angle of θ to the x-axis of the DP-QPSK is incorporated to combine the two orthogonally polarized optical signals, which can be expressed as

$$\begin{aligned} E_{Pol}(t) &= \cos\theta E_x + \sin\theta E_y \\ &= -2\cos\theta A_x J_1(\gamma) e^{j(\omega_0+\omega_m)t} \\ &\quad + \sin\theta A_y \left[I(t) + jQ(t)\right] e^{j\omega_0 t}. \end{aligned} \tag{5}$$

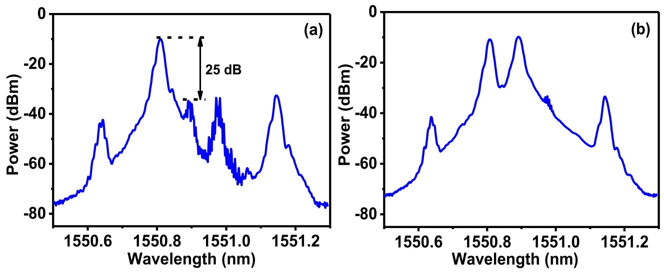

Fig. 2. Optical spectrum at the output of the DP-QPSK modulator when the lower QPSK modulator is configured to generate a SSB-CS signal while (a) the 3 biases of the upper QPSK modulator are set to be minimum point, (b) the upper QPSK modulator is configured to generate a vector signal.

According to (5), we can see the optical carrier and sideband are generated independently to form an equivalent SSB modulation. The optical signal after the polarizer is transmitted through a length of fiber. $\beta(\omega)$ is denoted as the propagation constant in the fiber at angular frequency ω and z is the fiber length, then the optical signal after transmission can be written as [13]

$$\begin{aligned} E'_{pol} = & -2\cos\theta A_x J_1(\beta) e^{j}[(\omega_0+\omega_m)t-\beta(\omega_0+\omega_m)z] \\ & + \sin\theta A_y \left[I\left(t-\frac{\beta(\omega_0)z}{\omega_0}\right) + jQ\left(t-\frac{\beta(\omega_0)z}{\omega_0}\right)\right] \\ & \times e^{j[\omega_0 t-\beta(\omega_0)z]}. \end{aligned} \tag{6}$$

The optical signal is received by a PD for square-law detection, then the converted electrical signal can be expressed as

$$\begin{aligned} I(t)\alpha|E'_{pol}(t)|^2 & \\ = & -4\cos\theta\sin\theta A_x A_y J_1(\beta) \\ & \cdot\left\{ I\left(t-\frac{\beta(\omega_0)z}{\omega_0}\right)\cos[\omega_m t+\beta(\omega_0+\omega_m)z] \right. \\ & \left. +Q\left(t-\frac{\beta(\omega_0)z}{\omega_0}\right)\sin[\omega_m t+\beta(\omega_0+\omega_m)z]\right\}. \end{aligned} \tag{7}$$

As can be seen, the generated RF vector signal is immune to the fiber dispersion induced power fading effect after transmission.

III. Experiment Setup and Results

An experiment based on the setup given in Fig. 1 is performed. A lightwave with a wavelength of 1550 nm and an optical power of 13 dBm from the TLS (Santec TL-510) is sent to the DP-QPSK modulator (Fujitsu FTM7977HQA) with modulation speed of up to 31.4 Gbaud. The half-wave voltage of the modulator is 3.5 V. A RF signal at 10.5 GHz is amplified to 25 dBm and divided by a 90° hybrid into two parts which drive the sub-MZMs of the lower QPSK modulator in the DP-QPSK modulator, respectively. The sub-MZMs are biased at minimum point, and the parent MZM is biased at quadrature point, then SSB-CS optical signal can be generated. When the 3 biases of the upper QPSK modulator are set to be minimum point, the optical spectrum at the output of the DP-QPSK modulator is shown in Fig. 2(a). As can be seen, the +1 order sideband is the strongest sideband which can serve as a new optical carrier while the original optical carrier is suppressed

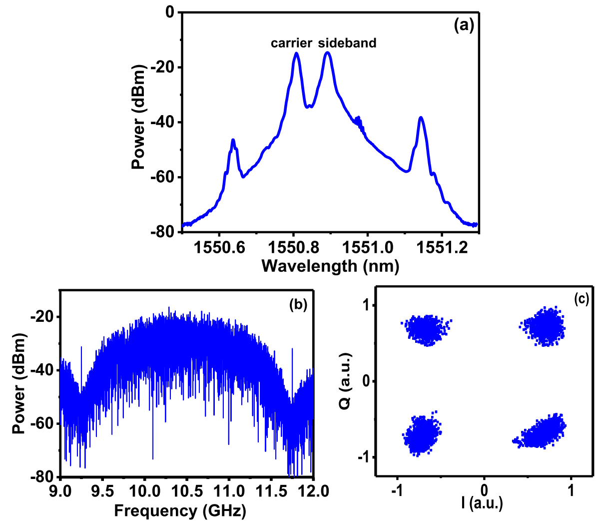

Fig. 3. (a) Optical spectrum after the polarizer, (b) electrical spectrum of the 1.25 Gbaud QPSK signal at 10.5 GHz, (c) the corresponding QPSK constellation.

by more than 25 dB. Then the upper QPSK modulator is driven by 1.25 Gbaud electrical binary signals, which are generated from a pulse pattern generator (PPG) with a $2^{15}-1$ pseudo-random binary sequence (PRBS). For QPSK modulation, its two sub-MZMs are both biased at minimum point and driven at the full swing to achieve 0- and π-phase modulation. The phase difference between the two branches of the upper QPSK modulator is controlled to be $\pi/2$, leading to the generation of a baseband vector signal carried by the original optical carrier. In this case, the measured optical spectrum at the output of the DP-QPSK modulator is shown in Fig. 2(b).

A polarizer is placed after the DP-QPSK modulator to combine the SSB-CS signal and the baseband vector signal, which are polarization multiplexed. According to [9], when CSR is 0 dB, the transmission performance is maximized. We adjust PC2 before the polarizer to achieve the optimal CSR, and the corresponding optical spectrum, the electrical spectrum and the constellation are shown in Fig. 3(a), (b) and (c). As can be seen from Fig. 3(a), the combined signal after the polarizer can be considered as an equivalent SSB signal.

The SSB signal after the polarizer is boosted by an erbium-doped fiber amplifier (EDFA), and an optical bandpass filter with a bandwidth of 0.8 nm is placed after the EDFA to filter out the amplified spontaneous emission (ASE) noise. Then the SSB signal is transmitted through 25 km SMF to a remote antenna unit (RAU). In order to evaluate the quality of the generated RF signal as a function of the received optical power, the power of the optical signal is adjusted by a variable optical attenuator. The error vector magnitudes (EVMs) of the generated QPSK signals as a function of the received optical power for back-to-back (BTB) and 25-km SMF transmission are measured and the experimental results are shown in Fig. 4(a). Based on the method given in [14], the bit-error-rate (BER) can be calculated from EVM and the results are given in Fig. 4(b). As can be seen, an error-free transmission over 25-km SMF can be achieved at a received optical power of −12 dBm and the power penalty is less than 1 dB.

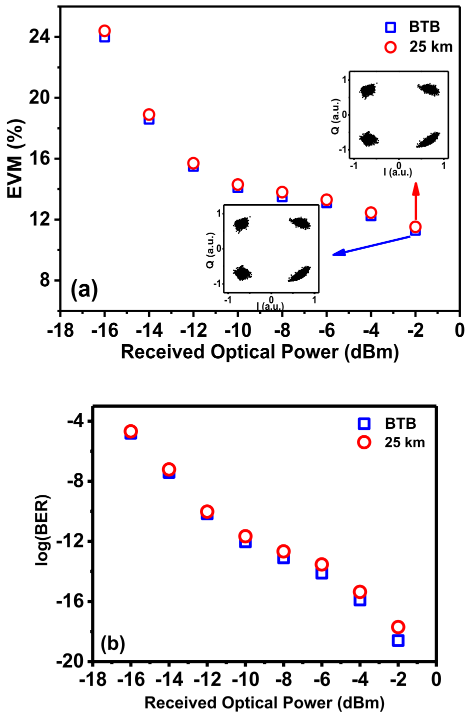

Fig. 4. (a) Measured EVM versus the received optical power (Insets: the constellations before and after 25 km SMF transmission), (b) calculated BER versus the received optical power.

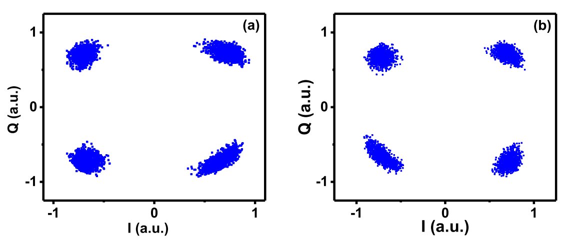

Fig. 5. Received signal constellation after 25-km SMF transmission (a) when coherent control is switched off and the linewidth of the TLS is 200 kHz, (b) when coherent control is switched on.

Although the optical carrier and sideband of the equivalent SSB signal are generated independently, the phase variations of the converted RF signal can be very small since the two QPSK modulators are integrated in one modulator which is free from environment disturbance. Furthermore, the SSB-CS and the baseband signal are generated from a same laser, so the linewidth of the laser has little effect on the performance of the SSB vector signal. The TLS has a coherent control option which can increase the linewidth of the laser from 200 kHz to 40 MHz. When the coherent control is switched off, the constellation of the QPSK signal after 25 km SMF transmission is shown in Fig. 5(a) and the corresponding EVM is 11.52%. When the coherent control is switched on, the constellation of the QPSK signal is shown in Fig. 5(b), and the corresponding EVM keeps unchanged, which is still 11.52%. Compared with the generation of SSB vector signal by two lasers, our proposed system greatly ease the burden of the DSP to correct the phase noise [9].

IV. Conclusion

In conclusion, we proposed a novel SSB vector signal generation scheme based on a DP-QPSK modulator where one QPSK modulator in the DP-QPSK modulator was configured to generate a SSB-CS signal which served as an optical carrier, and the other QPSK modulator in the DP-QPSK modulator was configured to generate a baseband vector signal. By combining the two polarization multiplexed signals, an equivalent SSB modulation was formed. We experimentally demonstrated the generation of 1.25 Gbaud QPSK signal at 10.5 GHz and the power penalty is less than 1 dB at BER of 10^{-9} after 25 km SMF transmission.

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