Optica Applicata, Vol. XLI, No. 1, 2011

Hybrid technique based on chirp effect and phase shifts for spectral Talbot effect in sampled fiber Bragg gratings (FBGs)

GUO DENG*, WEI PAN

Center for Information Photonics and Communications, School of Information Science and Technology, Southwest Jiaotong University, Chengdu 610031, Sichuan, China

*Corresponding author: cipc.swjtu@gmail.com

To implement the spectral Talbot effect in sampled fiber Bragg gratings (SFBGs), a hybrid technique based on a chirp effect and phase shifts is proposed. Firstly, the general phase condition is derived as the principle of this hybrid technique, and it also can be used to demonstrate other reported techniques, including the linear chirp, the periodical chirp, and the multiple phase shift technique. According to the general phase condition and the equivalent chirp coefficient in the Talbot effect, multi-channel dispersion compensators are designed with different arrangements of chirp coefficient and phase shifts. Moreover, the dispersion value can be tuned in these devices by dynamically adjusting the phase shifts of the hybrid technique. Numerical simulations are carried out to confirm the performance of such devices realized by using the hybrid technique.

Keywords: fiber Bragg gratings (FBGs), Talbot effect, dispersion, optical fiber communication.

1. Introduction

As a structured type of fiber Bragg gratings, the sampled fiber Bragg grating (SFBG) has aroused considerable interest in a wide range of applications. The most important feature of SFBG is its multi-channel characteristic, which provides the SFBG with tremendous advantages in optical communication systems and sensing systems. Therefore, lots of novel devices based on SFBGs are proposed recently, such as multi-channel comb filters [1–7], multi-channel dispersion compensators [7–12], multi-channel add/drop multiplexers [13], OCDMA en/decoders [14], and environmental parameter sensors [15], *etc*.

Among these applications, the spectral Talbot effect (*i.e*., the self-imaging effect) plays an important role in constructing the dense wavelength spacing devices. The Talbot phenomena can be realized by the chirp effect, including the linear chirp [2, 3, 16], the nonlinear chirp [17], and the periodical chirp [6]. The phase shifts technique is also used to obtain the Talbot phenomena, such as linear phase shift, multiple phase shift (MPS) technique [18]. Meanwhile, the Talbot phenomena can be observed by the combination of chirp effect and phase shifts [4, 12].

In this work, we focus on the implementation of the Talbot effect with a hybrid technique based on the chirp effect and phase shifts. It is noted that our technique is a general method compared with the previous investigations (chirp effect, phase shifts technique, or the combination technique). On the basis of this hybrid technique, various SFBGs with different channel spacing, different channel grid, or different dispersion are obtained. Such SFBGs can operate as multi-channel filters or multi-channel dispersion compensators. Furthermore, tunable characteristics are offered by tuning the phase shifts in SFBGs.

The remainder of this paper is organized as follows. In Section 2, according to the phase condition required by the Talbot effect under the linear chirp, the general phase condition for linear chirp and linear phase shifts technique is derived firstly. Under this general phase condition, the hybrid technique for the Talbot effect is proposed due to the equivalence between the chirp and the phase shifts. With this hybrid technique, different channel spacing can be realized by adjusting the chirp coefficient or the phase shifts. Moreover, on the basis of the general phase condition and the hybrid technique, we are convenient to demonstrate the linear chirp, the periodical chirp, the linear phase shifts technique, the MPS technique, and the approach developed by DAI *et al*. [4]. Dai's approach is considered as an expansion of the hybrid technique by inserting constant phase shift into each sampling period. Extensively, a non-zero constant phase is introduced to tune the wavelength channel grid. Then, in Section 3, we discuss the implementation of multi-channel dispersion compensators by the hybrid technique. A variation in either the chirp coefficient or the phase shifts leads to a similar influence on the dispersion. Therefore, we can get the expected dispersion characteristics by changing the chirp coefficient or the phase shifts. Combined with the tunable channel grid indicated in Section 2, dispersion compensators with the tunable channel grid and tunable dispersion are presented. Finally, we give concluding remarks about the hybrid technique in Section 4.

2. Hybrid technique for spectral Talbot effect

2.1. General phase condition and hybrid technique

Since the hybrid technique needs a general phase condition to support its principle, we firstly derive the general condition. Considering a sampled fiber Bragg grating (SFBG), the linear chirp ($\Lambda(z) = \Lambda_0 - Cz$) along the z-axis is adopted, where Λ_0 and C refer to the center grating period and the chirp coefficient, respectively. According to the expression (20) in [16], to realize the Talbot effect, the required general phase induced by the chirp at sampling points should be derived as the following equation:

$$\Phi(z = kP) = \frac{s}{m}k^2\pi, \qquad k = 0, 1, 2, ... \tag{1}$$

where P represents the sampling period, s and m are arbitrary positive integers with that (s/m) is a non-integer and irreducible number. If Eq. (1) is provided, the SFBG's spectrum presents a narrower channel spacing by m times and a similar dispersion characteristic, as compared with that of the uniform SFBG. It is called as the integer or fractional Talbot effect. The product $(s\times m)$ can be an even integer or an odd integer, which results in the direct Talbot effect or the inverse Talbot effect [16].

To construct the phase condition (1), various techniques are proposed and investigated. The linear chirp effect and the phase shift technique are the two most popular techniques. In our hybrid technique, the adopted chirp is linear and the adopted phase is also linear. In detail, the phase shifts θ_k are proportional to the order of sampling period:

$$\theta_k = (2k-1)\alpha, \quad k = 1, 2, 3, ... \tag{2}$$

where $\alpha = (s/m)\pi$ is a fixed phase value. Equation (2) gives rise to an accumulated quadratic phase condition, which is indistinguishable from the linear chirp. Therefore, Eq. (1) can be regarded as a general phase condition for the hybrid technique, more than a general condition only for the linear chirp.

Then, we propose our hybrid technique (*i.e.*, a combination of the chirp effect and the phase shifts technique) to implement the Talbot effect. For a given chirp coefficient C and a series of phase shifts $\theta_k = (2k-1)\alpha$, when the relationship between them is established as

$$\frac{CP^2}{\Lambda_0^2}\pi + \alpha = \frac{s}{m}\pi \tag{3}$$

the condition in direct analogy to (1) is also obtained for the hybrid technique:

$$\Phi(z = kP) = \left(\frac{CP^2}{\Lambda_0^2}\pi + \alpha\right)k^2 = \frac{s}{m}k^2\pi \tag{4}$$

Equation (4) is the principle base of the hybrid technique. It predicts that the observed phenomena are analogous to the phenomena in [16].

Note that the general phase condition (1) and (4) are the principle base of the hybrid technique. Furthermore, (1) and (4) are general conditions for other techniques, such as the chirp effect, the phase shift technique, and approach reported by Dai *et al*. [4]. We will orderly demonstrate these techniques by the general condition and the hybrid technique in the following subsections.

2.2. Linear chirp effect

With the same chirp effect indicated in the hybrid technique, the phase induced by the linear chirp effect is:

$$\Phi(z) = \frac{\pi C}{\Lambda_0^2}z^2 \tag{5}$$

If the chirp coefficient C is specified as:

$$C = \frac{s}{m}\frac{\Lambda_0^2}{P^2} \tag{6}$$

Equation (1) is derived by substituting (6) into (5) as $z = kP$. In other words, the linear chirp is a special type of the hybrid technique if we specify $\alpha = 0$ in (4). This is the most popular approach investigated for Talbot effect induced by chirp.

In particular, the periodically chirped SFBG (PC-SFBG), proposed in our previous work [6], is an expanded example of the linear chirp. With a phase distribution:

$$\Phi(z) = \sum_{k=0}^{N-1} \frac{s\pi}{mP^2}(z - kMP)^2, \quad 0 \le z - kMP \le MP \tag{7}$$

the phases of the grating samples located at $z = kP$ are:

$$\Phi(z = kP) = 0, \frac{s\pi}{m}, \ldots, \frac{m^2 s\pi}{m}, \frac{s\pi}{m}, \ldots \tag{8}$$

As pointed out in [6], (8) is equivalent to the general phase condition (1) when m is an even integer. Consequently, the fractional or integer Talbot phenomena are also observed in PC-SFBGs.

2.3. Phase shifts technique

For the linear phase shifts technique, a series of phase shifts described in (2) are inserted into the SFBG to derive the condition (9). The phase condition for this technique is as follows:

$$\Phi(z = kP) = \sum \theta_k = \frac{s}{m}k^2\pi \tag{9}$$

Evidently, this linear phase shift technique is a special example of the hybrid technique with $C = 0$ in (4).

Recently, YUSUKE NASU *et al*. have proposed the multiple phase shift (MPS) technique [18], which can be considered as a special branch of the hybrid technique too. If we introduce the θ'_k (according to the MPS) into the SFBG, (1) can be rewritten as

$$\Phi(z = kP) = \sum \theta'_k = \frac{s}{m}k^2\pi \pm 2K\pi \tag{10}$$

where K is a variable-integer associated with the order of sampling period k and detailed MPS parameters.

In addition, DAI *et al*. [4, 12] have proposed a novel approach to design multi--channel filters and multi-channel compensators, which also can be explained in

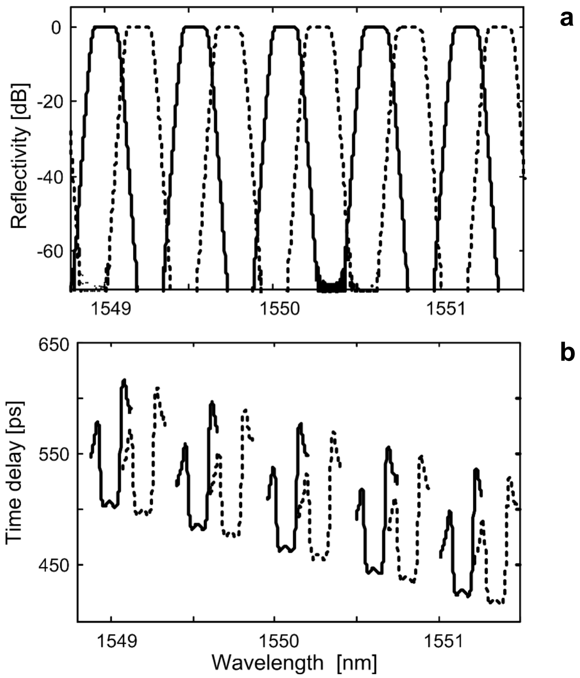

Fig. 1. Comparison of Talbot phenomena between our technique (solid line) and Dai's approach (dotted line): $s = 1$, $m = 3$, $\alpha = 0.25\pi$, $C = \Lambda_0^2/(12P^2)$. Reflection characteristics (**a**), and group delay characteristics (**b**).

the way of the hybrid technique. For Dai's approach, the phase shifts is $\theta_k = 2k\alpha$, not $\theta_k = (2k - 1)\alpha$ as in the hybrid technique. Obviously, after a constant phase shift α is inserted into each sampling period in the hybrid technique, Dai's approach is formed. This process is easier to understand as compared with the complex derivation in [4]. As illustrated in [18], the constant phase shift contributes to the shift of wavelength grid, without deviations in the reflection or dispersion characteristics. Figure 1 shows the corresponding shift in channel grid, including the reflection characteristic and the dispersion characteristic.

3. Hybrid technique for multi-channel dispersion compensators

In Section 2, we illustrate and discuss the hybrid technique which refers to multi-channel filters and tunable multi-channel filters. Meanwhile, the hybrid technique can be used to design multi-channel dispersion compensators. According to [12], we conclude the equivalent chirp coefficient C_0 with a more general expression:

$$k^2\left[\frac{CP^2}{\Lambda_0^2}\pi + \alpha\right] = k^2\left[\frac{C_0P^2}{\Lambda_0^2}\pi + \frac{s}{m}\pi\right] \qquad (11)$$

As long as (11) is offered, the SFBG realized by the hybrid technique has similar dispersion ($D = -1/(cC_0)$ derived in Appendix) to that of the SFBG with the equivalent chirp coefficient C_0 (a much less chirp coefficient). Also, we can see that the chirp effect and the phase shift exert the same contribution on C_0 in (11). Namely, the variation on the chirp coefficient C or the phase shift α determines the dispersion of the SFBG equivalently.

For instance, the parameters for the Talbot phenomena are $C = \Lambda_0^2/(12P^2)$ and $\alpha = 0.25\pi$. To obtain the linear group delay characteristics, we adopt the sinc-like profile [12] instead of the Hanning function. For one SFBG with $\alpha = 0.254\pi$ (C is fixed), its reflection characteristic and dispersion characteristic are shown in Fig. 2**a**; for another SFBG with $C = (1/12 + 0.04)\Lambda_0^2/P^2$ (α is fixed), the corresponding reflection characteristic and dispersion characteristic are shown in Fig. 2**b**. Evidently, the two SFBGs do have the same dispersion value and similar reflection peaks during the channels. A dispersion of –782 ps/nm, a channel spacing of 0.538 nm, and a 3-dB bandwidth of 0.25 nm are observed.

Therefore, different dispersion values can be obtained by adjusting the phase shift in SFBGs to the fixed chirp coefficient. This is analogous to the method that different dispersion compensators can be fabricated through the same phase mask [12].

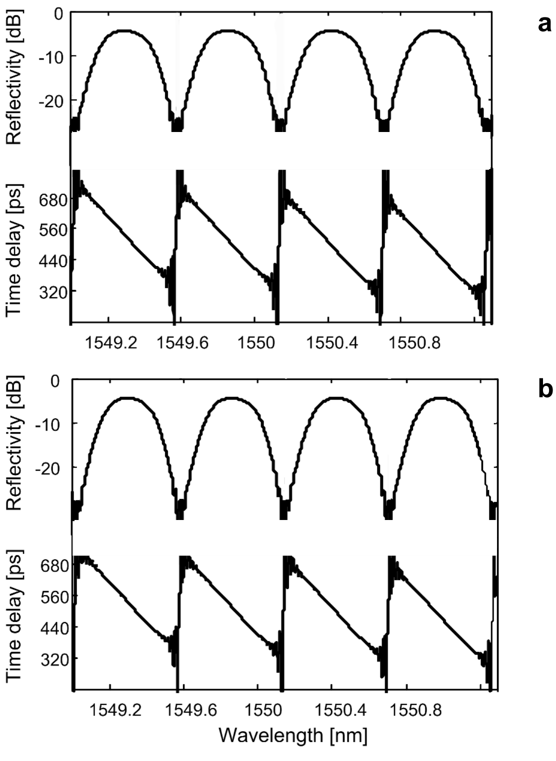

Fig. 2. Reflection and dispersion characteristics of SFBGs with different chirp coefficient or phase shifts: $\alpha = 0.254\pi$, $C = (1/12)\Lambda_0^2/P^2$ (**a**); $\alpha = 0.25\pi$, $C = (1/12 + 0.04)\Lambda_0^2/P^2$ (**b**).

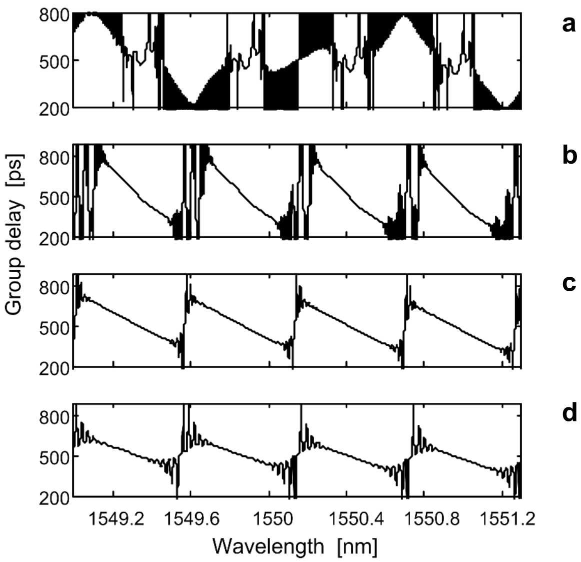

Fig. 3. Dispersion characteristics of SFBGs with different phase shifts: $\alpha = 0.25\pi$ (**a**), $\alpha = 0.252\pi$ (**b**), $\alpha = 0.254\pi$ (**c**), $\alpha = 0.256\pi$ (**d**) when a fixed chirp coefficient $C = \Lambda_0^2/(12P^2)$ is used.

Moreover, tunable dispersion compensators can be achieved by this hybrid technique. For an operating SFBG, variation on the phase shift α results in different dispersion values. Figure 3 illustrates the dispersion characteristics of this novel tunable dispersion compensator. The absolute value of dispersion (the slope of group delay) decreases as the deviation of α increases (*i.e.*, the increase of the equivalent chirp coefficient C_0), excepting that the dispersion is zero as $C_0 = 0$. In detail, we can get the fitting values of dispersion from Fig. 3, as shown in Fig. 4. These dispersion values are close to the theoretical value $D = -1/cC_0$. Similar to the tunable multi-channel filters mentioned in Section 2, if α and α' can be adjusted simultaneously and inde-

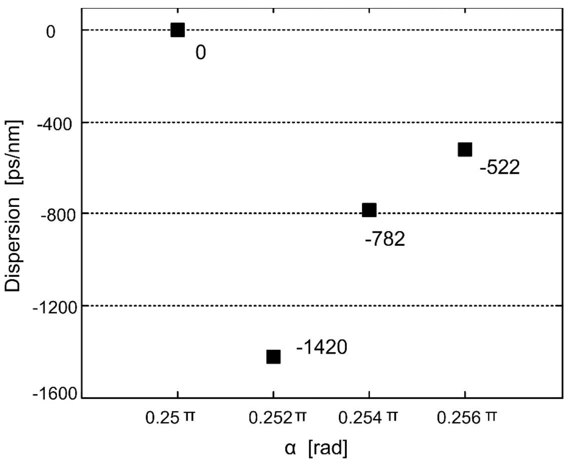

Fig. 4. Fitting values of dispersion corresponding to Fig. 3.

pendently, both the wavelength grid and the dispersion of SFBG can be tuned individually. Consequently, multi-channel tunable compensators (tunable channel grid and tunable dispersion) are realized by a phase mask (the same chirp coefficient).

Additionally, since the dynamic adjustments in α and α' should be controlled accurately, a suitable tuning approach with high accuracy is required for tunable characteristics. In this work, we are mainly devoted to the implementation of the hybrid technique in theory and the tuning approach is beyond the discussion of this paper. As long as such an approach is established, these SFBGs designed through the hybrid technique are excellent choices for optical communication systems.

4. Conclusions

In this work, we have proposed a hybrid technique to observe the Talbot phenomena in SFBGs. The principle base of this hybrid technique is a general phase condition realized by the linear chirp and the phase shift. With the use of the hybrid technique, multi-channel dispersion compensators are designed. Furthermore, the hybrid technique is characterized by several outstanding features. Firstly, it is able to act as a general technique for other similar techniques, such as the linear chirp and multiple phase shifts. Secondly, because of the equivalence between the chirp coefficient and the phase shifts in the general phase condition, different dispersions are realized by different arrangements between the chirp coefficient and the phase shift. Finally, tunable characteristics on the dispersion are introduced into these devices by dynamically tuning the phase shifts α and α'.

Appendix

In a chirped grating, the group delay τ_g results from the twice optical path length from the input of the grating to the reflection point:

$$\tau_g = \frac{2n}{c}\left(\frac{L}{2} + z\right), \qquad -\frac{L}{2} \le z \le \frac{L}{2} \tag{A1}$$

where c is the velocity of light in vacuum, L is the length of grating. In particular, for the linear chirp $\Lambda(z) = \Lambda_0 - C_0 z$, there is a relationship between the reflected wavelength and the reflection point z:

$$z = -\frac{\Lambda - \Lambda_0}{C_0} = -\frac{\lambda - \lambda_0}{2nC_0} \tag{A2}$$

where $\lambda = 2n\Lambda$ and $\lambda_0 = 2n\Lambda_0$ are the reflected wavelength and the Bragg wavelength, respectively. With (A1) and (A2), we can get the dispersion D as follows:

$$D = \frac{\mathrm{d}\tau_g}{\mathrm{d}\lambda} = \frac{\mathrm{d}}{\mathrm{d}\lambda}\left[\frac{nLC_0 - (\lambda - \lambda_0)}{cC_0}\right] = -\frac{1}{cC_0} \tag{A3}$$

References

[1] Ibsen M., Durkin M.K., Cole M.J., Laming R.I., *Sinc-sampled fiber Bragg gratings for identical multiple wavelength operation*, IEEE Photonics Technology Letters **10**(6), 1998, pp. 842–844.

[2] Xiang-Fei Chen, Chong-Cheng Fan, Luo Y., Shi-Zhong Xie, Hu S., *Novel flat multichannel filter based on strongly chirped sampled fiber Bragg grating*, IEEE Photonics Technology Letters **12**(11), 2000, pp. 1501–1503.

[3] Chinhua Wang, Azaña J., Chen L.R., *Efficient technique for increasing the channel density in multiwavelength sampled fiber Bragg grating filters*, IEEE Photonics Technology Letters **16**(8), 2004, pp. 1867–1869.

[4] Yitang Dai, Xiangfei Chen, Ximing Xu, Chongcheng Fan, Shizhong Xie, *High channel-count comb filter based on chirped sampled fiber Bragg grating and phase shift*, IEEE Photonics Technology Letters **17**(5), 2005, pp. 1040–1042.

[5] Xi-Hua Zou, Wei Pan, Luo B., Wei-Li Zhang, Meng-Yao Wang, *Accurate analytical expression for reflection-peak wavelengths of sampled Bragg grating*, IEEE Photonics Technology Letters **18**(3), 2006, pp. 529–531.

[6] Xi-Hua Zou, Wei Pan, Luo B., Zhang-Miao Qin, Meng-Yao Wang, Wei-Li Zhang, *Periodically chirped sampled fiber Bragg gratings for multichannel comb filter*, IEEE Photonics Technology Letters **18**(12), 2006, pp. 1371–1373.

[7] Qiang Wu, Chu P.L., Hau Ping Chan, *General design approach to multichannel fiber Bragg grating*, Journal of Lightwave Technology **24**(3), 2006, pp. 1571–1580.

[8] Ouellette F., Krug P.A., Stephens T., Dhosi G., Eggleton B., *Broadband and WDM dispersion compensation using chirped sampled fibre Bragg gratings*, Electronics Letters **31**(11), 1995, pp. 899–901.

[9] Loh W.H., Zhou F.Q., Pan J.J., *Sampled fiber grating based-dispersion slope compensator*, IEEE Photonics Technology Letters **11**(10), 1999, pp. 1280–1282.

[10] Hojoon Lee, Agrawal G.P., *Purely phase-sampled fiber Bragg gratings for broad-band dispersion and dispersion slope compensation*, IEEE Photonics Technology Letters **15**(8), 2003, pp. 1091–1093.

[11] Hongpu Li, Yunlong Sheng, Yao Li, Rothenberg J.E., *Phased-only sampled fiber Bragg gratings for high-channel-count chromatic dispersion compensation*, Journal of Lightwave Technology **21**(9), 2003, pp. 2074–2083.

[12] Dai Y., Chen X., Sun J., Xie S., *Wideband multichannel dispersion compensation based on a strongly chirped sampled Bragg grating and phase shifts*, Optics Letters **31**(3), 2006, pp. 311–313.

[13] Hojoon Lee, Agrawal G.P., *Add-drop multiplexers and interleavers with broad-band chromatic dispersion compensation based on purely phase-sampled fiber gratings*, IEEE Photonics Technology Letters **16**(2), 2004, pp. 635–637.

[14] Kumar M.S., Bekal A., *Performance evaluation of SSFBG based optical CDMA systems employing golden sequences*, Optical Fiber Technology **11**(1), 2005, pp. 56–68.

[15] Shu X., Chisholm K., Felmeri I., Sugden K., Gillooly A., Zhang L., Bennion I., *Highly sensitive transverse load sensing with reversible sampled fiber Bragg gratings*, Applied Physics Letters **83**(15), 2003, pp. 3003–3005.

[16] Azaña J., Wang C., Chen L.R., *Spectral self-imaging phenomena in sampled Bragg gratings*, Journal of the Optical Society of America B **22**(9), 2005, pp. 1829–1841.

[17] Chen L.R., Azaña J., *Spectral Talbot phenomena in sampled arbitrarily chirped Bragg gratings*, Optics Communications **250**(4–6), 2005, pp. 302–308.

[18] Yusuke Nasu, Shinji Yamashita, *Densification of sampled fiber Bragg gratings using multiple phase shift (MPS) technique*, Journal of Lightwave Technology **23**(4), 2005, pp.1808–1817.

Received July 15, 2010