Multichannel Dispersion Compensator Fabricated by Interleaving Several Sampled Fiber Bragg Gratings*

Yu Zhihui, Yu Chongxiu, Wu Qiang, Wang Xu, Wang Kuiru

College of Electronics Engineering, Beijing University of Posts & Telecommunications, Beijing 100876

Abstract By theoretic analysis of the interleaved sampled fiber Bragg gratings (ISFBG), the refractive index modulation expression of the ISFBG is deduced. It shows that the ISFBG can be equivalent to a conventional sample fiber Bragg grating. The interleaving technique makes it available that low refractive index modulation results in more channels with almost identical reflectivity. For the first time, two SFBG are interleaved in a fiber and a 10-channels dispersion compensator is fabricated with almost identical reflectivity. The group time delay ripples of each channel are almost less than 20 ps.

Keywords Fiber Bragg ratings; Dispersion compensator; Group time delay; Ripples

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0 Introduction

Sampled fiber Bragg Grating (SFBG) is widely used in wavelength-division-multiplexed (WDM) systems[1~4] and semiconductor laser system[5~7]. And these applications need the SFBG have more channels with identical reflectivity. However, according to the Fourier theory, the rectangular sampling results in a sinc-shape spectrum which has a little region with identical reflectivity channels[8]. To solve this problem, sinc-shape sampling[9] and phase sampling[10] are proposed to generate flat-top shape spectrum. But both of them need precision phase control of the index modulation, therefore the ways to realize them in the experiment are complicated. Interleaving several SFBGs together to fabricate a new SFBG is proposed theoretically by W. H. Loh et al[11]. In this paper, the characteristics of the ISFBG and its advantage are discussed in detail. It is the first time that a 10-channels dispersion compensator is fabricated with approximately 91% reflectivity by interleaving two SFBGs in a fiber. The group time delay ripples of each channel are almost less than 20ps.

1 Principle of interleaving techniques

The ISFBG consists of m SFBGs which have specific grating periods. These SFBGs are orderly interleaved in a fiber according to the grating period's increase. The SFBG which is interleaved for the m^{th} time is named as the m^{th} SFBG. So the refractive index changes of the ISFBG along the fiber could be presented as

$$\delta n_{\text{eff}}(z)=\delta n_0(z)+\overline{\delta n}_{\text{eff}}(z)\sum_{m=1}^{M}\{\text{rect}\,(\frac{z-b_m}{a})\otimes' \sum_{n=0}^{N}\delta(z-np)\exp\,[\mathrm{i}\,\frac{2\pi}{\Lambda_m}+\varphi(z)]\} \tag{1}$$

where z is the position along the grating, $\delta n_0(z)$ is the spatially dependent average refractive index, $\overline{\delta n}_{\text{eff}}(z)$ is the maximum value of ac index modulation, a is the grating section length, b_m and Λ_m are the initial position along z and the grating period of the m^{th} SFBG respectively, p is the sampling period of the SFBG, $\varphi(z)$ is the grating chirp, and M is the total number of the interleaved SFBG. Equation (1) shows that the ISFBG also can be seen as a summation of the M specific SFBGs.

To a conventional SFBG, the frequency separation of the reflection is the channel spacing which is given by[8]

$$\Delta\nu=c/2n_{\text{eff}}p \tag{2}$$

where n_{eff} is the effective index and c is the speed of light. However, to an ISFBG designed with M interleaved SFBG, the channel spacing is the frequency difference between any SFBG and its neighborhood. Hence to get the equal channel spacing, the frequency difference has to be $\Delta\nu_i=c/2n_{\text{eff}}Mp$. Noting the above analysis and using the equation (2), it can get the Bragg central wavelength (BCW) of the m^{st} SFBG.

$$\lambda_m=\frac{c}{\nu_m}=\frac{c}{\nu_1+(m-1)\Delta\nu_i}=\frac{2n_{\text{eff}}Mp\lambda_1}{2n_{\text{eff}}Mp+(m-1)\lambda_1} \quad (m=1,2,3\cdots\cdots M) \tag{3}$$

where the ν_1 and ν_m are the corresponding Bragg central frequency of the first and the m^{st} SFBG respectively. Using the fiber Bragg grating reflection condition $\lambda=2n_{\text{eff}}\Lambda$ where Λ is the grating period, Equation (3) becomes

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Tel: 010-62282040 Email: zhihui. yu@163. com

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$$\Lambda_m=\frac{MP\Lambda_1}{Mp+(m-1)\Lambda_1}\quad (m=1,2,3\cdots\cdots M) \quad (4)$$

Using Equation (4) in (1) and assuming that the M SFBGs are interleaved periodically, it arrives at

$$\delta n_{\mathrm{eff}}(z)=\delta n_0(z)+\overline{\delta n}_{\mathrm{eff}}(z)\sum_{m=1}^{M}\{\mathrm{rect}\,(\frac{z-(m-1)b}{a})\otimes \sum_{n=0}^{N}\delta(z-np)\exp\,[\mathrm{i}\,\frac{2\pi[Mp+(m-1)\Lambda_1]}{MP\Lambda_1}+\varphi(z)]\} \quad (5)$$

where b is the interleaving period. Fig. 1 shows the schematics of an ISFBG fabricated by interleaving 5 SFBGs. The above analysis shows that the channel spacing of the ISFBG is $\Delta\nu_i=c/2n_{\mathrm{eff}}Mp$, and obviously, it is equal to the channel spacing of a conventional SFBG with sampling period Mp. This means the ISFBG could be equivalent to a conventional SFBG which is called equivalent SFBG (E-SFBG).

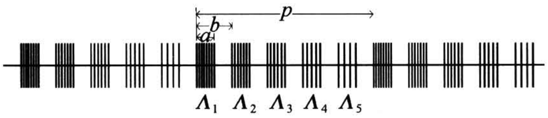


Fig. 1 Schematic of an ISFBG designed with 5 SFBGs

Compared with the E-SPFB, the advantages of ISFBG are obvious. If the fiber using efficiency of the grating is defined as $\eta=$ the length of the grating exposed on/ the total length of the grating, and given the same channel spacing $\Delta\lambda_{\mathrm{in}}$ and the same grating section length a, then the E-SFBG′s fiber using efficiency is $\eta_{\mathrm{SFBG}}=a/MP$, but the ISFBG′ fiber using efficiency is $\eta_{\mathrm{ISFBG}}=Ma/P$ (where $M=1,2,3\cdots$ and $M<p/a$) which is M^2 times better than the E-FBG′s. Another advantage is that the interleaving technique can reduce the required refractive index modulation with the same coupling coefficient. The coupling coefficient corresponding to the n^{th} Fourier component of a sampled grating is given by[5]

$$\kappa(n)=\kappa_0\,\frac{a}{P}\sin c(\pi na/P)\mathrm{e}^{-\mathrm{i}\pi na/P} \quad (6)$$

where the κ_0 is the coupling coefficient of the unsampled grating. From this expression it can be easily seen that the reducing of the sample period P would result in the increasing of the coupling coefficient $\kappa(n)$. So given κ_0 and a are constant, the reducing of sampling period P by interleaving M SFBGs would enable the ISFBG has more identical channels compared to its E-SFBG. This makes the more channels with low refractive index modulation viable.

The above analysis shows that the increasing of the number of the interleaved SFBG would result in the increasing of both the fiber using efficiency and the coupling coefficient. And this shows a practical way to get more identical reflectivity channels with low refractive index modulation by periodically interleaving several specific SFBGs in a fiber. Fig. 2 is a simulation example of an ISFBG fabricated by interleaving four SFBGs. The device parameters are: total grating length 100 mm, sample period 260 μm, interleaving period 65 μm, grating segment length 50 μm, effective index of the fiber 1.447, and refractive index modulation 7×10^{-4}.

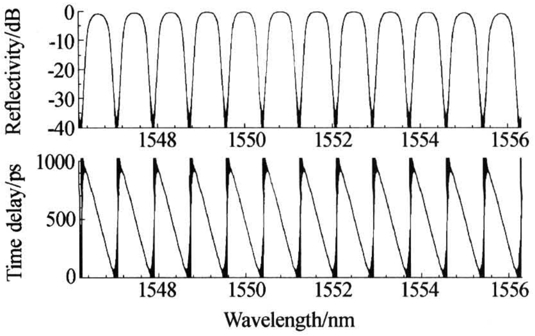


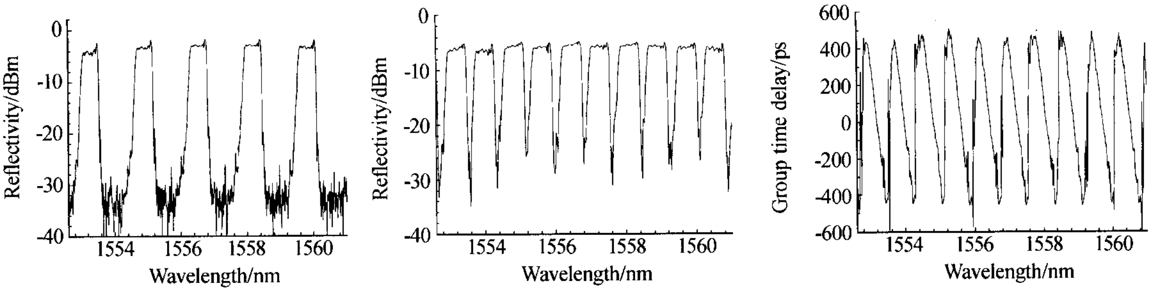
Fig. 2 Reflection and group time delay characteristics of ISFBG

2 Experimental results

Although the interleaving technique can improve the fiber use efficiency, it brings a new challenge in the fabrication. When writing the ISFBG, it should locate every SFBG accurately in order to avoid the overlapping of the interleaved SFBGs. The more SFBG interleaved, the higher precision needed.

In the experiment, a 110mm length chirp phase-mask and a metal rectangular sampled slit are overlapped on the fiber. The metal rectangular sampled slit is 100 mm long. The sampling period is 0.5 mm, and sampling duty cycle is 3 : 10. The photosensitive fiber is hydrogen-loaded. The step-scan exposure system is used. The channel spacing of the ISFBG designed with two interleaved SFBG is 100 GHz, and accordingly the wavelength channel spacing is about 0.8nm around 1556 nm. The process of fabricating the ISFBG is as following: firstly fabricate a SFBG with BCW of 1556.6 nm by exposing a photosensitive fiber with a scanning UV light, then move the slit 0.25 mm along the fiber in order to avoid the overlapping with the second SFBG, next strain the SFBG until the BCW shift 0.71 nm to the long wavelength direction. The wavelength shift is not 0.8 nm, because the strain on the fiber will cause the strain-optic effects and induce the BCW of the second SFBG shift to the short wavelength direction[12].

At last, the second UV exposure result in the second SFBG whose BCW is about 1556.51 nm. Both of the SFBGs, which are interleaved, are apodized by half-cosine function on the long wavelength-edge of gratings[13]. The corresponding results of the first SFBG and the ISFBG are shown in Fig. 3. The group delay characteristics of the ISFBG are measured by ADVANTEST Q7760 optical spectrum analyzer. The first SFBG almost has five equal reflectivity channels separated by about 1.6nm which can be easily seen from Fig. 3 (a). After interleaving the second SFBG, it obtains a 10-channel ISFBG whose reflectivities are almost equal to 91%. And the wavelength channel spacing is about 0.8 nm, the maximum difference of the channel's reflectivities is less than 0.9 dB.



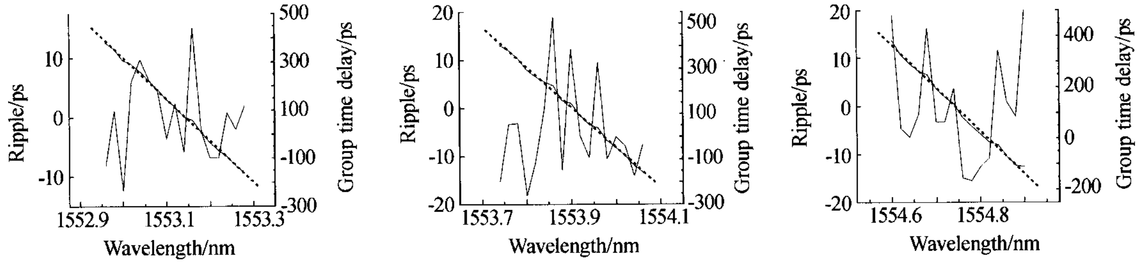
(a) Measured reflection characteristics of the first SFBG

(b) Measured reflection characteristics of the ISFBG

(c) Measured group time delay characteristics of the ISFBG

Fig. 3 Measured characteristics of the SFBGs'

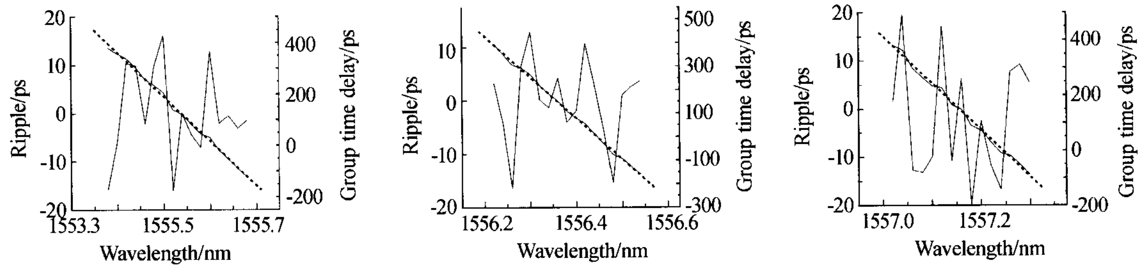
Fig. 4 shows the details of the 10-channel group time delay and the time delay ripples. The dispersion of the ten channels are following: −1726.8 ps/nm, −1751.2 ps/nm, −1749.7 ps/nm, −1752.6 ps/nm, −1761.0 ps/nm, −1712.1 ps/nm, −1693.3 ps/nm, −1762.3 ps/nm, −1717.5 ps/nm, −1727.4 ps/nm. The delay ripples of the former 9 channels are all less than ±20 ps. The delay ripples of the 10th channel are less than ps.



Channel 1

Channel 2

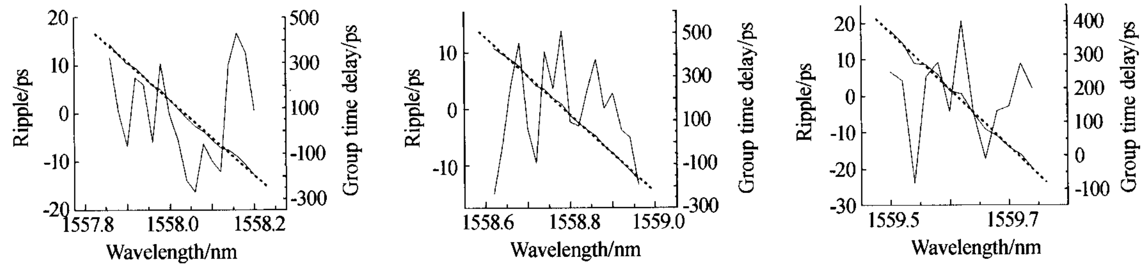
Channel 3



Channel 4

Channel 5

Channel 6



Channel 7

Channel 8

Channel 9

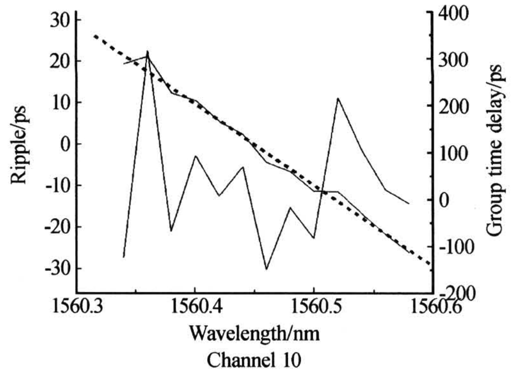


Fig. 4 Group time delay details of each channel

3 Conclusions

In conclusion, the interleaving technique is a practical way to fabricate an ISFBG with high fiber use efficiency and more identical reflectivity channels compared to its E-SFBG. By interleaving two SFBG together, a 10-channel compensator is fabricated with 0.8 nm wavelength channel spacing and the differences of the reflectivities of the channels′ are less than 1 dB. The time delay ripples of all channels are almost less than ±20 ps.

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间插取样光纤光栅多通道色散补偿器

于志辉　余重秀　吴　强　王葵如　王　旭
(北京邮电大学电子工程学院，北京 100876)

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摘　要　对间插取样光纤光栅(ISFBG)进行了理论分析和仿真，给出了 ISFBG 的折射率表达式，提出了一种在较低的折射率调制深度条件下实现通道间平坦度较好的色散补偿器的制作方法．实验制作了由两个取样光纤光栅间插而成的 10 通道色散补偿器，其时延抖动大都小于 20 ps，通道间平坦度小于 1 dB．

关键词　光纤光栅；色散补偿器；群时延；抖动

Yu Zhihui was born in 1978, Ph. D. student of Institute of Electronic Engineering, Beijing University of Posts & Telecommunications. His main research directions are about optical network, optical fiber grating & its applications, and wireless metropolitan area network.