Compensation of dispersion-induced power fading for highly linear radio-over-fiber link using carrier phase-shifted double sideband modulation

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A carrier phase-shifted (CPS) double sideband (DSB) modulation technique in radio-over-fiber (RoF) system is proposed and experimentally demonstrated. By tuning the biases in a single-drive dual parallel Mach–Zehnder modulator (SD-DPMZM), the optical carrier in the DSB spectrum acquires additional phase shift. The transmittance response of a dispersive RoF link is thus being controlled and shifted in the frequency domain. Experiments successfully turned the maximum transmission frequency to 10 GHz and 15 GHz for both 25 and 39 km fiber links. This is also a highly linear scheme, of which a spurious-free dynamic range (SFDR) of 111.3 dB · Hz2/3 is experimentally obtained. © 2011 Optical Society of America

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One of the major applications in microwave photonics, the radio-over-fiber (RoF), is considered to be a promising technique in providing broadband wireless access to optical-wireless networks. It has many benefits such as high bandwidth, low loss, and immunity to electromagnetic interference [1]. The double sideband (DSB) intensity modulation is the simplest scheme to modulate the rf signals onto the optical carrier (OC) using an external Mach–Zehnder modulator (MZM). However, it suffers from a power fading (PF) effect introduced by fiber dispersion [1,2].

Many researchers have focused on this problem. The single sideband (SSB) modulation has been proposed to eliminate one of the two sidebands in the DSB spectrum to overcome the PF. It can be realized using a dual-electrode MZM (DEMZM) [3,4] or a dual-parallel MZM (DPMZM) [4]. The nonideal 90° hybrid coupler introduces insertion loss and frequency dependent phase error, which degrade the antifading performance [5] and limit the operation frequency. The SSB spectrum can also be achieved by optical filtering [3,6], which reduces the flexibility of the RoF system in carrier wavelength and subcarrier frequency. We have presented a carrier-suppressed DSB (CS-DSB) technique to overcome the PF and double the frequency [7]. However, the phase of the vector-modulated signal (VMS) is doubled after fiber transmission, leading to missing data and doubled phase noise. We have also reported the multisideband detection technique in RoF systems [8]. The fiber dispersion is utilized to demodulate the phase modulated signal, achieving a 100 km VMS transmission with optimized subcarrier power. As the dispersion is small, it cannot be applied in short-reach scenarios. In these proposals, optical filtering [3] technique can be further implemented to suppress the intermodulation distortion (IMD) terms and improve the linearity, which is one of the important measures to evaluate an RoF system. As diverse optical paths exist in these schemes, they are very sensitive to environmental changes and are not stable. Using a chirped MZM [2], the fading at certain frequencies can also be avoided by shifting the transfer function through tuning its bias or the driven power, which either increases the IMD, or decreases the rf power efficiency.

In this Letter, a novel and simple method is proposed and experimentally demonstrated to compensate dispersion-induced PF, and to simultaneously achieve high linearity without any excess rf or optical components. A carrier phase-shifted DSB (CPS-DSB) modulation is generated using an x-cut integrated single-drive DPMZM(SD-DPMZM). The rf signal drives one of the two submodulators in the DPMZM to generate CS-DSB signal, where even-order harmonics and IMD terms are suppressed for better linearity [9,10]. The other submodulator allows a clean OC to pass through. They are combined together in the parent modulator to achieve a CS-DSB + C spectrum. By tuning the bias of the parent modulator, the phase of the OC is changed and controlled the transmittance response curve of a dispersive RoF link. Experiments demonstrate such shifts to achieve maximum transmission at 10 GHz and 15 GHz signal over 25 and 39 km single-mode fiber (SMF). A spurious-free dynamic range (SFDR) of 111.3 dB · Hz2/3 is also experimentally obtained, which is 10 dB more than the SSB modulation using a DPMZM.

The structure of a DPMZM is shown in Fig. 1. It can be modeled as two sub-MZMs, MZM-1 and MZM-2, lying on each arm of a parent MZM, MZM-3. In the modulator, MZM-1 is biased at null point to perform CS-DSB modulation. It is driven by an rf signal with a peak amplitude of \( V_E \) and an angular frequency of \( \Omega \). MZM-2 is biased at maximum transmission point and has no driven signal. The envelope of the optical field from these two MZMs can be respectively written as

\[
E_{O1}(t) = E_I \sin[(m \cos \Omega t)/2]/\sqrt{2},
\]

\[
E_{O2} = E_I/\sqrt{2},
\]

where \( m = \pi V_E/V_{x1} \) and \( V_{x1} \) is the half-wave voltage of MZM-1. They are then combined in MZM-3, which is
controlled by dc bias \( V_3 \). A phase difference \( \phi_3 \) between \( E_{O1} \) and \( E_{O2} \) is then generated. Such modulation process achieved a CS-DSB+\( C \) spectrum, \( E_O(t) \), which satisfies

\[
E_O = \left( E_{O1} + E_{O2}e^{i\phi_3} \right) / \sqrt{2} = E_I'\sin(m\cos\Omega/2 + e^{i\phi_3}) / 2, \tag{3}
\]

where \( \phi_3 = \pi(V_3 - V_o)/V_{\pi} \), \( V_o \) is the offset voltage when \( \phi_3 = 0 \), and \( V_{\pi} \) is the half-wave voltage of MZM-3.

The transfer function of a dispersive fiber link with a length of \( L \) is given as \( H(j\omega) = \exp\left(jL_2^2/\beta L\right) \), where \( \beta \) is the dispersion coefficient of the fiber. Expanding Eq. (3) using the Bessel function and considering the dispersion transfer function \( H(j\omega) \), the optical field after transmission is given by

\[
E_F(t) = \sum_{n=-\infty}^{\infty} \Gamma_n + E_I'\sin\phi_3 / 2 = E_{O1} + E_{O2}', \tag{4}
\]

where \( E_{O1}' \) and \( E_{O2}' \) denote the optical components from MZM-1 and MZM-2, respectively, and \( \Gamma_n \) satisfies

\[
\Gamma_n = \frac{E_I'}{4} \left[ 1 - (-1)^n \right] J_n\left( m/2 \right) e^{im\cos\Omega/2 + e^{i\phi_3}}. \tag{5}
\]

where \( J_n(\cdot) \) is the Bessel function of the first kind of order \( n \).

To feed the optical signal into a photodetector (PD), the photocurrent is given by \( i(t) = E_F(t) \cdot E_F^*(t) \). The infinity summation term in Eq. (4), \( E_{O1}' \), contains odd-order harmonics only. So the \( \kappa \)-th-order harmonics of the photocurrent, \( i_k(t) \), can be generated only from the cross products between \( \Gamma_k \) and \( E_{O2}' \), which are given by

\[
i_k(t) = \left( \Gamma_k E_{O2}' + \Gamma_k^* E_{O2}' \right)
= \frac{E_I'}{4} J_k\left( m/2 \right) \exp(jk\Omega) \cos\left( \frac{\beta L}{2}\Omega^2 - \phi_3 \right). \tag{6}
\]

For the first-order harmonic (FOH) signal, if \( m \ll 1 \) is satisfied, we can derive the small signal approximation for \( i_1(t) \) as

\[
i_1(t) = \frac{1}{16} m E_1^2 \cdot \exp(j\Omega) \cdot \cos(\beta L\Omega^2/2 - \phi_3). \tag{7}
\]

Equation (7) shows a coefficient \( \chi_{\text{DSB}} = \cos(\beta L\Omega^2/2 - \phi_3) \) of \( i_1(t) \), which is determined by both the link dispersion and the phase change in MZM-3. The FOH power varies periodically as the square of the angular frequency, \( \Omega^2 \). The phase shift of MZM-3, \( \phi_3 \), also appears in the \( \chi_{\text{DSB}} \).

We can derive such a coefficient for DSBS modulation using a conventional MZM biased at quadrature point, \( \chi_{\text{DSB}} \), satisfying \( \chi_{\text{DSB}} = \cos(\beta L\Omega^2/2) \). Both \( \chi_{\text{DSB}} \) and \( \chi_{\text{DSB}} \) are much alike, except for the phase shift \( \phi_3 \). When \( \phi_3 = 0 \), both the DSBS modulation and the CPS-DSB modulation have the same fading characteristic.

Considering the \( k \)-th zero transmission frequencies \( f_{Z,k} \) and the \( n \)-th maximum transmission frequencies \( f_{M,n} \) for both DSBS modulation and CPS-DSB modulation, they satisfy

\[
2\pi^2 \beta L f_{Z,k}^2 = 2\pi^2 \beta L f_{Z,k}^2 + \phi_3 = \kappa \pi - \frac{\phi_3}{2},
\]

\[
2\pi^2 \beta L f_{M,n}^2 = 2\pi^2 \beta L f_{M,n}^2 + \phi_3 = n \pi. \tag{8}
\]

A physical explanation comparing the CPS-DSB modulation with the DSBS modulation is illustrated in Fig. 2. Before dispersive transmission, the OC and the sidebands have the same initial phases in DSBS modulation, as shown in Fig. 2(a). The dispersive transmission introduces a phase shift \( \theta \) to both the upper and lower sidebands (USB and LSB) with respect to the OC, which satisfies \( \theta = \frac{1}{2} \beta L\Omega^2 \), as shown in Fig. 2(b). This leads to a destructive interference and PF after photodetection, as shown in Fig. 2(c). While using CPS-DSB modulation, biasing MZM-3 at \( \varphi = \theta \), the initial phase of the OC is shifted before the transmission, as shown in Fig. 2(d). The relative phase between the sidebands and the OC after transmission is then \( 0 \), as shown in Fig. 2(e). The detected photocurrent will have constructive interference, which has no PF for \( \Omega \), as shown in Fig. 2(f).

In the meantime, such a phase shift still maintains the highly linear conditions mentioned in [9]. The system will have better linearity and dynamic range compared to conventional methods with no linearization technique.
An experimental setup is built, as shown in Fig. 3. A cw laser at 1549.3 nm is modulated by an rf signal in the DPMZM (Covega, Mach-10 060) from a signal generator (Agilent, E8267D). The DPMZM is biased by three dc voltages. The modulated optical signal is then fed into the SMF, amplified by an erbium-doped fiber amplifier, and passed through a variable optical attenuator (VOA) to a wideband PD. The generated photocurrent is then measured by an electrical spectrum analyzer (ESA, Agilent E4446A) directly.

MZM-1 is biased at $-0.48$ V for CS modulation. MZM-2 is biased at $-2.4$ V for maximum transmission. MZM-3 is biased at $V_{3,25b} = -0.85$ V for maximum back-to-back (B2B) transmission, where $\phi_2 = 0$. The transmittance responses after 25 and 39 km SMF fiber links are measured and normalized to the B2B results. The response without using the CPS technique is shown in Fig. 4(a). The first fading frequencies are 12.5 GHz and 10.2 GHz for both links. To move the maximum transmission frequency to 10 GHz, additional phase shifts of 1.0 rad and 1.5 rad are required for both links, according to Eq. (8). So we have $V_{3,25 \text{ km}} = 1.0V_{s3}/\pi + V_{3,25b} = 0.65$ V and $V_{3,39 \text{ km}} = 1.5V_{s3}/\pi + V_{3,82b} = 1.4$ V, where $V_{s3} = 4.7$ V. When $V_{3}$ is set correspondingly, the link responses are measured as shown in Fig. 4(b). The maximum responses are moved to 10 GHz as expected. Under the similar process, the biases of 2.5 V and $-0.5$ V are calculated for both fiber links. The maximum responses are successfully shifted to 15 GHz.

We also measured the SFDR of the CPS-DSB modulation and an SSB modulation that obtained by a DPMZM with a hybrid coupler [4]. A two-tone signal centered at 10 GHz with a frequency separation of 50 MHz is used to drive the modulators. The optical power at the PD is 5 dB m in both schemes, leading to a noise power density of $-163.3$ dB m/Hz, including both the shot noise and the thermal noise. The SFDRs are measured as 11.3 dB · Hz$^{-1/2}$ and 100.1 dB · Hz$^{-1/2}$ for CPS-DSB and SSB modulation, respectively, shown in Fig. 5.

In conclusion, the CPS-DSB modulation is proposed to solve the PF effect and improve the dynamic range in RoF systems. Without any excess rf and optical components, the link response curve is controlled by tuning the bias of a DPMZM. The fading at certain frequencies can thus be shifted and avoided. Experiments verified this theory by shifting the maximum transmission frequency to 10 GHz and 15 GHz for 25 and 39 km SMF links. It is also a highly linear scheme such that a SFDR of 111.3 dB · Hz$^{-1/2}$ is achieved, which is 10 dB more than the conventional SSB modulation scheme.

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