Simultaneous Transmission of ASK, OCS-ASK and FSK Signals in A Radio over Fiber System Using A Single-drive Mach-Zehnder Modulator

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Abstract. We propose a bidirectional radio over fiber (RoF) system for simultaneous generation and transmission of amplitude shift keying (ASK), optical carrier suppressed amplitude shift keying (OCS-ASK) and frequency shift keying (FSK) signals based on one single-drive Mach-Zehnder modulator (MZM). The feasibility of the proposal is verified by experiments and error-free performances are achieved for all the data.

1. Introduction
With the development of optical and wireless technologies, it is attractive to simultaneously transmit baseband and radio-frequency (RF) signals using the same fiber infrastructure in an integrated platform [1-6]. In Ref. [1], individual light sources and modulators are required to generate wireline and wireless signals, which result in expensive transmitter architecture and complicated wavelength management. On the other hand, frequency shift keying (FSK) is gaining much more attentions due to its high tolerance to fiber nonlinear impairment and chromatic dispersion (CD). Furthermore, frequency shift keying (FSK) balanced detection enables 3-dB receiver-sensitivity enhancement [7]. In Ref. [8], FSK signal is used for amplitude shift keying (ASK) re-modulation for its constant-intensity property, where the generation of FSK signal requires two light sources modulated by two inversed data, which significantly increase system complexity and cost.

In this paper, we propose and experimentally demonstrate a bidirectional radio over fiber (RoF) system for simultaneous transmission of downstream baseband-ASK, optical carrier suppression-amplitude shift keying (OCS-ASK) and FSK signals based on one single-drive Mach-Zehnder modulator (MZM). At the central station (CS), a continuous-wave (CW) laser is launched into a MZM which is biased at its transmission null and driven by an electrical carrier-suppressed sub-carrier multiplexed (SCM) signal. With this modulation, the output of the MZM consists of two frequency components: the original optical carrier and the first-order sub-carriers, while the high-order sub-carriers are ignored due to the negligible optical power. After 12.5-km transmission of single mode fiber (SMF), at the base station (BS), the generated signal is split into two parts by a 50:50 optical coupler. One is separated by a fiber bragg grating (FBG) to obtain the baseband-ASK signal and 20-
GHz OCS-ASK signal, which are detected by individual receivers, respectively. For the other part, a band-pass filter is employed to filter out the original optical carrier and right tone of the first-order sub-carriers, to generate a FSK signal. To the best of our knowledge, this is the first time that FSK signal is realized using only a single MZM by both theoretical deviation and experimental demonstration. The generated FSK signal is re-modulated by upstream data, eliminating light sources and wavelength management in the BS. Compared with the previous works, the propose scheme processes two attractive advantages: 1) a cost-effective way to simultaneously generate wireline and wireless signals in a RoF system; 2) a novel method of producing FSK signal, which is used to realize ASK/FSK orthogonal modulation format, resulting in source-free ONUs.

2. Principles

![Figure 1. Principle of the generation of FSK signal.](image)

The principle of the generation of FSK based on one single-drive MZM is shown in Fig. 1. An electrical unipolar non-return-to-zero (NRZ) Data and an RF clock are combined together and then fed to the RF input of the MZM, which is biased at the transmission null. The Data is \( S_D = V \pi \varepsilon(t) \), and the RF clock is \( S_{RF} = \alpha V \pi \cos(\omega_{RF} + \theta) \), where \( V \pi \) is the half-wave voltage of the MZM, \( \omega_{RF} \) and \( \theta \) are the angle frequency and phase of the RF clock, respectively, and \( \varepsilon(t) = 0 \) or 1, depending on the Data.

According to Ref. [9], the output field of the MZM can be expressed by:

\[
E_{out} = E_0 J_0(\frac{\pi}{2} \alpha) \sin[\frac{\pi}{2} \varepsilon(t)] \cos(\omega_t + \theta_0) + E_0 J_1(\frac{\pi}{2} \alpha) \cos[\frac{\pi}{2} \varepsilon(t)] \cos[(\omega_t + \omega_{RF}) t + \theta_0 + \theta]
\]

(1)

where \( E_0 \), \( \omega_c \) and \( \theta_0 \) are the amplitude, angle frequency and phase of the input optical signal, respectively. In Eq. (1), only the baseband and the first-order components are considered, while the high-order components are ignored due to the negligible optical power.

When \( \varepsilon(t) \) is “1” (high electrical level), the first-order component are suppressed and the output signal only consists of the baseband carrier, which can be expressed by:

\[
E_{out1} = E_0 \sin[\frac{\pi}{2} \varepsilon(t)] J_0(\frac{\pi}{2} \alpha) \cos(\omega t + \theta_0)
\]

(2)

while, when \( \varepsilon(t) \) is set to “0” (low electrical level), the baseband carrier is suppressed and an optical carrier suppression (OCS) signal is generated which can be given by:
\[ E_{\text{out}2} = E_o \cos\left(\frac{\pi}{2} \epsilon(t)\right) J_1\left(\frac{\pi}{2} \alpha\right) \cos\left(\left(\omega_1 \pm \omega_{p}\right)_t + \theta_0 \pm \theta\right) \]  

(3)

As a result, the baseband component carries Data, while, the first-order component carries inversed Data. By properly adjusting the amplitude and phase of the RF clock, the generated signal could have the same optical power in each band. If a filter is used to select the baseband and the right band of the first-order carriers, a FSK signal will be obtained due to the inverse data on the selected two tones.

![Figure 2. Schematic diagram of the proposed bidirectional RoF system.](image)

The schematic diagram of the proposed bidirectional RoF system is depicted in Fig. 2. A continuous wave (CW) light is launched into a single-drive LiNbO3 MZM, which is modulated to simultaneously generate baseband ASK and OCS-ASK. After the transmission, at the BS, an optical filter is used to separate baseband ASK and OCS-ASK signals. A low-speed PD is employed to receive the baseband signal and a high-speed receiver is required for detection of the OCS-ASK signal. Thus the proposed scheme simultaneously provides wireline and wireless services for the end users. In order to save light sources at the BS, we use a pass-band filter to select the baseband and the right band of the OCS-ASK signal, to generate a frequency shifting keying (FSK) signal, which is used to be optical carrier for re-modulation of upstream data. The upstream signal is sent back to the CS and then detected by a low-speed receiver. Using this design, one can simultaneously deliver downstream wireline and wireless signals and upstream data with a single wavelength in a bidirectional RoF system.

3. Experiment and results
We perform an experiment to verify the feasibility of the proposed scheme, with its setup shown in Fig. 3. At the CS, a CW light from a tunable laser (Santec TSL-210F) at 1551.99 nm is launched into a single-drive MZM (JDSU OC-192). A 10-GHz clock is mixed with a 1.25-Gbps pseudorandom bit sequence (PRBS) data with a word length of $2^{31}-1$ to generate SCM signal, which is employed to drive the MZM biased at the transmission null. The output of the MZM (inset (a) of Fig. 3) consists of two components: the original optical carrier with Data and the first-order sub-carriers with inversed Data. The generated signal is amplified to reach a power level of 6 dBm using an erbium-doped fiber amplifier (EDFA). Then a tunable optical filter (TOF) with a 3-dB bandwidth of 1.6 nm is used to suppress amplified spontaneous emission (ASE) noise.

After transmission of 25-km standard single-mode fiber (SMF), at the BS, the signal is divided into two parts by a 50:50 optical coupler. One part is separated by an FBG with a 3-dB bandwidth of 0.106 nm and a reflection ratio of 90%. The baseband signal is reflected and its spectrum and optical eye diagram are shown in insets (c) and (e) of Fig. 3. The residual clock signal on the eye of baseband ASK signal is due to non-ideal filtering effect. The passing signals are injected into a high-speed PD for detection, whose spectrum and optical eye are provided in insets (d) and (f) of Fig 3, respectively. The other part is filtered by a FBG to generate a FSK signal, whose spectrum and optical eye diagram are shown in insets (b) and (g) of Fig. 3. After passing through a polarization controller (PC), the generated FSK signal is ASK re-modulated using a MZM driven by a 1.25-Gbps upstream data with a PRBS length of $2^{31}-1$. The optical eye diagram of the ASK/FSK orthogonal modulation signal is illustrated in inset (h) of Fig. 3. After transmission through 25-km SMF, at the CS, the upstream data is detected by a 2.5-GHz receiver.
Downstream base-band ASK

Downstream OCS-ASK

Upstream

Electrical waveform

Figure 4. BER curves and electrical eye diagrams. (a) Downstream ASK signal, (b) downstream OCS-ASK signal, (c) upstream re-modulation signal, (d) electrical waveforms of the baseband and first-order component.

The BER performances and electrical eye diagrams of the downstream baseband ASK and OCS-ASK signals, and upstream data are shown in Fig. 4. Error-free performances are obtained for both bandband ASK and OCS-ASK signals with 0.3 dB and 0.8 dB power penalties, respectively. For the upstream data, the power penalty is ~ 0.2 dB. The electrical eye diagrams of the downstream signals and upstream data are provided in insets of Fig. 4. We also measure the electrical waveforms of the baseband and the first-order components, inversed data are achieved, which are depicted in Fig. 4 (d).

4. Conclusion
We propose a simple and novel way to generate FSK signal using only a single-drive MZM. Base on this technology, we experimentally demonstrated a bidirectional RoF system for simultaneous generation and transmission of amplitude shift keying (ASK), optical carrier suppressed amplitude shift keying (OCS-ASK) and frequency shift keying (FSK) signals, which is used as upstream optical carrier. The feasibility of the proposal is verified by experiments and error-free performances are achieved for all the data.

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6. References

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