Optical Single-Sideband Modulation Using a Fiber-Bragg-Grating-Based Optical Hilbert Transformer

Ze Li, Hao Chi, Xianmin Zhang, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—An all-optical approach to realizing optical single-sideband (OSSB) modulation based on optical Hilbert transform implemented using a fiber Bragg grating (FBG) is proposed and demonstrated. In the proposed approach, an optical double-sideband (ODSB) signal is divided equally into two channels with the output at one channel being the in-phase (I) component and that at the other being the quadrature phase (Q) component. An FBG-based optical Hilbert transformer (HT) is incorporated in the Q channel, making the two sidebands out of phase at the output of the HT. The combination of the two optical signals from the two channels leads to the cancellation of one sideband, thus an OSSB signal is generated. An experiment is performed. An OSSB signal with a frequency from 6 to 15 GHz and a sideband suppression ratio (SSR) as large as 20 dB is generated. The transmission of the OSSB signal over a single-mode fiber of 45.6 km is also studied.**

***Index Terms*—Chromatic dispersion, Hilbert transform, microwave photonics, optical signal processing, optical single-sideband (OSSB) modulation.**

I. INTRODUCTION

TRANSMISSION of radio-frequency (RF) signals over optical fiber or radio over fiber (RoF) has been a topic of interest for the last few years, which can find numerous applications such as in broadband wireless access networks, antenna remoting and cable television (CATV) [1]. Since the distribution of a conventional optical double-sideband (ODSB) signal suffers from the dispersion-induced power fading in a fiber-optic link [2], the frequency of the radio signal to be distributed should be smaller than the 3-dB cutoff frequency, making the RoF system with limited bandwidth for a given transmission distance. To increase the frequency-distance product, a simple solution is to use optical single-sideband (OSSB) modulation. Numerous methods have been proposed and demonstrated to achieve OSSB modulation [3]–[12]. In [3], an optical filter was used to suppress one of the two sidebands of an ODSB signal. However, the transition bandwidth of an optical filter is usually large, which limits the smallest frequency for OSSB generation. OSSB modulation could also be achieved using an electroabsorption modulator (EAM) that is incorporated in a Sagnac fiber loop [4]. By controlling the phase difference between the clockwise and anti-clockwise optical signals, one of the sidebands will be canceled and an OSSB signal is generated.

Theoretically, the generation of an SSB signal can be considered as the suppression of one sideband of a DSB signal using a Hilbert transformer (HT) in the electrical domain. Based on this concept, an OSSB signal can also be generated using an electrical HT [5]–[8]. However, the operating bandwidth of an electrical HT is limited by the electrical circuits. In addition, a dual-electrode Mach–Zehnder modulator (DE-MZM) is needed [5], [6], which would increase the cost. On the other hand, an OSSB signal could be generated in the optical domain using an all-optical Hilbert transformer (OHT) [9], [10], in which the OHT is an optical transversal filter. The operating bandwidth could be larger than 100 GHz and no high-frequency electrical components are required. The major limitation of the technique is the implementation complexity, since multiple taps are needed in the optical transversal filter. If only two or four taps are employed [9], [10], the system is simplified but the passband of the OHT was not flat and the sideband suppression performance was poor.

In this letter, we propose and demonstrate a simple but novel approach to OSSB signal generation using an OHT that is implemented based on a fiber Bragg grating (FBG). Compared with the approach employing an optical transversal filter [9], [10], the use of an FBG provides a flat passband and an improved sideband suppression ratio (SSR). In addition, the use of a single FBG would simplify greatly the system. In the proposed approach, a single-electrode MZM, biased at the quadrature point, is used to generate an ODSB signal. The ODSB signal is then divided equally into two channels by an optical coupler (OC) with the signal at the output at one channel as the in-phase (I) component and that at the output of the other channel as the quadrature phase (Q) component. The Q component is realized using the FBG-based OHT, to introduce a π-phase shift between the two sidebands. By combining the I and Q components, one sideband is suppressed and an OSSB signal is generated. The

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Z. Li is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada, and also with the Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China.

H. Chi and X. Zhang are with the Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China.

J. Yao is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

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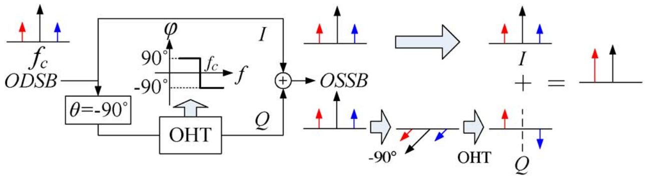

Fig. 1. Principle to generate an OSSB signal using an OHT.

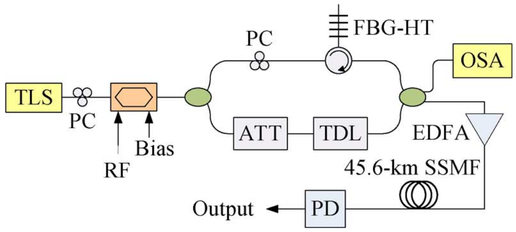

Fig. 2. Experimental setup of the OSSB modulation system.

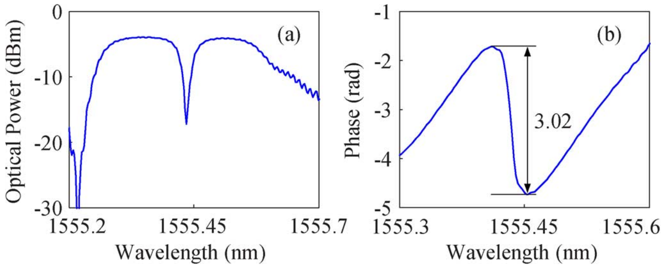

Fig. 3. (a) Reflection power spectrum of the FBG-based OHT. (b) Phase response of the FBG-based OHT.

proposed approach is experimentally verified. An OSSB signal with a microwave frequency from 6 to 15 GHz and an SSR as large as 20 dB is achieved. The transmission of the OSSB signal over a standard single mode fiber (SSMF) of 45.6 km is also studied.

II. PRINCIPLE

The principle of the proposed OSSB modulation technique is shown in Fig. 1. An ODSB signal is split equally into two channels by an OC with the signal at the output of the upper channel being the I component and that at the output of the lower channel being the Q component. The I component is obtained directly from the OC and the Q component is obtained by passing the ODSB signal through a $-90°$ optical phase shifter and an OHT; thus a π-phase difference is introduced between the two sidebands. By combining the I and Q components, one of the sidebands is suppressed and an OSSB signal is generated. The OSSB modulation process in the frequency domain is illustrated in Fig. 1. Note that the attenuations and the group delays of the two channels should be controlled identical.

Mathematically, the frequency response of an optical fractional Hilbert transformer (OFHT) with an order P can be expressed as [11]

$$H_{FHT}(\omega) = \begin{cases} e^{-j\varphi}, & \omega > \omega_c \\ 0, & \omega = \omega_c \\ e^{j\varphi}, & \omega < \omega_c \end{cases} \tag{1}$$

where $\varphi = P \times \pi/2$ and ω_c is the angular frequency of the optical carrier. The OFHT becomes a conventional OHT when $P = 1$. Assume that the phase shift introduced by the optical phase shifter is θ, the I and Q components can then be expressed as

$$E_I(t) = A\left[1 + \beta\cos(\omega_m t)\right]\exp(j\omega_c t) \tag{2a}$$
$$E_Q(t) = A\left[1 + \beta\cos(\omega_m t - \varphi)\right]\exp(j\omega_c t + j\theta) \tag{2b}$$

where A is the optical field amplitude, β is the modulation index and ω_m is the angular frequency of the RF modulation signal. Thus, the sum of the I and Q components is

$$\begin{aligned} E_S(t) &= E_I(t) + E_Q(t) \\ &= Ae^{j\omega_c t}\left\{(1+e^{j\theta}) + \frac{\beta}{2}\cdot e^{j\omega_m t}\cdot\left[1+e^{j(\theta-\varphi)}\right]\right. \\ &\qquad \left. + \frac{\beta}{2}\cdot e^{-j\omega_m t}\cdot\left[1+e^{j(\theta+\varphi)}\right]\right\} \end{aligned} \tag{3}$$

It can be seen from (3) that OSSB modulation could be achieved if the values of θ and φ are properly set. For example, when $\theta = \pm\pi/2$ and $\varphi = \pi/2$, an OSSB signal is generated.

III. EXPERIMENTAL RESULTS

An experiment based on the setup shown in Fig. 2 is performed. An FBG-based OHT with $\varphi = \pi/2$ is fabricated. For a given magnitude and phase response, the FBG is designed using the discrete layer-peeling (DLP) algorithm. The FBG is fabricated in a hydrogen-loaded single-mode optical fiber using uniform phase mask by illuminating the phase mask using a laser beam from a frequency-doubled argon-ion laser (Coherent FreD 300C) operating at 244 nm. The desired apodization profile is implemented by dephasing the subsequent exposures while the UV beam is scanning the phase mask [12]. The reflection power and phase responses of the fabricated FBG are measured by an optical vector analyzer (OVA), which are shown in Fig. 3. As can be seen, the operating bandwidth of the OHT is about 17 GHz and the phase shift is 3.02, which is very close to the ideal phase shift of π. Note that a notch is always found in the FBG reflection spectrum due to the introduction of a phase shift to the FBG in the fabrication process. Thus, the carrier in the Q channel is eliminated, which will make the optical carrier and the remaining sideband in phase, as shown in Fig. 1.

A CW light wave from a tunable laser source (TLS) is sent to an MZM, which is biased at the quadrature point, and the wavelength of the TLS is tuned to match the notch center of the OHT. A microwave signal from a signal generator (Agilent E8254A) is applied to the MZM to generate an ODSB signal. An optical variable attenuator (ATT) and an optical tunable delay line (TDL) are used in the lower channel to balance the sideband amplitudes and the group delays of the two channels. A polarization controller (PC) is used in the upper channel as a phase shifter. The FBG-based OHT is connected to the PC through an optical circulator. When a 10-GHz microwave signal is applied to the MZM, an OSSB signal is generated. Fig. 4(a) shows OSSB signal when the input the microwave power levels are at -5 dBm, 0 dBm, 5 dBm, 10 dBm and 15 dBm. As can be seen, a 20-dB SSR is achieved under different power levels. Fig. 4(b) shows an OSSB signal when the microwave frequency is tuned

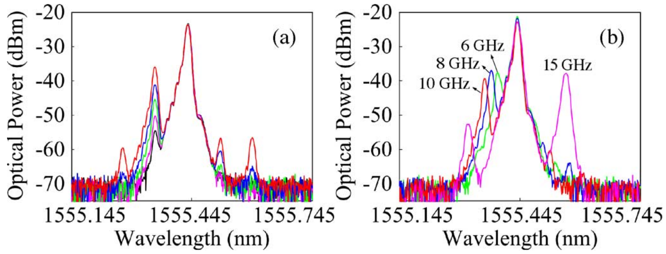

Fig. 4. (a) Generated 10-GHz OSSB signal at five different input microwave power levels. (b) Generated OSSB signal at different microwave frequencies. At 6, 8, and 10 GHz, the lower sideband is suppressed. At 15 GHz, the upper sideband is suppressed.

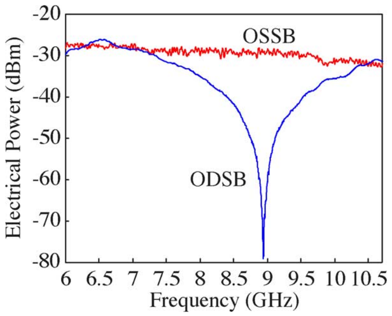

Fig. 5. Frequency response of the fiber link using either the proposed OSSB modulation or the standard ODSB modulation.

at 6 GHz, 8 GHz, 10 GHz and 15 GHz while the input microwave signal is set at 10 dBm. The SSR is maintained at 20 dB when the frequency is at 6 GHz, 8 GHz or 10 GHz. The suppressed sideband is then switched from the lower sideband to the upper sideband by tuning the PC when the microwave frequency is 15 GHz. The SSR is decreased due to the nonideal $\pi/2$ phase shift by the PC, but still kept above 15 dB.

The performance of the proposed OSSB modulation system for microwave signal transmission over fiber is investigated. As shown in Fig. 2, the generated OSSB signal is distributed over a SSMF of 45.6 km. An erbium-doped fiber amplifier (EDFA) is incorporated into the link to compensate for the loss of the link. The microwave signal is then detected at a photodetector (PD). A vector network analyzer (VNA, Agilent E8364A) is used to measure the frequency response. Fig. 5 shows the frequency responses of the fiber link when the OSSB signal and the ODSB signals are propagating over the link. It is seen that the dispersion-induced power fading notch is completely eliminated for the OSSB modulation.

IV. Discussion and Conclusion

In the experiment, the SSR is 20 dB which can be improved if more accurate phase shifts of the OHT and the PC can be achieved. For example, the SSR is 27.2 dB when a phase deviation from the ideal π phase is $\pm 5^\circ$, that is, $\theta + \varphi = \pi \pm 5^\circ$ or $\theta - \varphi = \pi \pm 5^\circ$ in (3), and the SSR is decreased to 21.2 dB when the phase deviation is $\pm 10^\circ$.

The minimum operating frequency of the proposed system is limited by the notch bandwidth of the FBG, which could be made smaller than 2 GHz. The maximum operating frequency is determined by the reflection bandwidth of the FBG, which could be larger than 100 GHz [12]. Thus, the operating frequency of the proposed OSSB modulation system can be 1–100 GHz.

In the experiment, a good short-term stability is observed, while the long-term stability is relatively poor due to the wavelength drift of the FBG. A solution to improve the stability is to use a packaged FBG with temperature compensation.

In conclusion, we have proposed and demonstrated a simple but novel approach to realizing OSSB signal generation using an FBG-based OHT. A brief theoretical analysis was presented, which was validated by an experiment. Thanks to the use of the FBG-based OHT, the entire system was simplified. An OSSB signal with a frequency from 6 to 15 GHz and an SSR as large as 20 dB was achieved. The transmission of the OSSB signal over an SSMF of 45.6 km without power fading was demonstrated.

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