# Implementation of a Digital Shadow for Fiber Bragg Gratings

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***Abstract*—We propose a synthesis model for fiber Bragg gratings (FBGs) to monitor temperature measurement errors due to aging behavior. This approach might be called a Digital Shadow since we are able to monitor all essential parameters of the grating to perform error prediction and consequently compensation. The model is tested during accelerated aging experiments, which furthermore reveal the shift of the center wavelength because of thermal decay.**

## I. Introduction

A fiber Bragg grating (FBG) is inscribed in optical fiber by inducing a periodic index change in the fiber core, consisting of an ac- and dc-component, respectively [1]. As the wavelength of light reflected by the structure depends on temperature and strain, FBGs are used widely in industrial sensing applications, pipeline monitoring or structural health monitoring due to their well-known advantages [2]. Upon installation, FBG sensors can withstand environmental impact for many years without further maintenance. Nevertheless, aging experiments have shown, that the maximum reflectivity of the grating thermally degrades over time [3,4]. Moreover, the degradation leads to an unwanted shift in the reflected wavelength not caused by temperature or strain variations but by decay of the dc-component of the refractive index modulation. Thus, the on-going aging process of the grating will inevitably result in an error of the measurand. To enable error correction and ensure the measurement quality, we propose the use of a Digital Shadow (DS) for fiber Bragg gratings. A Digital Shadow, similar to a Digital Twin (DT), is defined as an accurate digital model of an existing entity, being able to describe its whole life span and predict the behavior of the entity. The DT, other than conventional models, also can return information generated within itself to the entity. A DS on the contrary is updated constantly with information received from the physical entity, but not returning information [5]. So far, a DT has not been adapted to fiber sensors. Hence, in this paper we first describe the synthesis of FBG parameters from its reflection spectrum. However, since the FBG itself is a pure passive optical component not able to actually receive information, we name the implemented model a Digital Shadow. Accelerated aging experiments are carried out with the grating spectrum constantly monitored to determine if our model can monitor subtle changes in the reflection spectra of the grating. In this case, we are able to distinguish between the wavelength shift due to temperature change and aging, which enables the correction of the aging-induced temperature error.

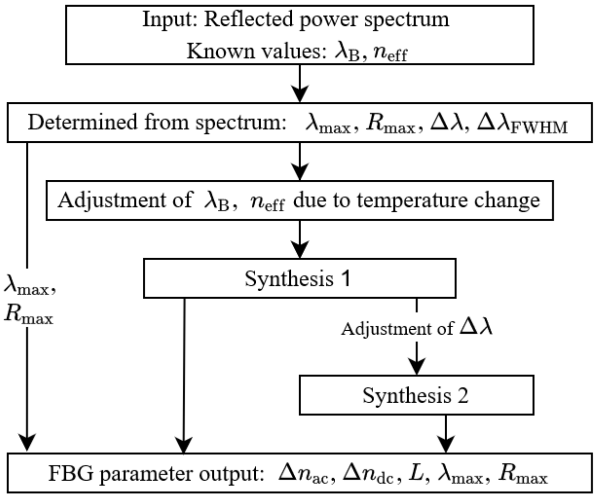


Fig. 1. Flow chart of the implemented FBG synthesis. The FBG parameters needed for the Digital Shadow are the output values.

## II. Model Description

The synthesis of an FBG is described as the inverse problem of FBG simulation and thus can be used to remodel the grating parameters from the reflected spectrum. This is especially interesting for the monitoring of FBGs used in industrial sensing applications since no prior information of the grating are needed, except the Bragg wavelength $\lambda_B$ and the effective refractive index $n_{eff}$ of the fiber. The Bragg wavelength is defined as $\lambda_B = 2n_{eff}\Lambda$, with $\Lambda$ being the period of the grating. The grating parameters of interest are the center wavelength $\lambda_{max}$ at the maximum reflectivity $R_{max}$, grating length $L$, ac-refractive index change $\Delta n_{ac}$, dc-refractive index change $\Delta n_{dc}$, and the bandwidth $\Delta\lambda$, defined as the distance between the first minima. Our approach to estimate all these parameters from the reflection spectrum is shown in Fig. 1. First, we perform a simple peak finding on the reflection spectrum to identify $R_{max}$, $\lambda_{max}$ and $\Delta\lambda$. Subsequently, $\lambda_B$ and $n_{eff}$ are adjusted for the thermo-optical effect and thermal expansion. In Synthesis 1 a preliminary set of the desired parameters is determined using a set of equations derived from the analytical solution of the coupled mode equations [1]:

$$R_{max} = \tanh^2\left(\frac{\pi}{\lambda_{max}}\Delta n_{ac}L\right), \tag{1}$$

$$\lambda_{max} = \lambda_B\left(1 + \frac{\Delta n_{dc}}{n_{eff}}\right) \tag{2}$$

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and

$$\Delta\lambda = \lambda_{\mathrm{max}} \frac{\Delta n_{\mathrm{ac}}}{n_{\mathrm{eff}}} \sqrt{1 + \left(\frac{\lambda_{\mathrm{B}}}{\Delta n_{\mathrm{ac}} L}\right)^2}. \tag{3}$$

With the values for $\lambda_{\mathrm{max}}$, $R_{\mathrm{max}}$ and $\Delta\lambda$ as well as $\lambda_{\mathrm{B}}$ and $n_{\mathrm{eff}}$, we can determine $R_{\mathrm{max}}$, $L$ , $\Delta n_{\mathrm{ac}}$ and $\Delta n_{\mathrm{dc}}$ from (1)-(3). In Synthesis 2 the calculations are repeated after performing an adjustment based on the ratio of the bandwidth $\Delta\lambda$ and the bandwidth at full width half maximum $\Delta\lambda_{\mathrm{FWHM}}$ accounting for non-uniform proportions of the grating. The results of the synthesis procedure are automatically stored and thus act as Digital Shadow. Due to the fact that we use the equations derived from the analytical solution, our synthesis is currently limited to uniform gratings.

## III. Aging Experiments

We conducted so-called accelerated aging experiments to test our synthesis and generate a Digital Shadow of a FBG. Experimental setup and results are described in the following.

### A. Experimental Setup

To monitor aging behavior, we used a uniform grating with a Bragg wavelength of 1540.48 nm and a reflectivity of 30 %, which we inscribed into Germanium-doped photosensitive fiber (GF1B, *Nufern*) by phase mask (period 1064.5 nm) technique with an UV-excimer laser (*Coherent*). The coating of the fiber is removed and the fiber with the inscribed grating is put into an oven (*Nabertherm*). For continuous grating interrogation, we use the amplified spontaneous emission (ASE) of an Erbium-doped fiber amplifier (*Oprel*) as incident light in combination with a fiber coupled circulator to guide the back reflected light to an optical spectrum analyzer (OSA, *Ando*) for detection. The oven is then first set to 200 °C for one week (168 hours). Measurements are recorded every 5 minutes for the first 5 hours and afterwards once per hour. This procedure is repeated for 300 °C and 400 °C. The accelerated aging process was concluded by 48 hours at 500 °C.

### B. Aging Results

The aging of our grating results in an exponential degradation of the reflectivity as described in [4]. Fig. 2 exemplary shows the degradation of the measured spectrum before and after accelerated aging at 300 °C. Clearly, a decrease (3.9 %) in reflectivity is visible; furthermore, a slight shift of 15.9 pm of the maximum wavelength because of the aging process is recognizable.

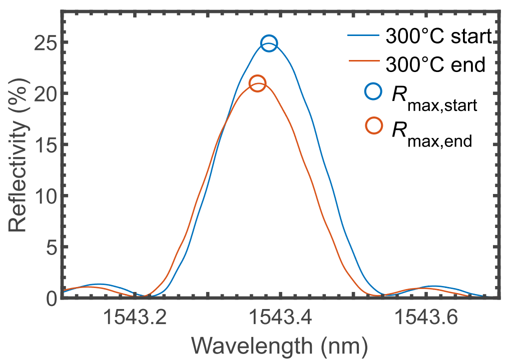


Fig. 2. Measured spectra at the beginning of the aging process (blue curve) and after 168 hours at 300 °C (red curve). The maximum reflectivity decreases 3.9 %. Also, a slight left shift of 15.9 pm of the maximum wavelength is visible.

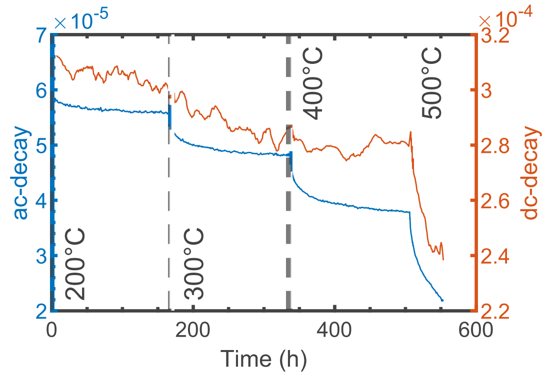


Fig. 3. Thermal decay of ac- and dc-refractive index change over the whole aging process from 200 °C to 500 °C. With the beginning of each temperature step, a drop in ac-index change $\Delta n_{\mathrm{ac}}$ is visible.

The DS synthesis is performed during a total time of 552 hours with the results for the ac- and dc-refractive index change depicted in Fig. 3. For the ac-refractive index change $\Delta n_{\mathrm{ac}}$ an exponential degradation in accordance with the degradation of the maximum reflectivity is observed. Further, the Digital Shadow reveals a linear decrease for the dc-refractive index change $\Delta n_{\mathrm{dc}}$ over time. The shift of the maximum wavelength in Fig. 2 illustrates the behavior of $\Delta n_{\mathrm{dc}}$ in accordance with (2). This proofs, that not only the reflectivity is affected by aging but also the observed center wavelength $\lambda_{\mathrm{max}}$, which consequently will lead to errors in the temperature or strain measurement.

## IV. Conclusion

We implemented a Digital Shadow for uniform fiber Bragg gratings. With this synthesis approach, we were able to monitor closely the aging behavior of a grating, which underwent an accelerated aging procedure. The model is able to determine all parameters needed for the reconstruction of the grating from the measured spectrum. In this context, a decrease in the dc-refractive index change was observed, which leads to an aging-induced shift of the maximum wavelength. With the DS, potential aging influences on the sensing performance of the FBG are revealed and can be compensated.

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