Digital system for suppression of relative intensity noise in the superfluorescent fiber source

Wei Chao, Xu Wenyuan, Yang Dewei, Zheng Yue, Li Lijing

(School of Instrument Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China)

Abstract: The superfluorescent fiber source (SFS) is an ideal source for fiber optic sensors (FOSs), because of the high stability. Relative intensity noise (RIN) of a SFS is proven to be an most important factor limiting the performance of FOSs. As the RIN cannot be suppressed effectively using an analog circuit, in this paper, a digital RIN suppressing system executed with intensity modulator was presented. To demonstrate this method, a semi-physical simulation was propose in which the RIN was reduced by 20 dB at the center frequency. This method is more effective than the former analog one by simulation. This digital RIN suppressing system is of great value to improve the performances of FOSs.

Key words: relative intensity noise(RIN); intensity modulator; fiber optical sensors

CLC number: TN29 Document code: A Article ID: 1007-2276(2016)01-0228-05

超荧光光纤光源相对强度噪声数字抑制系统

魏 超,许文渊,杨德伟,郑 月,李立京

(北京航空航天大学 仪器科学与光电工程学院,北京 100191)

摘 要:超荧光光纤光源(SFS)具有高稳定性,是光纤传感器(FOSs)中一种理想的光源。SFS 光源的相对强度噪声(RIN)是影响 FOSs 性能的一个重要的因素。由于使用模拟抑制电路的噪声抑制系统无法很好的抑制 RIN,文中提出了使用强度调制器的数字 RIN 抑制系统。为了验证此想法,建立了半实物仿真模型,该模型可以在中心频率处抑制 RIN 达到 20 dB。该数字系统相对原有模拟系统,性能有了很大的提高,因此对 FOSs 性能的提高有很大的贡献。

关键词:相对强度噪声(RIN); 强度调制器; 光纤传感器(FOSs)

收稿日期:2014-05-11; **修订日期**:2014-06-16

作者简介:魏超(1990-),男,硕士,主要从事光纤传感方面的研究。Email:wc199049@gmail.com

0 Introduction

In many applications of fiber optic sensors(FOSs) such as the fiber-optic gyroscope(FOG), superfluorescent fiber source (SFS) is used for optimum operation of the sensors. SFS generates light at wavelengths in the near-region, between 0.83 μm and 1.55 μm, which is the low-loss window of the silicon-based fibers[1]. The broadband spectral components of emitted light interact within the fiber optical channel and produce a type of noise called relative intensity noise (RIN). It is the main noise in the high-frequency domain when the power of output light reaches a certain value. Yurek[2] and Morkel[3] investigated the noise characteristics and found that RIN determines the fiber-optic sensors' fundamental measurement limit[4]. In a FOS, the RIN affects the signal-noise ratio of the detector, and then the accuracy of sensors. Therefore, the techniques for suppressing RIN become more and more important for improving performance of FOSs, especially FOGs[5].

Many methods have been proposed by researchers to reduce the level of RIN such as open loop noise subtraction, closed loop system using bias modulation feedback and closed loop system using light source pump feedback[1]. However, the gain stability cannot be achieved by open loop noise subtraction because of the use of reference channel[6]. Closed loop system using bias modulation feedback brings degradation in bias stability and closed loop system using light source pump feedback cannot reduce high-frequency components of RIN, which contribute significantly to the performance of sensors. In order to suppress RIN effectively, we build up a system to reduce RIN with a high-speed intensity modulator and a digital servo controller. With the digital servo controller, we can change bandwidth of the suppressed noise conveniently to adapt suppression of different needs of frequencies. The high-frequency components of RIN can also be reduced perfectly in this method.

With a semi-physical simulation with the SFS signal, we propose a new digital filter algorithm to reduce the RIN of FOSs. The result of semi-physical simulation and the algorithm are of great significance which provides guidance for RIN reduction in sensors. Experiments are conducted to certify the effectiveness of the system we proposed, and the algorithm for suppressing the RIN.

1 Principle of the system for suppressing RIN

1.1 The system structure

Compared with other methods, the system we have proposed, is the closed-loop structure to suppress RIN with intensity modulator. Figure 1 is the schematic of the system. In this system, the closed-loop is composed of a fiber coupler, an intensity modulator, a photo-detector and a servo-controller. This system controls intensity fluctuations in the light path to reduce RIN of specific frequencies.

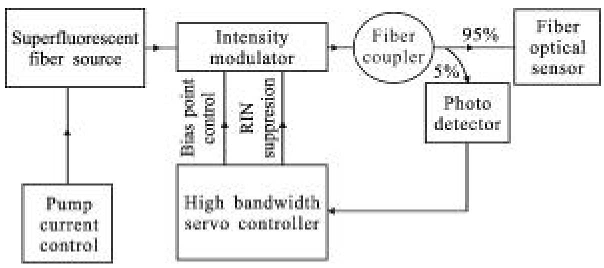

Fig.1 Schematic representation of system for suppression of RIN

In this system, we place a high-speed intensity modulator into the light path between the light source and fiber coupler. The modulator can adjust the power of noise with a high speed to reduce the intensity noise. After the modulator, a photo detector uses 5% signal of the source from a 95:5 fiber coupler, obtaining information of the light source. Then the digital servo controller uses the information and provides two controlling signals. One is used to control the bias of intensity modulator so that the intensity modulator could work effectively at a proper bias point. The other one provides the negative feedback for the intensity modulator. The signal for the sensors is from 95% channel of the coupler.

With the digital servo controller, we can conveniently suppress RIN of different frequencies. And this system is proven to be more effective compared with RIN subtraction and optical suppression techniques[7]. Moreover, this system works well in the outdoor environment and can prevent the distraction from external noise. This feedback system is easy to design, which makes it possible and convenient to massively upgrade the performance of FOSs.

1.2 The principle of the system

As the RIN represents the fluctuation of light source power, the output signal of light source can be written as:

$$I_0(t)=I_0+\Delta I_0(t) \tag{1}$$

Where I_0 is the average optical power, and $\Delta I_0(t)$ is the fluctuation of optical power in the suppressed frequencies which can be regarded as the noise.

We suppose that the light before the modulator can be expressed by the formula as:

$$\mathbf{E}_{in}(t)=|\mathbf{E}_0|e^{j\omega_0 t} \tag{2}$$

Where ω_0 is the angular frequency of the light, and $\mathbf{E}_0$ is the intensity of the light. Then the light after the modulator is expressed as:

$$\mathbf{E}_{out}(t)=\frac{|\mathbf{E}_0|}{2}\left[e^{j(\omega_0 t+\varphi_1)}+e^{j(\omega_0 t+\varphi_2)}\right] \tag{3}$$

For the modulator in the experiment, the bias of phase φ_1 and φ_2 can be expressed as:

$$\varphi_1=\frac{\pi \mathbf{V}_{RF}(t)}{2\mathbf{V}_\pi} \tag{4}$$

$$\varphi_2=\frac{2\pi \mathbf{V}_{Bias}-\pi \mathbf{V}_{RF}(t)}{2\mathbf{V}_\pi} \tag{5}$$

Where $\mathbf{V}_\pi$ denotes the drive voltage of the modulator, $\mathbf{V}_{Bias}$ denotes the bias voltage of the modulator, and $\mathbf{V}_{RF}(t)$ means the modulation voltage.

Substituting Eq. (3) into Eq. (1), we have the optical power after the modulator as

$$I_{out}(t)=|\mathbf{E}_{out}(t)|^2=\frac{I_0+\Delta I_0(t)}{2}\left[1+\cos\left(\frac{\pi[\mathbf{V}_{Bias}-\mathbf{V}_{RF}(t)]}{\mathbf{V}_\pi}\right)\right] \tag{6}$$

From Eq.(6), when the input light intensity $I_0(t)+\Delta I_0(t)$ changes, we can adjust the output power $I_{out}(t)$ through controlling the value of $\left[1+\cos\frac{\pi[\mathbf{V}_{Bias}-\mathbf{V}_{RF}(t)]}{\mathbf{V}_\pi}\right]$. Then we can suppress the RIN. When the bias point of modulator changes to the sensitive point, $\Delta\varphi=\frac{\pi \mathbf{V}_{Bias}}{\mathbf{V}_\pi}=\frac{\pi}{2}$, the Eq.(6) can be rewritten as:

$$I=\frac{1}{2}\left[I_0+\Delta I_0(t)+I_0\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)+\Delta I_0(t)\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)\right] \tag{7}$$

In Eq.(7), the first part $\frac{1}{2}I_0$ is a constant, and the second part is the noise to suppress. If the output of modulator stays steady, the value of $\Delta I_0(t)+I_0\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)+\Delta I_0(t)\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)$ will be lower, then the RIN of suppressed frequencies can be reduced.

Thus, when the noise part of Eq.(7) changed, we can change $\mathbf{V}_{RF}(t)$ to make the signal of light source changed to $I_0\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)+I_0(t)\times\sin\left(\frac{\pi}{\mathbf{V}_\pi}\mathbf{V}_{RF}(t)\right)\approx-\Delta I_0(t)$, then the RIN can be suppressed.

With the signal detected by the PIN-FET detector, we calculate the $\mathbf{V}_{RF}(t)$ using the digital servo controller. From the analysis of principle above, we can realize that the method to obtain the value of $\mathbf{V}_{RF}(t)$ by designing a band-pass filter to select the frequencies to reduce. So the structure of filter is very important. We choose the digital system to design the filter which can conveniently change the reduced frequencies. The suppressed frequencies we need is from 20 kHz to 200 kHz. And at last we choose Butterworth digital filter. The transfer function of the filter is:

$$0.009\,3\times\frac{s^2-1}{s^2-1.891\,7+0.902\,9}\cdot\frac{s^2-1}{s^2+0.404\,4+0.379\,8}\cdot\frac{s^2-1}{s^2-0.773\,1-0.104\,0}$$

From Fig.2 we can find that the magnitude response of this filter meets the demands of the controller, and the phase response in the pass-band is flat so that the delay of the filter is consistent and it can be used for compensation. And due to the delay time, we must compensate for the delay after the filter. After the compensation part, the DA convertor changes the digital signal to the analog which controls the intensity modulator for reducing the noise.

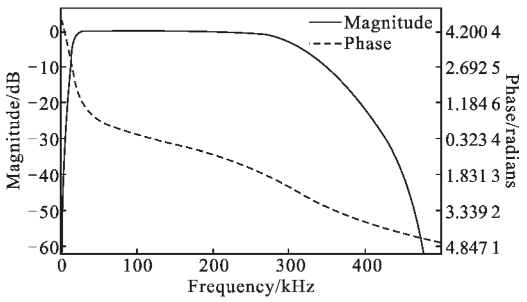

Fig.2 Magnitude(dB) and phase (rad) responses

So after the analysis of principle, we can get the conclusion: when modulator works at the sensitive point, the RIN can be suppressed by adjusting the modulated voltage of modulator.

2 Semi-physical simulation and results

In this paper, we use Matlab/Simulink to study the suppression of RIN. In order to simulate the real system effectively, we collect the real signal of SFS with oscilloscope and change it to the model in simulation. So the results of simulation can be more accurate and useful.

2.1 Schematic diagram

With Matlab, we execute a semi-physical simulation with real signal of SFS. Using the digital filter we designed, we reduce the components of noise and simulate the process of filtering signal. The step length in simulation is set to be 10^{-6} s, as shown in Fig.3.

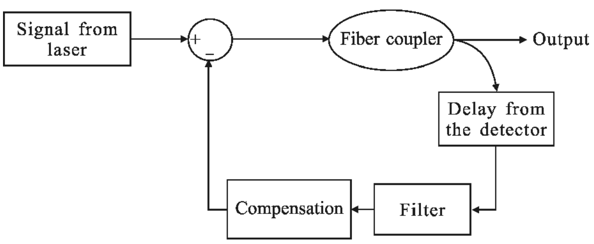

Fig.3 Simulation diagram

From Fig.3, we can find out that we take the noise of detector and modulator into account. This will bring more accuracy and reference value for the simulation.

2.2 Experimental instrument

We use SFS as the light source, and the RIN is the main noise in SFS. In the experiment, we use a high-speed oscilloscope and a high-bandwidth photo-detector to gather SFS signal with the sampling rate of 100 M per 2 ms. And the parameter of SFS source and detector shows as below.

Tab.1 Parameter of photo-detector and SFS source

Photo-detector		SFS source	
Transimpedance	40 kΩ	Mean wavelength	1 559 nm
Bandwidth	5.7 MHz	Full wave width at half maximum(FWHM)	11.5 nm

The SFS source is a kind of narrow-band source which has a 10 mW output power. And the SFS source has high stability which is tested to be 1%. Data of light source are gathered after 20 minutes when it works stably. The spectrum of SFS is in Fig.4.

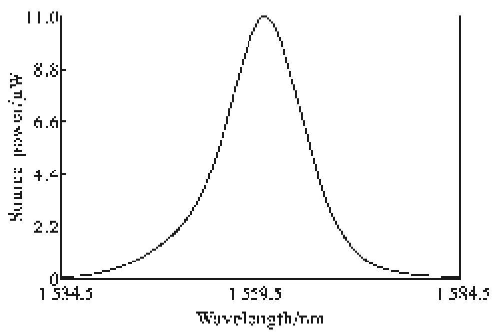

Fig.4 SFS source spectrum with ANDO AQ6319 optical spectrum analyzer

2.3 Results and discussion

The results of the simulation is shown in Fig.5.

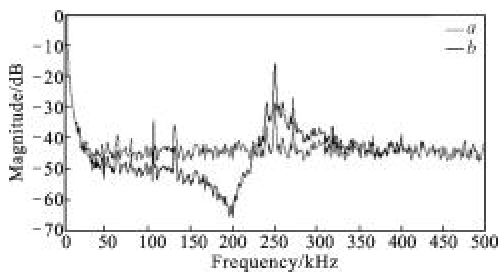

Fig.5 Curves of the frequency spectrum of SFS source signal with (**b**) and without (**a**) RIN suppression

The curve **a** in Fig.5 shows that the intensity of low frequency light is high in SFS source. By comparison, the components of high frequency are small. According to the Yurek[2] and Morkel's[3] paper, the frequency components in the intermediate and high frequency are produced by RIN in the SFS source.

From curve **b** in Fig.5, we can know that frequency components of 20-200 kHz are obviously suppressed, and the center frequency noise is reduced about 20 dB while the surrounding frequency components are suppressed similarly.

The former simulation using analog filter in Fig.6, which can only reduce 10 dB at the center frequency, is inconvenient to change the suppressed band of frequency[5].

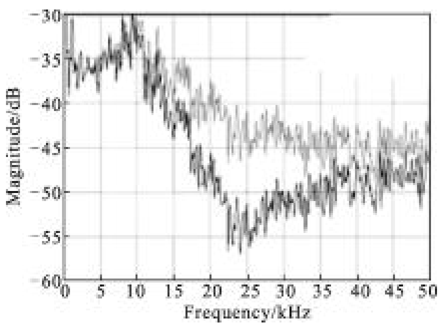

Fig.6 Former frequency spectrum of simulation using analog filter[5]

In this simulation, we should also focus on keeping the system stable and compensate the delay time to the minimum in the feedback system. These factors will affect the results of the reduction.

3 Conclusions

With the semi-physical simulation, this method for RIN suppression adopts the intensity modulator to reduce the RIN in SFS. And this kind of noise could reduce about 20 dB in the center of suppressed bandwidth. In the paper, we use the semi-physical simulation to imitate the process of noise suppression. The results of the simulation depict the guideline for the real experimental system. And our results demonstrate this system is effective in improving the performance of FOSs especially FOGs. And this digital algorithm is better than the former analog one because of the high suppressed level and the convenience of changing the reduced band. The effect of the suppression could be better through the further study.

References:

[1] Strandjore Lee K, Adams Gary W, Ang Dick, et al. System for suppression of relative intensity noise in a fiber optic gyroscope: US 6,204,921 B1[P]. 2001-03-20.

[2] Yurek A M, Taylor H F, Goldberg L, et al. Quantum noise in superluminescentdiodes [J]. IEEE Journal of Quantum Electronics, 1986, QE-22(4): 522-527.

[3] Morkel P R, Laming R I, Payne D N, et al. Noise characteristics of high-power doped-fiber superluminescent sources[J]. Electron Lett, 1990, 26(2): 96-98.

[4] Sunghwan Shin, Utkarsh Sharma, Hachua Tu, et al. Characterization and analysis of relative intensity noise in broadband optical sources for optical coherence to mography [J]. IEEE Photonics Technology Letters, 2010, 22(14): 15.

[5] Yu Haipeng, Xu Wenyuan, Zhang Chunxi. Relative intensity noise reduction in superfluorescent fiber source based on semi-physical simulation[C]//ICEOE 2011, V2: 399-402.

[6] Sun Guofei, Na Yonglin, Wu Yanjie. Research on suppression methods of Er-doped superfluorescent fiber source intensity noise [J]. Infrared and Laser Engineering, 2007, 36(S): 589-592. (in Chinese)

[7] Taylor H F. Intensity noise and spontaneous emission coupling in superluminescent light sources[J]. IEEE Journal of Quantum Electronics, 1990, 26(1): 94-97.