Characterizing Fiber Bragg Grating Index Profiles to Improve the Writing Process

R. Joseph Espejo, Mikael Svalgaard, and Shellee D. Dyer

Abstract—**We demonstrate an accurate method for identifying both systematic and random errors in a fiber Bragg grating (FBG) writing system and show its application to calibration of the writing process. We first measure the FBG impulse response using low-coherence interferometry, and then we calculate the refractive index profile using layer peeling. This yields the complex longitudinal refractive index profile, which includes both the index modulation amplitude and the effective index as a function of position along the FBG. We demonstrate how this measurement can be applied to the calibration of a scanning-beam dithered phase mask FBG writing system. We demonstrate the ability to identify errors in the writing process that would not likely be found from a measurement of the FBG reflection spectrum alone.**

Index Terms—**Fiber Bragg gratings (FBGs), layer peeling, low coherence interferometry, refractive index profile.**

I. Introduction

A FIBER Bragg grating (FBG) is often analyzed by the examination of the reflected power spectrum. This does little to indicate the origins of errors that can degrade the spectral quality: systematic problems with the writing system such as phase-mask imperfections are difficult to diagnose in this manner. Thus, FBG writing often involves a process of trial and error, ending when the correct spectrum is achieved, but without clear knowledge of the actual index structure.

Better quality control of the writing process can be accomplished by measuring the FBG's index profile, having the potential to greatly improve the quality of the FBGs produced and reduce the number of iterations required to achieve the desired result. Recently, the index profiles of FBGs were assessed by an interferometric technique combined with a layer peeling algorithm (LPA) [1]–[5]. Previous work has often focused on iterative processes to correct writing errors [3]. In this letter, we demonstrate a characterization and calibration procedure of an FBG writing system, and show how it can be used to assess the quality and accuracy of written FBGs and to identify specific systematic errors in the writing process. Once identified, these systematic errors can then be avoided in all future gratings, regardless of the desired FBG profile.

II. Measurement System

The impulse response of the FBG is measured using a fiber-optic Michelson low-coherence interferometer (LCI). We have previously shown that accurate, high-resolution measurements of the dispersive and spectral properties of optical components can be achieved using this measurement system [4]–[6].

We describe the index profile of an FBG by its index modulation amplitude $\Delta n_{\rm ac}$, effective index $\Delta n_{\rm dc}$, and its Bragg period Λ. The quantity $\Delta n_{\rm ac}$ is the magnitude of the FBG, and $\Delta n_{\rm dc}$ and Λ are the phase relevant terms. The complex reflection spectrum is found by calculating the fast Fourier transform (FFT) of the measured interferogram. The LPA is then applied to the calculated complex spectrum to determine the values of $\Delta n_{\rm ac}$ and $\Delta n_{\rm dc}$ of the FBG [7]. The period Λ is found from the peak of the FFT spectrum. The spatial resolution of the calculated FBG index profile is inversely related to the bandwidth of the low-coherence source [7]. The low-coherence illumination is provided by a commercial $C + L$ band superfluorescent source with a 3-dB bandwidth of 85 nm centered at 1565 nm, giving a maximum longitudinal spatial resolution for the FBG of 15 μm inside the fiber.

III. Writing System and Calibration

It has been shown that an effective method for controlling the FBG index profile during writing is by scanning a narrow ultraviolet (UV) beam across a phase mask (PM) while the position of the PM is dithered in a sinusoidal manner by a piezoelectric transducer (PZT) [8]. The dithering amplitude controls the induced index modulation; for example, dithering with an amplitude of one-half the interference pattern period has the effect of completely washing out the fringe visibility. The dithering frequency should be chosen to be high enough so that a significant number of oscillations occur during the UV illumination time. The UV beam $1/e^2$ diameter at the PM was 0.5×0.11 mm with the long axis oriented parallel to the fiber. A typical scanning velocity was 20 μm/s and the dithering frequency was 4 Hz.

Nonuniformity of the PM diffraction efficiency can lead to undesirable variations in the $\Delta n_{\rm dc}$ of the FBG. It is, therefore, vital that the PM is well characterized before it is used to write an FBG. To check our PM for nonuniformities, we wrote 18 gratings in a single fiber under identical conditions across the full 25-mm width of the mask. Sampling of the PM in this manner was chosen rather than writing a single uniform grating, due to the difficulties in measuring long, strong gratings with the LCI-LPA technique [9].

The measured $\Delta n_{\rm ac}$ is shown in Fig. 1. The slight nonuniformity shows a similar trend as seen in direct measurements of the diffraction efficiencies for this mask. Our results show that the achieved index modulation amplitude decreases in a slow manner across the PM, with a total variation of about 8%. After mapping the PM nonuniformity, we can adjust the PM dither

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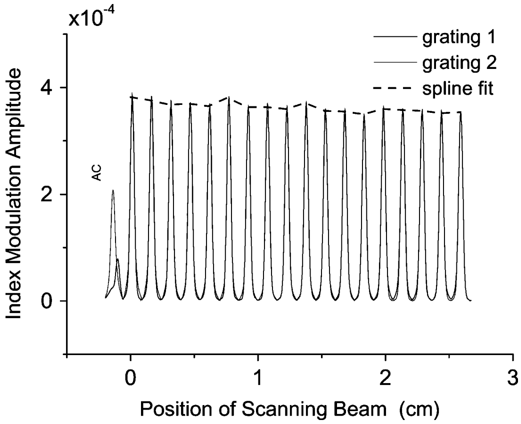

Fig. 1. Grating series for mapping PM nonuniformity. For the peak labeled AC (alignment check), the beam was walked on to the edge of the mask to ensure that the writing began in the same place each time. Two different grating sets were used and the results for each are shown. The two curves are practically indistinguishable.

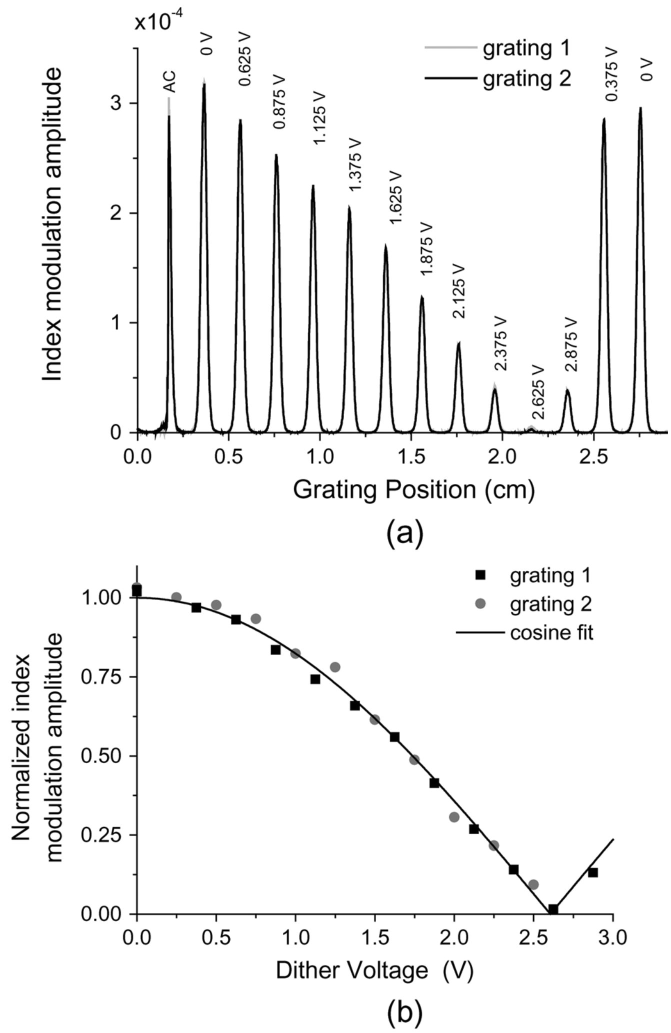

Fig. 2. (a) Measured $\Delta n_{\rm ac}$ of the grating series. Each grating has the same exposure; only the PZT dither amplitude is changed, and each is the width of the writing beam (~0.5 mm). Shown is the average of ten measurements. (b) Index modulation ($\Delta n_{\rm ac}$) versus PM PZT dither voltage. Calibration curve fit is used for determining the appropriate dither voltage needed in order to achieve a desired index modulation when writing an FBG. Two separate grating sets fabricated several weeks apart were used.

voltage or the UV exposure time when writing subsequent gratings with the same PM to compensate for the nonuniformity.

The dither voltage amplitude applied to the PZT affects the $\Delta n_{\rm ac}$ in a cosinusoidal manner, with the period of the cosine determined by the PM period and the PZT's response [8]. These variables necessitate a calibration of the dither voltage applied to the PZT in order to have accurate control over $\Delta n_{\rm ac}$ for a particular writing system.

To obtain this calibration, we wrote a series of gratings with equal exposure times but different dither amplitudes along a single fiber. A position-dependent correction factor was added to compensate for the measured PM nonuniformity. The measured $\Delta n_{\rm ac}$ for each grating is shown in Fig. 2(a). In Fig. 2(b), we show the peak $\Delta n_{\rm ac}$ of each grating as a function of the corrected dither voltage that was applied when that grating was written. The peak $\Delta n_{\rm ac}$ of each grating is normalized to the maximum possible index modulation amplitude, which occurs when no dither is applied. We calculated a least-squares cosinusoidal curve fit to the measured data in Fig. 2(b) using the cosine period as the free parameter. Fig. 2(b) allows us to predict the dither voltage needed to achieve a desired $\Delta n_{\rm ac}$. By varying the dither voltage as the UV writing beam is scanned along the fiber, gratings with a wide variety of index modulation profiles can be written.

IV. Troubleshooting Errors in the Writing Process

Our measurements can be used to identify problems in the grating fabrication process. Once these problems are identified and characterized they can then be compensated and the desired spectrum achieved.

Cosine-apodized FBGs are desirable since their reflection spectra have suppressed sidelobes. We produced a cosine-apodized grating by applying a dither amplitude that decreased linearly from $\Lambda/2$ at the grating edges to zero at the grating center. The measured index modulation amplitude and a cosine curve fit to the data are shown in Fig. 3(a). Although the measured $\Delta n_{\rm ac}$ fits the intended cosine curve reasonably well, several obvious imperfections can be seen. The one that is labeled "mask defect" is $\sim$30 μm long and likely a defect on the PM since it appears in the same location on several other gratings written with this mask. A high resolution measurement as provided by the LCI-LPA technique used here is essential for identifying such defects. The second, narrow grating (labeled "writing error") seen to the right of the main grating is the result of an error that occurred when the writing beam was not shuttered at the appropriate time. Fig. 3(b) shows the $\Delta n_{\rm dc}$ of the FBG. An ideal apodized FBG should have a constant dc component to its index profile. The linear increase of approximately 7.8×10^{-5}/cm in $\Delta n_{\rm dc}$ detected in the measured FBG will cause a chirped broadening of the reflection spectrum. This error in $\Delta n_{\rm dc}$ caused by the nonuniformity of the PM was not considered in the above calibration. However, it is possible to characterize the $\Delta n_{\rm dc}$ with a weak uniform FBG and then

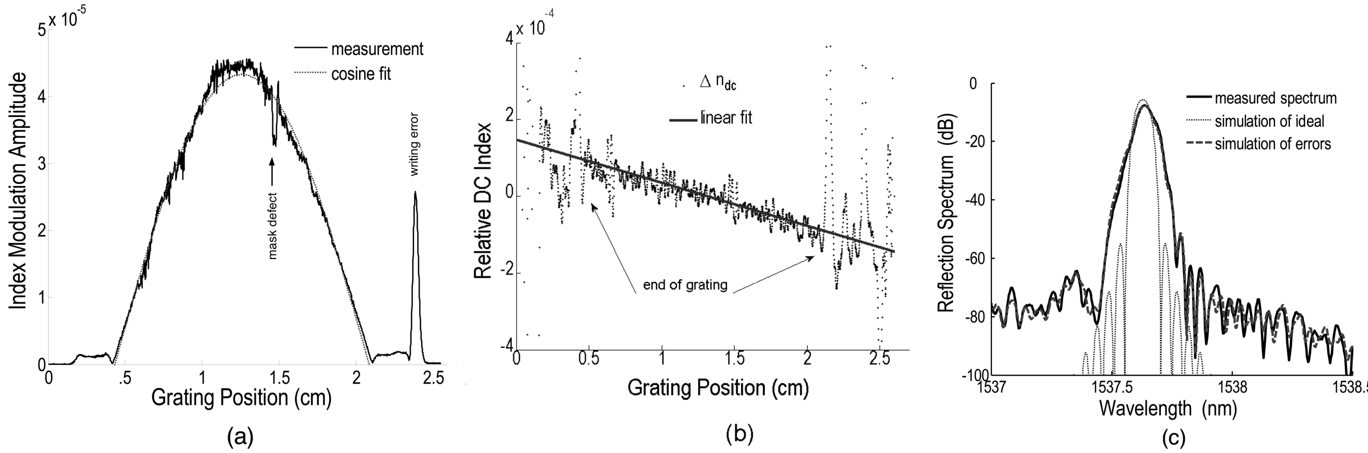

Fig. 3. (a) Measured (Δn_{ac}) of the cosine apodized FBG. Also shown is a cosine curve fit to the measured (Δn_{ac}). (b) Measured Δn_{ac} with linear curve fit. The phase of the coupling coefficient and, therefore, (Δn_{dc}), diverges into noise at the edges of the grating. (c) Measured and simulated reflection spectra of the FBG.

compensate for this error by varying the exposure time and PM dither appropriately.

We simulated the combined effect of these writing errors on the FBG reflection spectrum using the well-known matrix-transfer method to produce a simulated spectrum for a given refractive index profile [7]. The simulated spectrum is shown in Fig. 3(c) along with the reflection spectrum of an ideal cosine-apodized grating and the reflection spectrum measured by LCI. The measured index profile of the FBG provides valuable information as to why the reflection spectrum does not match the ideal case. It is unlikely that these errors could have been identified by spectral analysis alone.

V. Conclusion

We have demonstrated a fast and accurate method for the calibration and analysis of an FBG writing process. Our measurement spatially characterizes the FBG at high resolution. The calibration allows us to write any arbitrary apodization and chirp profile in a single step. Further measurements of grating index profiles are only needed in cases where there is suspected random error. In such cases, we have also shown that we can identify imperfections in the written grating, and we have shown that these imperfections can have a significant impact on the FBG's reflection spectrum.

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