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Performance analysis of an optical single sideband modulation approach with tunable optical carrier-to-sideband ratio

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A B S T R A C T

In this work, we report an all-optical approach to tune the optical carrier-to-sideband ratio (OCSR) of the typical optical single sideband (OSSB) modulation signals. The key component is a broadband polarization-maintaining fiber Bragg grating (PMF-FBG), which can be fabricated using a chirped grating phase mask. Firstly, we employed this PMF-FBG to reflect two subcarriers (carrier and sideband) of the typical OSSB modulation signals with orthogonal polarization, simultaneously. Since chirped fiber gratings have broadband reflection bandwidth, it will be easy to align the target subcarriers to the grating's reflection bandwidth. Then, a linear polarizer is connected with its principal axes aligned at 45° relative to the fast axis of the PMF-FBG. By doing this, the OCSR is strictly dependent on the injected polarization direction at the PMF-FBG. In other words, the OCSR's tunablity can be realized by tuning a polarization controller placed in front of the grating. Thus continuous tunability of the OCSR can be done. To investigate this technique, a more normal case is considered, with multi tones as the RF source (N denotes the number of RF tones). It is found that when OCSR$=N$ (in value) is satisfied, best receiver sensitivity can be predicted.

1. Introduction

Radio over fiber (RoF) is a promising technology for the next generation wireless communication networks [1,2]. A RoF link uses optical fiber to distribute high capacity wireless signals, such as ultrawideband and millimeter–wave between one central station (CS) and several base stations (BSs). One popular modulation technique used in RoF links is optical double sideband (ODSB) modulation, which can be realized by direct modulation of semiconductor laser or external modulation via electro-optic modulators. However, due to the chromatic dispersion in fiber links, the converted RF signals will experience dispersion-induced power fading [3], which makes long-distance fiber transmission unpredictable. To solve this problem, adaptable dispersion compensators were used [4–7]. The fading can be removed by using midway optical phase conjugation [4], pre-compensation in electrical domain with phase shifting [5], carrier phase-shifted double sideband modulation [6] and mixed polarization modulation [7]. However, a practical RoF network with hundreds of BSs needs hundreds of adaptable dispersion compensators since the dispersion between the CS and every BS are not identical. It will be costful to construct and maintain such a network.

Optical single sideband (OSSB) modulation with an optimum optical carrier-to-sideband ratio (OCSR) is a good solution to improve modulation efficiency, receiver sensitivity, and remove fiber dispersion-induced power fading. So far, some techniques have been reported [8–12]. In [8], an optical carrier-suppressed SSB modulation was proposed using a hyperfine blocking filter based on a virtually imaged phase-array (VIPA). It was found that the hyperfine blocking filter can be tuned for simultaneous OSSB and carrier suppression up to ~30 dB lower than the sideband. However, this technique suffers from high insertion loss (more than 13 dB) and high power penalty caused by the blocking filtering effects. In [9], fiber grating was first proposed to improve link performance. By suppressing optical carrier via a narrow-band FBG, the OCSR can be decreased and receiver sensitivity can be improved. However, such an approach suffers from poor OCSR tunability. In [10], triangular chirped fiber Bragg gratings (CFBG) were used to filter out one sideband from the ODSB signals and balance the OCSR simultaneously. Also, its OCSR cannot be tuned continuously. Then in [11], a triple-arm Mach-Zehnder modulator is used to generate OSSB signal. The OCSR can be tuned by varying the DC-voltage applied to one arm which is without RF modulation. But the OCSR cannot reach 0 dB at small signal modulation. Later in [12], an OSSB modulation approach with tunable OCSR using an dual parallel Mach-Zehnder modulator, was reported.

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By changing the applied bias voltages the OCSR can be tuned continuously. However, it needs careful adjustment of the bias voltage and an expensive modulator.

In this work, we report an all-optical approach to tune the OCSR of typical OSSB modulation signals. Unlike the previous reported ones [11,12], which rely on active bias control of modulator and also expensive modulators, this work uses polarization-maintaining fiber Bragg grating (PMF-FBG) as the key component, which is cheap and easy to fabricate. Besides, since OSSB modulators are already commercially available, approaches using fiber gratings [9,10] seem to be more attractive. Also differ from the previous works [8–10], this approach is characterized by its continuously tunability of the OCSR and also low attenuation (or loss). In this work, a more normal case is considered, with multi tones as the RF source. It is found that when OCSR=N (in value) is satisfied (N denotes the number of RF tones), best receiver sensitivity can be predicted. Numerical analysis and some simulations are carried out to investigate the mechanism. Good agreement between the theory and the simulation has been found.

2. Principle and discussion

2.1. Theory

Fig. 1 shows the diagram of our proposed OSSB modulation approach with tunable OCSR. As shown in the figure, a continuous-wave (CW) laser serves as the source. A typical OSSB modulator consists of a 90° hybrid coupler and a dual-electrode Mach-Zehnder modulator (De-MZM). By applying proper bias voltage to the De-MZM, optical lower ($V_{\rm bias}=V_\pi/2$) or upper ($V_{\rm bias}=3V_\pi/2$) sideband modulation can be achieved.

Suppose that the driving RF signal (form local oscillator, LO) is given by $V_{\rm RF}\cos\Omega t$, where $V_{\rm RF}$ and $\Omega=2\pi f$ represent the voltage magnitude and angular frequency of RF signal. The optical field at the input and the output of De-MZM are given as:

$$E_0(t)=E_0\exp(j\omega_0 t) \quad (1)$$

$$E_1(t)=\frac{E_0(t)}{\sqrt{t_{ff}}}\left[\gamma\exp(jb_i m\cos\Omega t)+(1-\gamma)\exp\left(jm\cos\left(\Omega t+\frac{\pi}{2}\right)+j\frac{V_{\rm bias}}{V_\pi}\pi\right)\right]$$
$$=\frac{E_0(t)}{\sqrt{t_{ff}}}\sum_{n=-\infty}^{\infty}a_n\exp(jn\Omega t) \quad (2)$$

where E_0 and ω_0 denote the magnitude and angular frequency of optical carrier, t_{ff} is the insertion loss of modulator, $\gamma=(1-1/\sqrt{\varepsilon_r})/2$ is the power splitting (combining) ratio for the Y-branch waveguide, in which ε_r is De-MZM's extinction ratio. $m=\pi(V_{\rm RF}/\sqrt{2}V_\pi)$ is defined as the modulation index and V_π is half-switching voltage of De-MZM. Here, α_n represents the weight value of the nth order sideband and stands for

$$a_n=\left[\gamma j^n+(1-\gamma)(-1)^n\exp\left(j\frac{V_{\rm bias}}{V_\pi}\pi\right)\right]J_n(m) \quad (3)$$

As shown in (3), lower or upper sideband modulation can be achieved by setting bias voltage to $V_{\rm bias}=V_\pi/2$ or $V_{\rm bias}=3V_\pi/2$, respectively. To simplify the analysis, in the rest part of this work we will focus on lower sideband modulation, which means $V_{\rm bias}=V_\pi/2$ is always satisfied.

In practice, the modulation index m should be kept small, since large signal modulation will significantly increase the power level in third order inter-modulation distortion and in high order harmonic distortion, especially the third order inter-modulation distortion, it will lead to serious cross-talk in subcarrier multiplexing (SCM) optical links. Normally, small signal modulation is preferred, since it will hardly lead to any strong distortion. Therefore, with a small m, (2) can be simplified to

$$E_1(t)\approx\frac{E_0}{\sqrt{t_{ff}}}[a_0\exp(j\omega_0 t)+a_{-1}\exp(j\omega_0 t-j\Omega t)] \quad (4)$$

In other words, only the carrier and -1st order sideband are considered. As shown in Fig. 1, a polarization controller (PC) is employed to adjust the inject polarization direction at the PMF-FBG. Here, we need to align the optical carrier and the lower sideband, respectively, corresponding to two separate reflection bands, with orthogonal polarization. Since chirped fiber gratings have a broadband reflection bandwidth, it will be easy to align the target subcarriers to the grating's reflection band. Assume that $E_1(t)$ is oriented at an angle of θ to the fast axis of PMF-FBG, which is defined as $\hat{x}$. The optical field reflected by the grating is

$$E_2(t)\approx\hat{x}\frac{E_0\cos\theta}{\sqrt{t_{ff}}}a_0\exp(j\omega_0 t)+\hat{y}\frac{E_0\sin\theta}{\sqrt{t_{ff}}}a_{-1}\exp(j\omega_0 t-j\Omega t) \quad (5)$$

where $\hat{x}$ and $\hat{y}$ are the polarization directions corresponding to the fast and slow axis of PMF-FBG. Thus the carrier (ω_0) and sideband ($\omega_0-\Omega$) are orthogonally polarized.

Then by passing E_2(t) through a linear polarizer (LP) with its principal axes aligned at 45° relative to $\hat{x}$, the polarization direction of the carrier and sideband are aligned with the principal axes of the LP, which is a linearly polarized lightwave. The optical field at the output of the LP can be expressed as

$$E_3(t)=\frac{\sqrt{2}}{2}\frac{E_0\cos\theta}{\sqrt{t_{ff}}}a_0\exp(j\omega_0 t)+\frac{\sqrt{2}}{2}\frac{E_0\sin\theta}{\sqrt{t_{ff}}}a_{-1}\exp(j\omega_0 t-j\Omega t) \quad (6)$$

Since the OCSR is defined by the optical power ratio of optical carrier to the desired sideband, it can be expressed as:

$$\mathrm{OCSR}=\left|\frac{\cos\theta}{\sin\theta}\right|^2\left|\frac{a_0}{a_{-1}}\right|^2=(2\gamma^2-2\gamma+1)\frac{J_0^2(m)\cos^2\theta}{J_1^2(m)\sin^2\theta} \quad (7)$$

As expressed in (7), the desired OCSR is determined by three parameters, namely, extinction ratio ε_r, modulation index m, and polarization angle θ. For a given ε_r and m, OCSR is strictly dependent on θ, the angle between the injected polarization direction at the PMF-FBG and $\hat{x}$, the fast axes of PMF-FBG. By tuning it, a continuous tunability of OCSR can be achieved.

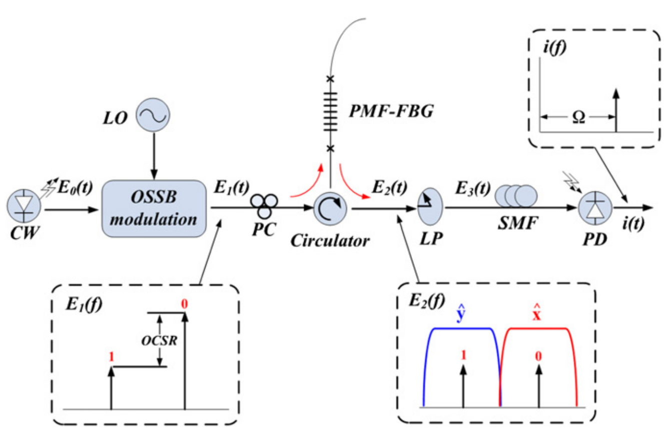

Fig. 1. Analytical model of the proposal with schematic spectrum (inserted); (CW, continuous-wave laser; LO, local oscillator; PC; polarization controller; PMF-FBG; polarization-maintaining fiber Bragg grating; LP, linear polarizer; SMF, single mode fiber; PD, photodiode).

2.2. Discussion on impact of modulation index

Taken $\varepsilon_r=25$ dB for example, Fig. 2 illustrate the evolution of OCSR corresponding to θ. For a single RF tone modulation, the optimum OCSR of 0 dB was found in [10–12]. It can be