Optical Single Sideband Modulation Using an Ultranarrow Dual-Transmission-Band Fiber Bragg Grating

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***Abstract*—A novel and simple optical single sideband with carrier (SSB+C) modulation scheme implemented using an ultranarrow dual-transmission-band superstructured equivalent phase shift (EPS) fiber Bragg grating (FBG) is presented. The FBG with two ultranarrow transmission bands is created by introducing two EPSs in its structure during the fabrication process. The use of EPSs instead of true phase shifts allows the reduction of the stringent requirement for accurate phase shifts during the fabrication process. An experimental setup using the EPS FBG to implement SSB+C modulation is demonstrated. The performance of the SSB filter is studied by analyzing the eye diagrams and bit-error-rate measurements.**

***Index Terms*—Chromatic dispersion, equivalent phase shift (EPS), fiber Bragg grating (FBG), radio-over-fiber (RoF), single sideband (SSB) modulation.**

I. INTRODUCTION

MUCH effort has been invested in finding ways to combat the chromatic-dispersion-induced power penalty that occurs when optical subcarrier signal with double-disband with carrier (DSB+C) modulation propagates through standard single-mode fiber [1]–[4]. The power penalty is caused by the beating of both sidebands with the optical carrier upon being detected at a photodetector (PD). This beating generates two RF signals, one for each sideband. The relative phase difference between both signals leads to a power penalty, should the signals be out of phase. The use of single sideband with carrier (SSB+C) modulation can eliminate completely the chromatic-dispersion-induced power penalty as only one sideband is being transmitted and thus, only one RF signal is generated by the beating of this sideband with the optical carrier at the PD.

Several approaches have been proposed to implement SSB+C modulation for radio-over-fiber (RoF) systems. The use of narrowband filters such as a regular FBG [1], [2] to attenuate one of the two sidebands has been reported. Since regular FBGs have relatively broad bandwidth, for RoF system operating at a few gigahertz, such as at 2.4 or 5.8 GHz, it is hard to remove only one sideband without affecting the optical carrier and the other sideband. Another technique using a dual-electrode Mach–Zehnder modulator [3] does not have this problem, but the configuration requires an electrical phase shifter to introduce a $\pi/2$ phase shift in the RF signal. Optical SSB+C modulation scheme can also be implemented based on stimulated Brillouin scattering [4], but the approach is only suitable for an RoF system operating at 11 GHz.

In this letter, we present a novel approach to realizing optical SSB+C modulation by using an ultranarrow dual-transmission-band equivalent phase shift (EPS) fiber Bragg grating (FBG). In the proposed system, a DSB+C modulated optical signal is sent to an optical SSB filter. This filter, consisting of an EPS FBG and a regular FBG, serves as a dual-transmission-band filter and is used to select the optical carrier and one sideband, thus achieving optical SSB+C modulation. Superstructured FBGs with EPSs can produce ultranarrow transmission bands [5]–[8]. The use of EPSs instead of true phase shifts reduces significantly the stringent requirement for accurate phase shifts during the fabrication process. In this experiment, an EPS FBG with two EPSs to produce two transmission bands is fabricated. The use of the EPS FBG in combination with a regular FBG to implement the SSB+C modulation is demonstrated. The system performance is studied by analyzing the eye diagrams and the bit-error-rate (BER) measurements.

II. SUPERSTRUCTURED FBG

A superstructured FBG, also called a sampled FBG, is composed of several sections, each containing a subgrating of a given length and a blank space. Both the subgrating and the blank space may have different lengths in different sections. The period of the superstructured FBG corresponds to the sum of the length of the subgrating and the length of the blank space. The duty cycle, which is the ratio of the length of the subgrating to the period of the superstructured FBG, can be varied to create transmission and reflection spectra with desired characteristics [9]. It is also possible to extend the period of specific sections to create EPSs [5]–[8]. This is the technique used in the fabrication of the superstructured FBG with EPSs for the SSB generation.

The refractive index profile of a superstructured grating with constant period is given by [8]

$$\partial n_{\text{eff}}(z) = \overline{\partial n_{\text{eff}}}(z)\{1 + s(z)\exp(j2\pi z/\Lambda)\} \tag{1}$$

where $\overline{\partial n_{\text{eff}}}(z)$ is the dc level of the refractive index change, Λ is the period of the grating, and $s(z)$ can be expressed as

$$s(z) = \sum_{m} F_m \exp(j2\pi m z/P) \tag{2}$$

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Color versions of Figs. 1–6 are available online at http://ieeexplore.ieee.org.

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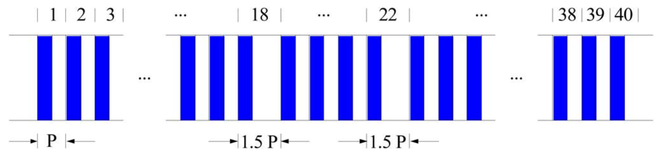

Fig. 1. Schematic diagram of the superstructured FBG for SSB generation.

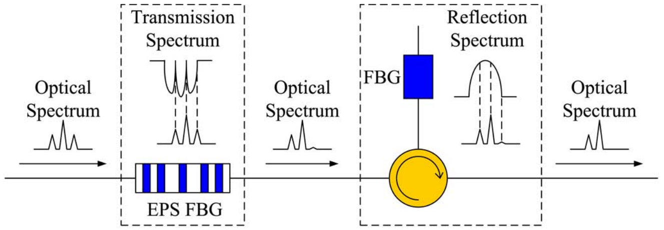

Fig. 2. Configuration of the SSB filter based on a superstructured FBG with two EPSs.

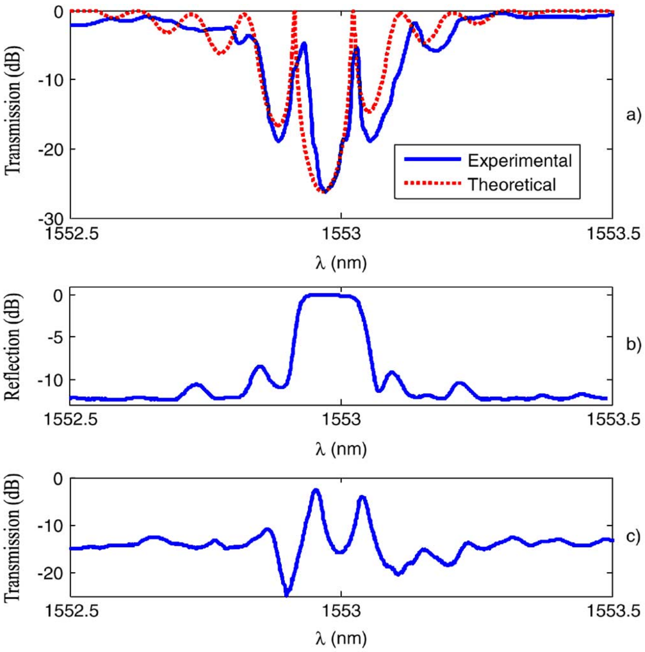

Fig. 3. Optical spectra of the SSB filter. (a) Transmission spectrum of the superstructured FBG with two EPSs, (b) reflection spectrum of a sine-square apodized uniform FBG, and (c) transmission spectrum of the SSB filter.

where m is the order of the channel, F_m is the Fourier coefficient of the mth -order channel, and P is the period of the section, which is usually kept constant along the length of the superstructured FBG.

By extending the period of specific sections in the superstructured FBG, it is possible to create EPSs [8]

$$\theta_{\mathrm{PS}} = 2\pi m(P_{\mathrm{ext}} - P)/P \tag{3}$$

where θ_{PS} corresponds to the angle of the phase shift and P_{ext} is the period of the extended section.

From (3), it is possible to achieve a π phase shift in the ±1st-order channel by extending a period by 50%.

In order to create two peaks in the transmission spectrum of a superstructured FBG, two equivalent π-phase shifts must be created. This is realized by extending the lengths of two sections by 50%. In this work, a 40-section superstructured FBG with a duty cycle of 0.5 and with the 18th and the 22nd sections extended by 50% is fabricated. The length of the subgratings is kept constant for all sections in the structure. The transmission spectrum of the superstructure presents two transmission peaks separated by 0.09 nm, which corresponds to 11.2 GHz in the 1550-nm region. Fig. 1 shows a schematic diagram of the fabricated superstructured EFS FBG.

III. SSB MODULATION BASED ON SUPERSTRUCTURED EPS FBG

The SSB filter proposed in this letter is composed of a superstructured EPS FBG used as a transmission grating and a uniform FBG used in reflection. The spectrum of the uniform FBG used in reflection should be complementary to that of the superstructured EPS FBG, with the exception of the two transmission peaks, as shown in Fig. 2. By aligning one of the sidebands and the optical carrier with the two transmission peaks, it is possible to suppress the other sideband, leading to the generation of an optical SSB+C signal. The use of a dual-transmission-band EPS FBG, instead of a single- transmission-band EPS FBG as a band rejection filter to obtain SSB+C modulation is motivated by the fact that the 3-dB bandwidth of a reflection EPS FBG is not broad enough to allow the reflection of one sideband and the optical carrier, and to reject the other sideband.

IV. EXPERIMENTAL RESULTS

The transmission spectrum of the realized SSB filter based on an EFS FBG is shown in Fig. 3(a). A theoretical spectrum is also shown for comparison purposes. As can be seen, the experimental and the theoretical spectra coincide well, which confirms the theoretical model presented.

The spacing of the two transmission peaks of the EPS FBG is measured to be 0.09 nm. This corresponds to a frequency of 11.2 GHz in the 1550-nm region. Based on this value, an apodized uniform FBG is fabricated. The passband of the reflection filter must allow the reflection of both the optical carrier and one sideband while attenuating the other sideband. Fig. 3(b) shows the reflection spectrum of the fabricated uniform FBG. The 3-dB bandwidth is measured to be 0.12 nm, which satisfies the requirement of the EPS FBG. Fig. 3(c) shows the transmission spectrum of the constructed SSB filter. Both transmission peaks are 7.5 dB above any other point in the spectrum.

The experimental setup displayed in Fig. 4 is constructed to study the performance of the system. In the electrical domain, a nonreturn-to-zero 100-Mb/s pseudorandom bit sequence with a word length of $2^{23} - 1$ is generated by a BER tester (BERT). This data stream is frequency-upconverted at 11.2 GHz via a mixer before being amplified. An optical carrier is modulated via an electrooptic modulator (EOM) by this electrical signal. A polarization controller is used to minimize the polarization-dependent loss associated with the EOM. To achieve SSB+C modulation, the modulated optical signal is sent to the SSB filter. Fig. 5(a) shows the spectrum of the optical signal after the SSB filter. The lower-sideband-to-upper-sideband ratio is equal to 23.1 dB. The electrical signal recovered by the PD is amplified

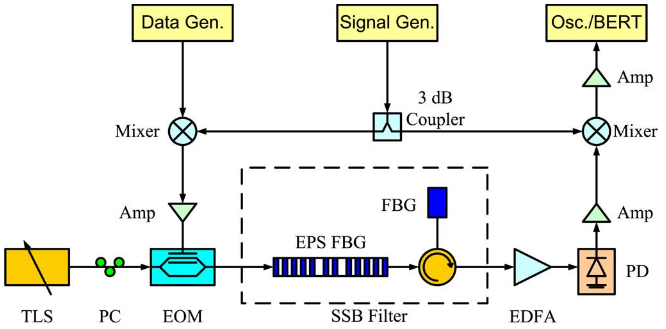

Fig. 4. Schematic diagram of the SSB generation system. TLS: tunable laser source. PC: polarization controller. EDFA: erbium-doped fiber amplifier. Data Gen.: data generator. Signal Gen.: signal generator. Osc.: oscilloscope.

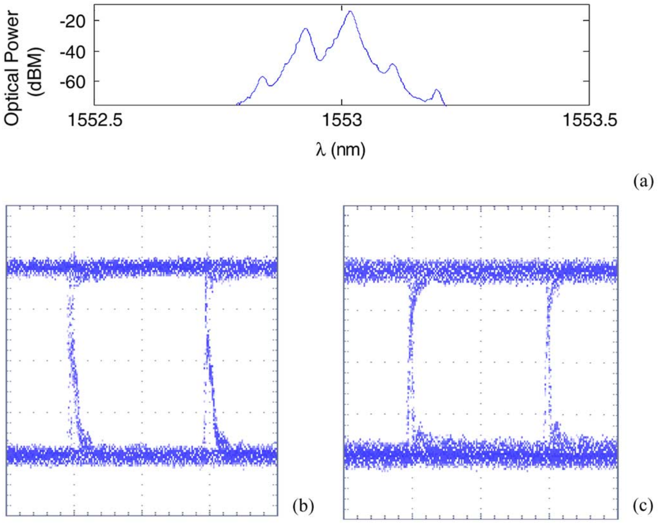

Fig. 5. (a) Spectrum of the SSB+C modulated optical signal; (b) eye diagram of the recovered electrical signal using optical SSB modulation; and (c) eye diagram of the recovered electrical signal using optical DSB+C modulation.

and sent to a second mixer for frequency down-conversion, to recover the 100-Mb/s bit sequence. The recovered bit sequence is then amplified and sent to the oscilloscope or the BERT.

Fig. 5(b) and (c) shows the eye diagrams of the recovered electrical signal using optical SSB+C modulation and optical DSB+C modulation, respectively. The signal has been slightly distorted by the SSB filter, especially at the rising and falling edges, but the eye diagram is still widely open.

Fig. 6 shows the BER measurements (back-to-back) of the recovered electrical signals. The power penalty for the SSB modulation, which is attributable to the distortion and the power loss caused by the SSB filter, is 2.5 dB.

V. CONCLUSION

In this letter, a novel SSB filter based on a superstructured FBG with two EPSs was constructed. Two ultranarrow transmission bands in the superstructured EPS FBG, separated by 11.2 GHz, allow the selection of the optical carrier and of one sideband to generate an optical SSB+C signal. The experimental optical SSB signal realized shows a lower-sideband-to-upper-sideband ratio of 23.1 dB. It was experimentally demonstrated that the back-to-back BER power penalty caused by the SSB filter is 2.5 dB for a 100-Mb/s pseudorandom bit sequence. This approach is thus well suited for the transmission of data up to 100 Mb/s.

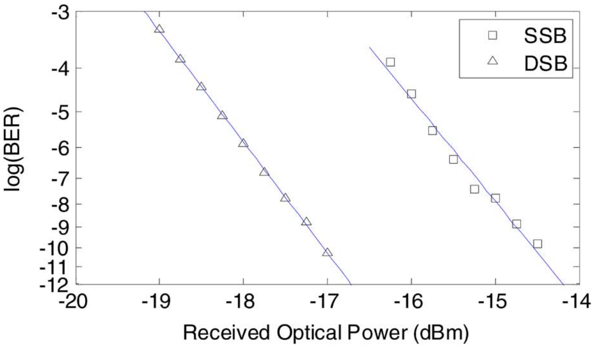

Fig. 6. BER power penalty caused by the SSB filter.

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