FIBRE OPTIC SENSOR GRIDS IN STRUCTURAL TESTING

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ABSTRACT

Studying the failure of structural components requires effective experimental in-situ analysis of stress states, including local strain distributions and stress conditions varying over time. Adequate measurement technology facilitates calculation of residual lifetime and assessment of structural health under realistic conditions.
For many decades already, stress analysis using strain gauges has been a tried and tested method for analysing loading conditions in structural mechanics. Strain gauges are particularly suited for determining such mechanical loads on engineering structures or components, because they detect minimal structural deformations. The quality and reliability of the sensors determine the durability of the structural system. Especially in the content of lightweight materials, fibre optic sensors are increasingly used today, inter alia because of:

- *The low weight of sensors, cables and data acquisition unit as well as their ease of assembly work load*
- *The sensors fatigue behaviour in the event of applied high mechanical strain.*

Considerations will be presented on how fibre optic Bragg gratings can be used to enable special approaches to studying damage and fracture mechanics, where small local distributions of stress states and their gradients need to be determined.
Related to measuring bare fiber grids' behaviour in spectral view is shown in the paper and their application in the event of structural damage , their potential use in plastically deformed areas will be considered.

INTRODUCTION

The possibility of producing both higher refraction index cores and periodic variation in the refractive index of the fiber core allows multiple applications of fiber-optic technology in the field of sensors. The difference of refraction indices between core and cladding causes the light to propagate only inside the small core. The glass fiber recommended for strain measuring purposes is coated with an ORMOCER (organic modulated ceramic) coating to guarantee perfect strain transfer from the measuring object to the inner core of the glass fiber. The coating also protects it, in particular against water and hydrogen which may cause crack formation reducing mechanical stability.

Bragg Grating

A further small periodic modulation of the refractive index of the optical fiber core carried out over a certain length (e.g. 4 …6 mm) forms a Bragg grating [1]. This area operates like a sensor. The reflected wavelength (λ_B), called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_e\Lambda \tag{1}$$

where ne is the effective refractive index of the grating in the fiber core and Λ is the grating period.
The principle of a fiber Bragg grating is illustrated in Fig. 1.

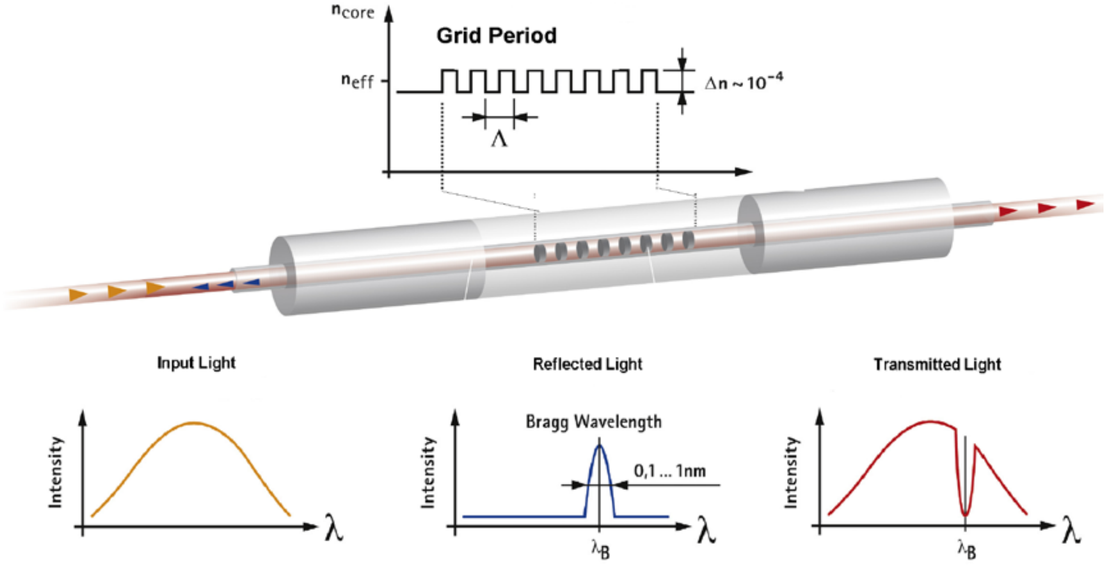

Figure 1. Bragg grating sensor in an optical fiber.

The shift of the Bragg grating wavelength due to strain and temperature changes is given by partial differentiation of (Eq. 1). Periodic spacings between the fringes and the effective index of refraction are independent of each other. According to the total differential for small variations it may be written as [2]:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T$$

(2)

In the formula, Δl stands for the effect of strain and ΔT for the effect of temperature.
In most of the cases, measurement of strain properties requires temperature compensation, mainly if static or quasistatic values are requested. Methods for this type of compensation are described in [3].

Information of grid spectrum

Each single fringe of that Bragg grating reflects a very small part of all incoming wavelengths. The reflection factor per single fringe is in the range of only 0.001% …0.1% depending on how much energy was used to write the Bragg grating and on the percentage of Germanium doping of the fiber core. All single reflections therefore have different phases, they interfere and compensate each other to zero resulting in a pole of the reflection function [4].
A typical distance of the lattice, the so called grid spacing is calculated as follows:

$$G_s = \frac{\lambda_0}{2n} \tag{3}$$

Related to typical values the resulting grid spacing is:

$$\begin{aligned} \lambda_0 &= 1545nm \\ n &= 1{,}46 \\ G_S &= 529{,}1nm \end{aligned}$$

Over the typical grid length of 6 mm, the number of gratings is more than 11340 fringes.
In the case of weak gratings, the dominant Bragg peak at λ_B is typically accompanied by a number of sidebands and due to light propagation and single slit reflection at a regular pattern the entire reflection spectrum R(λ) including all sidebands can be described by the sinc function

$$\text{sinc}\ (x) = \sin(x) / x \tag{4}$$

which is the Laplace transform of the rectangular function without scaling.

Assuming a homogeneously distributed pattern due to a uniformly distributed strain under the sensor area gives

$$R_i = \frac{\lambda_0}{\pi \cdot N \cdot \Delta\lambda_i} \cdot \sin\left(\frac{\pi \cdot N \cdot \Delta\lambda_i}{\lambda_0}\right) \tag{5}$$

Fig. 2 shows the measured reflection spectrum of a fiber Bragg grating (a) and a calculated reflection spectrum (b) with Bragg peak and symmetric sidebands around the Bragg wavelength $\lambda_B \sim 1570$nm [5].

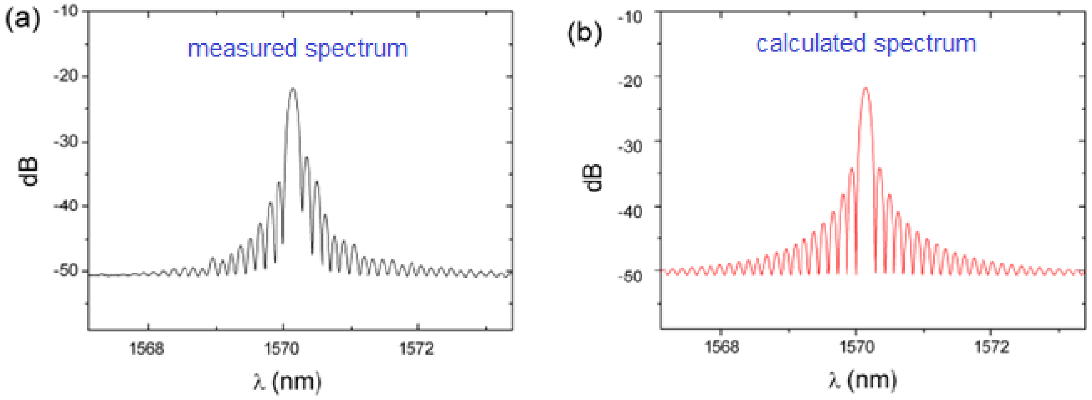

Figure 2. Measured and calculated peak shape of an optical Bragg grating.

Optical strain gauges of HBM’s production (see Fig. 3) are dedicated to the use on test specimens where a homogeneous distribution of inherent strain can be supposed.

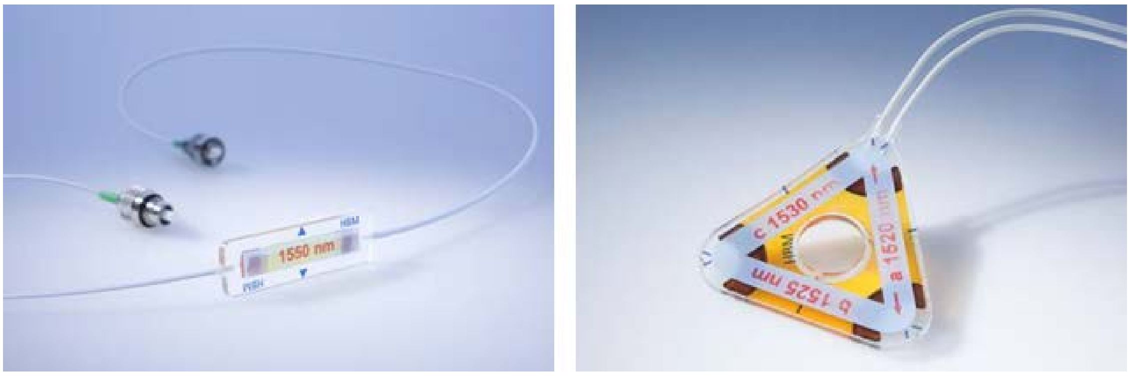

Figure 3. Optical strain gages [6].

The OptiMet by HBM™ system for fiber-optic sensors is a new reliable measurement product for strain detection and signal transmission of measurement data. HBM has completed its range of optical strain gauges with the OptiMet by HBM™ system of fiber-optic components. The OptiMet system offers singlemode optical fibers with integrated functional grids, in case of OptiMet-OMF (Ormocer fiber) and OptiMet-PKF (coated fiber) with integrated Bragg grating measurement function.

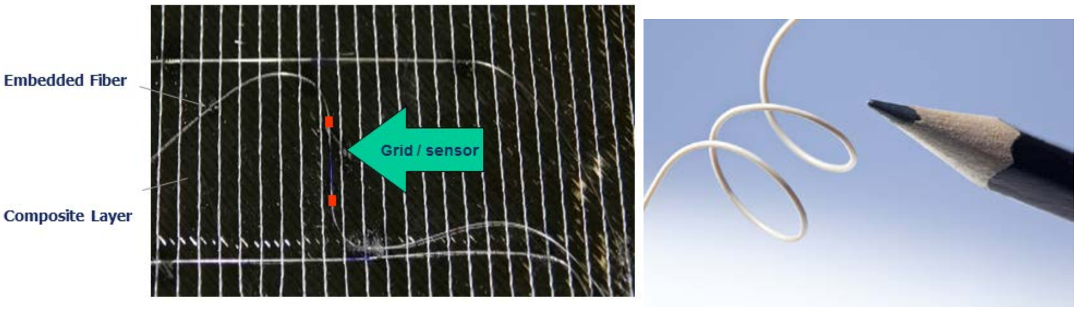

Figure 4. Bare grated fibers - OptiMet by HBM.

In case of installation on the surface, the fibers are fixed with HBM bonding cements X120 (OptiMet PKF) or X280 (OptiMet OMF) [7].

In practical application, an optical-electrical DAQ unit, a so called interrogator permits measurement using an appropriate hardware and software setup. An internal peak detection algorithm using one or more thresholds enables the actual wavelength of the measurement to be verified. In compliance with a guideline for FBG-based optical strain sensors in experimental stress analysis [8] the normative peak shape of the reflected spectrum of the optical strain gauge is presupposed i.e. of stable figure. The assumption is that the form of a single peak shape is maintained over the complete range specified in the data sheet.

However, the peak shape varies in the event of non-linear strain distribution under a Bragg grating. For example, in case of a linear strain gradient (see both, practical measurement and mathematical simulation through superposition of Laplace transforms in fig. 5), the peak in the spectrum representation is extended. The example peak deformation in fig. 6 shows extended and shortened square strain fields under the Bragg grating. Mathematical reconstruction allowes conclusions to be drawn about distributions and stress concentration levels in the strain field, to a certain extent.

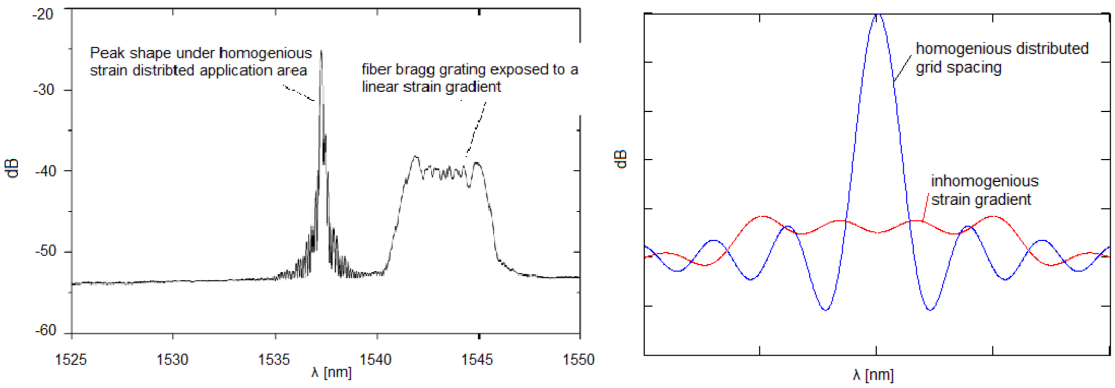

Figure 5. Measurement and simulation of unequal distributed strain fields.

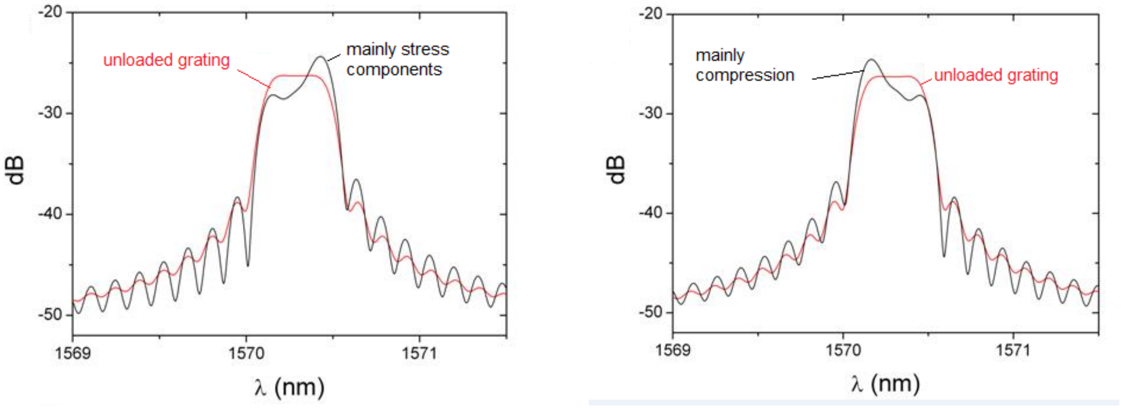

Figure 6. Strain fields under tension and compression.

Practial Example

Below you find a practical example: A saw slit was cut into an aluminum specimen of flat material as shown in fig. 7, with a corresponding Bragg grating of an OptiMet OMF fiber in the strain range shown.

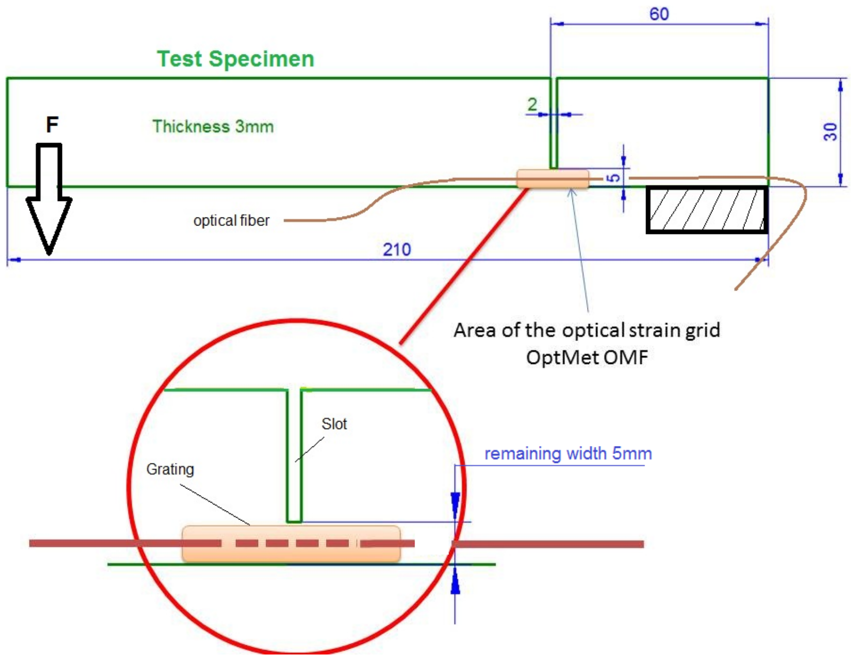

Figure 7. Test specimen with OptiMet OMF fiber at the strain field.

Fig. 8a shows the spectrum of the measuring spot in an initial crack phase with mainly compressive components, while subfigure 8b shows the increasing local, non-linear stress components. HBM's catman software enables the spectra to be read out and converted into other file formats.

In the event of crack formation, the spectral peak is extended accordingly (see fig. 8c).

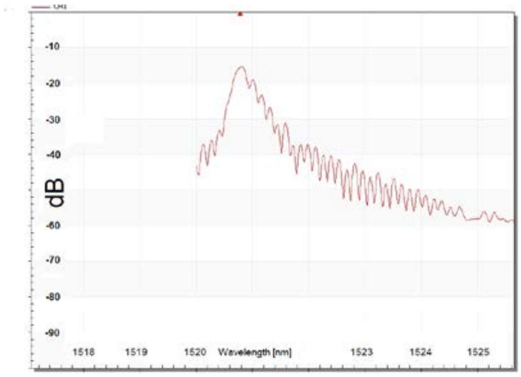

Fig. 8a

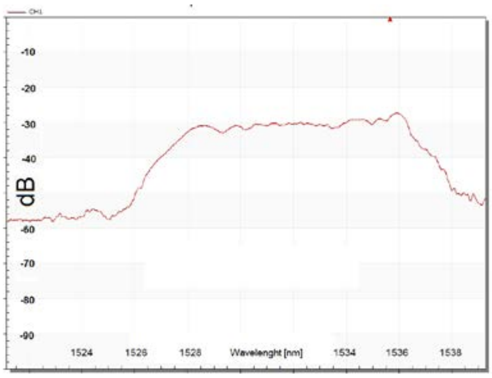

Fig. 8b

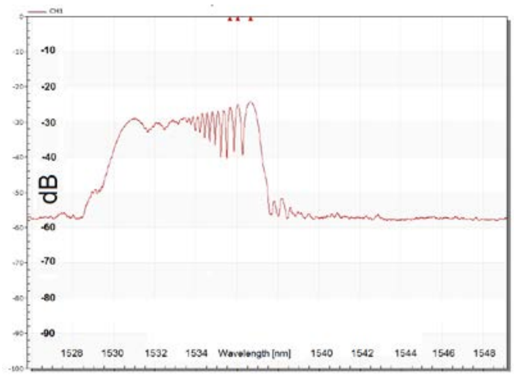

Fig. 8c

Figure 8. Stress propagation in the strain field under the slot.

Conclusion

The behavior of bare fiber Bragg grids in spectral view is shown in the paper and their application in the event of structural damage is discussed in a practical approach.

A current limitation of this technique is the dynamic required to process the data as well as the ambiguous local allocation when interpreting spectral information.

Nevertheless, improvements in the field of optical Bragg technology are on the way and their potential use in plastically deformed areas should be considered for further research .

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