The generation of group delay ripple of chirped fiber gratings

Zhongwei Tan (谭中伟), Yan Liu (刘 艳), Tigang Ning (宁提纲), and Shuisheng Jian (简水生)

Institute of Lightwave Technology, Northern Jiaotong University, Beijing 100044

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The analysis of the group delay ripple (GDR) generated by chirped fiber gratings is developed based on the Fabry-Perot (F-P) resonator. It shows clearly how the GDR is generated and why the periods of GDR varies along the chirped fiber gratings. It could also explain why apodization could suppress the GDR and how apodization affects the chirp of the grating. The theory could be used to devise the apodization of fiber gratings.

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Dispersion-compensating chirped fiber gratings provide a compact low-loss means of compensating fiber dispersion[1]. They are potential candidates for per-channel tunable dispersion compensation devices[2]. Group delay ripple (GDR) is the principal reason restraining the practical implementation of chirped fiber Bragg gratings and many papers indicate how the GDR impairs the systems performance[1,3−5].

The basic GDR was generated due to the interference between the light reflected from the grating and the small broadband reflection from the ends of the grating. It could be seen as the instinct GDR of the chirped fiber grating. It acts even in the process of the theory computation. The perturbations during the fabrication process could also induce GDR. They could be described as the random spatial variations[6]. The random spatial variations could affect the characteristics of the group delay. The random spatial variations' effect was based on the instinct GDR. It is necessary to analyze the interference between the light reflected from the grating and the small broadband reflection from the ends of the grating.

For a chirped fiber grating with high reflectivity, because the grating reflected most of the light, the light reflected from the grating rear end was so slight that it could be neglected. The interference between the light reflected from the grating and the small broadband reflection from the front end of the grating was just like a Fabry-Perot (F-P) resonator. It is different from the ordinary F-P resonator in that the reflectivity of the front mirror was much less than the rear mirror and the resonator length was linearly changed with the wavelength. For a F-P resonator shown in Fig. 1(a), the reflectivities of the two mirrors were r_1 and r_2, the transmissions i_1 and i_2. The length of the resonator was L, and the input light was E_1. The output was

$$E_r = \frac{r_1 - r_2 \mathrm{e}^{2ikL} + 2r_1 r_2 \mathrm{e}^{2ikL}}{1 - r_1 r_2 \mathrm{e}^{2ikL}}. \tag{1}$$

If we denote $\theta = \text{phase}(E_r)$, then at a local frequency ω_0, we may expand in a Taylor series about ω_0. Since the first derivative $\mathrm{d}\theta/\mathrm{d}\tilde{\omega}$ is directly proportional to the frequency $\tilde{\omega}$, this quantity can be identified as a group delay. Thus, the delay time for light reflected off of a grating is[7]

$$\tau_r = \frac{\mathrm{d}\theta}{\mathrm{d}\omega} = -\frac{\lambda^2}{2\pi c}\frac{\mathrm{d}\theta}{\mathrm{d}\lambda}. \tag{2}$$

Figure 1(b) shows the group delay of the light reflected from the F-P resonator. In this case, we suppose the length of the resonator is 100 mm, and $r_1 = 0.05$, $r_2 = 0.5$, the vertical axis represents the group delay, the horizontal axis represents the wavelength of the light. The difference of the maximum and the minimum can be seen as the ripple of the F-P resonator. Thus we can get the relationship between r_1, r_2 and the ripple, as shown in Fig. 2.

A simple explanation of the properties of the instinct GDR is shown in Fig. 3, which is a band diagram[2,8] of the chirped fiber Bragg grating (CFBG). The solid line represents the main reflection band and the dotted line represents the small broadband reflection from the end of the grating.

Because the light was reflected mainly from the main reflection band, the interference between the lights reflected from the grating and the small broadband reflection from the front end of the grating is much larger

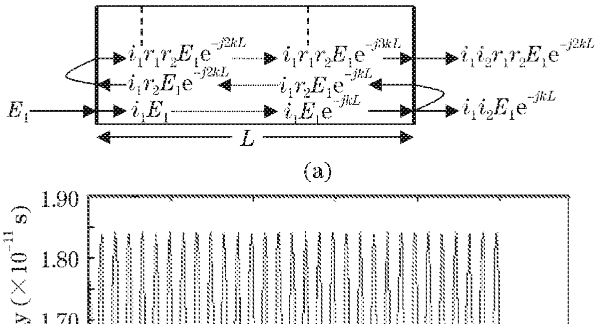

Fig. 1. (a) F-P resonator; (b) the group delay of the reflected light.

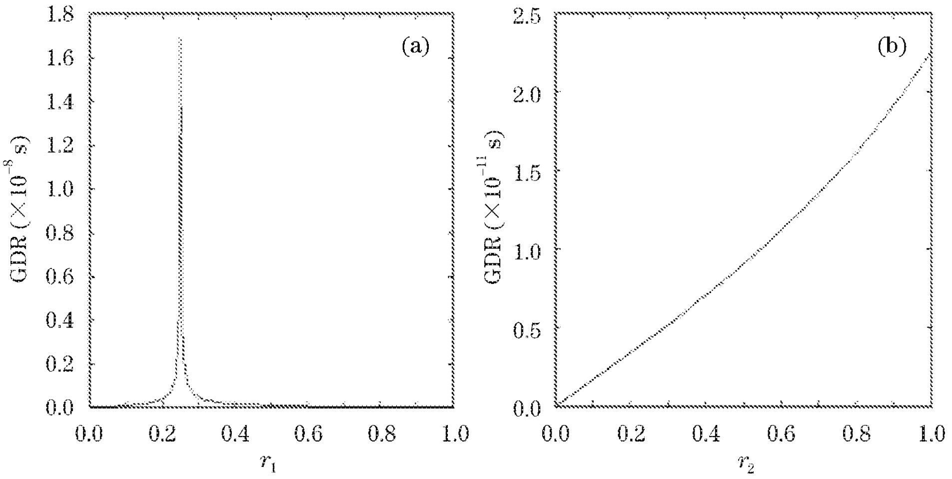

Fig. 2. The ripple of the F-P resonator. (a) $r_2 = 0.5$; (b) $r_1 = 0.5$.

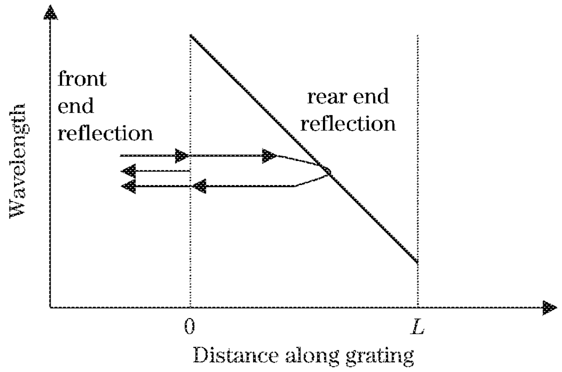

Fig. 3. The reflection picture of the CFBG.

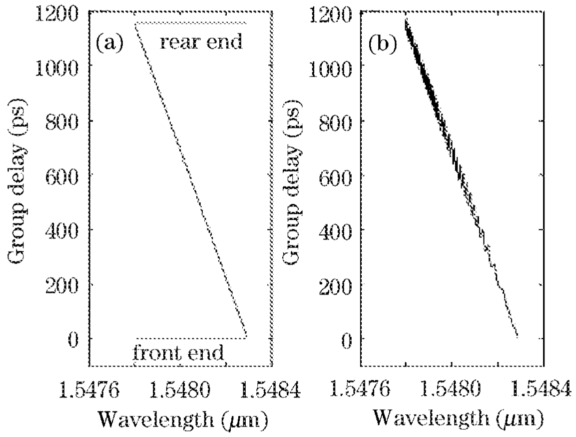

Fig. 4. (a) The group delay of the main reflection band and the front and rear end; (b) the result of the interference with the front end.

than that from the rear end. So when the reflectivity is high, the interference with the rear end could almost be neglected. It is well known that the period of the F-P resonator is proportional to $1/L$. As the length of the grating increases, the bandwidth increases, but the period of the resonator decreases. When the bandwidth of the CFBG surpasses the period of the resonator, the ripple will appear. The reflected light and

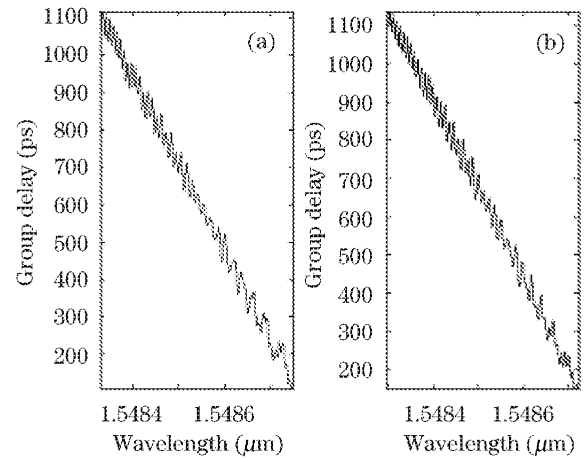

Fig. 5. (a) The group delay calculated by the coupled mode equation; (b) the group delay of the interference between the light reflected from the main reflectivity band and the front and rear ends of the grating.

the group delay can be calculated by Eqs. (1) and (2), and the result was shown in Fig. 4. Because the wavelength decreases along the grating and the period of the F-P resonator gets small, the high-frequency ripple is mainly located near the short wavelength. The period of the GDR increases gradually along the grating when the wavelength gets longer.

We have discussed the high reflectivity grating. However, when the reflectivity is low, there is still quite a lot of light transmitting through the main reflection band, so the interference between the light reflected from the grating and the small broadband reflection from the rear end of the grating cannot be neglected. Figure 5(a) shows the group delay of the grating calculated by the coupled mode equation. We can see the distribution of the period of the GDR is not as simple as that in Fig. 1. Figure 5(b) shows the group delay of the interference between the light reflected from the grating and the small broadband reflection from the front and the rear ends of the grating.

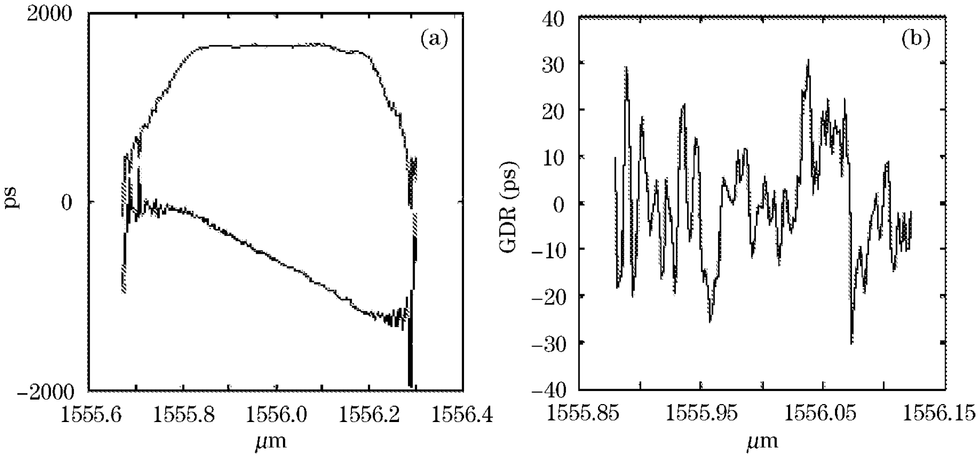

Fig. 6. (a) The reflectivity and group delay of the grating; (b) the GDR of the grating.

We could see that the two results are quite similar. From the figures, it could be concluded that the basic GDR was just the F-P resonator ripple induced by the interference of the light reflected from the main reflectivity band and the front and rear ends of the grating. The high frequency components not only located near the short wavelength, but also near the long wavelength. The only difference is that it is stronger in the short wavelength, because the light reflected from the front end is stronger than the rear end.

So we can see that the GDR was connected with both the reflectivity of the main reflectivity band and the small broadband reflection from the ends. Obviously, the refractive modulation amplitude decides the reflectivity of the small broadband reflection from the ends. However, the effective grating strength is approximately[8]

$$\kappa_0 L_{\text{eff}} = \frac{\pi h_0^2}{|C|\Lambda_0}, \qquad (3)$$

where h_0 is the refractive modulation amplitude, C and Λ_0 are respectively the chirp parameter and the period of the grating. Although the refractive modulation amplitude unchanged, the strength must get small when C gets small. The small broadband reflection from the end unchanged too. According to Fig. 2, the interference will turn strong and the GDR gets large. That's why the gratings with small C have the large GDR when the refractive modulation amplitude of the grating is constant.

The ripple was nearly linear with the reflectivity of the end as shown in Fig. 2, when the reflectivity of the front end or the rear end was much small than the reflectivity of the grating. So reducing the reflectivity of the ends of the grating could decrease the GDR, which is just the purpose of apodization. As we have presented above that because the light reflected from the front end is much larger than that from the rear end, the interference between the grating and the front end contributes more to the GDR. That's the reason why asymmetric apodization has been used. The experimental result was shown in Fig. 6(a). The length of the grating was about 140 mm and $C = 0.34$. The refractive modulation amplitude near the long wavelength of the grating was slightly weaker than the other place. So the interference between the front end and the main reflectivity band was suppressed. The GDR was shown in Fig. 6(b), we could see that high-frequency ripple mainly located near the long wavelength. It was just contrary to the results above, because the GDR was mainly generated by the interference between the front end and the main reflectivity band in this case.

In summary, the GDR of the chirped fiber grating is mainly generated by the interference between the main reflectivity band and the front and rear ends of the grating. The amplitude and the period of the GDR can be changed by changing the end reflectivity using apodization. And the GDR is mainly determined by the interference with the front end, so the asymmetric apodization has to be used to save the bandwidth.

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