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Suppression of the interactions between fibre gratings used as dispersion compensators in dense wavelength-division multiplexing systems*

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Chirped fibre Bragg gratings (CFBGs) are required to be concatenated to compensate the fibre dispersion in the dense wavelength-division multiplexing (DWDM) systems. When the channel spacing is small, the performance of CFBGs is degraded, which restricts the usage of fibre gratings. The origin of the interactions between the gratings is analysed and methods of suppressing the interactions are also proposed.

Keywords: optical communication, dispersion compensation, chirped fibre grating
PACC: 4280F, 4280S, 4281D

1. Introduction

Since the commercial use of erbium-doped fibre amplifiers (EDFAs), the transmission loss has been solved but the dispersion has become a major obstacle to the upgrading of the optical fibre communication systems. Among the different dispersion compensation schemes, two methods are very popular. One is to use the dispersion compensation fibres (DCFs), but DCFs are expensive and their insertion losses typically exceed 5 dB. Sometimes, the EDFA is required to compensate its insertion loss. Besides, because of the small mode diameter of DCF, the nonlinear effects are considerably enhanced. The other is to use a chirped fibre Bragg grating (CFBG). When used for dispersion compensation, CFBGs present important advantages over the other fibre-based solutions, such as low insertion loss, small package size, and significantly reduced nonlinear optical interactions.[1] Grating fabrication technologies have advanced considerably over the past several years and high quality devices have been fabricated.[2] Recent improvements in broadband grating fabrication have led to a number of dense wavelength-division multiplexing (DWDM) demonstrations for 1.5-μm systems.[3] However, many factors can disrupt a grating fabrication system, such as vibrations and air currents. So it is difficult to preserve the quality of a long-grating. Besides, the maintaining of mechanical integrity and the packaging of a long grating are difficult, too.

In contrast, short gratings have several advantages: ease of fabrication, better characteristics than those of a long grating, and ease of tuning the dispersion of each grating as well as the dispersion slope. But one of shortcomings of the concatenated short gratings is the interactions between gratings at different channels.[4] The effects of adjacent non-chirped gratings have been reported in Ref.[5], but few papers are found that discuss CFBGs.

2. Experiment

When short gratings are used in DWDM systems, the gratings must be concatenated. However, there are some effects degenerating the grating performance when they are concatenated. The first thing that should be mentioned is the loss of grating radiation mode. Since the wavelength of a radiation mode of grating is shorter than the wavelength of the main reflection peak, the grating with a longer wavelength is always located after that with a shorter wavelength. Here we use three gratings with central wavelengths 1547.5 nm, 1549.1 nm and 1550.7 nm respectively, and the wavelength spacing is 1.6 nm. The structures are

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shown in Fig.1(a) and the reflection spectra are shown in Fig.1 (b). The length of the fibre used to connect the gratings is about 40 cm.

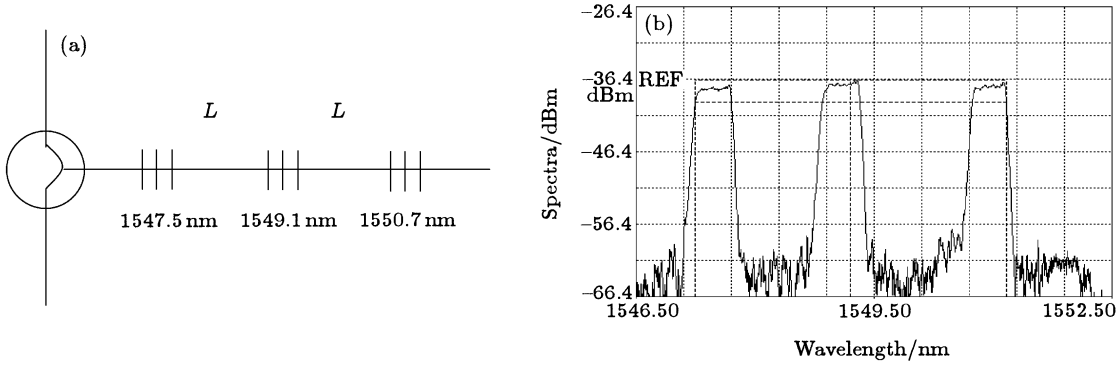


Fig.1. (a) The concatenated gratings as dispersion compensators. (b) The reflection spectra of the gratings.

The group delay of the middle grating is measured using the standard modulation phase-shift method with a step-size of 0.001 nm by chromatic delay analyser CD400 from EG&G. The modulation frequency of the instrument is fixed at 70 MHz. The group delay of the gratings after they are connected is compared with that of the original grating in Fig.2. The group delay is degraded obviously after the grating is concatenated. Some high frequency ripples are added to the grating group delay. They are generated by interactions between gratings at different wavelengths.

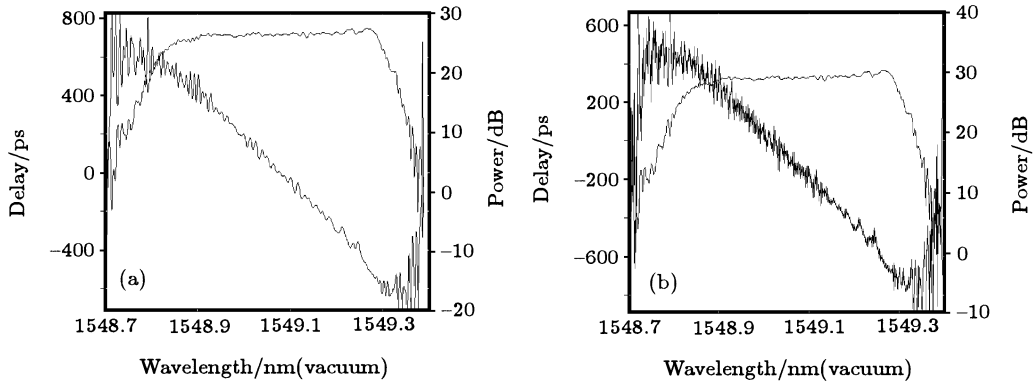


Fig.2. (a) The original group delay. (b) The group delay of the concatenated gratings.

3. Theoretical analysis

The interference with the out-of-band reflections of gratings at different wavelengths is the main reason to deteriorate the characteristics of gratings. The reflection includes the sideband reflection and the small reflection from the ends of the gratings at other channels.

The basic group delay ripple (GDR) is generated from the interference between the main band reflection and the small broadband end reflection of the grating.[6,7] Because the end reflection of the grating is of broadband, it will affect the gratings at other wavelengths. The band diagram of CFBGs is shown in Fig.3. Poladian formulated the band diagram in 1993 to calculate the group delay of gratings,[8] which was developed in Refs.[9] and [10] to analyse the GDR generated by random errors. The solid lines represent the main reflection band and the dotted lines represent the low small broadband reflection from the end of the grating. The reflection from the two ends is r_{f}, and the reflection from the local band gap is r_{gap}.

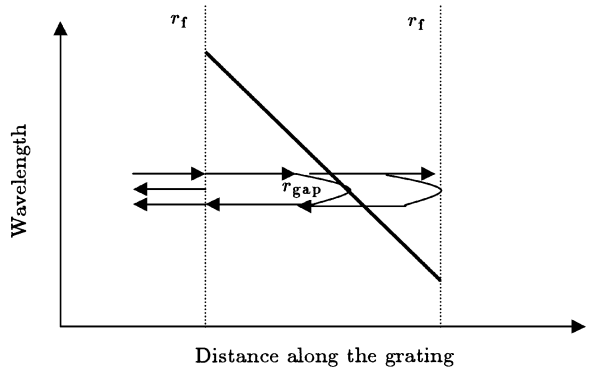


Fig.3. The reflection diagram of the CFBG.

The out-of-band reflections of the different gratings on the other gratings can be seen as an interferometric noise. The Fabry–Perot interferometer is formed between the gratings. The characteristics of the interferometer are determined by the field reflection coefficient A (the outward band reflection from the prior grating), B (the reflection of the main band from the grating) and C (the outward band reflection from the prior grating). τ is the delay time due to round-trip path between gratings. The model developed in Ref. [10] can be used here to describe the reflected field of the concatenated chirped fibre gratings shown in Fig.1 (a) as follows:

$$\begin{aligned} E_{\mathrm{r}}(k,t) =& \mathrm{e}^{\mathrm{i}\varphi}(AE_0(t-\tau) + BE_0(t) \\ &+ (-AB^2 + C(1-B^2))E_0(t+\tau) \\ &+ O(A^2, B^2, AB)...), \end{aligned} \tag{1}$$

in which φ is the ideal phase response and $\tau = 2nL/c$ is the optical propagation delay time due to the optical path length L between the gratings, with n being the refractive index of the fibre. If the source is partially coherent, the complex coherence coefficient can then be determined by

$$R(t,\tau) = \frac{\langle E(t+\tau)E^*(t)\rangle}{I}. \tag{2}$$

When the source has a Lorentzian line shape, the complex coherence coefficient is

$$R(\tau) = \mathrm{e}^{-\pi\Delta\nu|\tau|}\mathrm{e}^{-\mathrm{i}2\pi\nu_0\tau}, \tag{3}$$

According to the relationships $\mathrm{Re}(R(\tau))$=$\mathrm{Re}(R(-\tau))$, and $\mathrm{Im}(R(\tau)$=–$\mathrm{Im}(R(-\tau))$; using the approximation that A, $C \ll 1$, the intensity of the output is obtained as follows:

$$I = E_r^* E_r \approx (B^2 + 2B(A+C)(1-B^2)\mathrm{Re}(R(\tau)))E_0^2, \tag{4}$$

and the phase can be calculated by

$$\begin{aligned} \alpha =& \tan^{-1}\frac{\mathrm{Im}(E_r)}{\mathrm{Re}(E_r)} \\ \approx& \varphi - (1+B^2)\frac{A}{B}\mathrm{Im}(R(\tau)) \\ &- (1-B^2)\frac{C}{B}\mathrm{Im}(R(\tau)), \end{aligned} \tag{5}$$

where φ is the original phase of the grating.

The additional GDR induced by the interactions between gratings at other wavelengths may be calculated as the departure of $c^{-1}(\partial\alpha/\partial k)$ from the original group delay $c^{-1}(\partial\varphi/\partial k)$ as follows:[10]

$$\Delta\tau = \left(-(1+B^2)\frac{A}{B} + (1-B^2)\frac{C}{B}\right)\frac{\partial(\mathrm{Im}(R(\tau)))}{\partial k}, \tag{6}$$

where $\tau = 2nL/c$. From the expressions (3) and (6) we obtain

$$\Delta\tau = M\left(-(1+B^2)\frac{A}{B} + (1-B^2)\frac{C}{B}\right)\cos(2knL), \tag{7}$$

where $M = \dfrac{2nL}{c}\mathrm{e}^{-2\pi\Delta\nu|nL|/c}$.

According to the expression (7), the out-of-band reflections A and C and the distance between the gratings L can affect GDR due to the generation of the interference. The magnitude of GDR is a function of the reflectivity of the three gratings. The GDR will increase with the increase of the out-of-band reflectivity. A will affect the grating more than C, in fact, the effect of the rear grating could be ignored if the local reflection is very strong, i.e. $(1+B^2) \gg (1-B^2)$.

The distance between the gratings at different channels affects the grating GDR in a more complex way. The frequency of the additional ripples is determined by L. The minimum GDR period of a single grating is determined by the length of grating.[10] Because the distance between gratings is large compared with the size of the gratings, the frequency of the ripples generated by other gratings is higher. We can see that the high frequency components cover the whole range of the grating in Fig.2(b). The amplitude of the GDR is also affected by L. We can obtain the value of M versus the distance L by numerical computation. M is proportional to the additional GDR. The results computed at different modulation frequencies are shown in Fig.4.

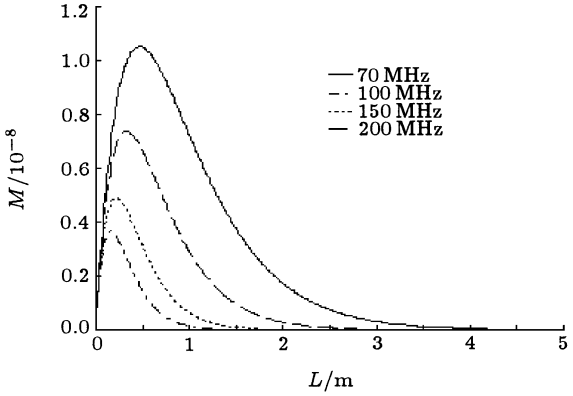


Fig.4. The value of M vs the distance between gratings L at different modulation frequencies.

We can see that each GDR increases first with the increase of the distance L and reaches a maximum and then decreases as the light loses its coherence gradually as the distance increases. The wider the modulation frequency band, the smaller the GDR and the shorter the length through which the GDR reaches its maximum. The dependence of the measured GDR on the modulation frequency is explained in Ref.[11]. The bandwidth of our source is 70 MHz, and the GDR achieves its peak value when the distance is about 0.5 m. After that, the GDR decreases. When the distance is larger than 3 m, the interference can be ignored.

4. Suppression of the interactions between the gratings at different wavelengths

Two methods can be used to suppress the interactions between the gratings at different channels according to the above analysis. One method is to reduce the out-of-band reflections of the gratings. The other is to extend the distance between gratings to suppress the interaction between the gratings at different wavelengths.

When the grating is apodized, the refractive modulation amplitude of the whole grating is kept unchanged, but the reflection from the grating end is reduced,[5] thus the interference turns weaker.[6] However, there are still some periodic sidebands beside the main reflection peak as shown in Fig.5(a). The sideband can be produced by the long-period index modulation.[9] Stitching errors generate periodic phase errors in gratings, which cause periodic sideband named as 'ghost grating'.[12] We use the phase mask fabricated by multiple-overwriting electron-beam lithography method,[13] and the sidebands beside the main reflection peak of the grating are suppressed obviously as shown in the Fig.5(b). The side-mode suppression ratio (SMSR) of the grating increases from 25 dBm to more than 30 dBm. However, the out-of-band reflection cannot be eliminated at all. The interactions between gratings still exist. According to Fig.4, when the distance is larger than 3 m, the interference can be ignored. We expect that the interferometric noise could degenerate to non-interferometric noise by extending the distance between gratings. Figure 6 shows the experimental results in which when the distance between the gratings is as long as 3 m, comparing with Fig.3, we can see that the other gratings at different wavelengths will not change their characteristics any more.

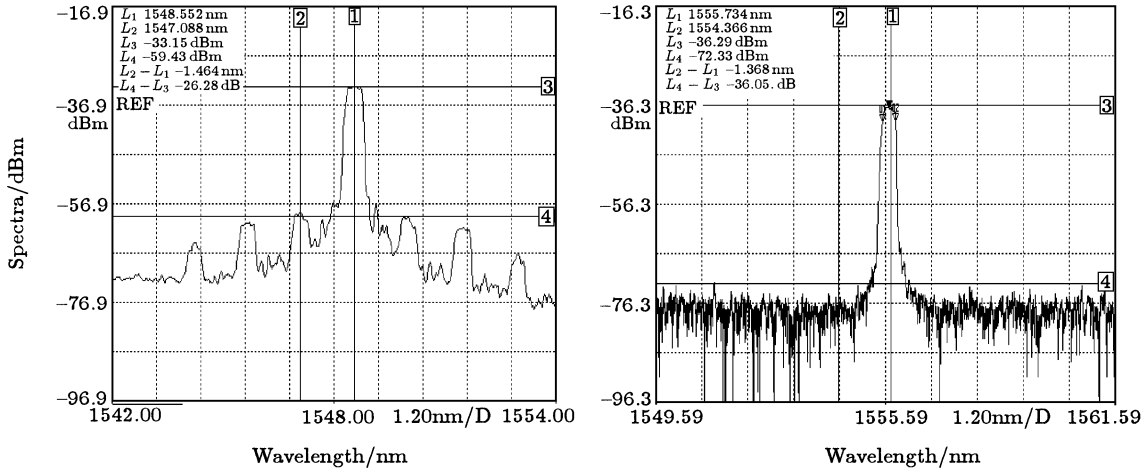


Fig.5. (a) Using an ordinary phase mask. (b) Using a phase mask fabricated by multiple-overwriting electron-beam lithography.

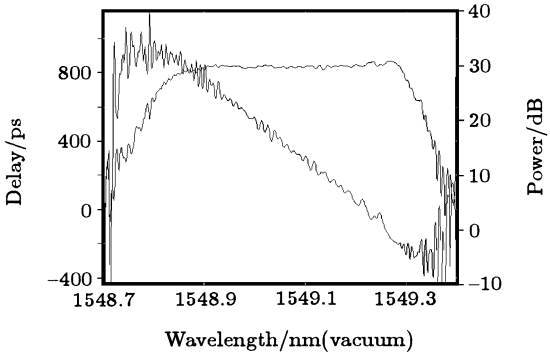


Fig.6. The group delay of the concatenated grating with the distance between gratings extended.

Not only the measured GDR amplitude decreases, but also its system effects are weakened. As we know that the phase ripple ($\phi_j = |\Delta\tau_j|\, P_j$) of dispersion compensation (DC) device provides a more intuitive way of evaluating the system performance of the DC device than the GDR data,[14] to the first order of approximation, the worst eye-closure is proportional to the amplitude of the phase ripple. We know that $P_j = c/(2nL)$ is the period of the GDR, so the induced phase ripple is

$$\begin{aligned}\phi_j = |\Delta\tau_j|\, P_j =& M\left(-(1+B^2)\frac{A}{B} + (1-B^2)\frac{C}{B}\right) \times c/(2nL) \\ =& \left(-(1+B^2)\frac{A}{B} + (1-B^2)\frac{C}{B}\right) \mathrm{e}^{-2\pi\Delta\nu|nL|/c}. \end{aligned} \tag{8}$$

We can see that the phase ripple decreases exponentially with the increase of the distance L, which means that the system influence induced by the interactions between gratings at different wavelengths is greatly suppressed when the distance L is extended.

5. Conclusions

The interactions between the chirped fibre gratings at different wavelengths in a DWDM system are analysed in detail. We find that the interactions between gratings are determined by the out-of-band reflection, the coherence of the light source and the difference in wavelength between the gratings. Phase mask fabricated by using the multiple-overwriting electron-beam lithography and apodization are used here to suppress the out-of-band reflection. Another method is to extend the distance between the gratings. According to the experimental results, the interactions between the chirped fibre gratings at different wavelengths in the DWDM system can be suppressed efficiently.

References

[1] Pei L, Jian S S, Ni T G, Jian W and Li T J 2003 *Acta Phys. Sin.* **52** 615 (in Chinese)
[2] Xu X H, Lü C G and Cui Y P 2003 *Chin. Phys.* **12** 1011
[3] Brennan J OFC2003, FC1
[4] Ning T G, Zheng K, Dong X W, Pei L, Liu Y, Tan Z W and Jian S S 2004 *Microwave Opt. Technol. Lett.* **42** 100
[5] Eggleton B J, Lenz G, Litchinitser N, Patterson D B and Slusher R E 1997 *IEEE Photon. Technol. Lett.* **9** 1403
[6] Kashyap R 1999 *Fiber Bragg Gratings* (New York: Academic) 324
[7] Tan Z W, Liu Y, Ning T G and Jian S S 2004 *Chin. Opt. Lett.* **1** 18
[8] Poladian L 1993 *Phys. Rev.* E **48** 4758
[9] Sumetsky M, Eggleton B J, Martijn de Sterke C 2002 *Opt. Express* **10** 332
[10] Matthews M R, Porque J, Hoyle C D, Vos M J and Smith T L 2004 *Opt. Express* **12** 189
[11] Tapoio N, Maria U and Hanne L 2001 *IEEE Photon. Technol. Lett.* **13** 1334
[12] Broderick N G R and de Sterke C M 1997 *Phys. Rev.* E **55** 3634
[13] Tetsuro K, Tetsuro I and Masataka N 2000 *IEEE Photon. Technol. Lett.* **12** 816
[14] Litchinitser N, Li Y, Sumetsky M and Westbrook P OFC2003 TuD2