Extracting the structure of highly reflecting fiber Bragg gratings by measuring both the transmission and the reflection spectra

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We demonstrate a novel method that enables one to measure the structure of highly reflecting fiber Bragg gratings. The method is based on measuring both the transmission and reflection spectra of the grating and applying an inverse-scattering algorithm. The use of the transmission spectrum significantly reduces the sensitivity of the reconstruction to measurement noise, and therefore it significantly decreases the measurement duration. We experimentally demonstrate our method for reconstructing the structure of an apodized grating with a reflectivity of 99.91%. © 2007 Optical Society of America

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Fiber Bragg gratings (FBGs) are important elements for several important applications in the fields of optical communication and optical metrology. In spite of the important advantages of FBGs, such as small dimensions, low weight, and low cost, the use of these elements is limited owing to grating imperfections. By developing methods to accurately measure the structure of FBGs, it may become possible to significantly improve performance of these elements.[1]

The structure of a FBG can be extracted by measuring its complex reflection spectrum and using an inverse-scattering (IS) algorithm.[2] The main drawback of this measurement technique is that IS algorithms are highly sensitive to noise when the grating reflectivity is high.[3,4] This sensitivity exists because a large change in the refractive index of the grating corresponds to a small change in the reflectivity inside the bandgap. The sensitivity of the reconstruction to measurement errors can be significantly decreased by combining measurements from both sides of a FBG.[2] However, this method still requires a low-noise measurement that enables reconstructing at least half of the grating length. Side-diffraction techniques were used to directly measure the refractive index profile of highly reflecting FBGs.[5] However, these methods are limited by their spatial resolution and accuracy. Another method that was demonstrated for reconstructing highly reflecting FBGs is based on creating a thermal chirp in the grating to reduce its reflectivity.[6] The main drawbacks of this method are its limited accuracy and its long measurement duration. A different approach for reducing the signal-to-noise ratio (SNR) required for extracting FBGs is based on a mathematical regularization of the measured data.[3,4] However, such methods have been proved to be effective only for specific grating structures.[4]

In this Letter we demonstrate a novel and yet simple method that enables one to reconstruct highly reflecting FBGs from noisy measurements. The method is based on simultaneously measuring both the complex reflection spectrum and the transmission intensity spectrum. The transmission spectrum is used to correct the amplitude of the reflection spectrum in the frequency regime that corresponds to the grating bandgap. Since the reconstruction error in the IS algorithm is determined mainly by the amplitude noise within the bandgap,[3,4] the grating can be accurately reconstructed after correcting the reflection spectrum. Using our method we have demonstrated the reconstruction of a grating with a Gaussian profile and a reflectivity of 99.91%. The method described here gave accurate results even in the case where the SNR was significantly lower than that required for using the method of Ref. 2, in which the grating is reconstructed from both its sides. Our method was successfully tested in numerical simulations for Gaussian gratings with reflectivities up to 99.999%. In these simulations white Gaussian noise, whose standard deviation was similar to that obtained in our experiments, was added to the complex reflection spectrum. The possibility of reconstructing the profile of FBGs from noisy measurements enables one to significantly reduce the minimum measurement duration. This property makes our method very attractive for real-time monitoring of FBGs during their writing process.

When using an IS algorithm, the error in the reflection spectrum for a given wavelength λ is amplified by a factor of $(1-|r(\lambda)|^2)^{-1}$,[3] where $r(\lambda)$ is the complex reflection spectrum. Thus, in the case of highly reflecting gratings, the absolute noise should be extremely small within the grating bandgap, where the reflectivity is close to one. However, the amplitude of the noise in an interferometric measurement, required for obtaining the complex reflection spectrum, becomes maximal for wavelengths within the grating bandgap. In such systems, extremely small changes in environmental conditions induce a large noise in the measurement. To solve the noise problem in the reconstruction, we use the transmission intensity function $|t(\lambda)|^2$ to correct the amplitude of the complex reflection spectrum at the bandgap frequencies by using the conservation of energy relation: $|r(\lambda)|^2+|t(\lambda)|^2=1$. The transmission spectrum is measured directly without using an interferometer, and hence the noise in the measurement is small compared with that in the complex reflection spectrum. Moreover, the dynamic range of the transmission measurement within the grating bandgap is very high. Thus, in contrast to the reflection spectrum, the required accuracy for the transmission spectrum measurement is not high. After correcting the absolute value of the reflection spectrum, we use the integral layer-peeling IS algorithm[7] to reconstruct the grating profile.

Our experimental setup, shown in Fig. 1, is composed of a tunable laser (TLS), an optical spectrum analyzer (OSA), and a Michelson interferometer. In the first spectral measurement (OSA 1) the interference spectrum between the reflection from the grating and a signal reflected from a mirror is measured and used to extract the complex reflection spectrum.[2] In the second spectral measurement (OSA 2) the intensity of the grating transmission spectrum is obtained. The grating that was extracted had a Gaussian profile, a reflectivity of 99.91%, and a central wavelength of 1549.8 nm.

The interference spectrum at the input of the spectrum analyzer (OSA 1, Fig. 1) is given by

$$I(\lambda) = |r(\lambda) + e^{-ik(\lambda)\cdot dL} e^{i\phi(\lambda)}|^2 \cdot S(\lambda), \quad (1)$$

where dL is the optical path difference between two interferometer arms, $\phi(\lambda)$ is a phase noise caused by changes in the optical path dL, $S(\lambda)$ is proportional to the source power spectrum, and k is the wavelength number. The effect of the source power spectrum can be measured and eliminated from Eq. (1). The error in the measured interference spectrum due to the phase noise $\phi(\lambda)$ is equal to $r(\lambda)\exp(ikdL)\{1-\exp[\phi(\lambda)]\}$+c.c., and thus it is proportional to the reflection spectrum. The complex reflectivity of the grating can be calculated by extracting the grating impulse response from the Fourier transform of the interference spectrum.[8] One of the sources of the phase noise $\phi(\lambda)$ is mechanical vibrations.[9] In most of our experiments, the phase noise had a small amplitude with a time periodicity of 1–5 s. Since our OSA measures the optical spectrum by moving a diffraction grating, the periodic noise in time was converted into a periodic noise in the function $\phi(\lambda)$. When calculating the impulse response of the grating, the periodic noise in $\phi(\lambda)$ caused the formation of several replicas of the impulse response of the grating with different amplitudes.

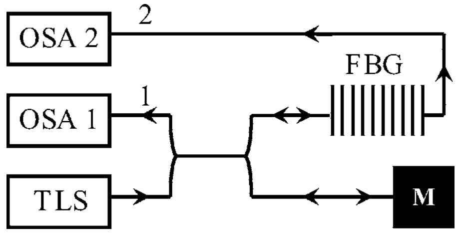

Fig. 1. Schematic description of experimental setup used for measuring structure of strong FBGs. FBG is the interrogated fiber Bragg grating and M is a mirror. The intensity transmission spectrum and the interference spectrum between a reflection from the grating and a reference signal, obtained by using a mirror, are measured.

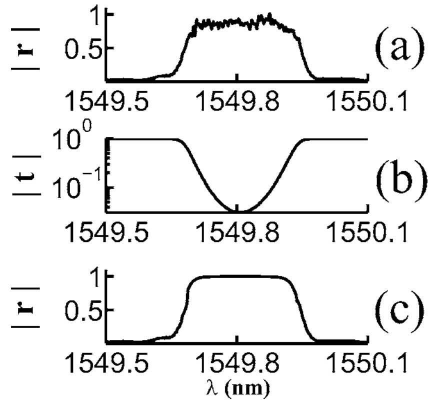

Fig. 2. (a) Amplitude of the reflection spectrum, obtained from interference spectrum, (b) amplitude of the transmission spectrum of the grating, and (c) amplitude of the reflection spectrum after the correction.

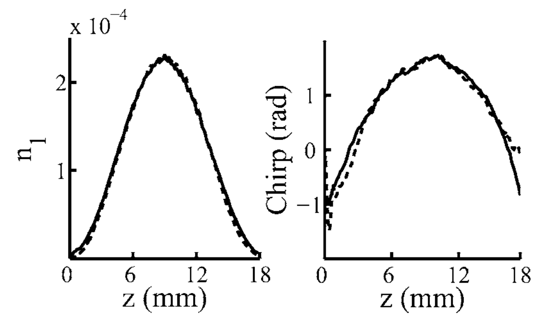

Fig. 3. Refractive index amplitude n_1 and the chirp extracted from both sides of the grating.

Figure 2(a) shows the amplitude of the grating complex reflection spectrum, obtained from the measured interference spectrum. The figure shows that, owing to the interferometric measurement, the noise becomes maximum within the grating bandgap. In numerical simulations, we have found that the average error in the extracted spectrum is approximately proportional to the amplitude of the reflection spectrum for the case of a white Gaussian noise in $\phi(\lambda)$. Figure 2(b) shows the measured transmission amplitude that was used to obtain the corrected reflection spectrum, shown in Fig. 2(c). The interference spectrum and transmission spectrum were measured with a resolution of 2 pm, a bandwidth of 10 nm, a measurement duration of 1 ms per sampled wavelength, and a total measurement time of 5 s.

Figure 3 (solid curve) shows the reconstructed grating profile, obtained from the corrected reflection spectrum given in Fig. 2(c). To validate our result, we extracted the grating profile from its other side, as shown in Fig. 3 (dashed curve). The difference between the two reconstructed refractive index profiles was less than 3.8% of their maximum value. The error in the phase noise was significant ($\lesssim 0.23\pi$) only for two 1 mm long sections located at the two ends of the grating. In the other grating regions the phase error was less than 0.062π.

The SNR of the reflection amplitude shown in Fig. 2(a) was 10.2 dB within the grating bandgap. The power of the noise in calculating the SNR was equal to the standard deviation of the noise amplitude within the grating bandgap. To allow us to reconstruct the grating structure, the SNR within the grating bandgap should be greater than $(1-|r(\lambda)|^2)^{-1} \simeq 30.0$ dB for a grating with a maximum reflectivity of 99.91%, as used in our experiment. Therefore the grating could not be reconstructed without correcting the spectrum as demonstrated in Fig. 4. The figure shows the reconstruction results for two different sensitivity options of the OSA and from both sides of the grating. In the first case, shown in Fig. 4(a), the SNR of the reflection spectrum within the bandgap was 10.2 dB and the total measurement duration was 5 s (1 ms per a single wavelength measurement). In the second case, shown in Fig. 4(b), the SNR was 12.8 dB and the total measurement duration was 220 s (44 ms per a single wavelength measurement). The extracted profiles, measured from both sides of the grating and obtained without correcting the spectrum, are shown in Fig. 4 by the dashed and the dotted curves. The profile obtained by using the method described here is shown by a solid curve. The figures clearly demonstrate that without correcting the reflection spectrum, even half of the grating length could not be reconstructed for the SNRs obtained in our setup. We note that in Ref. 2 we reconstructed the same grating used in this work by measuring the grating from both its sides. The reconstruction in Ref. 2 was possible because the environmental isolation of the system, and thus the measurement SNR, was better than the one obtained in our current work.

The spectral resolution and the sensitivity of the equipment used in our measurements impose a limitation on the maximum length and maximum reflectivity of the gratings that can be measured. The maximum length of the reconstructed grating ($L_{\max}$) is determined by the spectral resolution of the measurement ($\Delta\lambda$):[8] $L_{\max} = \lambda_B^2/(4n_{\text{avg}}\Delta\lambda)$, where n_{avg} is the average refractive index of the fiber and λ_B is the central wavelength of the grating. Thus, for our measurement resolution of 2 pm, the grating length should be shorter than 20 cm. The sensitivity of the transmission measurement limits the maximum reflectivity of the gratings that can be reconstructed. In our setup, the maximum power of the laser was 10 dBm, and the noise level of the detector was about −90 dBm. Assuming that the measured transmission intensity should be at least about an order of magnitude higher than the noise level of the detector, we obtain that we can accurately measure gratings with a reflectivity of up to $1-10^{-9}$.

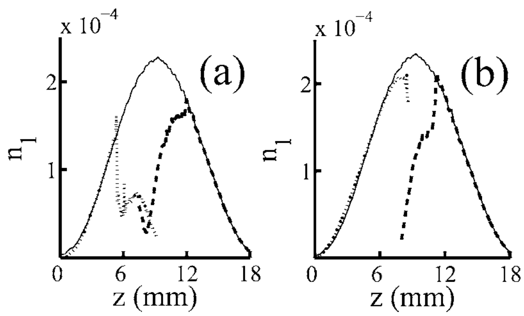

Fig. 4. Profile of the grating, extracted from the reflection spectrum after performing the correction (solid curve) and before performing the correction obtained for both sides of the grating (dotted and dashed curves). The grating was extracted for two different measurement durations of (a) 1 ms and (b) 44 ms per wavelength measurement.

To demonstrate the robustness of our method, we also tested it in numerical simulations for Gaussian gratings. In the simulations, we added a white Gaussian noise to the complex reflection spectrum and to the transmission spectrum. The standard deviations of the noise added to the complex reflection spectrum and transmission intensity spectrum were 0.1 and 10^{-6}, respectively. This noise level is similar to that measured in the experiment, though the noise characteristic in the experiment was different than the white Gaussian noise used in our simplified model. Using the method described here, we were able to accurately reconstruct gratings with a reflectivity of up to 99.999%.

In conclusion, we have demonstrated a new technique that enables one to accurately measure the structure of highly reflecting FBGs. Our method is based on simultaneously measuring the complex reflection spectrum and the transmission intensity spectrum of the grating. We used our method to reconstruct the structure of a Gaussian grating with a maximum reflectivity of 99.91%. Our technique can be used to reconstruct strong gratings measured with a high noise level that prevents direct use of an IS algorithm. Therefore the new technique also enables one to significantly decrease the time required for characterizing FBGs.

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