Experimental reconstruction of a highly reflecting fiber Bragg grating by using spectral regularization and inverse scattering

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We demonstrate experimentally, for the first time to our knowledge, a reconstruction of a highly reflecting fiber Bragg grating from its complex reflection spectrum by using a regularization algorithm. The regularization method is based on correcting the measured reflection spectrum at the Bragg zone frequencies and enables the reconstruction of the grating profile using the integral-layer-peeling algorithm. A grating with an approximately uniform profile and with a maximum reflectivity of 99.98% was accurately reconstructed by measuring only its complex reflection spectrum.

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1. INTRODUCTION

Fiber Bragg gratings (FBGs) are important elements in optical communication systems and in systems for optical metrology [1]. However, in many applications, the use of FBGs is limited because of imperfections in the manufactured gratings. In a previous work it has been shown that when a feedback on the grating structure is used, the quality of the produced grating can be improved by locating the grating imperfections and correcting them during the writing process [2]. The structure of an FBG can be extracted by measuring its complex reflection spectrum and using an inverse-scattering (IS) algorithm. However, in the case of highly reflecting gratings, which are often used in optical communication systems, the extraction of the grating structure may not be possible when an IS algorithm is used directly on the measured reflection spectrum.

In theory, the complex reflection spectrum of FBGs uniquely defines their structure [3]. However, in practice, when the grating reflectivity is high, the reconstruction is limited by noise in the measurement. Theoretical analysis of this problem has shown that an accurate reconstruction of the grating profile requires that the noise within the Bragg zone of the reflection spectrum be lower than the minimum of the transmission intensity of the grating [4,5]. However, since interferometric measurements are used to measure the complex reflection spectrum, the noise level is highest at the Bragg-zone frequencies of the spectrum [6]. As a result, the structure of highly reflecting FBGs cannot be reconstructed by applying an IS algorithm directly on their measured complex reflection spectrum.

In previous works, we have experimentally demonstrated methods for reconstructing highly reflecting gratings by combining the results from two different spectrum measurements. In [7], the grating was reconstructed using the reflection spectrum measured from both sides of the grating, and in [6] the grating was reconstructed by measuring both its transmission and reflection spectra. One of the main disadvantages of these methods is the requirement to access the grating from both of its sides. In many cases, such an experimental setup may be difficult to implement.

When only the reflection spectrum is known, several regularization methods have been theoretically demonstrated to enable the reconstruction of highly reflecting gratings [4,5,8]. For a regularization method to be useful, it is required that it be able to produce good results at a realistic noise level, which is on the order of a few percentage points of the complex reflection spectrum amplitude. Only the method developed in [5] has been theoretically demonstrated to reconstruct FBGs from reflection spectra that contained significant noise, which is comparable with experimental noise. For example, the regularization method in [5] was used to accurately reconstruct a uniform grating with a maximum reflectivity of 0.9999 after adding white Gaussian noise with a standard deviation of up to 0.1 to the complex reflection spectrum. Such a problem cannot be analyzed using other regularization methods. The reconstruction method developed in [5] does not require any *a priori* information about the grating except for its approximate length, which can be easily determined during the writing of the grating. In cases where the grating profile ends with a discontinuity, the grating length can also be estimated directly from the measured complex reflection spectrum.

The regularization method developed in [5] is based on correcting the amplitude of the Bragg zone of the reflection spectrum by using the reflection outside the Bragg zone. This procedure is most accurate when the spectral width of the Bragg zone is narrow and may become unstable if the spectral width of the Bragg zone is too wide. Thus, the method is most suitable for reconstructing quasi-uniform gratings, which are characterized by a narrow Bragg zone. The method is not suitable for analyzing gratings that have a significant chirp or for apodized gratings with suppressed sidelobes because such gratings have a significantly wider Bragg zone than quasi-uniform gratings. Quantitative conditions on the width of the Bragg zone that is required for an accurate reconstruction are given in Section 2.

In this paper we demonstrate, for what we believe is the first time, the experimental reconstruction of a highly reflecting FBG using only the measurement of the grating reflection spectrum. To reconstruct the grating, we use the regularization method developed in [5] and the integral-layer-peeling (ILP) IS algorithm [9]. We note that this is the first experimental use of a regularization method for reconstructing highly reflecting FBGs. The reconstructed grating had an approximately uniform profile and a maximum reflectivity of 99.98%. We verified the accuracy of the reconstruction method by extracting the grating from both of its sides. The difference between the grating amplitude of the two reconstructions was less than 4% of the maximum grating amplitude.

2. REGULARIZATION ALGORITHM

In this section, we briefly describe the regularization algorithm used in our work. A detailed description of the method is given in [5]. The algorithm is based on correcting the amplitude of the Bragg zone of the reflection spectrum by using the reflection outside the Bragg zone. The correction is based on the mathematical properties of the complex reflection spectrum. Since IS algorithms are sensitive mainly to noise in the amplitude of the Bragg zone [5], the corrected spectrum enables us to accurately reconstruct the grating.

The accuracy of the regularization algorithm is determined by the maximum reflectivity of the grating and the product of the grating length, L, and the full width at half-maximum (FWHM) of the main lobe of the grating intensity reflection function, which we denote by bandwidth (BW) [5]. For a given grating reflectivity, the algorithm is most accurate when the product BWL is the smallest. In accordance, we found in numerical simulations that the algorithm gives the most accurate results for quasi-uniform gratings, which are characterized by a narrow Bragg zone and a high level of sidelobes. In our numerical simulations, we found that for gratings with a maximum reflectivity of 99.98%, an accurate reconstruction is obtained for gratings that fulfill BW$L \lesssim 0.37$ nm cm when white noise with a standard deviation of 0.02 is added to the complex reflection amplitude. For comparison, in a grating with a uniform profile, and with a maximum reflectivity of 99.98%, the product BWL is equal to BWL=0.29 nm cm. In the case of apodized gratings with highly suppressed spectral sidelobes or in gratings with a strong chirp, the product BWL may be too high, and the algorithm may not be useful.

We define the function $B(k)$:

$$B(k) = \frac{|r(k)|^2}{1-|r(k)|^2}, \tag{1}$$

where k is the wavenumber detuning [9]. The Fourier transform of $B(k)$ is denoted by $B(\tau)$:

$$B(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} B(k)\exp(-ik\tau)\mathrm{d}\tau. \tag{2}$$

In [5], it is shown that when the reflection spectrum $r(k)$ does not contain an error, the function $B(\tau)$ equals zero outside the interval $[-2L,2L]$, where L is the grating length. This property is used to regularize the reflection spectrum.

We denote the error in the reflection spectrum by $\Delta r(k)=\bar{r}(k)-r(k)$, where $\bar{r}(k)$ and $r(k)$ are the noisy and the accurate reflection spectra, respectively. The functions $\bar{B}(k)$ and $B(k)$ can be calculated from the reflection functions $\bar{r}(k)$ and $r(k)$ by using Eq. (1). Assuming that the reflection spectrum is sampled, the error function $\Delta B(k) = \bar{B}(k)-B(k)$ can be approximated by [5]:

$$\Delta B(\tau) = \sum_{1}^{N} c_n \exp(-ik_n\tau), \tag{3}$$

where N is the number of sampled spectral points inside the Bragg zone, k_n are the corresponding wavenumber components, and the coefficients c_n correspond to the samples of $\Delta B(k)$ at the frequencies k_n.

In contrast to [8], where the function $\bar{B}(\tau)$ was set to zero outside the interval $[-2L,2L]$, we use the data outside that interval to calculate the error function $\Delta B(\tau)$ and correct the reflection spectrum inside the Bragg zone of the grating. Since $B(\tau)=0$ for $|\tau|>2L$, the function $\bar{B}(\tau)$ is equal to the error function $\Delta B(\tau)$ outside the interval $[-2L,2L]$. Thus, the coefficients c_n can be calculated by minimizing the square error between $\bar{B}(\tau)$ and $\Sigma_1^N c_n \exp(ik_n\tau)$ outside the interval $[-2L,2L]$. Since the square error is the quadratic function of the coefficients c_n, only a single solution exists.

Once the coefficients c_n are recovered, the error function $\Delta B(\tau)$ can be calculated by using Eq. (3). The error function $\Delta B(\tau)$ is then used to calculate the function $B(k)$, which in turn is used to correct the amplitude of the reflection spectrum $r(k)$ by using Eq. (1). Afterward, the ILP algorithm [9] is used to accurately reconstruct the grating structure from the regularized reflection spectrum.

3. EXPERIMENT AND RESULTS

The grating that was reconstructed in our work was written using a uniform phase mask with an approximate length of 1.5 cm. The complex reflection spectrum of the grating was measured using the interferometric setup described in [2,6]. The spectral bandwidth and the resolution of the measurement were 10 nm and 1 pm, respectively.

The intensity of the measured complex reflection spectrum of the grating is shown in Fig. 1. The impulse response of the grating is calculated by using the Fourier

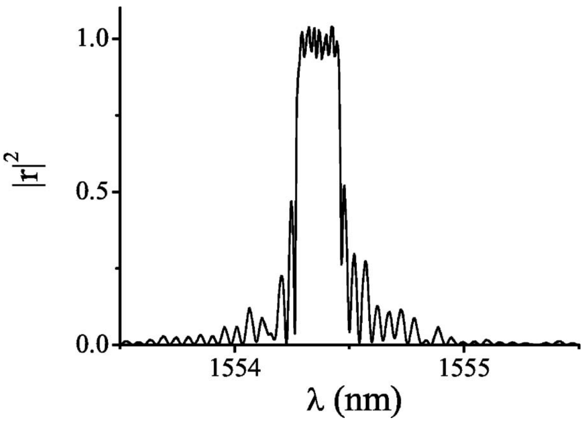

Fig. 1. Intensity of the measured complex reflection spectrum.

transform on the complex reflection spectrum [7], and is shown in Fig. 2. Since the grating profile ends abruptly, we can estimate the grating length from the impulse response function of the grating. The discontinuity in the impulse response at approximately $t=149.5$ ps, indicates that the round-trip time between the two grating ends is approximately equal to 149.5 ps, which corresponds to a grating length of 1.55 cm. The location of the discontinuity was taken as the midpoint of the sharp rise in the impulse response amplitude near $t=150$ ps. We note that the reconstruction is not sensitive to the exact grating length. An accurate reconstruction can also be obtained if the grating length is estimated as the length of the phase mask used to write the grating—1.5 cm.

The FWHM of the main lobe in the reflection intensity is approximately equal to BW=0.194 nm. The maximum reflectivity obtained by measuring the intensity of the backreflected wave is approximately equal to 99.98%. Thus, according to the analysis in [4,5], in order to accurately reconstruct the grating, it is required that the noise level at the Bragg-zone frequencies be considerably lower than 2×10^{-4}. However, Fig. 1 shows that the maximum error at the Bragg zone of the grating reflectivity is approximately equal to 0.05, which is considerably larger than required for accurately reconstructing the grating. Therefore, the grating cannot be reconstructed without regularizing its reflection spectrum. The bandwidth-

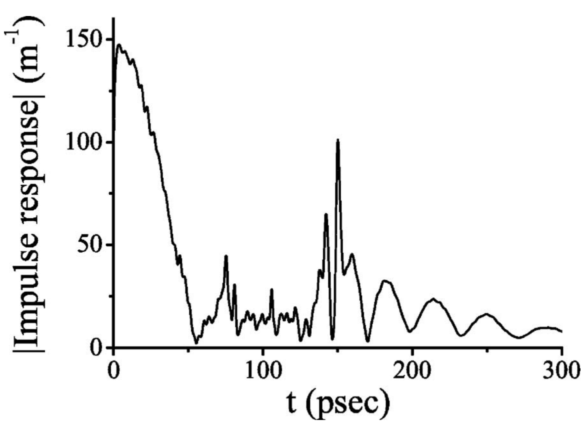

Fig. 2. Amplitude of the grating impulse response. The discontinuity at approximately $t=150$ ps is caused by a reflection from the grating end.

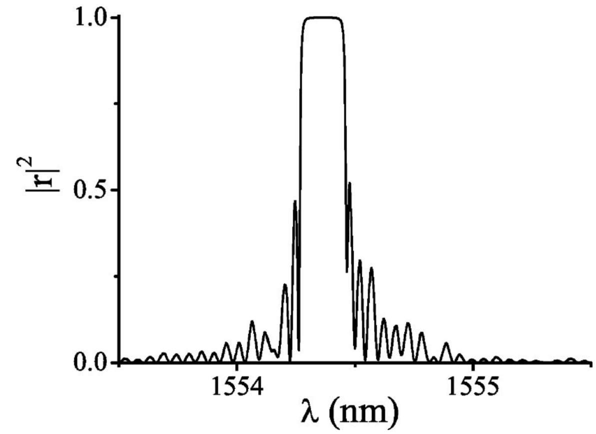

Fig. 3. Intensity of the measured complex reflection spectrum after performing spectrum regularization.

length product of the grating is approximately equal to BWL=0.31 nm cm, and thus the grating is suitable for our regularization method.

Using our regularization algorithm, we corrected the amplitude of the measured complex reflection spectrum. In the regularization algorithm, we used $L=1.55$ cm, and the reflection spectrum was corrected at frequencies at which the reflection intensity exceeded 60%. The regularized reflection spectrum had a maximum reflectivity of 99.98%, according to the measured result. The intensity of the regularized reflection spectrum is shown in Fig. 3. The figure clearly shows that the high frequency noise components inside the Bragg region of the grating cannot be observed after the spectrum regularization. The grating was reconstructed from the regularized reflection spectrum by using the ILP algorithm [9].

To validate our results, we reconstructed the grating from both of its sides using the same reconstruction procedure. The amplitude and phase of the two reconstructed profiles are shown in Figs. 4 and 5, respectively, where the solid curve corresponds to the data shown in Figs. 1 and 2 and the dashed curve corresponds to the recon-

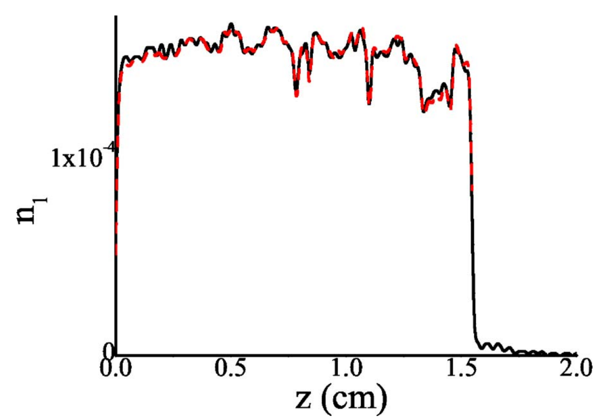

Fig. 4. (Color online) Amplitude of the reconstructed grating performed from the two grating sides. The solid curve corresponds to the data shown in Figs. 1 and 2, whereas the dashed curve corresponds to the reconstruction from the other side of the grating. The figure shows an excellent agreement between the two reconstructions. The maximum difference between the two reconstructed amplitude profiles is equal to 4% of the maximum grating amplitude.

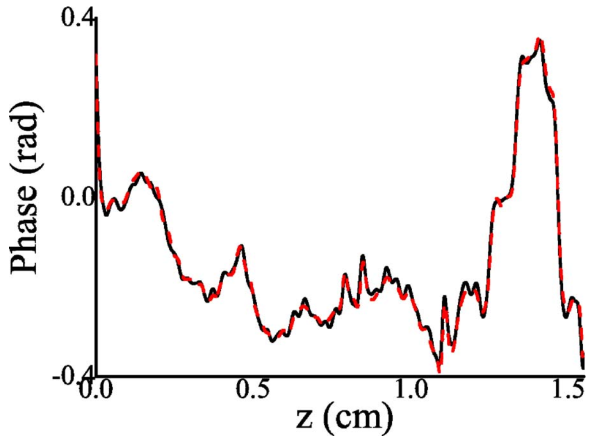

Fig. 5. (Color online) Phase of the reconstructed grating performed from the two grating sides. The maximum difference between the two reconstructed phase profiles is 0.03 rad. Curve definitions as in Fig. 4.

struction performed from the other grating end. The figure shows excellent agreement between the two reconstructions. Thus, we can conclude that the nonuniformities in the reconstructed grating profile, shown in Figs. 4 and 5, are a result of grating defects and were not caused by errors in the reconstruction. The maximum difference between the two reconstructions is equal to 4% of the maximum grating amplitude. The maximum difference between the two reconstructed phase profiles is 0.03 rad. We note that similar results were obtained when the grating length used in our regularization algorithm was in the interval between 1.5 and 1.7 cm. Therefore, the reconstruction method is not sensitive to the exact choice of the grating length.

To obtain an accurate reconstruction of the grating, it was essential to use both the regularization algorithm and the ILP algorithm. Figure 6 shows the reconstruction of the grating from both its sides in the case where only the ILP algorithm was used and the spectrum was not regularized. The figure clearly shows that the noise in the measurement prevented the reconstruction of the grating. Figure 7 shows the reconstruction of the grating from both its sides in the case where the regularization algorithm was used, but instead of using the ILP algorithm, the discrete-layer-peeling (DLP) algorithm [10] was used. In this case, the reconstruction is again not accurate because the DLP algorithm is not suitable for reconstructing uniform gratings with a reflectivity higher than approximately 99%. We also note that the regularization methods given in [4,8] were not suitable for reconstructing the profile of our grating.

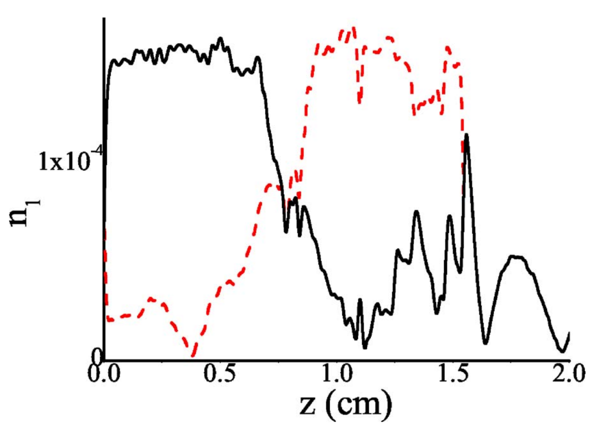

Fig. 6. (Color online) Grating amplitude, reconstructed from both grating sides when the reflection spectrum is not regularized and the ILP algorithm is used. The figure shows that the grating cannot be reconstructed without regularizing its reflection spectrum. Curve definitions as in Fig. 4.

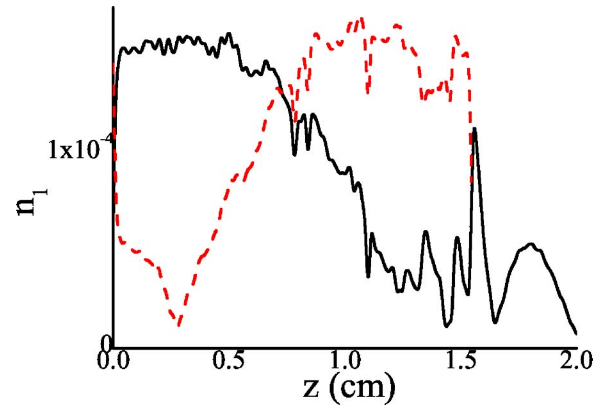

Fig. 7. (Color online) Grating amplitude, reconstructed from both grating sides when the reflection spectrum is regularized, but the DLP algorithm is used instead of the ILP algorithm. The figure shows that the grating cannot be reconstructed using the DLP algorithm. Thus, it is essential that the ILP IS algorithm be used. Curve definitions as in Fig. 4.

4. CONCLUSION

We have experimentally demonstrated the use of a regularization method for reconstructing the structure of a highly reflecting FBG using only a measurement of its complex reflection spectrum. In our experiment, we have successfully reconstructed the structure of an approximately uniform grating with a maximum reflectivity of 99.98%. To the best of our knowledge, this is the first accurate reconstruction of a highly reflecting grating using only a measurement of the complex reflection spectrum. Our method can be used for improving the manufacturing process of highly reflecting FBGs.

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