A novel successive demultiplexing scheme based on optical-CDMA balanced demodulation for FBG sensor systems

Huijuan Dong (董惠娟)*, Jian Wu (武 剑), and Guangyu Zhang (张广玉)

School of Mechanical and Electronical Engineering, Harbin Institute of Technology, Harbin 150001

**E-mail: dhj@hit.edu.cn*

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In order to increase the multiplexing density of the fiber Bragg gratings (FBGs) for a low cost per-sensor, based on the analysis of the spectrum shadow distortion (SSD), a novel successive demultiplexing scheme for FBG sensors has been developed. It is based on the optical code division multiple access (CDMA) balanced demodulation. A high-density multiplexing-demultiplexing system for FBG sensors has been designed, and corresponding simulation carried out has demonstrated that the FBG sensors' reflective signals can still be obtained accurately and respectively, even if FBG sensors' operating bandwidths heavily overlap. The SSD has been greatly mitigated.

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The fiber Bragg grating (FBG)[1] sensors are usually serial-connected into an array, so the array's multiplexing density, i.e., the proposed number of sensors can be accomodated in a given bandwidth, is very important, because all of the sensors in the array are sharing one demultiplexer. The multiplexing schemes reported are the wavelength division multiplexing (WDM)[2], the time division multiplexing (TDM)[3], and the space division multiplexing (SDM)[4]. In any of them, as the light fed back to the demultiplexer transmit and retransmit all the object sensor's upstream sensors, its spectrum will be distorted if the sensors' operating bandwidths are overlapped, which is defined as the spectrum shadow distortion (SSD)[5]. The higher the sensors' density is, the worse the distortion becomes. So all sensors' bandwidths in an array must be set precisely to prevent spectrums' overlap, which leads to a very low multiplexing density. Further to this problem, we have brought up a successive demultiplexing scheme and developed a code division multiple access (CDMA) balanced demodulation[6,7] based high-density FBG sensors multiplexing-demultiplexing system. A simulation carried out has demonstrated that the SSD in high density multiplexing can be mitigated effectively. Even if the sensors' operating bandwidths overlap, the sensors' density has dramatically increased.

The successive demultiplexing processes for FBG_1, FBG_2, $\cdots$, and FBG_n, whose reflectivities are $R_1(\lambda)$, $R_2(\lambda)$, $\cdots$, and $R_n(\lambda)$, less than 100%, are illustrated in Figs. 1(a)—(c). The sensors' transmittivities are $T_i(\lambda) = 1 - R_i(\lambda)$, and $\text{Rec}_i(\lambda)$ are the raw signals received by the demultiplexer, where $i = 1, 2, \cdots, n$. Assuming that the intensity of incidence light is 1, all the FBG sensors' operating bandwidths overlap randomly.

In Fig. 1(a), FBG_1 is the most upstream sensor, so it is not affected by any SSD. That is

$$R_1(\lambda) = \text{Rec}_1(\lambda). \tag{1}$$

In Fig. 1(b), FBG_2 is only in the shadow of FBG_1. The light goes through FBG_1 twice before feeding back to the demultiplexer, therefore

$$\text{Rec}_2(\lambda) = T_1(\lambda) \cdot R_2(\lambda) \cdot T_1(\lambda) = (1 - R_1(\lambda))^2 R_2(\lambda),$$

or

$$R_2(\lambda) = \text{Rec}_2(\lambda)/(1 - R_1(\lambda))^2, \tag{2}$$

where $R_1(\lambda)$ has already been given in Eq. (1). FBG_n's light goes through $\text{FBG}_1 \sim \text{FBG}_{n-1}$ twice, therefore

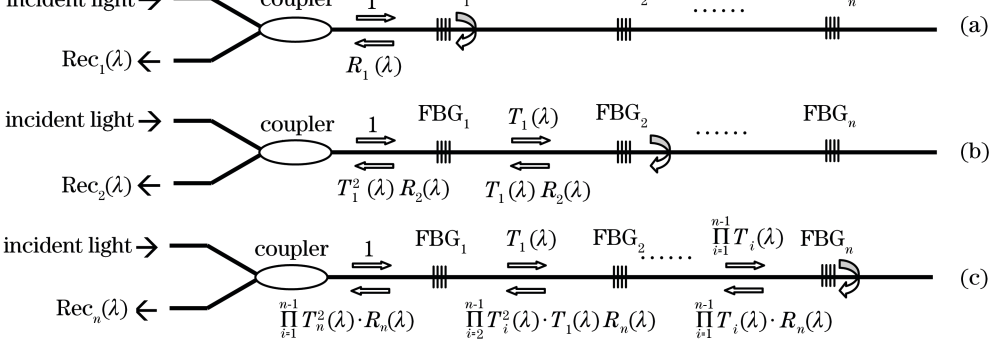

Fig. 1. Process of successive demultiplexing scheme.

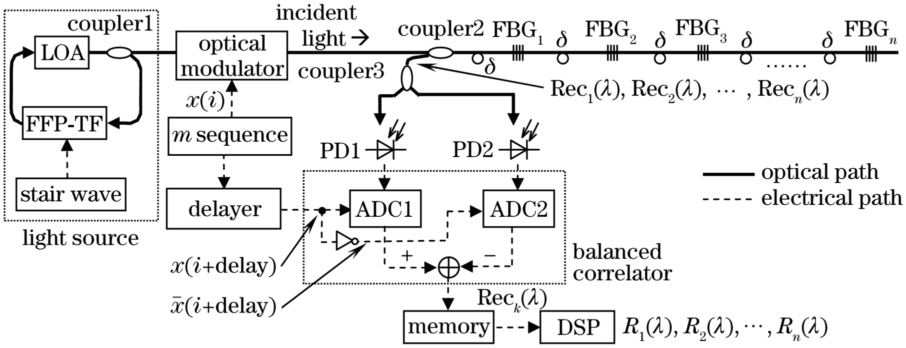

Fig. 2. Diagram of high density FBG multiplexing-demultiplexing system.

$$R_n(\lambda) = \mathrm{Rec}_n(\lambda) \Bigg/ \prod_{i=1}^{n-1} (1 - R_i(\lambda))^2 \ . \qquad (3)$$

In practice, fibers have losses. Assuming that the loss per unit length of the fiber is $K(\lambda)$, which is given by the manufacturer or obtained by measuring and the fiber's length between FBG_n and the demultiplexer is L_n, Eq. (3) is revised to

$$R_n(\lambda) = \mathrm{Rec}_n(\lambda) \Bigg/ (\prod_{i=1}^{n-1} (1 - R_i(\lambda))^2 \cdot K(\lambda) \cdot 2L_n) \ . \qquad (4)$$

As long as the demultiplexer can distinguish $R_1(\lambda)$, $R_2(\lambda)$, $\cdots$, $R_n(\lambda)$ accurately, which are mixed in time-domain, no matter how densely the sensors' reflective spectrums overlap, their reflectivities can be obtained using this scheme. Demultiplexing an FBG sensor is just the process of obtaining its reflectivity at different wavelengths. During the process using this scheme, all the sensors' reflectivities are obtained one by one. Therefore we appropriately named it a successive demultiplexing scheme.

In order to distinguish the sensors' reflective signals accurately, the m sequence-based CDMA balanced demodulation is applied. Equation (5) shows its principle:

$$R_{\mathrm{B}}(\tau) = R_{\mathrm{X}}(\tau) - R_{\bar{\mathrm{X}}\mathrm{X}}(\tau) = \begin{cases} 2^{N-1} & \tau = 0 \\ 0 & \tau \neq 0 \end{cases} , \qquad (5)$$

where τ is the time shift, $R_{\bar{\mathrm{X}}\mathrm{X}}(\tau)$ is the cross-correlation function of the code and its inversion, $R_{\mathrm{X}}(\tau)$ is the auto-correlation function of the m sequence code used in the system, N is the period of the code ($\tau < N$). According to Eq. (5), only if two uniform m sequences codes' time shift is 0, the balanced correlator will output 2^{N-1}, otherwise it will be 0, which is a very strong selectivity in time domain.

Based on the analysis above, we have designed a high density FBG sensor multiplexing-demultiplexing system, which has the advantages of high multiplexing density, as shown in Fig. 2.

A tunable narrow-band light source is composed of the linear optical amplifier (LOA), the fiber Fabry-Perot tunable filter (FFP-TF), the stair wave generator, and coupler 1. Its output light is modulated by the m sequence code $x(i)$ by means of an optical modulator. The modulated light pulse is sent to the FBG array through coupler 2. In the FBG array, there are n optical delayers δ, as shown in Fig. 2. The signals fed back from the array, i.e., $\mathrm{Rec}_1(\lambda)$, $\mathrm{Rec}_2(\lambda)$, $\cdots$, $\mathrm{Rec}_n(\lambda)$, are divided averagely into two halves by coupler 3, then acquired by the photo detectors PD1 and PD2, before being sent to the balanced correlator as input signals. Another input signal is $x(i)$'s shift signal $x(i + \text{delay})$. The output signals of the correlator are stored into the memory and finally processed by the digital signal processing (DSP) based successive demultiplexing program.

Firstly, the light source outputs the light at the wavelength of λ_1. The light is then on-off modulated into a serial pulse by $x(i)$ (its pulse width is w). For the effect of delay and multi-reflection of the array, the incidence light pulse is shifted into $\mathrm{Rec}_1(\lambda_1)$, $\mathrm{Rec}_2(\lambda_1)$, $\cdots$, $\mathrm{Rec}_n(\lambda_1)$, which are blended in time domain. Secondly, the delayer is tuned to make the delay equal to $2\delta + w/2$, which locates at the middle of the shifted pulse of FBG_1. According to the principle of the CDMA balanced demodulation, $\mathrm{Rec}_1(\lambda)$ can be extracted from the mixed reflective signals and stored into the memory. Thirdly, the delayer is tuned to $4\delta + w/2$ to aim at FBG_2 and $\mathrm{Rec}_2(\lambda)$ is extracted and then stored. By tuning the delayer, $\mathrm{Rec}_1(\lambda_1)$, $\mathrm{Rec}_2(\lambda_1)$, $\cdots$, $\mathrm{Rec}_n(\lambda_1)$ could be separated and stored, so $R_1(\lambda_1)$, $R_2(\lambda_1)$, $\cdots$, $R_n(\lambda_1)$ could be obtained using the successive demultiplexing scheme. Subsequently, the stair wave generator is tuned to make the light sources output the lights of λ_2, λ_3, $\cdots$, λ_m (the end of the bandwidth), when the scanning process above is repeated, $R_1(\lambda_2)$, $R_2(\lambda_2)$, $\cdots$, $R_n(\lambda_2)$, $R_1(\lambda_3)$, $R_2(\lambda_3)$, $\cdots$, $R_n(\lambda_3)$, $\cdots$, and $R_1(\lambda_m)$, $R_2(\lambda_m)$, $\cdots$, $R_n(\lambda_m)$ can be obtained. Now, each of the sensors' reflectivities at different wavelengths is achieved. Then these data are listed along the wavelength, so its reflective central wavelength can be obtained. The sensors are demultiplexed.

The sensors' overlapped operating bandwidth will bring the F-P interference. The light interfering between two FBGs has excess time shift and the balanced correlator is set to be only sensitive to a FBG's minimal time shift, so the F-P interference doesn't affect the CDMA balanced demodulation. For real application, the optical delayers in the array will not be precisely equal to δ, which makes an accumulatable time shift error. As mentioned above, the correlator samples the input signal at the middle of the optical pulse, so all the FBGs' reflective signals can be exactly sampled under the condition below:

$$\sum_{i=1}^{k} 2(\delta_i - \delta) < \pm w/2 \quad (k = 1, 2, \cdots, n), \tag{6}$$

where δ_i is the real time shift of the ith FBG's frontal optical delayer.

The simulation has been designed for this system. The given bandwidth is 1534 − 1537 nm and there are 20 sensors in the array. The interval between every two sensors' central wavelength is 0.01 nm, the sensors' peak reflectivity is 10%, the m sequence code's period should be longer than the light's max delay in the array. The code applied is 111111010101100110111011010010011100010111100101000110000 100000 ($N = 63$) and the pulse width $w = 5$ ns. Figures 3(a)—(c) are FBG$_1$, FBG$_{10}$, and FBG$_{20}$'s ideal (undistorted by any spectrum shadow), un-dealt, and dealt reflective signals processed by the successive demultiplexing scheme. In Fig. 3(a), because FBG$_1$ is the most upstream and not affected by any SSD, its central wavelength of the un-dealt reflective signal is the same as that of its ideal reflective signal. In Figs. 3(b) and (c), the central wavelengths of the un-dealt reflective signals are rather different from that of the ideal reflective signals. After the process of the successive demultiplexing scheme, their dealt reflective signals' central wavelengths are nearly equal to those of their ideal reflective signals. The SSD is effectively mitigated. Both the un-dealt and the dealt reflective signals are properly zoomed in for clearly contrast.

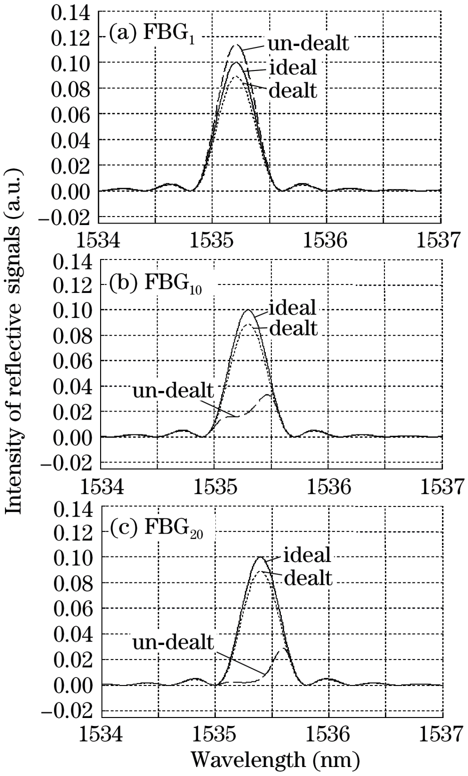

Fig. 3. Ideal, un-dealt and dealt reflective signals by the successive demultiplexing scheme of FBG$_1$, FBG$_{10}$, and FBG$_{20}$.

We have designed a high-density FBG sensor multiplexing-demultiplexing system based on the m sequence code's O-CDMA balanced demodulation, in which all the FBG sensors' operating bandwidth can be overlapped randomly. Based on the analysis of the SSD, the successive demultiplexing scheme has been presented. The simulation carried out has shown that the system designed can effectively mitigate the SSD. It has a perfect performance for anti-crosstalk and can accurately demultiplex all the FBG sensors in the array.

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