Purely Phase-Sampled Fiber Bragg Gratings for Broad-Band Dispersion and Dispersion Slope Compensation

Hojoon Lee, *Member, IEEE,* and Govind P. Agrawal, *Fellow, IEEE*

***Abstract*—We demonstrated numerically that both the chromatic dispersion and the dispersion slope can be compensated by using purely phase-sampled superstructure fiber Bragg gratings provided both the grating period and the sampling period are chirped linearly along the grating. Adjusting the refractive index modulation and the chirp of sampling function, they can be designed to compensate dispersion of a large number of wavelength-division-multiplexing channels.**

***Index Terms*—Bragg gratings, dispersion compensation, dispersion-slope compensation, optical fiber devices, wavelength-division multiplexing (WDM).**

FIBER BRAGG gratings (FBGs) developed during the 1990s have found application in the fields of both optical communication systems and optical fiber sensors [1]. A superstructure grating is useful for wavelength-division multiplexing (WDM) because it can provide multiple, equally spaced, reflective channels [2]. Several such gratings have been developed using an amplitude sampling approach [3], [4]. However, this approach becomes impractical as the number of reflective channels increases because it requires a large index modulation. One solution is provided by superstructure FBGs in which multiple reflective channels are created through phase sampling (rather than amplitude sampling). The phase sampling technique has been used with success for making tunable semiconductor lasers and can provide a multiple reflective channels with a uniform reflectivity across all channels [5], [6]. It has also been recently used for making FBGs [7]–[9]. The required index modulation scales with the number N of channels as $\sqrt{N}$, rather than N as found in the case of amplitude sampling. Although it was not developed for this purpose, the interleaving technique [10] can also provide purely phase-sampled grating in the continuous limit of constant amplitude. An analytical theory of amplitude-sampled Bragg gratings with chirp in sampling period has also been developed [11].

Use of FBGs for multichannel dispersion and dispersion-slope compensation has attracted considerable attention [12]–[14]. Although a single chirped FBG can be used when number of channels is relatively small [14], a superstructure FBG or superimposed gratings provide a better alternative for high-capacity WDM systems [12], [13]. However, a superimposed grating requires multiple exposures during fabrication. In this letter, we show that a purely phase-sampled superstructure grating can provide both dispersion and dispersion-slope compensation over a broad bandwidth when it is designed appropriately. As an example, we design a 10-cm-long grating that can compensate dispersion of up to 16 WDM channels with 100-GHz spacing.

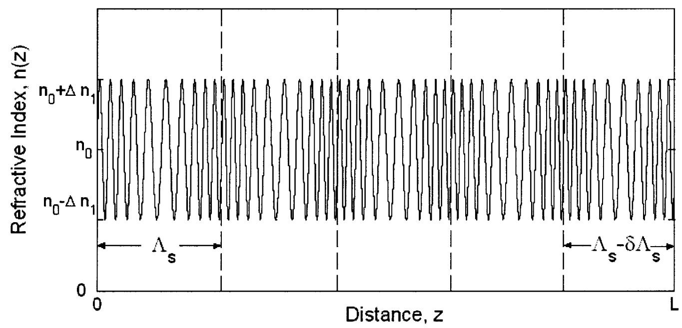

Fig. 1. Schematics of a purely phase-sampled Bragg grating. The sampling period Λ_s is chirped such that it is reduced by $\delta\lambda_s$ at the end of grating.

Fig. 1 shows a phase-sampled grating schematically. Using the Fourier analysis, the effective mode index within the fiber core can be written as

$$\begin{aligned} n(z) &= n_0 + \Delta n_1 \operatorname{Re}\{\exp[i(2\beta_0 z + \phi(z))]\} \\ &= n_0 + \Delta n_1 \operatorname{Re}\left\{\sum_m F_m \exp[2i(\beta_0 + m\beta_s)z]\right\} \end{aligned} \quad (1)$$

where n_0 is the average refractive index, Δn_1 is the constant modulation amplitude, $\beta_0 = \pi/\Lambda_0$, $\beta_s = \pi/\Lambda_s$, Λ_0 is the average grating period, and Λ_s is the period of the sampling function.

The period Λ_s of the phase-sampling function $\phi(z)$ determines the reflectivity spectrum $R_g(\nu)$ that is periodic in frequency with a channel spacing $\Delta\nu = c/(2n_0\Lambda_s)$. The actual shape of $\phi(z)$ governs the peak reflectivity R_p for each channel. Our objective is to design the phase profile such that R_p is nearly the same for all WDM channels. The peak reflectivity can be calculated using the coupled-mode equations and is given by

$$R_p = \sum_m R_m = \sum_m \tanh^2(|\kappa_m| L) \quad (2)$$

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H. Lee is with the Department of Information and Communication Engineering, Hoseo University, Asan 336-795, Republic of Korea (e-mail: hojoon@office.hoseo.ac.kr).

G. P. Agrawal is with the Institute of Optics, University of Rochester, Rochester, NY 14627 USA.

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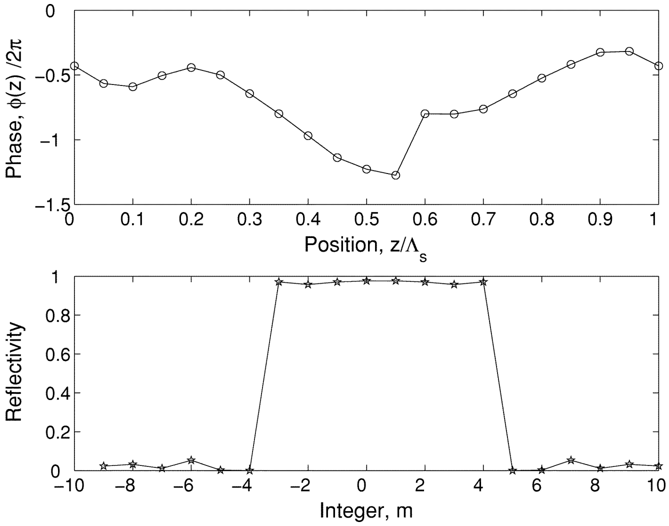

Fig. 2. Optimized phase profile for each sample (top) and resulting reflectivity spectrum (bottom). Stars denote the location of wavelength channels.

where the coupling coefficient κ_m depends linearly on the Fourier coefficient F_m in (1) as $\kappa_m = \pi \Delta n_1 F_m / \lambda_B$, where $\lambda_B = 2n_0\Lambda_0$ is the Bragg wavelength.

To design a grating such that R_p is the same for all WDM channels, we use a multidimensional minimization algorithm available in the Matlab package. We divide the period Λ_s into many small segments to discretize a trial form of $\phi(z)$. We then calculate the partial reflectivities R_m corresponding to each Fourier coefficient in (1) using (2) and compute the mean-square deviation from the ideal value R_0 (a constant) using

$$T = \frac{1}{M}\sum_{m=1}^{M} W_m (R_m - R_0)^2 \tag{3}$$

where W_m is a weighting factor. The algorithm changes $\phi(z)$ iteratively to minimize T. Fig. 2 shows the optimized phase profile obtained using only 20 segments. The peak reflectivity R_p for this phase profile is almost constant for eight WDM channels (see Fig. 2).

We show in Fig. 3 the reflectivity, delay time τ, and dispersion $D = d\tau/d\lambda$ at the WDM channel wavelength calculated for the phase profile shown in Fig. 2 using a transfer-matrix approach. The grating parameters are chosen to be $L = 10$ cm, $\Delta n_1 = 4 \times 10^{-4}$, and $\Lambda_s = 1$ mm. We also chirp the grating period at a rate $\delta\Lambda_0 = 0.08$ nm/cm. We find that D is nearly constant for all reflected channels. Thus, such a chirped grating cannot compensate for the dispersion slope. The transmittivity of all reflected channels is below -70 dB in Fig. 3. Small fluctuations in dispersion values come from numerical differentiation and have their origin in group-delay ripple.

To compensate for the dispersion slope $S = dD/d\lambda$, we introduce a chirp in the sample period Λ_s as well. The required chirp depends on the value of S for the fiber used for WDM transmission and is given by $\delta\Lambda_s = (S/D)\Lambda_s\Delta\lambda_{\mathrm{ch}}$, where $\Delta\lambda_{\mathrm{ch}}$ is the channel spacing [10]. By optimizing the two chirps (in Λ_0 and Λ_s), it is possible to match the relative dispersion slope S/D for most fibers. As an example, Fig. 4 shows the reflectivity, the delay time τ, and dispersion D as a function of

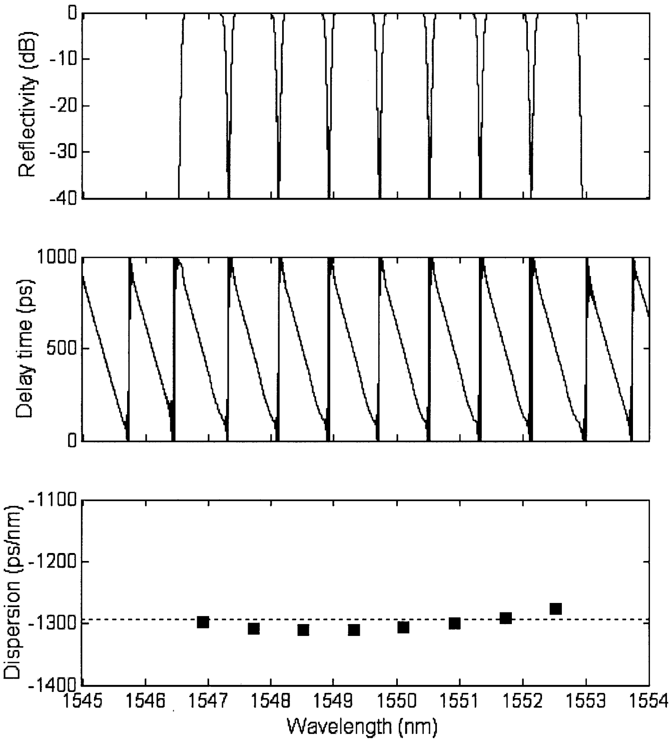

Fig. 3. Reflectivity, group delay, and dispersion of a phase-sampled FBG designed for eight WDM channels. The grating period is chirped but the sampling period is constant.

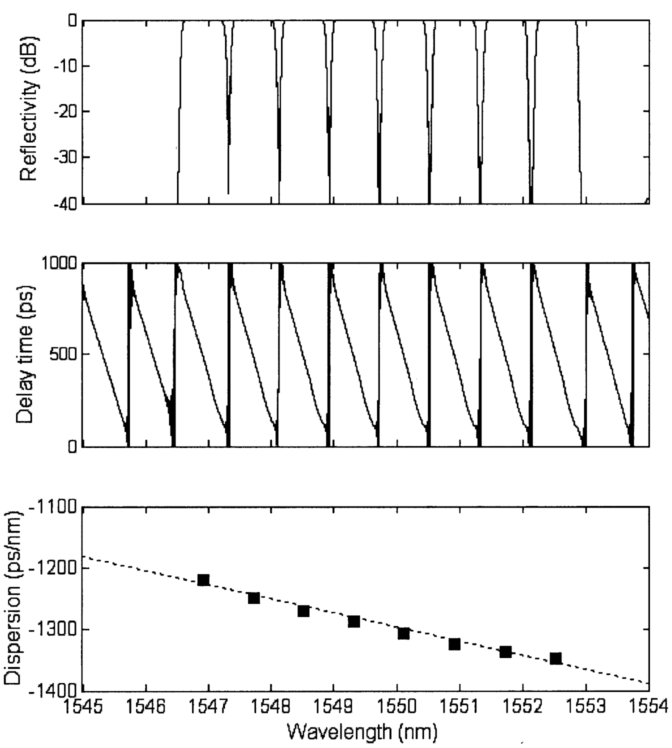

Fig. 4. Same as in Fig. 3, except that the sampling period is chirped such that it reduced by 1.5% over the grating length.

wavelength for the same 10-cm-long grating used for Fig. 3 except that its sampling period was chirped such that $\delta\Lambda_s/\Lambda_s = 1.5\%$ (see Fig. 1). As seen in Fig. 4, D is no longer the same for all channels but changes at a constant rate that matches the

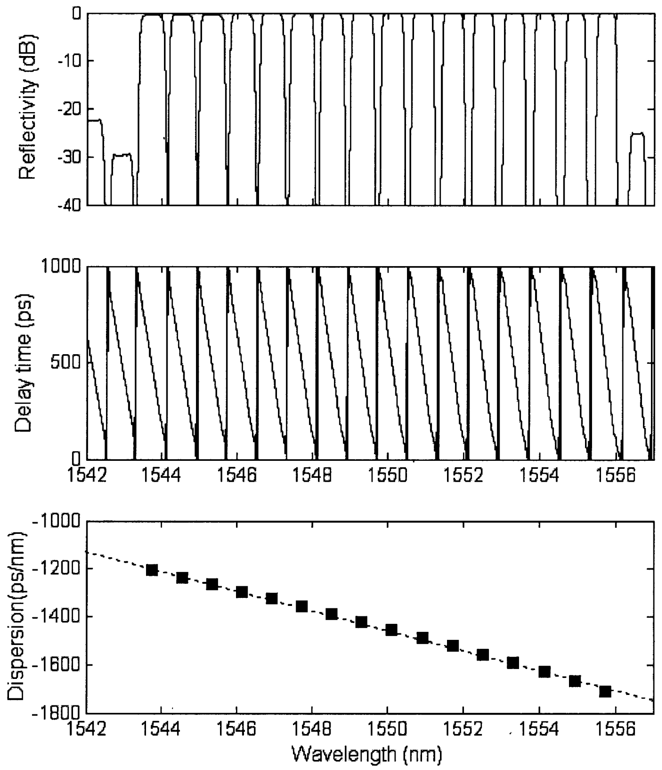

Fig. 5. Reflectivity, group delay, and dispersion of a phase-sampled grating designed for 16 WDM channels. The sampling period is chirped such that it reduced by 2.1% over the grating length.

dispersion slope of the fiber. Such a grating can compensate dispersion of eight WDM channels with 100-GHz spacing over 320 km of Corning LEAF fiber while providing the same reflectivity for all channels. It is possible to increase the number of channels by changing the grating parameters. Fig. 5 shows our attempt to compensate dispersion of 16 channels simultaneously. The superstructure grating has the same parameters used for Fig. 4 except that the chirps for the grating period and the sampling period were changed to $\delta\Lambda_0 = 0.07$ nm/cm and 2.1%, respectively, and the optimum phase profile was obtained using 30 segments. The maximum number of channels whose dispersion can be compensated simultaneously by using the proposed technique is limited in practice, especially for fibers with a large dispersion slope S. However, for a link of length L, values of SL up to 80 ps/nm^2 can be compensated for 16 channels, each operating at a bit rate of 40 Gb/s.

In conclusion, we have demonstrated numerically that both the chromatic dispersion and the dispersion slope can be compensated by using purely phase-sampled superstructure FBGs provided both the grating period and the sampling period are chirped linearly along the grating. Such gratings are easier to fabricate than amplitude-sampled gratings because they require much reduced index modulation. Adjusting the refractive index modulation and the chirp of sampling function, they can be designed to compensate dispersion of a relatively large number of WDM channels.

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