System Impact of the Physical Length of Unapodized Chirped Fiber Bragg Gratings on Dispersion Compensation

Mônica L. Rocha, Raman Kashyap, Rui F. Souza, *Member, IEEE*, Alberto Paradisi, Miriam R. X. Barros, and Claudemir Coral

***Abstract*—It is shown, for the first time, how the group-delay ripple, due to a pair of identical unapodized dispersion compensating gratings, can be affected by a small change in the physical length of one of the gratings. It is theoretical and experimentally demonstrated that the ripple can be smoothened by a slight difference in length between the gratings. The pair is arranged in a four-port optical circulator in a cascading configuration. System simulations indicate that the performance of the unapodized gratings may be improved by using such a scheme. This has implications for dispersion compensation in high-speed long-haul transmission systems.**

***Index Terms*—Apodization, chirped fiber Bragg grating, dispersion compensating grating, group-delay ripple.**

I. Introduction

CHIRPED fiber Bragg gratings, or dispersion compensating gratings (DCGs), are known to efficiently operate in high-speed long-haul optical transmission systems [1]. They work as low-loss highly dispersive reflective filters, where a linearly chirped refractive index perturbation is directly written into the core of optical fibers. There are several methods for their fabrication, but the most popular one is the phase mask technique [2]. Although typical DCGs are more adequate for operation in a band narrower than 10 nm, it has been shown that it is possible to fabricate long wide-band chirped gratings [3]. To function properly, a DCG requires an optical circulator, which is a device that typically has an insertion loss as low as 1 dB between ports. Furthermore, regardless of being sensitive to polarization effects [4], DCGs have the advantages of short interaction lengths and low nonlinearities [5]. Based on such suitable aspects, chirped fiber Bragg gratings are a very good option for upgrading installed optical networks for broad-band operation in single-mode standard fiber spans longer than ~60 km.

There are, however, some drawbacks that still challenge the engineers such as the reliability of the grating packaging, necessary for stable operation, since the gratings are very sensitive to thermal and mechanical variations. Another issue that still needs attention is how to control the oscillatory behavior of the dispersion, also known as group-delay ripple (GDR), which is induced by the nature of the reflection on the grating and by the fabrication process imperfections. In linearly chirped fiber gratings, this ripple has a constant average slope, whereas its frequency becomes smaller toward the end from which the reflection is taken [6]. Such an effect results in incomplete recompression of a dispersed pulse so that a short-pulse, with spectral components sampling a major part of the bandwidth of the device, develops a pedestal when it is recompressed [7]. The deleterious consequences of this pedestal are crosstalk and inter-symbol interference with a degradation in the eye opening and, thus, a degradation of the bit-error-rate (BER) performance. It has been shown that the eye-opening penalty is dependent on the ripple frequency, mainly when it becomes closer to the transmission frequency, i.e., at the longer wavelength side of the device band [8]. Furthermore, when combined with polarization mode dispersion (PMD), the ripple causes an additional dispersion penalty [4]. Another important aspect refers to the apodization profile, necessary for the spectral sidelobes' suppression and the ripple smoothening. A symmetrical apodization can reduce the GDR amplitude from $\sim \pm 50$ ps down to $\sim \pm 10$ ps [9]. In this case, the profile of the index modulation along the grating length is given a bell-like functional shape [10], [11]. Apodization techniques still require improvements, but have already allowed fiber Bragg gratings to become commercial devices.

This paper describes a study on how a small change in the physical length of chirped fiber Bragg gratings can influence the spectral behavior of the GDR. The purpose is to evaluate the Bragg wavelength shift as a function of the length reduction, both theoretical and experimentally. Such variations provide an efficient way of reducing the ripple amplitude. The grating effective length L_{eff} in terms of the phase (Φ) of a reflected signal (ω, λ) is a function of the detuning from the Bragg condition and is defined as [12]

$$L_{\text{eff}} \equiv \left(\frac{v_g}{2}\right)\frac{\partial \Phi}{\partial \omega} = -\left(\frac{\lambda^2}{4\pi n_g}\right)\frac{\partial \Phi}{\partial \lambda} \tag{1}$$

where v_g is the signal group velocity and n_g is the group index. The effective length has a relatively simple interpretation: a pulse launched into the grating "sees" a virtual mirror at a distance L_{eff} from the launching point; therefore, the relation

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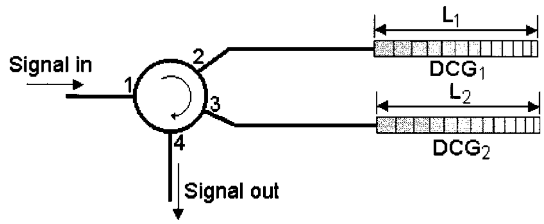

Fig. 1. Configuration of a pair of DCGs.

($2\,L_{\text{eff}}/v_g$) defines the group delay of the reflected pulse. The GDR is strongly dependent on the state of the refractive index modulation at the input end of the grating [6]. It has also been demonstrated that apodization may alter the ripple frequency. Changing the Bragg wavelength at the start of the grating influences the ripple as well. The concept is intuitive: the phase detuning can be changed by the physical length itself, while keeping the chirp rate constant. This principle establishes a simple method for controlling the ripple, with important system implications, as demonstrated below.

II. Numerical and Experimental Results

The broadest bandwidth available from a chirped grating is achieved when it is unapodized [1], where the ripple is more pronounced. Thus, the gratings chosen as the basis of the present study were chirped, but unapodized. Once the relation between the GDR and grating length is optimized, the same principle can be applied to apodized chirped gratings as well. Remember that the delay oscillations of unapodized dispersion compensators have a periodicity that varies along the wavelength band, although their amplitude remains nearly constant. Furthermore, as already stated, studies on the asymmetry in the apodization demonstrated that the input end apodization of the grating has a strong effect on the GDR [6].

The simulations were based on the concatenated operation of two 100-mm-long unapodized step-chirped fiber gratings [2], DCG_1 and DCG_2. Initially identical, with a bandwidth of ~0.7 nm, the gratings were connected to a four-port circulator, as indicated in Fig. 1, and the signal was launched into the longer wavelength end of each grating. Here, the launching side is also referred to as *front end* or *input end* (the other side is named *back end* or *output end* in reflection).

Although the pairing scheme reduces the available bandwidth, due to filtering at the edges of the grating [1], it allows the signal to see a dispersion of twice that of a single grating. Furthermore, the reflectivity of both gratings should be as high as possible in order to compensate the cumulative losses due to the double reflection and the insertion of the second circulator port. Nevertheless, a compromise between the refractive index modulation depth, which defines the grating reflectivity, and the insertion loss of the whole device is needed since the amplitude of the oscillations increases with the reflectivity. The increased reflectivity tends to remove the linear trend in the group delay as well, thus, it is necessary to avoid reaching this condition [13].

Initially, DCG_1 and DCG_2, with spectral reflectivity of 95%, were numerically simulated with $L_1 = L_2 = 100$ mm. By reducing L_2 in steps of 0.1 mm and by keeping L_1 constant, the effect of combining two slightly different grating lengths on the amplitude of the delay oscillations may then be observed. The following three cases were considered, where L_2, C, λ_{B0}, and λ_B stand for the length, the chirp parameter, and the initial and central Bragg wavelength of DCG_2, respectively.

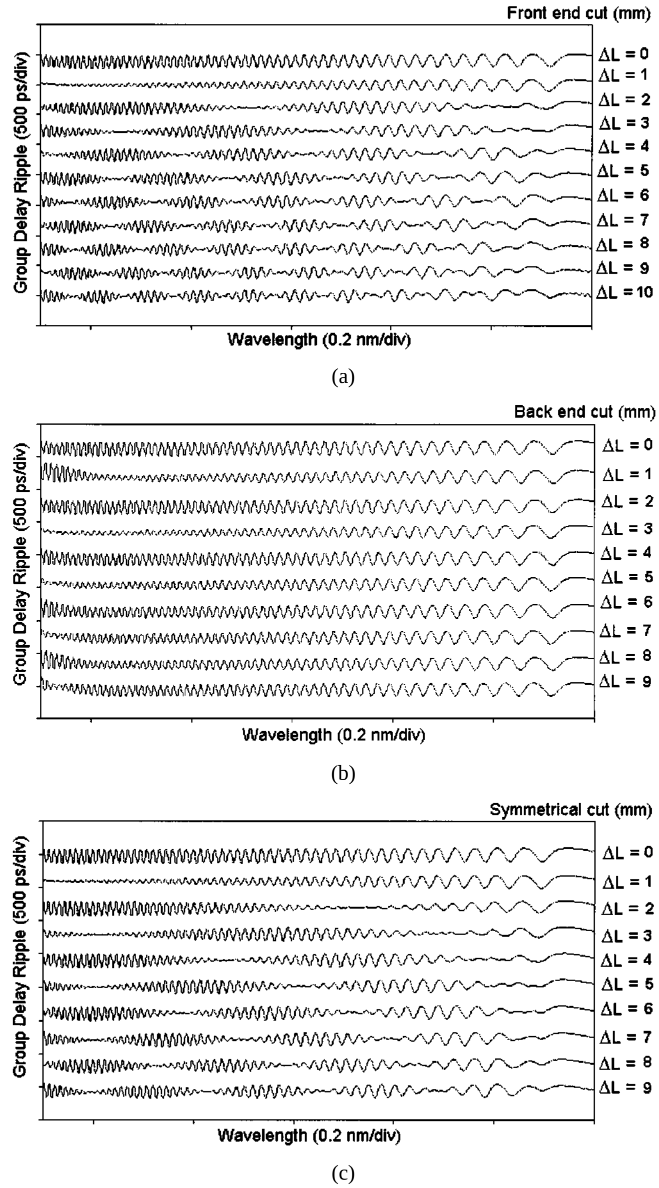

Fig. 2. Numerical results of the relative GDR, after the concatenation of DCG_1 and DCG_2 for different length reductions ΔL at: (a) the front end, (b) the back end, and (c) both ends, where $\Delta L/2$ corresponds to each end cut.

Case 1) Cut the front end. The central Bragg wavelength of DCG_2 shifts as

$$\lambda_B = \lambda_{B0}\left(1 - \frac{CL_2}{2}\right). \tag{2}$$

Case 2) Cut the back end. The central Bragg wavelength of DCG_2 shifts as

$$\lambda_B = \lambda_{B0}\left(1 + \frac{CL_2}{2}\right). \tag{3}$$

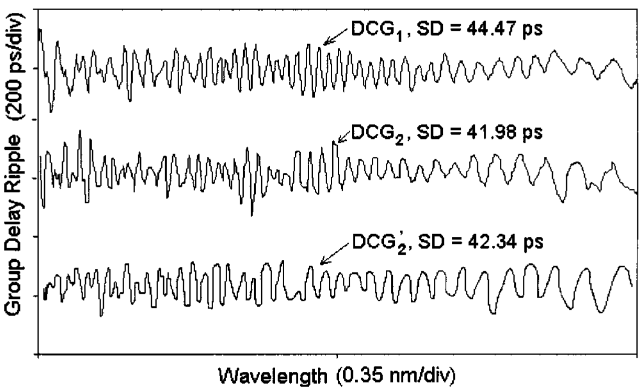

Fig. 3. GDR of DGC_1, which remained unchanged during the experiments, and of DCG_2 and DCG_2', before being cut.

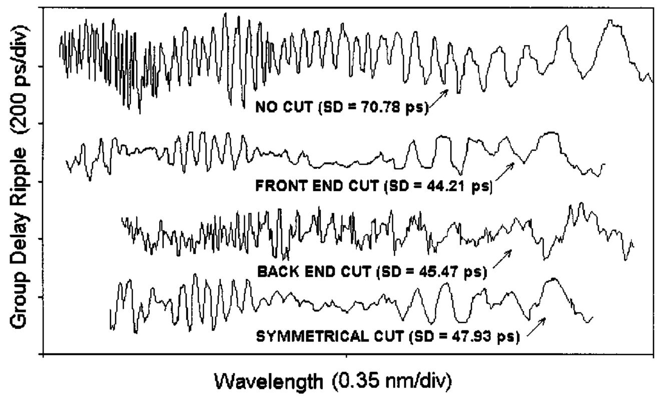

Fig. 4. Group delay after combining DCG_1 and DCG_2 both with no cut (each 100-mm long) and after cuts of $\sim$1 mm at DCG_2 front end, $\sim$1 mm at DCG_2' back end, and finally, of $\sim$1 mm at each end of DCG_2 (symmetrical case).

Case 3) Equally cut both ends (case also referred to as *symmetrical cut*). The central Bragg wavelength of DCG_2 does not shift in this case.

Fig. 2 summarizes the GDRs resultant from the concatenation of DCG_1 and DCG_2 in terms of the standard deviation (SD) from a linear slope of $\sim$2000 ps/nm for some of the length cuttings. Fig. 2(a)–(c) shows the deviation from a linear slope, computed for a reduction of $L_2(\Delta L)$ up to 10 mm in the above Cases 1–3, respectively. It can be seen that, at certain wavelength regions of the gratings bandwidth, some combinations act in a way to reduce the ripple amplitude, and in Cases 1 and 2, form a kind of stationary wave pattern with a variable period.

The same configuration was experimentally implemented with a set of unapodized step-chirped fiber gratings, successively manufactured by the phase-mask technique in the same setup. For this experiment, three DCGs, namely DCG_1, DCG_2, and $\mathrm{DCG}_2{}'$, were necessary due to the excluding nature of the front and back-end cuts. The gratings, with reflectivity of about 95%, were initially 100-mm long, with almost the same wavelength band of $\sim$0.7 nm. The group delay of each grating is presented in Fig. 3 in terms of the SD relative to the linear fitting (slope of $\sim$800 ps/nm). The characterization of the gratings, made with a resolution of 1 pm and 1 ps, is based on the phase-delay technique, described in [14] and [15].

Again, the length of DCG_1 was kept constant, whereas the other length (L_2) was reduced, first by a $\sim$1-mm cut of the front end only, second by a $\sim$1-mm cut of the back end only, and third by a cut of $\sim$1 mm at both ends. It should be noticed that a slight inaccuracy occurred in relation to the exact location of each grating ends, implying that there is a small margin of error on the actual readings of ΔL. For each cut, special care was taken to guarantee the good cleaving quality and to keep both gratings (when in the cascading configuration) at the same room temperature and not subjected to any mechanical stress. The experimental results are presented in Fig. 4 in terms of SD from a linear slope of $\sim$1600 ps/nm. A better method of acquiring the correct lengths is to fabricate successively shorter gratings using the fabrication setup rather than cutting them.

Fig. 5 shows the relative SD of the ripple amplitudes from the ideal case, i.e., a linear delay, as a function of the cut length, obtained from a linear fitting of the delay spectra seen in Fig. 2. It indicates the existence of an optimum value for ΔL (around 1 mm) capable of reducing nearly 40% of the worst SD ($\Delta L = 0$). From Fig. 5, it becomes clear that the front-end cut has a strong effect in order to get a minimum SD, confirming previous predictions related to the input end influence on the GDR [6]. Although there are optimum points that can be achieved if the cut is from the back end, the effect of cutting the output end can cause an oscillation amplitude of the same order of the one caused by the direct combination of two identical gratings. Furthermore, from the numerical results, it can be noticed that the minimum SD is achieved after a symmetrical cut of about $\sim$1.2 mm ($\sim$0.6 mm of length reduction at each end). Fig. 5 also presents the experimental results, in terms of relative SD, showing a good agreement with the numerical predictions.

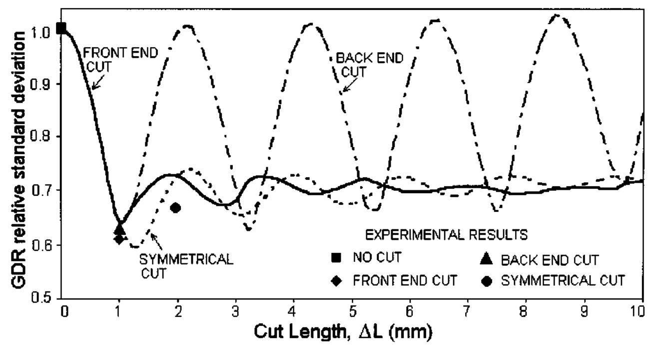

Fig. 5. Numerical and experimental GDR SD, normalized to the "no-cut" situation, for the studied cases of length reduction.

One should note that it is possible to cancel the ripple in some regions of the grating by taking two identical gratings and shifting a small amount of the central wavelength of one of the gratings. Although the wavelength shift technique also represents an improvement of the ripple SD, the ripple will be smoothened in small regions of the spectrum response, where the oscillations are in antiphase, whereas in other regions it will be worsened. The main advantage of the length cutting technique is that it can provide an average smoothening everywhere, although the ripple period is nonuniform. In addition to that, random variations in the grating profile may act to reduce the resultant ripple. For that case, dynamic tuning mechanisms of the DCGs [16] could be used as a way to improve even more the cascading scheme performance.

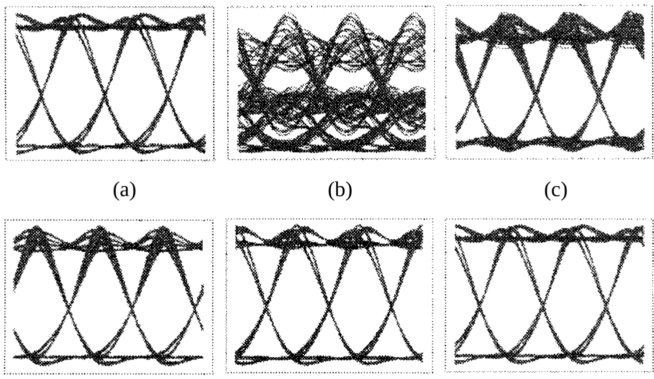

Fig. 6. Eye diagrams for: (a) the input baseline of a 10-Gb/s data stream and (b) after 160 km of a single-mode standard fiber without dispersion compensation. For the same distance, eye diagrams after a pair of unapodized DCGs in the: (c) no-cut case ($\Delta L = 0$), (d) back-end cut ($\Delta L = 1$ mm), (e) front-end cut ($\Delta L = 1$ mm), and (f) symmetrical cut ($\Delta L/2 = 0.6$ mm).

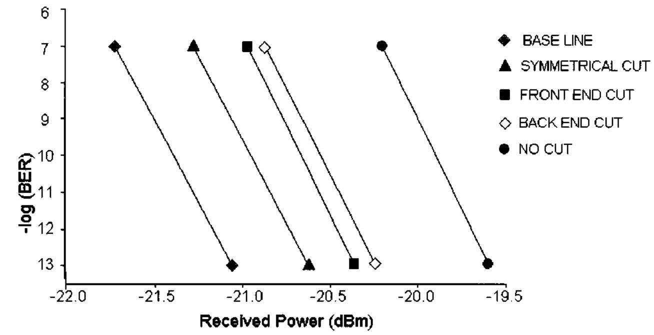

Fig. 7. BER calculations, for the cascading of two unapodized DCGs, indicate error-free transmission. In comparison to the baseline, the power penalties are of 1.5, 0.8, 0.7, and 0.4 dB for the no-cut, back-end cut, front-end cut, and symmetrical-cut cases, respectively.

Finally, to evaluate the system impact that such a GDR reduction can cause, numerical simulations were made for a nonreturn to zero (NRZ) single channel, modulated at 10 Gb/s and transmitted through 160 km of a single-mode standard fiber. In order to isolate the fiber dispersion effects, the losses and nonlinearities were made equal to zero. The following five situations were analyzed:

1) without dispersion compensation and with a pair of unapodized step-chirped fiber gratings;
2) no-cut case $\Delta L = 0$;
3) front-end ($\Delta L = 1$ mm) cuts;
4) back-end ($\Delta L = 1$ mm) cuts;
5) symmetrical cut ($\Delta L_{\mathrm{FRONT}} = \Delta L_{\mathrm{BACK}} = 0.6$ mm).

Fig. 6 shows some results, obtained by using the optical systems numerical simulator LightD.[1] The improvement in the eye opening due to the combination of the pair of gratings slightly different in lengths is confirmed by the BER calculations, as seen in Fig. 7. For the best case, the symmetrical cut, in comparison to the worst one, i.e., the no-cut situation, the power penalty improvement is approximately 1 dB.

III. Discussion

The combination of two identical unapodized DCGs allows one to compensate twice the dispersion that would be due to just one grating for almost the same wavelength band. The proposed cascading can be useful to increase the transmission distance in 10-Gb/s-long distance systems [17]. However, in order to keep the amplitude of the delay ripple low, in that configuration, it is necessary to apply a Bragg wavelength shift ($\Delta\lambda_B$) on one of the gratings. That effect can be achieved by turning the identical (in physical length) compensators into two quasi-identical compensators, where the length of one of the gratings differs from the other by a small amount. Alternatively, rather than cutting the length of one DCG, we observed, in later experiments and simulations, almost equivalent improvements when applying either a temperature gradient or a mechanical stretching on a 100-mm-long DCG.

[1][Online]. Available: http://www.cpqd.com.br/lightd

Furthermore, despite limitations of the length-cutting technique, the experimental results confirm the predictions reasonably well, with a significant improvement on the GDR SD from the linear delay (almost one-half of the deviation due to the worse case, i.e., $\Delta L = 0$). The optimum reduction of the length (ΔL) for a minimum bandwidth reduction was numerical and experimentally estimated to be $\sim$1 mm on the front or back ends. Although the dispersion efficiency can be doubled by the method, further reductions of the lengths, to smooth the delay, are less beneficial because they would penalize the bandwidth of the compensators.

In unapodized DCGs, the delay has a low-frequency ripple at the wavelengths closest to the launch end, while the ripple amplitude remains approximately constant. The ripple is mainly due to the interference between the reflection sidebands, caused by the unapodized edges and the point of reflection within the grating [6]. In fact, the front-end cut technique has been proven to be more effective in reducing the SD of the ripple amplitude, rather than the back-end cut since the contribution to the interference from the sidebands is stronger at the input end (most of the input energy is reflected before it reaches the output end of the gratings). Therefore, it is expected that changes in the input end will have a stronger effect on the GDR.

Currently, the best DCGs feature a delay ripple of $\pm$10 ps and it has not yet been possible to reduce the GDR in gratings much below this value [9]. Therefore, a mode of operation that permits error-free performance of a system using DCGs is useful. The method suggested here can be combined with the existing techniques for reducing the GDR, such as apodization [6], [11], [13], linearity, and a writing process that do not induce birefringence [4], choice of a writing technique: holographic versus e-beam written phase-masks [18], tuning mechanisms [16], and a stable package. This way, the system limitations imposed by the delay ripple could be further reduced. In fact, in later studies of BER versus bandwidth of the cascading configuration, we confirmed the influence of the GDR on BER fluctuations, as also observed in [8]. Our preliminary results indicated that a temperature tuning of one of the gratings may lead to a ripple smoothening along a major part of the grating bandwidth, in comparison with the other methods alone, i.e., length cutting and mechanical tuning. Although requiring further investigations, those studies suggest that, for better system performance, the signal bandwidth must be adjusted within the grating band by some sort of fine-tuning mechanism.

IV. Conclusion

In this paper, it has been demonstrated for the first time, to the authors' knowledge, that an arrangement of two unapodized chirped fiber Bragg gratings can provide a significant reduction of the GDR amplitude. The technique is based on the combination of two gratings, written with the same phase mask, though slightly different in their physical lengths, connected to two consecutive ports of a four-port optical circulator. In that configuration, the signal must be launched into the long wavelength side of both gratings, for standard fiber dispersion compensation.

The gratings studied here were not subjected to any apodization, but it is believed that the method should be useful in reducing the GDR of apodized gratings as well. The suggested configuration can provide an increase in the "dispersion/bandwidth" ratio, and since its predominant losses are only due to the circulator and the incomplete reflection, without introduction of nonlinearities, they can be easily loss compensated by the use of an optical amplifier.

The numerical simulation of a 10-Gb/s data stream, transmitted in a linear regime through 160 km of standard fiber, confirmed the technique efficiency. The improved system performance can be noticed from the estimated power penalty reduction of ∼1 dB. As stated before, the length-cutting technique can be simply implemented during the fabrication of the gratings, which simplifies the whole setup. The impact of such a technique can be significant and it is likely to find applications as passive dispersion compensator operating in high-speed long-haul systems with critical power constrains, where every decibels in sensitivity counts, such as repeaterless systems [17].

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