Generation and Transmission of Optical Carrier Suppressed-Optical Differential (Quadrature) Phase-Shift Keying (OCS-OD(Q)PSK) Signals in Radio Over Fiber Systems

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Abstract—We propose and experimentally demonstrate generation of optical carrier suppressed-optical differential phase-shift keying (OCS-oDPSK) modulation format in radio-over-fiber (RoF) systems using one single-drive Mach–Zehnder modulator (MZM). This scheme realizes up-conversion of baseband data for downlink wireless service delivery, generation of remote local oscillator (LO) signal for down-conversion of uplink radio frequency (RF) signal, and remodulation of down-converted uplink data, thus lowering the cost of base stations (BSs) in full-duplex RoF systems. The proposed scheme is expected to be simple and compact due to the use of a single MZM. Furthermore, the OCS-oDPSK generation principle is extended to obtain an OCS-optical differential quadrature phase-shift keying (OCS-oDQPSK) signal by employing a dual-parallel MZM (DPMZM), which is useful to deliver multiple wireless services on the same RF carrier.

Index Terms—Differential (quadrature) phase-shift keying (D(Q)PSK), dual-parallel Mach–Zehnder modulator (DPMZM), optical carrier suppression (OCS), radio-over-fiber (RoF), single-drive Mach–Zehnder modulator (MZM),

I. INTRODUCTION

The convergence of wireless and optical fiber systems in an integrated platform has become a promising technique for providing broadband wireless access services with increased mobility and reduced cost [1]. In order to meet the requirement of high signal bandwidth and overcome the spectral congestion at the low frequency, future radio-over-fiber (RoF) systems would utilize millimeter-wave (MMW) frequency band for high-speed data delivery [2], [3]. However, the base station (BS) picocells have small coverage due to the high atmospheric attenuation in the MMW frequency band, which results in the need of many BSs to cover the operational area and thus greatly adds configuration cost of the overall system. Therefore, it is desirable to shift the system complexity and expensive devices to the central station (CS) to minimize the cost of BSs, which shows the advantages of concentrating the expensive equipments in the CS and sharing these equipments by all BSs. In this situation, the overall architecture design and the scheme for delivery of downlink and uplink services to realize full-duplex transmission play the key roles in the successful deployment in practical networks.

In RoF systems, for the downlink transmission, the generations of MMW for optical up-conversion of baseband data using external Mach–Zehnder modulator (MZM) or phase modulator in the CS have been demonstrated [4]–[16], where optical carrier suppression with optical amplitude shift keying (OCS-oASK) [7]–[14] or optical differential phase-shift keying (OCS-oDPSK) format [15], [16] is considered as a potential candidate technique due to the simplicity in system configuration and the good performance in long distance transmission. Moreover, the OCS technique can generate frequency-doubled MMW signal after beating in a photo-detector (PD), thus it has low bandwidth requirement for opto-electrical components.

On the other hand, realization of the uplink RoF transmission is more challenging. In some situations, a high-frequency radio frequency (RF) signal carrying data from the end users via an antenna has to be down-converted to baseband or intermediate frequency (IF) using a local oscillator (LO) signal, which is then modulated onto the optical carrier in the BS and sent back to the CS over the optical fiber. This requires a high-speed LO signal and a light source in the BS, thus resulting in difficulty in achieving the low-cost BSs. Many effective methods have been reported to provide solutions for the uplink transmission. Remote delivery of an unmodulated RF carrier from the CS was demonstrated to provide the LO signal for down-converting uplink signal [3], [17], [18]. In addition, other schemes were proposed to avoid the necessity for a light source in the BSs, such as reusing the optical carrier from the downlink [2], [3], [10]–[14], [19], employing a Fabry–Pérot laser diode with an optical bandpass filter at the CS [20], and remodulating the DPSK format [15], [16].

However, these previous schemes only realized either full-duplex links without the generation of LO signal or unidirectional transmission with LO delivery, and the transmitter requires multiple discrete components. Simultaneous realization of bidirectional RoF links and remote LO delivery with cost-effective configuration has not been demonstrated.
In this paper, we propose a simple yet effective OCS-oDPSK modulation scheme to simultaneously realize three key functions in RoF systems: 1) up-conversion of downlink baseband data to RF band; 2) generation of remote LO signal for downconverting uplink RF signal to baseband or IF; and 3) remodulation of uplink signal without the need of light source at the BSs. Moreover, in our scheme, the OCS-oDPSK is generated by using only one single-drive MZM (MZM), which exhibits the advantages of compact architecture, low cost, easy monitoring and control, and low insertion loss compared with previously proposed OCS-oDPSK transmitters [15], [16]. Based on the principle of OCS-oDPSK generation, an OCS-optical differential quadrature phase-shift keying (OCS-oDQPSK) signal is also obtained using a dual-parallel MZM (DPMZM) [21]. This format can deliver multiple RoF services [22], [23] on the same RF carrier and then improve the RF spectrum efficiency.

II. OPERATION PRINCIPLE

The proposed configuration for OCS-oDPSK signal generation is shown in Fig. 1(a), where the CS consists of a MZM in push–pull operation and an electrical mixer. An alternating current (AC)-coupled bipolar baseband data (Fig. 1(b-i)) mixes with an RF signal [Fig. 1(b-ii)] to produce an electrical sub-carrier multiplexed (SCM) signal [Fig. 1(b-iii)], which can be expressed as

\[ V_{\text{SCM}}(t) = V_s \cdot \text{data}(t) \cdot \sin(\omega_b t) \]  

(1)

where \( \text{data}(t) \) represents the AC-coupled random bit sequence, \( V_s \) is the amplitude of the mixed signal and \( \omega_b \) is the angular frequency of the RF signal. The MZM is driven by the mixed SCM signal plus the bias voltage, which can be described by

\[ V(t) = eV_{\pi} + \alpha V_{\pi} \cdot \text{data}(t) \cdot \sin(\omega_b t) \]  

(2)

where \( e \) and \( \alpha \) are the bias voltage of the modulator and the amplitude of the SCM signal normalized to the half-wave voltage \( V_{\pi} \), respectively. The output field of the MZM can be given by

\[ E_{\text{out}}(t) = E_{\text{in}}(t) \cdot \cos(\omega_c t) \cdot \cos \left( \frac{\pi}{2} e + \alpha \cdot \text{data}(t) \cdot \sin(\omega_b t) \right) \]  

(3)

where \( \omega_c \) and \( E_{\text{in}}(t) \) are the angular frequency and optical field amplitude of the input optical signal, respectively. When \( e = 1 \), i.e., the MZM is biased at the transmission null, the even-order sidebands as well as the optical carrier can be suppressed, thus resulting in the generation of an OCS modulation format. An expansion of (3) with Bessel functions leads to an approximate expression for the output field as

\[ E_{\text{out}}(t) \approx AE_{\text{in}}(t) \cdot \cos(\omega_c t) \]  

\[ \cdot \sum_{n=1}^{\infty} J_{2n-1} \left( \frac{\pi}{2} \alpha \cdot |\text{data}(t)| \right) \cdot \sin(\omega_b t) \]  

(4)

where only the first-order sidebands are considered, the higher order sidebands are ignored due to the small optical powers. Equation (4) can be further described by

\[ E_{\text{out}}(t) = AE_{\text{in}}(t) \cdot \text{sgn}(\text{data}(t)) \cdot J_1 \left( \frac{\pi}{2} \alpha \cdot |\text{data}(t)| \right) \]  

\[ \cdot \sin(\omega_b t) \cdot \cos(\omega_c t) \]  

\[ = AE_{\text{in}}(t) \cdot \text{sgn}(\text{data}(t)) \cdot J_1 \left( \frac{\pi}{2} \alpha \right) \]  

\[ \cdot \left[ \cos(\omega_c - \omega_b) t - \cos(\omega_c + \omega_b) t \right]. \]  

(5)

Equation (5) shows that the envelope of the output signal is given by \( AE_{\text{in}}(t)J_1(\alpha)|\text{sgn}(\text{data}(t))(|\text{data}(t)|)\), which exhibits a periodic waveform in time domain [Fig. 1(b-iv)] and two tones in spectral domain. The phase of the optical output signal is determined by the sign of \( \text{sgn}(\text{data}(t)) \) and inverts instantaneously as the \( \text{data}(t) \) is changed. Between the bit “1” and the bit “−1”, there is a phase jump at the transmission null. Consequently, the bit “1” corresponds to a carrier phase shift of \( \pi \), while the bit “−1” leads to a carrier phase shift of 0, and both states have the same optical power, as shown in Fig. 1(b-iv). Therefore, the output signal is an OCS-oDPSK format.

The generated OCS-oDPSK is a two-tone signal, and each tone carries the same DPSK modulation data; thus, (5) can be further simplified to obtain the electrical field of the OCS-oDPSK

\[ E_{\text{out}}(t) = AE_{\text{in}}(t) \cdot \left[ \cos(\omega_c - \omega_b) t + \phi(t) \right] \]  

\[ - \left[ \cos(\omega_c + \omega_b) t + \phi(t) \right]. \]  

(6)
where \( \phi(t) \) (\( \equiv 0 \) or \( \pi \)) represents the instantaneous phase shifting of the DPSK data. Then the OCS-oDPSK is injected into a Mach–Zehnder delay interferometer (MZDI) to realize phase to intensity conversion. The MZDI has a relative time delay between its two arms equal to the bit period. Assuming that the coupling ratio of the two couplers in the MZDI is exactly 3 dB, the output electrical field from one output port of the MZDI can be expressed by

\[
E_{\text{out, MZDI}}(t) = \frac{1}{2} |E_{\text{in}}(t-T) + E_{\text{in}}(t)|. \tag{7}
\]

Therefore, the two DPSK tones of the OCS-oDPSK are independently demodulated by the MZDI to generate two ASK signals, i.e., an OCS-oASK format is obtained and then an up-converted signal is produced after PD detection. One key aspect is that the central frequency of the MZDI must be matched to the wavelength of the OCS-ODPSK signal, and any frequency offset will cause a power penalty in the receiver sensitivity due to the phase mismatching at the output of the MZDI. In addition, the bit delay mismatch of the MZDI results in a penalty due to inter-symbol interference. Moreover, the low extinction ratio of the MZDI induces power difference between the two arms of the MZDI, which also causes amplitude fluctuations of the generated OCS-oASK signal. Since the DPSK signal is a phase-modulated format, one sideband of the OCS-oDPSK can be utilized as an optical carrier for remodulation of the down-converted uplink signal, which avoids the need of a light source for upstream signal modulation and thus eliminates complicated wavelength management in the BSs. On the other hand, if the OCS-oDPSK signal is directly detected by a PD, the two tones carried the same DPSK signals beat each other, one can obtain a clock signal that has twice the frequency of the RF signal, which can be used as the LO signal for the down-conversion of uplink RF signal. The obtained clock signal can be expressed as

\[
V_{\text{out}}(t) = A^2 |E_{\text{in}}(t)|^2 \cdot \cos(2\omega_d t). \tag{8}
\]

Using this simple and compact scheme, we realize the three key functions in RoF systems including the up-conversion of the downlink baseband data, the generation of remote LO signal, and the re-modulation of upstream data, by using a single MZM. Therefore, the system cost and complication could be potentially reduced.

We further extend the OCS-oDPSK generation principle to obtain an OCS-oDQPSK signal using a single DPMZM. The DPMZM [21] consists of a pair of x-cut LiNbO3 MZMs (MZMA, MZMB) embedded in the two arms of a main MZM structure. The two sub-MZMs have the same architecture and performance, and the main MZM combines the outputs of the two sub-MZMs. The schematic diagram of the OCS-oDQPSK signal generation is shown in Fig. 2, where the two sub-modulators are biased at the transmission null and driven by individual SCM modulating signals, respectively, to generate two independent OCS-oDPSK signals. Similarly, the SCM signal is produced by mixing a bipolar data with an RF signal. By adjusting the bias of the main modulator to ensure an optical \( \pi/2 \) phase difference between the outputs of the two sub-modulators, an OCS-oDQPSK signal is obtained, which is useful in providing multiple wireless access services on a common RF carrier in RoF systems. The two wireless signals carried at the common frequency band would interfere with each other in the same wireless link, resulting in worse performance of the received signals. However, this limitation can be resolved by using two antennas with orthogonal polarizations [24]. Furthermore, some optimization techniques of antenna polarization have been reported to minimize the interference through transmission [25]. Since the DPMZM is a commercial off-the-shelf device fabricated on a single chip, this scheme enables a cost-effective configuration for the generation of OCS-oDQPSK in RoF systems.

### III. Experimental Results

We first perform an experiment to verify the feasibility of the proposed OCS-oDPSK scheme, as shown in Fig. 3. At the CS, a 10-GHz MZM is used to modulate a continuous wave (CW) light from a tunable laser at 1549.86 nm. The electrical SCM signal is obtained by mixing an AC-coupled 1.25-Gbps pseudorandom bit sequence (PRBS) baseband data of 231 − 1 with a 10-GHz RF signal, the waveform and the eye diagram are shown in Fig. 3(i) and (ii), respectively. In the experiment, a pulse pattern generator (PPG) (ANRITSU pulse pattern generator-MP1763c) is used to generate the 1.25-Gb/s data and provide the trigger signal for the oscilloscope. The 10-GHz clock is derived from an RF synthesizer (Agilent E8257D). To keep the synchronization between the PPG and the RF synthesizer, the PPG is set to take a 10-MHz reference from the output of the synthesizer. Then the electrical SCM signal is amplified to drive the MZM, which is biased at the transmission null to obtain an OCS-oDPSK signal with a 20-GHz repetition rate, the optical eye diagram and the optical spectrum are provided in Fig. 3(iii) and (iv), respectively. We use a fiber Bragg grating (FBG) to filter one sideband of the OCS-oDPSK signal for detection, the eye diagrams of the filtered tone before [Fig. 3(vi)] and after [Fig. 3(vi)] demodulation by a 1-bit MZDI further verify that the generated signal is the OCS-oDPSK modulation format. The OCS-oDPSK signal is amplified by an erbium-doped fiber amplifier (EDFA) to a power level of ~8 dBm before transmission. Considering the fiber length and the power of the OCS-oDPSK signal, the nonlinear effects are not significant in this transmission system. A tunable optical filter (TOF) is employed to suppress the amplified spontaneous emission (ASE) noise. After transmission over 25-km standard single-
Fig. 3. Experimental setup for the generation and transmission of the OCS-oDPSK signal based on a MZM. Spectrum resolution: 0.07 nm; start wavelength: 1548.86 nm; stop wavelength: 1550.86 nm; /axis scale: 0.2 nm/div, /axis scale: 5 dB/div. (i) The waveform of the mixed SCM signal. (ii) The electrical eye diagram of the mixed SCM signal. (iii) The optical eye diagram of the OCS-oDPSK signal. (iv) The optical spectrum of the OCS-oDPSK signal. (v) The optical eye diagram of one sideband of the OCS-oDPSK before demodulation. (vi) The optical eye diagram of one sideband of the OCS-oDPSK after demodulation. (vii) The optical eye diagram of the OCS-oDPSK after demodulation. (viii) The optical eye diagram before the PD. (ix) The optical eye diagram after the optical filter. (x) The optical eye diagram of the remodulated uplink signal.

mode fiber (SMF), at the BS, the OCS-oDPSK signal is divided into three parts by a three-way optical splitter, which consists of two 50:50 couplers and has a 1:1:2 splitting ratio for the downlink signal to be converted, the LO signal, and the uplink signal for remodulation, respectively. One part is demodulated by a 1-bit MZDI to convert the OCS-oDPSK signal into an OCS-oASK intensity signal, with the optical eye diagram after MZDI demodulation provided in Fig. 3(vii). The MZDI is made of two couplers, where the length difference between the two arms to realize 1-bit delay is \(15.96 \text{ cm}\) for the 1.25-Gb/s DPSK data. Since the MZDI used in the experiment shows slight mismatched bit-delay between the two arms, there are some imperfections in the eye diagram. A balanced PD is required to convert the demodulated OCS-oDPSK signal to a 20-GHz electrical wireless signal for broadcasting through an antenna. In this particular demonstration, a 40-GHz high-speed PD is employed to realize single-end detection, thus generating a 20-GHz RF signal carrying the 1.25-Gb/s baseband data. The generated signal is input to an electrical spectrum analyzer (ESA) (ANRITSU MS2667C) for the measurement of the electrical spectrum, as shown in Fig. 4, where the spectrum range is from 18 to 22 GHz. Due to the lack of a fast-speed electrical mixer to down-convert the received 20-GHz RF signal to baseband, the signal is detected using a method similar to that in [15], where the bit-error-ratio (BER) measurements are performed by detecting the upper-sideband component employing a 2.5-GHz low-speed PD. Fig. 5 shows the measured BER performances and the electrical eye diagram after transmission of 25-km SMF, where the power penalty of the downlink OCS-oDPSK signal is less than 0.5 dB. In practice, however, at the receiver, the 20-GHz wireless signal should be down-converted to baseband by mixing with a 20-GHz LO signal [2] for BER detection. We compare the difference of the BER performances in the receivers between filtering one side-band and using a mixer for the down-conversion [2] by VPI simulation software. Simulation results show that the recovered signals based on the two detection methods have similar quality, and the difference of the penalties for the signal through 25-km transmission with the two detection schemes are negligible.

The second part is directly detected by the 40-GHz PD to generate a LO signal, the eye diagram before the PD is indicated in Fig. 3(viii). Since the generated OCS-oDPSK has residual amplitude modulations, the intensity dips of the DPSK format would be translated to the electrical domain, which result in harmonic components and affect the spectrum purity of the obtained LO signal. Fig. 6 shows the electrical spectrum from 0 GHz to 25 GHz, where the amplitude of the harmonics...
are 20-dB lower than the generated LO signal. Moreover, a narrow-band filter should be used to further improve the spectrum purity of the LO signal. Fig. 7 indicates the phase noise performance of the received 20-GHz signal, relative to the 10-GHz clock from the low-noise RF synthesizer (Agilent E8257D). The phase noise is obtained by the ESA with a resolution of 30 Hz. The results show that the received 20-GHz clock signal has a phase noise $\sim -93$ dBc/Hz at 1-kHz offset. Compared to the 10-GHz signal with low phase noise of $\sim -100$ dBc/Hz at 1-kHz offset, $\sim 7$-dB phase noise degradation is observed. Theoretically, a frequency-doubled signal has a phase noise degradation of about $10 \log_{10}(2^2) = 6$ dB [26]. Therefore, the measurements show good phase-noise performance of the received 20-GHz clock signal, which is close to the level of the RF synthesizer if the frequency doubling process is taken into account.

The third part is injected into an optical filter (3-dB bandwidth of $\sim 0.114$ nm) to filter one sideband, which is remodulated by a 1.25-Gb/s PRBS baseband data with a word length of $2^{31} - 1$ to produce an ASK format, the optical eye diagram before and after the uplink MZM are provided in Fig. 3(ix) and Fig. 3(x), respectively. In real network implementations, a diplexer connected with the antenna is needed to broadcast up-converted downstream wireless signals and receive upstream RF signals at the BS. The baseband upstream data is obtained by down-converting the RF signals from the diplexer. For the remodulated uplink ASK signal, the power penalty is $\sim 0.3$ dB, and the electrical eye diagram is shown in inset of Fig. 8. Compared with the downlink BER performances, the uplink signal experiences $\sim 2$-dB penalty, which could be attributed to the additional ASE noise from another EDFA. Moreover, the downlink signal is demodulated by a 1.25-Gb/s narrow-band MZDI filter, while the uplink signal passes through an optical filter with a 3-dB bandwidth of $\sim 0.114$ nm, thus resulting in more noise power at the uplink receiver and degrading the receiver sensitivity of the uplink signal.

Therefore, a full-duplex RoF system with remote LO generation is realized, where the downlink signal transmission, the LO signal generation, and the uplink remodulation are simultaneously demonstrated.

We also demonstrate the generation of the OCS-oDQPSK signal using one 10-GHz DPMZM (COVEGA Mach-10060, 5.8-dB insertion loss), as shown in Fig. 9. The two submodulators are biased at the transmission null and driven by two independent SCM signals to generate the OCS-oDPSK format, respectively. The SCM is obtained by mixing the AC-coupled 1.25-Gb/s data with a 10-GHz RF signal. The bias of the main MZM is adjusted to obtain $\pi/2$ phase difference between the two OCS-oDPSK tributaries, the optical eye diagrams, and the spectra are shown in insets of Fig. 9, respectively. Then the two OCS-oDPSK tributaries are combined to achieve an OCS-oDQPSK signal at the output port of the main modulator. The optical eye diagram of the generated OCS-oDQPSK with
20-GHz repetition rate is indicated in Fig. 10(i). After amplified by an EDFA and 25-km SMF transmission, the signal is received by an OCS-oDQPSK receiver. For OCS-oDQPSK receivers, two 1-bit delay MZDIs with two separate balanced PDs are generally required to simultaneously demodulate the two tributaries. Here, we utilize a single MZDI to demodulate each tributary by adjusting the differential optical phase between the two MZDI arms to be $\pi/4$ or $-\pi/4$. Since the eye diagrams after MZDI demodulation between the two tributaries are basically identical, we only show the eye diagram of one tributary, as provided in Fig. 10(ii). There are some ripples in the eye diagram due to the imperfect MZDI. Using a detection method similar to that for the OCS-oDQPSK signal, one sideband of the demodulated OCS-oDQPSK is filtered by an optical filter from one output port of the de-modulator, which is connected to a single 2.5-GHz low-speed PD without the use of a balance receiver, the optical and electrical eye diagrams are shown in Fig. 10(iii) and (iv), respectively. Fig. 11 gives the BER results of the in-phase and quadrature tributaries, respectively. For the two data channels, less than 0.3-dB power penalties after 25-km transmission are obtained.

IV. CONCLUSION

We have proposed a simple and effective scheme to obtain the OCS-oDQPSK signal using only a MZM driven by a SCM signal. We experimentally demonstrated that the OCS-oDPSK can be used to simultaneously realize the up-conversion of baseband data for downlink wireless service delivery, the generation of remote LO signal, and the remodulation of the uplink data. Based on the OCS-oDPSK generation principle, an OCS-oDQPSK signal is also obtained using a DPMZM for simultaneously delivering multiple RoF services at the common RF carrier. The results show that our scheme provides a candidate technique to enable a compact and cost-effective configuration for future RoF applications.

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