Group-delay ripple correction in chirped fiber Bragg gratings

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Group-delay ripple (GDR) introduced by systematic and random errors in chirped fiber Bragg grating fabrication is the most significant impediment to application of these devices in optical communication systems. We suggest and demonstrate a novel iterative procedure for GDR correction by subsequent UV exposure by use of a simple solution of the inverse problem for the coupled-wave equation. Our method is partly based but does not fully rely on the accuracy of this solution. In the experiment we achieved substantial reduction of the low-frequency group-delay ripple, from ±15 to ±2 ps, which resulted in dramatic improvement of the optical signal-to-noise-ratio system penalty, from 7 to less than 1 dB, for a chirped fiber Bragg grating used as a dispersion compensator in a 40-Gbit/s carrier-suppressed return-to-zero system.

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Essential progress has been achieved in the past few years in implementing chirped fiber Bragg gratings (CFBGs) as dispersion compensators and tunable dispersion compensators.[1,2] One of the most significant impediments to application of fiber-grating-based devices is the group-delay ripple (GDR) that gives rise to substantial degradation in the performance of optical communication systems in which the devices are employed. A GDR originates from random and systematic errors introduced during fiber grating fabrication and is defined as a deviation of the group delay from the target (usually linear) behavior. Several research groups have reported modification of the fiber grating fabrication process to achieve reduced GDR.[1,3–5] More recently Buryak and Stepanov proposed a method for adjusting the grating profile to account for systematic grating imperfections by numerical solution of the inverse problem for the coupled-wave equations.[6] Although these approaches allow for significant reduction of GDR, the previous studies did not deal with random errors introduced in fiber grating fabrication, which in typical fiber grating fabrication systems are larger than or comparable to systematic errors.

In this Letter we demonstrate a novel technique for reducing the GDR in CFBGs by interatively characterizing and subjecting the grating to additional UV corrective postprocessing. Our technique does not rely fully on the accuracy of the solution of the coupled-wave equations; it uses them as iterations only and thus is equally well suited for correction of systematic as well as random deviations in CFBG parameters.

Our approach is illustrated in Fig. 1. After fabrication of a CFBG by the conventional UV grating writing technique, e.g., with a phase mask,[1] the GDR ripple of the grating is as characterized in Fig. 1a. The suggested grating correction is based on the fact that it is only a relatively low frequency GDR that affects the performance of CFBG devices.[2,7] For this reason the correction of CFBGs can be performed in the adiabatic approximation when a compensating dc index variation can be determined by simple rescaling of the low-frequency GDR component, as shown schematically in Figs. 1b and 1c and described further below. In this Letter we consider strong gratings for which the numerical solution of coupled-wave equations becomes unstable and its accuracy is questionable.[8] The corrective index variation is introduced by direct UV exposure to produce the GDR that has the reduced low-frequency component (Fig. 1d). We continue the iterative steps (b → c → d → b) until the desired reduction of the GDR of the grating under consideration is achieved. Also, we obtain an analytical solution of the coupled-wave equations that allows us to apply this correction procedure for high-frequency GDR compensation and is convenient for a local iterative correction.

Although our correction technique is based on an approximate solution of an inverse problem for the coupled-wave equations, to a certain extent the

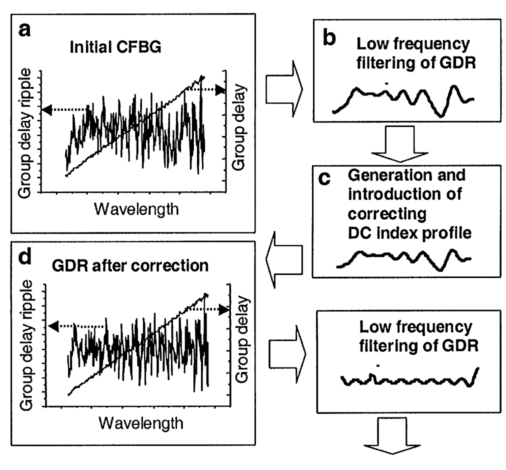

Fig. 1. Iterative CFBG correction: a, group delay and GDR of the initial CFBG; b, the result of low-frequency filtering of the GDR shown in a; c, determination of the corrective dc index and introduction of it into the CFBG by direct UV exposure; d, group delay and GDR after the first correction.

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accuracy of this solution is not critical. In practice, the errors that occur at each cycle of the GDR trimming are characterized and fixed at the subsequent cycles of correction. The important feature of our approach is that the correction may be performed locally in the CFBG reflection band by successive elimination of the individual local peaks in the GDR.

Our correction algorithm is based on a simple solution of the inverse problem for the coupled-wave equations for a CFBG. The GDR is usually relatively small, and therefore the relation between the refractive-index variation and the corresponding GDR is linear. In the simplest adiabatic approximation, which is valid for a slowly varying GDR, the dc index variation $\delta n_{\mathrm{dc}}(x)$ needed for compensation of the GDR, $\delta\tau(\lambda)$, is defined by

$$\delta n_{\mathrm{dc}}(x) = const\,\frac{cC_{\mathrm{gr}}}{\Lambda_{\mathrm{gr}}}\,\delta\tau(2n_{\mathrm{eff}}C_{\mathrm{gr}}x)\,, \qquad (1)$$

where c is the speed of light in vacuum, n_{eff} is the effective index, $C_{\mathrm{gr}} = \mathrm{d}\Lambda_{\mathrm{gr}}/\mathrm{d}x$ is the chirp rate of the grating period, and the constant is of the order of 1. This constant is determined below by experimental calibration. Equation (1) shows that in the adiabatic approximation one determines the dc index needed to compensate for the GDR simply by rescaling the plot of the GDR (see Figs. 1b and 1c). It follows from Eq. (1) that $\delta n_{\mathrm{dc}}(x)$, which compensates for 10 ps in the GDR amplitude, is $\sim 10^{-5}$. Note that if the grating is strong (as in the experiment considered below) the reflection amplitude is close to unity and the reflection amplitude ripple introduced by $\delta n_{\mathrm{dc}}(x)$ is negligible. Interestingly, our simple inverse procedure is valid in the limit of strong gratings, for which layer-peeling algorithms are prone to errors.[8]

If the characteristic frequency of the GDR becomes large enough, Eq. (1) fails. In this case the local spatial peak in the dc index no longer corresponds to a local peak in group delay but generates a complex GDR as a result of the interference of light reflected from this peak and from the Bragg reflection turning point, as illustrated in Figs. 2a and 2b. To permit local correction of the higher-frequency ripple it is necessary to determine a dc index profile that corresponds to a narrow peak in a GDR. Generally one can determine this profile by solving the inverse problem for the coupled-wave equations.[8] For practical purposes and also for general understanding it is desirable to have a simple relation that determines the dc index profile that corresponds to a local GDR peak. We have found that, for the high-frequency ripple, the relation between the spatial noise in the dc index and the GDR introduced by this noise is approximately defined by

$$\delta n_{\mathrm{dc}}(x) = \int_{-\infty}^{\infty} \mathrm{d}\lambda\,\delta\tau(\lambda)\Phi(x,\lambda)\,,$$

$$\Phi(x,\lambda) = const\,\frac{c(C_{\mathrm{gr}})^{1/2}}{2^{3/2}\pi^2\Lambda_{\mathrm{gr}}\Delta n_{\mathrm{ac}}}\int_0^{\infty}\mathrm{d}q \times \cos\left[\left(x - \frac{\lambda}{2n_{\mathrm{eff}}C_{\mathrm{gr}}}\right)q + \frac{{\Lambda_{\mathrm{gr}}}^2}{4\pi C_{\mathrm{gr}}}\,q^2\right], \qquad (2)$$

where $\Phi(x,\lambda)$ is a Fresnel-type integral, Δn_{ac} is the amplitude of ac index modulation, and $const \sim 1$ is a constant similar to the one introduced in Eq. (1). Equation (2) is derived by solution of the coupled-wave equations to first order in the perturbation dc index profile δn_{dc} and by use of the WKB approximation for the unperturbed solutions of these equations.[9] Similarly to the results reported in Ref. 9, for the high-frequency GDR the relation between spectral components of $\delta\tau$ and δn_{dc} is defined by a Fourier transform that is inverted to arrive at Eq. (2). For simplicity, the high-frequency cutoff effect[9] is ignored and, thus, Eq. (2) is valid for characteristic frequencies of the GDR, which do not exceed the cutoff frequencies. According to Eq. (2), for large chirp C_{gr}, function $\Phi(x,\lambda)$ is proportional to a δ function, $\Phi(x,\lambda) \propto \delta[x - (\lambda/2n_{\mathrm{eff}}C_{\mathrm{gr}})]$, and Eq. (2) coincides with Eq. (1) within a constant factor. Thus, within a constant factor of order 1, which is usually unknown and should be defined experimentally by calibration, Eq. (2) is valid for the low-frequency GDR as well. However, this equation may lose its accuracy for intermediate frequencies. Assuming that the GDR has a Gaussian shape, $\delta\tau(\lambda) = \delta\tau_0 \exp[-(\lambda - \lambda_0)^2/{\lambda_w}^2]$, we obtain from Eq. (2)

$$\delta n_{\mathrm{dc}}(x) = const\,\frac{c(C_{\mathrm{gr}})^{1/2}\lambda_w\delta\tau_0}{2\pi^{3/2}\Delta n_{\mathrm{ac}}} \times \int_0^{\infty}\mathrm{d}q\,\exp\left(-\frac{{\lambda_w}^2q^2}{16{n_{\mathrm{eff}}}^2{C_{\mathrm{gr}}}^2}\right) \times \cos\left[\left(x - \frac{\lambda_0}{2n_{\mathrm{eff}}C_{\mathrm{gr}}}\right)q + \frac{{\Lambda_{\mathrm{gr}}}^2q^2}{4\pi C_{\mathrm{gr}}}\right]. \qquad (3)$$

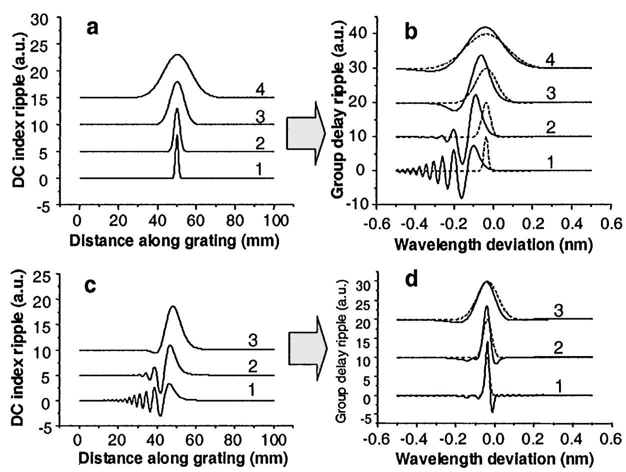

Fig. 2. a, Gaussian peak dc index perturbations and b, corresponding GDR obtained by numerical solution of the coupled-wave equation for peak widths equal to 1, 1 mm; 2, 2 mm; 3, 5 mm; and 4, 10 mm (solid curves) compared with the desired Gaussian GDR peaks obtained from Eq. (1) (dashed curves). c, dc index perturbation profiles corresponding to Gaussian peaks in the GDR computed with Eq. (3). d, GDR found by numerical solution of the coupled-wave equation by use of the dc index perturbation profiles of c (solid curves). The peaks in d are close to the desired Gaussian GDR peaks (dashed curves).

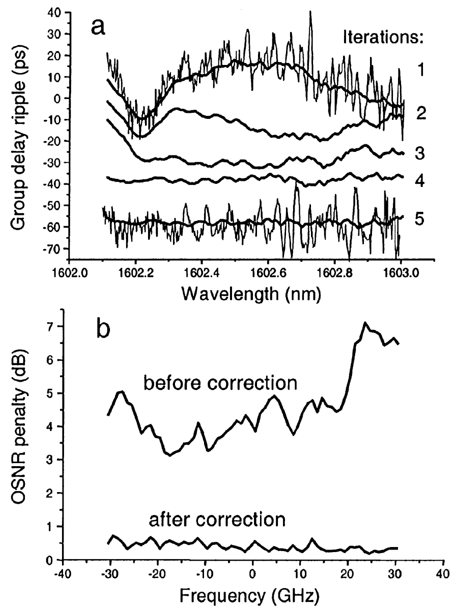

Fig. 3. a, Iterative process of grating correction: GDR (finer curves) and GDR averaged over 0.1 nm (bolder curves) after several correction steps, from 1 (initial step) to 5 (final step). b, Computed OSNR penalties for initial (1) and final corrected (5) gratings.

Figure 2c shows the plot of $\delta n_{\mathrm{dc}}(x)$ determined by Eq. (3) for grating chirp $C_{\mathrm{gr}} = 0.05$ nm/cm (corresponding to 750-ps/nm dispersion); $n_{\mathrm{eff}} = 1.5$; $\Lambda_{\mathrm{gr}} = 0.5\ \mu$m; and peak widths of 0.015, 0.03, and 0.075-nm, which, if the adiabatic approximation of Eq. (1) were correct, would correspond to spatial peaks of widths 1, 2, and 5 mm, respectively. Figure 2d shows the result of accurate numerical solution of the coupled-wave equations for dc index perturbations of Fig. 2c and demonstrates good accuracy for Eq. (3). The small deviation of the peaks from a Gaussian shape can be explained by the presence of intermediate, low-frequency, and cutoff components in the Fourier expansion of the Gaussian peaks considered.

In our experiment we consider a CFBG written in hydrogen-loaded single-mode fiber, which has grating period $\Lambda_{\mathrm{gr}} = 548$ nm, chirp $C_{\mathrm{gr}} = 0.048$ nm/cm, grating length 10 cm, and amplitude of index modulation $\sim 3 \times 10^{-4}$, corresponding to reflection coefficient 99.998%. The dispersion generated by this CFBG is ~780 ps/nm, the bandwidth is ~1.2 nm, and the GDR observed is ±25 ps peak to peak. For these grating parameters Eq. (1) is reasonably accurate if the spatial resolution of index variation is ≥1 cm and the characteristic wavelength of the GDR variation is ≥0.1 nm. Fortunately, this range of wavelength variation corresponds to the low-frequency GDR, which introduces the major contribution to the optical signal-to-noise ratio system (OSNR) penalty for the 40-Gbit/s systems.[2,7]

Figure 3a shows the original GDR of the grating considered (1, finer curve) and the result of its averaging over 0.1 nm (1, bolder curve). The average GDR was corrected in several iterations by successive elimination of individual ripples by use of a 5-mm-wide UV laser beam. The corresponding dc index variation was found from Eq. (1) with the constant determined by calibration of the beam power at each step of GDR trimming. Curves 1–5 of Fig. 3a show the actual results of several steps of correction. They demonstrate reduction of the average GDR from ±15 ps (curve 1) to ±2 ps (curve 5). The OSNR penalty curves of Fig. 3b calculated for the unsmoothed GDR demonstrate the dramatic improvement obtained when the corrected device was used in a 40-Gbit/s carrier-suppressed return-to-zero transmissions system simulation. The OSNR penalty is reduced from 7 to less than 1 dB in the ±30-GHz bandwidth. Note that this comparison also highlights the dominant contribution of the low-frequency GDR, which can be improved through our procedure, relative to the small effect of the high-frequency GDR component.

We have demonstrated an iterative GDR correction procedure by using a simple analytical solution of the inverse problem for the coupled-wave equations and have shown a substantial reduction in the average GDR and a dramatic improvement in the OSNR penalty of a CBFG used as a dispersion compensator for a 40-Gbit/s system. Further development of this technique will open the possibility of refining the grating correction, increasing its accuracy, and, potentially, reducing the GDR to levels that will enable chirped fiber gratings to be part of a practical chromatic dispersion compensation technology.

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