Continuously variable modulation frequency optical single sideband with a Sagnac interferometer and photonic crystal fibers

Zhigang Liu, Hanyi Zhang, and Xiaoping Zheng
Tsinghua University, Department of Electronic Engineering, Beijing 100084, China
E-mail: liuzg03@mails.tsinghua.edu.cn

Abstract. A continuous variable modulation frequency optical single sideband (OSSB) can be generated by a Sagnac interferometer and a continuous variable differential group delay (DGD) element of photonic crystal fibers (PCFs). Furthermore, the OSSB signals with different modulation frequencies can be generated simultaneously. *© 2007 Society of Photo-Optical Instrumentation Engineers.*
[DOI: 10.1117/1.2775945]

Subject terms: optical single sideband; Sagnac interferometer; differential group delay; photonic crystal fibers.

Paper 070232LR received Mar. 14, 2007; revised manuscript received May 19, 2007; accepted for publication Jun. 11, 2007; published online Oct. 19, 2007.

1 Introduction

In recent years, microwave fiber optic links have raised extensive interest due to the low loss and wide band of the fiber. People have proposed various applications such as high-speed wireless local area networks (LAN) and remote antenna.[1] Such systems cover a spectral range from a few gigahertz to tens of gigahertz. However, when standard fiber and conventional optical double-sideband (ODSB) modulation are employed, the fiber distance for millimeter-wave transmission is limited to several kilometers, due to fiber-dispersion-induced signal fading.[2] Optical single-sideband (OSSB) modulation can overcome serious power fading in microwave fiber optic links owing to fiber dispersion.[3] In addition, OSSB can also reduce the required bandwidth to almost one half, because of the suppression of one sideband of ODSB signals.[4] This is important in high-capacity wavelength division multiplex (WDM) systems. However, most of the existing OSSB schemes usually implement OSSB in a special range of frequency. When the modulation frequency is changed to another wave band, the SSB cannot be obtained. In WDM systems, we have to employ several subsystems to generate different frequency OSSB.

We present, for the first time to our knowledge, an experimental demonstration to obtain OSSB with a Sagnac interferometer in a wide range of modulation frequencies. It is based on the continuous variable differential group delay (DGD) component—photonic crystal fibers (PCF). Thus, when the modulation signal is changed to another wave band, it can still maintain the OSSB, only requiring an adjustment in the wavelength of the tunable laser in this OSSB subsystem. Moreover, several OSSB signals with different modulation frequencies can be obtained with one Sagnac interferometer. So it can be used in WDM networks conveniently.

2 Theory

Connecting two output ports of a 2×2 coupler forms a Sagnac interferometer. The polarization properties of the fiber can be described by $E_{out}=\boldsymbol{J}(\lambda)E_{in}$, where $E_{in,out}$ denotes the electrical field vectors into and out from the interferometer, and $\boldsymbol{J}$ is the Jones matrix of the interferometer. Assuming no polarization-dependent losses in the path, we can write $\boldsymbol{J}(\lambda)$ as

$$\boldsymbol{J}(\omega)=\begin{bmatrix} a(\lambda) & b(\lambda) \\ -b^*(\lambda) & a^*(\lambda)\end{bmatrix}, \tag{1}$$

where a and b are complex functions of λ, restricted by $|a|^2+|b|^2=1$, and λ is the light wavelength. The loop transmission coefficient is given by $T_s(\lambda)=\mathrm{Im}[b(\lambda)]^2$, which is deduced in Refs. 5 and 6 in detail. The light inputting port 1 would be totally reflected if there are no extra effects in the loop (here, the coupling ratio is 50:50). But if a DGD element is placed in the loop, in this instance, the light power cannot be reflected entirely. The transmission through the interferometer will vary with the light wavelength, since only light with the same polarization state will interfere in the coupler. If light with a broad spectrum, like ASE from an EDFA, is injected into the interferometer, the output spectrum will contain a number of maxima and minima,[1] shown in Fig. 1 due to the birefringence of the DGD element. The DGD element we used in the loop is the PCF, which has the characteristic of continuous variable DGD value from nearly 0 to 80 ps, with the wavelength changing from 1520 to 1580 nm within our measurement range. From Fig. 1, we can see that the interferometer can be used for OSSB in many special wavelengths. The ODSB signals (1, 2, and 3) with different modulation frequencies are shown at the bottom of Fig. 1. The OSSB signals can be generated if one of the sidebands of these ODSB signals is placed at the minimum, and another sideband is placed at the adjacent maximum for maximum sideband suppression.

The phase difference of the ordinary light and extraordinary light traveling around the fiber loop can be written by[5]

$$\Delta\phi=\frac{2\pi}{\lambda}L(|n_0-n_e|), \tag{2}$$

where λ is the wavelength, L is the length of the PCF, and n_0, n_e are the effective refractive indices of the slow and fast axes. The phase differences at the adjacent maxima or minima can be given by

$$2m\pi=\frac{2\pi}{\lambda_1}L(|n_0-n_e|), \tag{3}$$

and

0091-3286/2007/$25.00 © 2007 SPIE

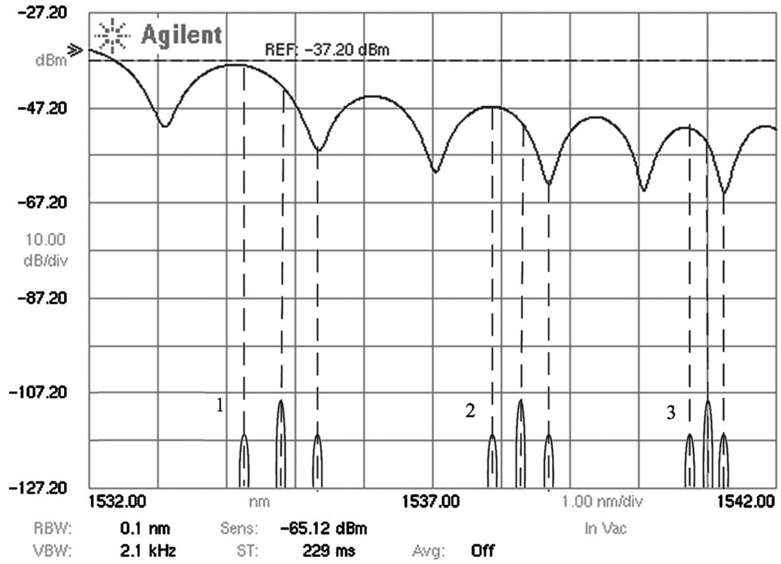

Fig. 1 The interfered spectrum of ASE of EDFA and the OSSB generation principle.

$$2(m+1)\pi = \frac{2\pi}{\lambda_2} L(|n_0 - n_e|), \tag{4}$$

where $\lambda_{1,2}$ denote the two adjacent wavelengths of interference maxima or minima, and $m=0,1,2,3\ldots$. The DGD value is defined as

$$\Delta\tau = \frac{L(|n_0 - n_e|)}{c}, \tag{5}$$

where c is the light velocity in the vacuum.

From Eqs. (3)–(5), we get that

$$\Delta\tau = \frac{\lambda_1 \lambda_2}{c(\lambda_2 - \lambda_1)}. \tag{6}$$

For the purpose of our analysis, we assume the DGD is invariable between the two wavelengths, which is reasonable in general. To generate OSSB, we should select a particular wavelength and modulation frequency. From the bottom of Fig. 1, we can easily deduce that the modulation frequency can be given by

$$f_{\text{mod}} \approx \frac{1}{4\Delta\tau}. \tag{7}$$

3 Experiment

The experimental setup is shown in Fig. 2. The rf signal modulates the light from a tunable laser at an electro-optical modulator, then injects into port 1 of a 2×2 coupler. Here, light is divided into two light beams that travel in the loop conversely. The output light from port 2 is measured by an optical spectrum analyzer. The two polarization controllers are used to regulate the polarization of light for better performance.

In the experiment, we apply one tunable laser to validate the generation of continuously variable modulation frequency OSSB, choosing the proper wavelength of the tunable laser according to the modulation frequency based on Fig. 1 and Eq. (7). We have produced different modulation frequency OSSBs of 25, 20, 15, and 10 GHz, and the corresponding light wavelengths are 1548.800, 1550.704, 1558.010, 1566.489 nm, respectively. We can also change the positions of the interference maxima or minima by adjusting the polarization controller (PC) in the loop. So the modulation frequency to generate OSSB can be discretionarily changed.

From Eq. (7), the inverse proportion between the modulation frequency and DGD value can be drawn, and the DGD value of the PCF used in the Sagnac interferometer is bigger with longer wavelengths, so the higher modulation frequency corresponds to longer wavelengths. The OSSB spectrum is shown in Fig. 3. From the spectrum, we can see that the suppression ratio of two sidebands is more than 15 dBm at different modulation frequencies of 10, 15, 20, and 25 GHz. In addition, although the Sagnac interferometer is sensitive to the polarization change, it is immune to the length change of the fiber loop. The length change of the fiber loop due to environment transformations such as temperature cannot affect the OSSB subsystem, since the effects on the two light beams conversely traveling in the loop could be cancelled. In the experiment, as the polarization is maintained effectively, we discovered the high stability of the Sagnac structure for OSSB.

By only changing the rf frequency, we measured that the 3-dB bandwidth for the passband is no less than 2 GHz in

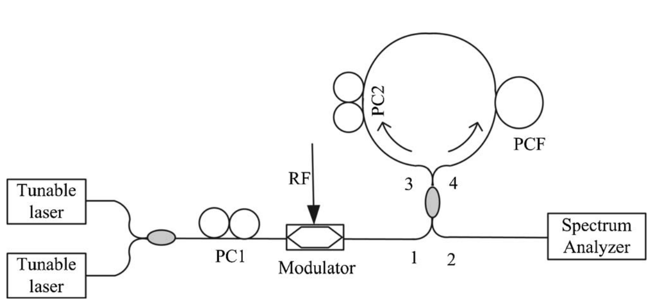

Fig. 2 The experimental setup of generating OSSB.

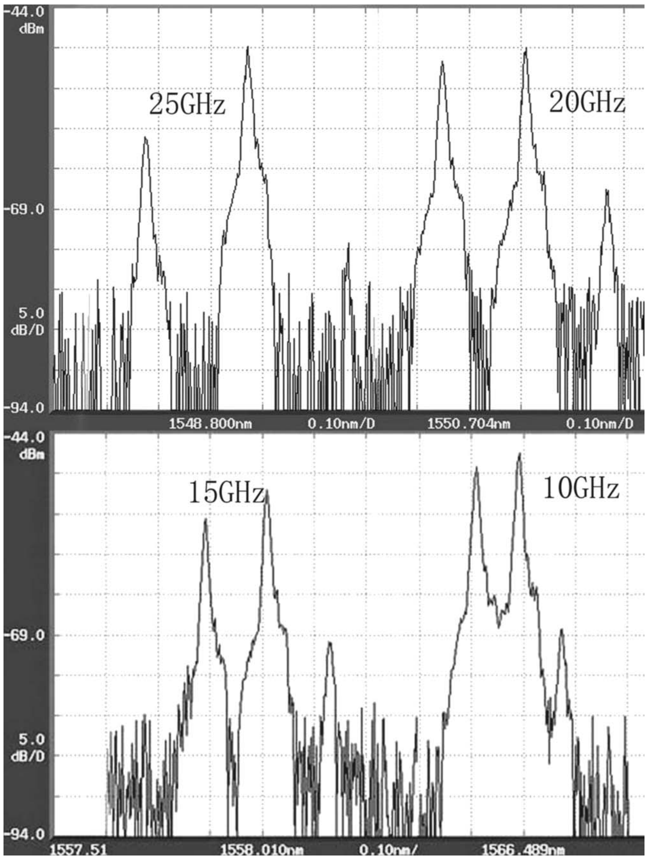

Fig. 3 OSSB spectrum of 25, 20, 15, and 10 GHz modulation frequencies.

these four frequencies, which agrees with Fig. 1. Obviously, different modulation frequencies would induce different 3-dB bandwidths. To our pleasure, the higher frequency corresponds to the wider 3-dB bandwidth. Hence, we can implement OSSB in a continuous frequency range. Furthermore, the inverse proportion between the modulation frequency and DGD value draws the conclusion that OSSB can much more easily be realized with the higher modulation frequency. This subsystem can also be employed in the WDM system, since the operation range of optical carriers covers a band range more than the whole C-band.

4 Conclusions

We demonstrate an OSSB generation scheme using a Sagnac interferometer and PCF possessing continuous variable DGD. In our experiment, as the polarization is maintained effectively, we discover the high stability of the Sagnac structure for OSSB. This subsystem can satisfy continuously variable modulating of the modulation frequency. Moreover, it can also be employed in WDM systems.

Acknowledgments

We are grateful to the Natural Scientific Foundation of China (NSFC) and the 973 Program of China for support of this work through grant numbers 60432020 and 2006CB302805.

References

1. A. J. Seeds, "Microwave photonics," *IEEE Trans. Microwave Theory Tech.* **50**(3), 877–887 (2002).
2. U. Gliese, S. Norskov, and T. N. Nielsen, "Chromatic dispersion in fiber-optic microwave and millimeter-wave links," *IEEE Trans. Microwave Theory Tech.* **44**(10), 1716–1724 (1996).
3. G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Trans. Microwave Theory Tech.* **45**(8), 1410–1415 (1997).
4. M. Sieben, J. Conradi, and D. E. Dodds, "Optical single sideband transmission at 10 Gb/s using only electrical dispersion compensation," *J. Lightwave Technol.* **17**(10), 1742–1749 (1999).
5. D. B. Mortimore, "Fiber loop reflectors," *J. Lightwave Technol.* **6**(7), 1217–1224 (1988).
6. T. A. Birks and P. Morkel, "Jones calculus analysis of single-mode fiber Sagnac reflector," *Appl. Opt.* **27**(15), 3107–3113 (1988).