An orthogonal subcarrier based optical tandem single sideband system

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Abstract: The authors propose an Optical Tandem Single Sideband (OTSSB) system using orthogonal subcarriers that double bandwidth efficiency by allowing transmission of different channels in the upper and lower sidebands of the same optical carrier. A mathematical model and simulation results are presented to demonstrate this new technique.

Keywords: Optical Tandem Single Sideband, Optical Single Sideband, Subcarrier Multiplexing, Orthogonal Subcarriers

Classification: Photonics devices, circuits, and systems

References

1 Introduction

Subcarrier Multiplexed (SCM) systems [1] have received a considerable amount of interest in the last decade, mainly in areas such as radio-on-fiber systems and multi-channel video distribution [2, 3]. A significant advantage of optical SCM systems is that the RF components needed are more mature compared to their optical counterpart, for instance, the availability of a stable RF oscillator and the high resolution RF filters. SCM transmission systems however experience high dispersion penalty [4]. Optical single sideband (OSSB) modulation has been proposed to reduce chromatic dispersion related penalty [2]. Recently, an optical tandem single sideband (OTSSB) technique that enables transmission of different channels on each of the two sidebands, thus effectively doubling the bandwidth efficiency was proposed. Reflective fiber grating and optical image rejection mixer was proposed for detection of OTSSB signals [5, 6]. The technique presented in this letter uses orthogonal subcarriers as a new way to transmit and receive in OTSSB system, avoiding complexities reported in [5, 6]. In this technique, the OTSSB signal is directly detected using a PIN photodiode and further demodulated using quadrature demodulators.

In this letter, we present the mathematical model of OTSSB systems using orthogonal subcarriers. We verify this model by simulating the independent transmission of two 200 Mb/s channel in the upper and lower sidebands of a 1550 nm optical carrier.

2 Mathematical Model

The optical carrier and single sideband modulation are generated using a dual-electrode Mach-Zehnder modulator (DE-MZM). A distributed feedback (DFB) laser with amplitude $A$ and frequency $f_c$ is externally modulated by a pair of orthogonal subcarrier with signal frequency $f_m$, amplitude $V_1$ and $V_2$. The orthogonal subcarriers, denoted as $V_1 \cos(\omega_m t)$ and $V_2 \sin(\omega_m t)$, are applied to both the electrodes through two $90^\circ$ hybrid couplers. The first arm of the DE-MZM is biased at $V_{DC}$, while the other arm is grounded. A DE-MZM with a switching voltage of $V_\pi$ can be modeled as two optical phase-modulators in parallel with output signal $E_o(t)$. The output signal $E_o(t)$ can be represented by

$$E_o(t) = \frac{A}{2} \left[ \cos\{\omega_c t + \beta \pi + \gamma \pi \cos(\omega_m t)\} + \cos\{\omega_c t + \varepsilon \pi \sin(\omega_m t)\} \right]$$

(1)

where $\omega_c = 2\pi f_c$, $\omega_m = 2\pi f_m$, $\beta = (V_{DC}/V_\pi)$, $\gamma = (V_1 + V_2)/V_\pi$ and $\varepsilon = (V_2 - V_1)/V_\pi$.

When the DE-MZM is biased at quadrature and both the modulating signal drives are $\gamma \pi < 1$ and $\varepsilon \pi < 1$; then equation (1) can be expanded using the Bessel functions to

$$E_o(t) = \frac{A}{2} \left[ \begin{array}{c} J_0(\varepsilon \pi) \cos(\omega_c t) - J_0(\gamma \pi) \sin(\omega_c t) \\ - J_1(\gamma \pi) \left\{ \cos((\omega_c - \omega_m) t + \cos((\omega_c + \omega_m) t) \right\} \\ - J_1(\varepsilon \pi) \left\{ \cos((\omega_c - \omega_m) t - \cos((\omega_c + \omega_m) t) \right\} \end{array} \right]$$

(2)
The power spectral density (PSD) $P_o(\omega)$ of the DE-MZM output can be derived from the Fourier transform of the autocorrelation of equation (2) as

$$
P_o(\omega) = \frac{A^2}{8} \left\{ J_0^2(\epsilon \pi) + J_0^2(\gamma \pi) \right\} \pi \delta(\omega + \omega_c)$$

$$+ \frac{A^2}{8} \left\{ J_1^2(\gamma \pi) + J_1^2(\epsilon \pi) \right\} \pi \delta(\omega + \omega_c - \omega_m)$$

$$+ \frac{A^2}{8} \left\{ J_1^2(\gamma \pi) + J_1^2(\epsilon \pi) \right\} \pi \delta(\omega + \omega_c + \omega_m)$$

(3)

Although equation (3) resembles the PSD of an optical double sideband signal, the in-phase and quadrature subcarrier channels are separately transmitted in the USB and LSB respectively. This can be shown if we consider only the in-phase subcarrier $V_1 \cos \omega_m t$ is being transmitted and the quadrature subcarrier is turned off, then $V_2 = 0$. The PSD can now be written as

$$
P_o(\omega) = \frac{A^2}{4} \left[ J_0^2(\gamma \epsilon = 0 \cdot \pi) \pi \delta(\omega + \omega_c) + \right.$$}

$$+ \frac{1}{2} \left\{ J_0^2(\gamma \pi) + J_0^2(\epsilon \pi) \right\} \pi \delta(\omega + \omega_c + \omega_m)$$

$$- J_0(\epsilon \pi) \cdot J_1(\gamma \pi) \{ 2 \cos(\omega_m) t \}$$

$$+ J_1(\epsilon \pi) \cdot J_0(\gamma \pi) \{ 2 \sin(\omega_m) t \}$$

(5)

where $\mathcal{R}$ is the responsivity of the photodetector, $LP\{\bullet\}$ operator denotes the low pass filter function of the photodetector. Equation (5) consists of $DC$ terms, terms with radial frequencies at $2\omega_m$ and orthogonal subcarriers with radial frequencies at $\omega_m$. If $I(t)$ is passed through a bandpass filter centered at $\omega_m$, then the orthogonal subcarriers $\cos \omega_m t$ and $\sin \omega_m t$ can be demodulated using a quadrature demodulator.

### 3 Simulation Results

The proposed system is simulated for transmission of two 200 Mb/s baseband data channels $A$ and $B$ that modulate a pair of orthogonal subcarriers at frequency $f_m = 5.0$ GHz. The modulated orthogonal subcarriers are then fed into a 90° hybrid coupler, producing a duplicate of the same signal differentiated by a 90° phase shift. These signals are used to externally modulate
Fig. 1. Simulation setup of an Optical Tandem Single Sideband (OTSSB) system using orthogonal subcarriers.

the CW laser using a dual-electrode Mach-Zehnder modulator (DE-MZM) as shown in the simulation setup in Fig. 1.

The light source is a CW laser with 10 MHz linewidth and 0 dBm output power. The light from the CW laser is coupled into a dual-electrode Mach-Zehnder (DE-MZM) modulator that has a switching voltage \( V_\pi \) value of 5.0 V and biased at quadrature point. The two BPSK 200 Mb/s baseband data channels are generated by two pseudorandom generators clocked at 200 MHz with a \( 2^{20} - 1 \) pseudorandom bit sequence (PRBS). A hybrid 90° phase shifter is used to shift each of the modulated signals and the composite signal is used to drive the DE-MZ modulator as shown in Fig. 1. The DE-MZM is coupled back-to-back with the receiver through single mode fiber. At the receiver, the optical signal is detected using a PIN diode with 0.7 responsivity. The channels A and B are demodulated using a quadrature demodulator. The output of the demodulator is shaped using a low pass filter with a cut-off frequency of 200 MHz.

Fig. 2 shows the optical spectrum of the OTSSB signal when both the quadrature and in-phase subcarriers are turned on. The inset figure (left) of Fig. 2 shows the optical spectrum of the OTSSB signal when only the quadrature subcarrier channel is transmitted is shown. The right inset figure in Fig. 2 shows the optical spectrum of the OTSSB signal when only the in-phase subcarrier channel is transmitted. These optical spectrum figures show that the proposed OTSSB signal has two sidebands with the quadrature and in-phase subcarriers transmitted in the lower and upper sidebands respectively, as shown earlier in Equation (3).

The Bit Error Rate (BER) vs. Received Power (dBm) graph in Fig. 3 demonstrates the successful transmission for both the channels A and B, with BER of \( 10^{-9} \) at received power of \(-28.0 \) dBm and \(-28.5 \) dBm respectively. The eye diagrams of channels A and B shown as an inset in Fig. 3 demonstrates further the successful transmission, detection and demodulation of the two channels using the proposed technique.
Fig. 2. Optical Spectrum of the Optical Tandem Single Sideband (OTSSB) system using orthogonal subcarriers.

Fig. 3. Optical Spectrum of the Optical Tandem Single Sideband (OTSSB) system using orthogonal subcarriers.

4 Conclusion

We have demonstrated the mathematical model of an alternative technique to transmit and receive OTSSB signals using orthogonal subcarriers. This mathematical model was verified through a simulation exercise, which proved the successful independent transmission of two 200 Mb/s in the upper and lower sidebands of the optical carrier. The promising virtues of OTSSB such as the bandwidth efficiency improvement are further enhanced by this simple and less complex technique.