Fiber Bragg Grating Dispersion Compensator by Single-Period Overlap-Step-Scan Exposure

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***Abstract*—We theoretically demonstrate that a high-quality fiber Bragg grating dispersion compensator can be fabricated by a properly designed single-period overlap-step-scan exposure method. A practical design example and a detailed tolerance analysis of this new fabrication method are given.**

***Index Terms*—Discrete layer-peeling method, dispersion compensator, overlap-step-scan method, phase-shifted fiber Bragg gratings (PS-FBGs), step-chirped fiber Bragg gratings (SC-FBGs).**

I. Introduction

FIBER BRAGG gratings (FBGs) have recently become an enabling technology that provides convenient, cost-effective, and reliable solutions to some of the important problems in the high bit-rate wavelength-division multiplexed systems [1]–[4]. For the application of chromatic dispersion compensation, the chirped FBGs (CFBGs) are typically used by incorporating wavelength-dependent reflective differential delay characteristics along the grating [1]. Although the CFBG exhibits many attractive features such as compactness and low insertion loss, its fabrication is not easy due to the required nonuniform period distribution [5], [6]. In practice, it is difficult to fabricate long chirped phase masks with small-period errors and the imperfect fabrication of chirped phase masks will eventually introduce stochastic variations of the group time delay and the reflectivity which will limit the performance of CFBGs [7].

In the present letter, we investigate a new way to design and fabricate high-quality FBG dispersion compensators by utilizing a properly designed single-period overlap-step-scan exposure method. The grating index profile of the ideal dispersion compensating FBG is synthesized first by using the layer-peeling method [8] and then a new overlap-step-scan exposure method is proposed for fabricating the designed FBG. The fabrication method utilizes a single-period phase mask (or a fixed-angle interferometer) for exposing the FBG segment-by-segment with suitable phase shifts between adjacent segments to match the required grating phase profile in the design so that the function of dispersion compensation can be achieved. In this way, we avoid the use of chirped phase masks as well as the difficulties associated with them. During the exposure a Gaussian beam with a suitable beam width is used and the translation length per step is adjusted in such a way that adjacent exposure segments are strongly overlapped so that the abrupt phase changes between adjacent segments can be smoothed out by overlap-averaging. We will also carry out the tolerance analyses for the phase and apodization errors in the grating and the results are compared with those of step-chirped FBGs (SC-FBGs) for completeness.

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II. Design of a Dispersion-Compensating Multiphase-Shifted FBG

In order to design a good dispersion compensating FBG, we apply the discrete layer-peeling method [8] to synthesize the grating index profile with the following targeted reflection spectrum:

$$r(\delta)=\sqrt{R}\exp\left[-\left(\frac{\delta}{\delta_b}\right)^{20}\right]\cdot\exp\left[\frac{-j\beta_2 L_f\left(\frac{c\delta}{n}\right)^2}{2}\right] \quad (1)$$

where $\delta=\beta-\pi/\Lambda$ is the wave-number detuning. In this design example, the reflection bandwidth is set to be $\delta_b=11.3$ cm^{-1}, and the maximum reflectivity is $R=0.99$. The dispersion is described by the product of $\beta_2 L_f=-2040$ ps^2, which is equivalent to the dispersion of a standard single-mode fiber ($D=17$ ps/nm $\cdot$ km) with a length of 94 km. The calculated coupling coefficient profile of the synthesized grating is shown in Fig. 1(a). Just as expected, the phase distribution of the coupling coefficient is quite similar to a parabolic shape. According to the derivation of the coupled-mode equations [8], the coupling coefficient of the fiber grating can be expressed as

$$q(z)=j\frac{\eta\pi\Delta n_{\rm ac}(z)}{\lambda}\exp\left[j\left(\theta(z)-\frac{4\pi\eta}{\lambda}\int_0^2\Delta n_{\rm dc}(z')dz'\right)\right] \quad (2)$$

where $\Delta n_{\rm ac}(z)$ and $\Delta n_{\rm dc}(z)$ are the "ac" (peak-to-mean) and "dc" index change of the grating, respectively, and η is the confinement factor of the fiber. We use the modulus $|q(z)|$ to determine $\Delta n_{\rm ac}(z)$, and assume $\Delta n_{\rm ac}(z)=\Delta n_{\rm dc}(z)$ (i.e., the modulation depth of the grating is equal to one). In this way, the spatial grating phase $\theta(z)$ can be obtained by using (2) and is plotted in Fig. 1(b) for the design example. In the following, we shall approximate this required phase distribution in Fig. 1(b) by a single-period multiphased-shifted FBG so that such an FBG can be used as a dispersion compensator in a way similar to the usual chirped FBGs.

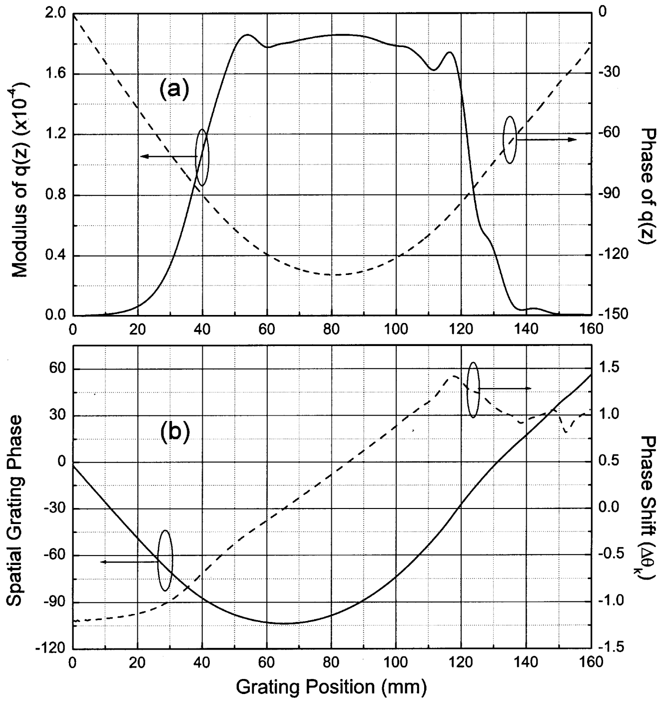

Fig. 1. (a) Coupling coefficient profile and (b) spatial phase distribution of the synthesized grating.

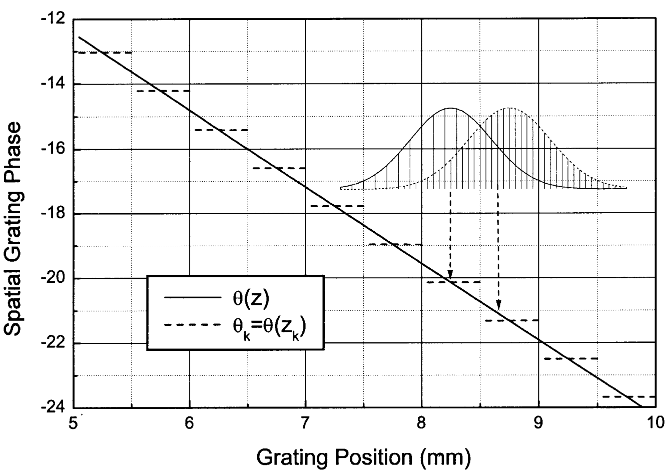

Fig. 2. Discretization and smoothing of the spatial grating phase.

As illustrated in Fig. 2, by properly choosing the values of the N phase shifts inserted in a single-period FBG with equal distance separation $\Delta z(= z_k - z_{k-1})$, the spatial phase distribution of the phase-shifted grating will represent a discretized approximation to the required phase distribution. In comparison to an SC-FBG, the phase approximation of this phase-shifted FBG (PS-FBG) is actually worse. This is the reason why usually a chirped FBG is used as a dispersion compensator and a phase-shifted grating is not. In order to reduce the discrepancy of such an approximation, we propose to employ the overlap-step-scan method to expose the synthesized PS-FBG. As is shown in the inset of Fig. 2, in this fabrication method, a narrow Gaussian ultraviolet (UV) light is used to expose the PS-FBG segment-by-segment with some overlap between the adjacent segments. In this way, the abrupt phase change and the apodization ripple of the multiphase-shifted FBG can be effectively reduced by the smoothing effects and, thus, a better dispersion-compensating FBG can be expected. Of course the exposure magnitude of each segment also needs to be properly designed in order to achieve not only the required phase distribution but also the required apodization profile.

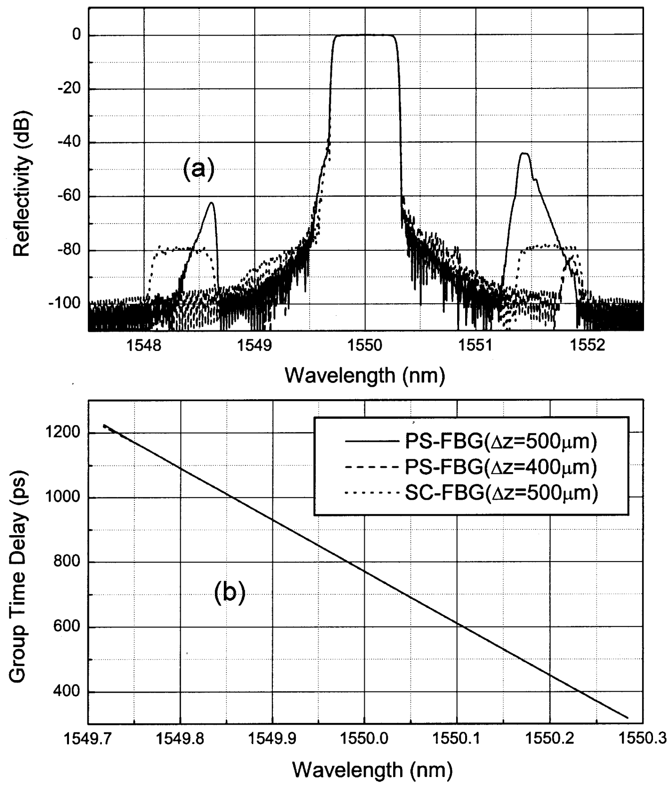

Fig. 3. (a) Reflection spectra and (b) group time delays of SC-FBG and PS-FBGs with two different scan step Δz.

III. Simulation Results and Tolerance Analyses

In order to verify the validity of the above idea, we have designed the single-period PS-FBGs with two different scan-step lengths $\Delta z = 400$, 500 μm and one SC-FBG with the scan-step length $\Delta z = 500$ μm according to the target index profiles in Fig. 1. The same UV exposure beam width $w = 500$ μm is used in all the cases. We calculate the complex reflection spectra of PS-FBG and SC-FBG by using the discretized grating model method [9]. The calculated results are shown in Fig. 3, where the solid and dashed lines describing the calculated results for PS-FBGs with the scan-step length $\Delta z = 400$ and 500 μm, respectively, and the dotted lines describing those of SC-FBG. From the comparison in Fig. 3(b), we note that the PS-FBGs have the linear group time delay with a negative slope. This proves that the PS-FBGs indeed can be used as dispersion compensators as the usual chirped FBGs. However, due to the spatial modulation of the periodic phase shift, there are two small sidebands in the reflection spectra of PS-FBG and SC-FBG, as shown in Fig. 3(a). Moreover, one can see that more overlapping of the adjacent segments helps to enhance the smoothing effects so that the sidebands in the reflection spectra of PS-FBG can be effectively reduced with a smaller scan-step length. This proves

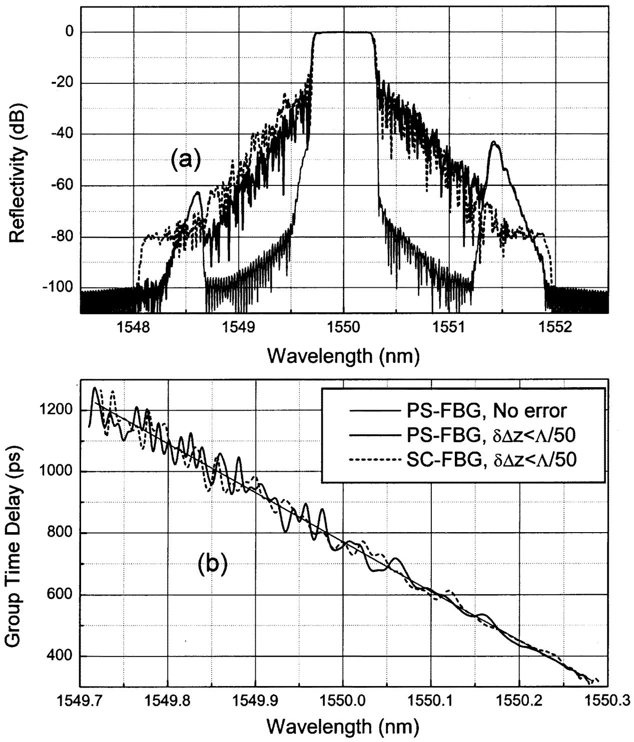

Fig. 4. (a) Reflection spectra and (b) group time delays of PS-FBG and SC-FBG with random position-shift errors.

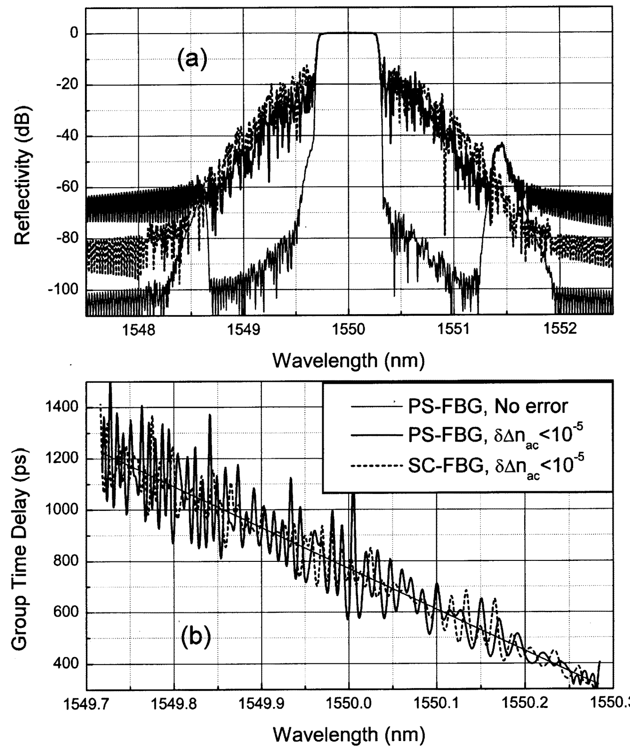

Fig. 5. (a) Reflection spectra and (b) group time delays of PS-FBG and SC-FBG with random index (apodization) errors.

that the abrupt phase change of the PS-FBG can be smoothed by the overlapping exposure. For both cases of PS-FBG and SC-FBG, the magnitudes of the sidebands are below -40 dB, which should not cause any problem in practical applications.

As regarding the overlap-step-scan exposure method, we have evaluated the fabrication tolerances of the position-shifts and the apodization errors for fabricating the PS-FBG and SC-FBG. Random phase errors caused by random position-shift errors and random apodization errors are added to each segment, respectively, and the spectral characteristics of both FBGs are calculated after assuming the variances of the errors. The calculated results are shown in Figs. 4 and 5, in which the variances of the position-shift and the apodization (or index) errors are chosen to be $\Lambda/50$ and 10^{-5}, respectively. One can see that both the position-shift and the apodization errors increase not only the background noise near the stopband, but also the ripple amplitude of the group time delay [7]. According to the results in Figs. 4 and 5, the required accuracies of the translation and exposure time in actual experiments for exposing the designed multiphase-shifted FBG dispersion compensators is similar to the case of SC-FBG fabrication. However, if the period errors in fabricating the SC-FBG are considered, then the present single-period approach will have certain advantages for fabricating dispersion compensating FBGs with high performance.

IV. Conclusion

We have theoretically shown that a high-quality FBG dispersion compensator can be obtained by a properly designed single-period overlap-step-scan exposure method. The required grating phase profile can be introduced during the scan and the proper overlap between adjacent segments is demonstrated to be able to smooth the abrupt phase shifts between grating segments. Although the tolerances of the position translation and apodization errors for fabricating a multiphase-shifted FBG is similar to those for fabricating an SC-FBG, the present single-period design can effectively avoid some of the fabrication difficulties caused by the period errors for the SC-FBGs and, thus, may help to fabricate practical dispersion compensating FBGs with high performance.

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