Spectral Phase Optical CDMA Coding Based on Step Chirped Fiber Bragg Gratings*

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Abstract A new method for realizing spectral phase optical CDMA coding based on step chirped fiber Bragg Gratings (SCFBGs) is proposed. In this method, a mapping code is introduced and designed phase shift is inserted to the corresponding subgrating of SCFBG according to the mapping code. The structure of encoder/decoder is simple and good correlation property can be readily obtained as demonstrated by numerical simulation results.

Keywords Spectral phase OCDMA coding; SCFBG; Mapping code; Encoder/decoder
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0 Introduction

Fiber optical CDMA encoder/decoder based on fiber Bragg gratings (FBGs) has attracted much research attention due to its simple fabrication method and compatibility with optical fibers. Moreover, grating technology has progress to the point that optical phase of light reflected from individual gratings can also be exploited, allowing optical phase as a coding parameter[1~3]. In phase coding schemes, bipolar codes can be adopted to achieve good correlation property and support a large number of simultaneous users for a given code length. Recently, spectral phase encoder/decoder based on step chirped fiber Bragg Grating (SCFBG) is proposed[3], which originates from traditional spectral phase encoding/decoding using free-space grating-pair (FSGP) configuration[4], and has the advantage of high coupling efficiency into optical fibers. However, the method to realize effective coding has not been reported yet. The coding scheme based on SCFBG has to be designed differently from that based on FSGP. For FSGP, the phase shift on each pixel on the spatial mask is independent from each other. However, in an encoder/decoder based on SCFBGs, the phase shift on one of the subgratings not only influences on the phase of the reflection coefficients of its own, but also on all the subgratings connected subsequently, i.e. the phase shift on any subgrating is not independent from each other.

1 Theoretical basis for encoding/decoding based on SCFBGs

The structure of encoder and matched decoder based on SCFBGs is shown in Fig. 1. The encoder consists of a pair of SCFBGs in series arrangement. When an optical pulse is incident on the first chirped FBG, the wavelength elements contained in the pulse are dispersed and the reflected pulse is temporally expanded. When this expanded pulse is reflected from the second chirped FBG which exhibits the opposite dispersion slope with the first one, the wavelength elements are resynchronized and the original pulse is reconstructed. However, when the second chirped FBG contains phase-shifts between its segments according to the address code, the output pulse represents a spectral-phase-encoded bit. The encoded data bit will be transmitted in the network until it reaches receiver. The structure of decoder is just the same as encoder except the step dispersion order of G3 and G4 is set to be opposite to that of G1 and G2 respectively. For the data bit of the desired user, we can get his original date in the auto-correlator by the address code which matches the desired user, otherwise

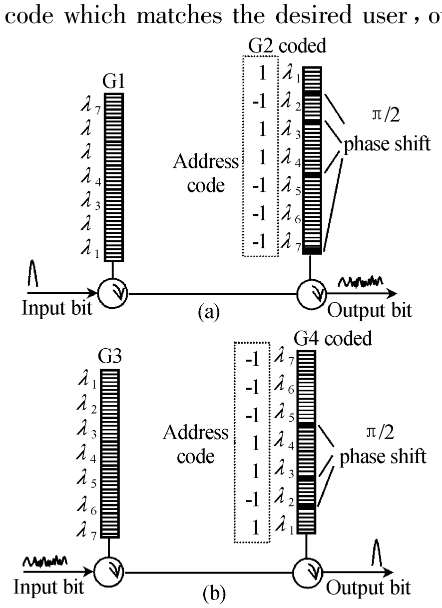

Fig. 1 Schematic diagram of all fiber encoder/decoder based on step chirped FBGs

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cross-correlation operation is performed in the decoder, and multi-access interference will appear in the output.

In the proposed method, the structure of decoder is essentially the same except the phase shifts in G2 is different with those in G4, so we first take consideration of encoder, then decoder.

The length of every subgrating in the SCFBG is required to be the same and there is little overlap between the central peaks of the adjacent spectrums. Thus when the index modulation Δn is small, the reflection characteristics of spectral band $\lambda_n \pm \Delta\lambda/2$ can be approximately expressed by reflection coefficients of the nth subgrating, hence[5]

$$r_n \approx \frac{i\frac{\kappa}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]}{\cosh[\alpha_n(z_n - z_{n-1})] - i\frac{\delta\beta_n}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]} \cdot \exp(i\delta\beta_m z_{n-1}) \quad (1)$$

when phase shifts are incorporated into the subgratings, we have

$$r_n \approx \frac{i\frac{\kappa}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]}{\cosh[\alpha_n(z_n - z_{n-1})] - i\frac{\delta\beta_n}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]} \cdot \exp(i\delta\beta_m z_{n-1})\exp(i\sum_{l=1}^{n}\varphi_l) \quad (2)$$

where κ is coupling constant, $\delta\beta_n$ is the detuning from Bragg resonance, $\alpha_n = \sqrt{\kappa^2 - \delta\beta_n^2}$, $\varphi_l^k/2 \in \{\pi/2, 0\}$, $\sum_{l=1}^{n}\varphi_l^k$ (k means the k-th user) is additional phase shift of reflection coefficient r_n. According to Eq. (1) and (2), the phase shifts between subgratings only produce a term of additional phase shift for reflection coefficient r_n. The total reflection coefficient is the sum of the reflection coefficients of all the subgratings.

$$r \approx \sum_{n=1}^{N} r_n \quad (3)$$

if phase shift (i.e., 0 or $\pi/2$) are inserted between subgratings according to the address code, which satisfy the relationship

$$\exp(i\sum_{l=1}^{n}\varphi_l^k) = c_n^k \quad (4)$$

where c_n^k represents the n-th code element of the address code sequence $c^k = (c_1^k, c_2^k, \cdots, c_N^k)$ of the k-th user, then

$$r_n \approx \frac{i\frac{\kappa}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]}{\cosh[\alpha_n(z_n - z_{n-1})] - i\frac{\delta\beta_n}{\alpha_n}\sinh[\alpha_n(z_n - z_{n-1})]} \cdot \exp(i\delta\beta_m z_{n-1}) c_n^k \quad (5)$$

The n-th code element information is involved in the refelection coefficient r_n. Thus spectral phase optical CDMA coding based on step chirped fiber Bragg grating can be constructed.

In order to satisfy $\exp(i\sum_{l=1}^{n}\varphi_l^k) = c_n^k$, a mapping for address code needs to be established: no change for the first code element; for the others, each has to be compared with the one in front of it, if they are the same, the mapping code element is 1, otherwise -1. For example, the mapping code of the m sequence address code with length 7 (-1 -1 -1 1 1 -1 1) is (-1 1 1 -1 1 -1 -1). The sequence elements $\varphi_l^k/2 \in \{\pi/2, 0\}$, $l \in \{1, N\}$, corresponding to $\{-1\ 1\}$ of mapping code element, is added in front of the corresponding subgrating. Thus, for G2 in Fig. 1, from $\lambda_7 \pm \Delta\lambda/2$ to $\lambda_1 \pm \Delta\lambda/2$, the additional phase shift of the reflection coefficient of each subgrating is: $\{\psi_n^k\} = \{\sum_{l=1}^{n}\varphi_l^k\} = \{\pi, \pi, \pi, 2\pi, 2\pi, 3\pi, 4\pi\}$.

m-sequence is used as the address code in our system. Assigning an address code to the k^{th} and v^{th} user respectively: $c^k = (c_1^k, c_2^k, \cdots, c_N^k)$ and $c^v = (c_1^v, c_2^v, \cdots, c_N^v)$, where $c_n^{k,v} \in \{1, -1\}$, $k, v \in \{1, N\}$. It is widely known that the correlation function of c^k and c^v can be written as

$$\theta_{kv}(l) = \frac{1}{N}\sum_{i=1}^{N} c_i^k c_i^v = \frac{1}{N}\sum_{i=1}^{N} c_i^k c_{i+l}^k \quad (6)$$

which result to $\theta_{kv}(0) = 1$ for $l = 0$ and $\theta_{kv}(l) = 1/N$ for $l = 1$ to N. By assigning N cycle shifts to N subscribers, an OCDMA network that supports up to N simultaneous users can be obtained.

In the decoder, correlation operation is realized. In order to compensate the additional phase shift in the reflection coefficients, the step dispersion order of G4 in the decoder is set to be opposite to that of G2 in the encoder, the code element in decoder is also set in the reverse order with that in the encoder as shown in Fig. 1 (b). Thus from $\lambda_1 \pm \Delta\lambda/2$ to $\lambda_7 \pm \Delta\lambda/2$, the additional phase shift of each reflection coefficient is: $\{\psi_n^k\} = \{\sum_{l=1}^{n}\varphi_l^k\} = \{0, \pi, 2\pi, 2\pi, 3\pi, 3\pi, 3\pi\}$. If the decoder does not match the encoder, no compensation can be provided, and a cross-correlation output will appear. It should be noted that if the first code element of mapping code is -1, no phase shift is added to the first subgrating, as a phase shift of π in the first subgrating leads to all the reflection coefficient spectral band experience the same phase shift and as a result, no influence on the correlation property.

2 Numerical simulation results and discussions

Numerical simulation method is used to investigate the performance of the proposed system. Transmission property of encoder/decoder based on SCFBGs is simulated by the use of transfer matrix method. A series of Gaussuan shape pulse trains of 0.1 ps pulse width is introduced to the encoder. The configuration of encoder/decoder is shown in Fig. 1, where an m-sequence address code with code length of 7 is demonstrated for simplicity. Actually the m-sequence with code length of 15 is used as the address code, thus SCFBG consists of 15 subgratings, each of length of 2.7 mm, and bandwidth of about 0.3 nm. Bragg wavelength of the subgrating is increased by a step of 0.3 nm from 1540.3 nm to 1545.0 nm. Effective mode index $n_{\mathrm{eff}} = 1.456$ and $\Delta n = 2.5 \times 10^{-4}$ are used in simulation.

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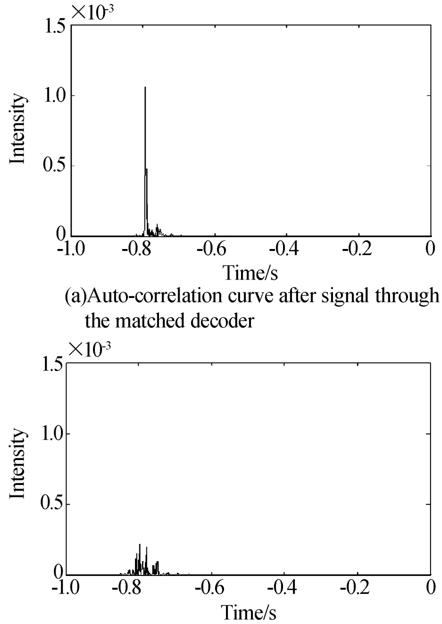
Fig. 2 shows the correlation curves corresponding to the encoded signal passed through the decoder. When the decoder matches the encoder, auto-correlation output can be observed in Fig. 2 (a); otherwise, cross-correlation output appears as shown in Fig. 2 (b). The intensity ratio of autocorrelation to cross-correlation obtained is 5:1. From Fig. 2 (a), it can be seen that autocorrelation peak is not situated exactly at zero point, which is due to the time delay of the pulses passed through 4 SCFBGs.

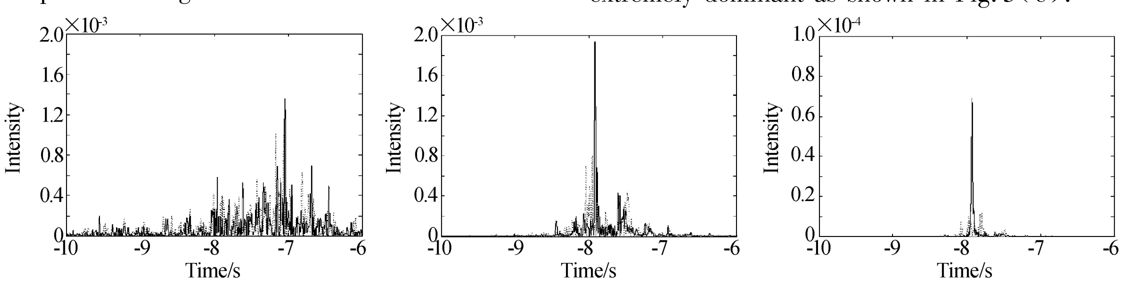


(a)Auto-correlation curve after signal through the matched decoder

(b)Cross-correlation curve after signal through the mismatched decoder

Fig. 2 Correlation curve based on step chirped FBGs decoder with m sequence of code length 15

In order to satisfy Eq. (1), a small Δn is required in writing the encoder/decoder based on SCFBGs. Fig. 3 demonstrates the auto-correlation and cross-correlation output curves corresponding to different values of Δn. When $\Delta n = 1 \times 10^{-3}$, it is difficult to distinguish between auto-correlation and cross-correlation outputs as shown in Fig. 3(a). If $\Delta n = 3.5 \times 10^{-4}$, the intensity ratio of the auto-correlation to cross-correlation becomes 2.4:1 and the auto-correlation output can be clearly recognized as demonstrated in Fig. 3(b). For $\Delta n = 1.5 \times 10^{-4}$, the intensity ratio becomes 7:1 and the auto-correlation output becomes extremely dominant as shown in Fig. 3(c).



(a)Δn=1×10⁻³ (b)Δn=3.5×10⁻⁴ (c)Δn=1.5×10⁻⁴

Fig. 3 Correlation curves with code length 15 under different Δn

For m-sequence address code, better correlation property will be got when increasing code length.

3 Fabrication of specially designed SCFBG

With the development of fabrication technology of fiber grating, it is possible to fabricate SCFBGs with precise control of phase shift that needs to be incorporated into the subgrating. The most direct method is to use the phase mask with specially designed phase shift, but such a method is expensive. Another method is the so called " continuous grating writing " technique[2,6], which effectively writes gratings on a grating plane and allows the fabrication of gratings with truly complex refractive index profiles. This technique uses a simple phase mask with uniform pitch and relies upon precise control of the positioning of the fiber relative to the mask and the exposure of ultraviolet light used to write the grating. A single phase mask can thus be used to write a wide range of complex grating structures.

It is worth notice that too small index modulation Δn will result in large loss in the encoder/decoder, while too large Δn will influence performance of encoding/decoding. So appropriate value for Δn is need to be consideration in fabrication.

In summary, we have proposed and numerically simulated a new method for realizing spectral phase optical CDMA coding based on SCFBGs. By appropriately choose the value of , good correlation property can be obtained.

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基于步进啁啾光纤光栅的 OCDMA 频阈相位编码

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摘　要　本文提出了一种在步进啁啾光纤光栅实现 OCDMA 频阈相位编码的方案, 该方案中引入了影射码, 根据影射码在相应的子光栅之间加入相移以实现正确的编解码. 该编解码器结构简单, 数值模拟得到了好的相关输出.

关键词　光谱相位编码; 步进啁啾光纤光栅; 影射码; 编/解码器

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