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Strain measurement with the Fiber Bragg Grating optical sensors

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Abstract: The article focuses on strain measurement using the optical sensors. Configuration of optical fibers is described and classification of optical sensors is introduced. The main part of the article is about Fiber Bragg Grating sensors. Their sensing principle is described and influence of non-uniform loading conditions (including change in temperature, non-uniform strain, change in curvature etc.) is presented. Following sections describe sensor manufacturing techniques and ways of multiplexing. In the final chapter examples of measurements are shown.

Keywords: Fiber optic; Optical sensor; FBG sensor; Bragg Grating;

1. Introduction

Fiber optic based sensors have been derived from data transmission fiber optic technology systems since its invention in 1970s. They are light with small dimensions, they are immune to electromagnetic field influence with multiplexing capability, they can be embedded into the composite structure, hence they are suitable for Structural Health Monitoring (SHM) purposes.

2. Fiber optic sensors

Optical fiber consist of an inner core with a high refractive index that transmits light, and an outer glass cladding with a lower index of refraction that keeps the light signal in the core by total internal reflection. Single-mode fibers (SMF; core diameter up to 10 µm) support only a single-mode light path and are used for communication links longer then approximately 1 km. Multi-mode fibers (MMF; core diameter 50 – 100 µm) support multiple propagation paths and are used for transmission of high-power signals and for short-distance communication.

The cladding diameter is usually 125 µm and it is coated by a protective buffer – primary coating, that protects fiber from chemicals, moisture etc. Outer diameter of the coating depends on the material; overall diameter of the polyacrylate coating is 250 usually 250 µm, polyimide – 155 µm, hybrid polymers – 195 µm. Another protective layers and armor (resin buffer layer, stiffening glass/aramid

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yarns, outer plastic jacket) are applied in the optical cables. The structure of a typical optical cable can be seen in the Fig. 1.

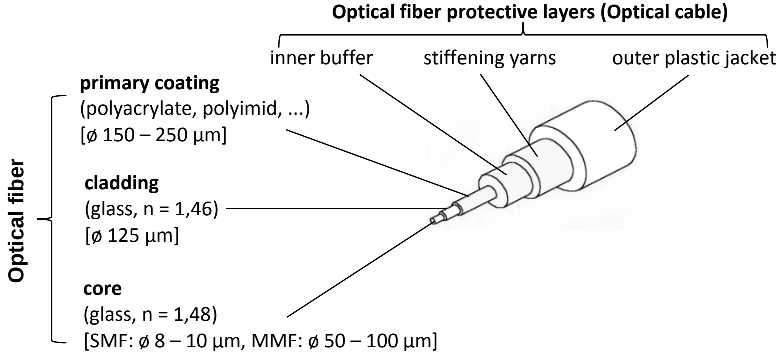

Fig. 1. Typical configuration of the optical cable.

Optical fibers are made from the extremely pure optical glass. The most commonly used fiber material is *silica*; *fluoride glass*, *phosphate glass* or *chalcogenides* are also used. The higher index of refraction of the core is achieved by doping. The most common dopant is *Germanium*; *Phosphorus*, *Fluorine* and *Boron* can be used as well [1]. Manufacturing process is based on drawing the fibers from glass preforms.

Optical fibers are produced in three optical transmission windows [2]:

- (800 – 900) nm (high losses, relatively cheap electronic devices, main wavelength for optical communication systems)
- around 1300 nm (lower losses, low level of intramodal dispersion)
- around 1500 nm (the lowest attenuation losses with some dispersion, expensive electronic devices)

Fiber optic sensors can be basically classified into two groups, depending on their function. In case of an *intrinsic* sensor the sensing mechanism is a part of the optical fiber. An *extrinsic* sensor uses optical fiber only as a connection between the sensing element/device and detector. Fiber optic sensors can be further classified by measured physical parameters (strain, temperature, pressure, displacement, moisture, etc.). Another classification can be done according to the topology of the sensor (local, quasi-distributed and distributed). Depending on the transduction mechanism, fiber optic sensors can be classified as follows:

- *Intensiometric:* a change of the intensity of light transmitted through the optical fiber is detected (for example displacement sensor, detection of broken fiber)
- *Interferometric:* a change in the phase of a lightwave is detected (Fabry-Perot sensor, Michelson interferometer)
- *Polarimetric:* a change in the two polarization eigenmodes is detected

- *Modalmetric:* a change in the transverse spatial mode distribution of the light is detected
- *Spectrometric:* a change in the reflected or propagating spectrum is detected (Raman/Brillouin backscatter, Fiber Bragg Grating sensor)

In the following text, we will focus on spectrometric Fiber optic Bragg Grating sensors.

3. Fiber Bragg Grating sensors

A Fiber Bragg Grating (FBG) sensor is intrinsic spectrometric type of sensor. FBG sensors are intensively developed since their discovery in early 1990s [3]. They are based on a periodic variation in the refractive index of the fiber core, which reflects particular wavelengths of light and transmits all the rest.

Two types of grating period are mainly used for the FBG sensing purposes:

- *Uniform*: the grating period is constant along the FBG sensing area. Reflected peak is narrow.
- *Chirped*: the grating period is gradually distributed along the optical fiber. Reflected spectrum is wider than the one from uniform FBG. Moreover the wavelength of the reflected light is corresponding to the position in the grating/sensor section of the fiber.

Another grating structures are for example *tilted* gratings or *superstructured* gratings (long-period fiber gratings). For more details see [4].

Typical measurement configuration for the FBG sensor is pictured in Fig. 2.

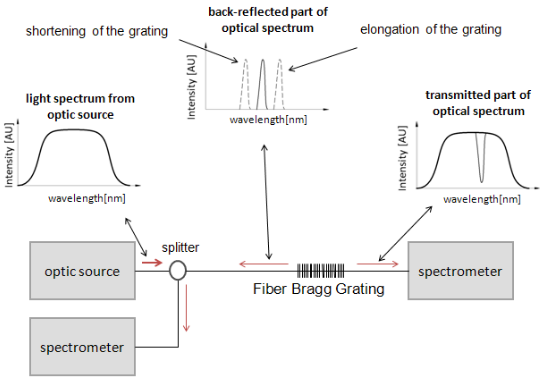

Fig. 2. Experimental configuration for measurement with the FBG sensor.

Broadband light spectrum from optic source is guided by the optic fiber into the FBG sensor. Part of the light is reflected by grating (in a form of narrow Gaussian peak), the rest is transmitted. For sensing purposes, the reflected peak is commonly measured using a spectrometer.

FBG sensor working principle is based on a sensitivity of grating period and refractive index to changes in strain and temperature. Each Bragg grating is characterized by so-called Bragg wavelength λ_B, which is defined as follows:

$$\lambda_B = 2.n.\Lambda \tag{1}$$

where: n … core refractive index
Λ … grating pitch

Central (Bragg) wavelength is shifting according to deformation of grating. Elongation causes positive shift, shortening causes negative shift. Wavelength shift response to strain ε and temperature change ΔT is expressed [4] by equation:

$$\frac{\Delta\lambda_B}{\lambda_B} = P.\varepsilon + \left[P.\left(\alpha_S - \alpha_F\right) + \xi\right]\Delta T \tag{2}$$

where: P … strain-optic coefficient
α_S … coefficient of thermal expansion of specimen
α_F … coefficient of thermal expansion of fiber
ξ … thermo-optic coefficient

Linear response of FBG sensor to strain and temperature was observed. Typical values of sensitivity of the FBG sensor to change in strain and temperature were measured for two common fiber coating materials: *Polyacrylate* (fiber diameter 125 μm, coating diameter 250 μm) and *ORMOCER®* (fiber diameter 125 μm, coating diameter 195 μm). Values are listed in the Table. 1.

Table 1. Sensitivity to strain and temperature (measured for two coating materials)

fiber coating material	sensitivity to strain	sensitivity to temperature
Polyacrylate	0.7 pm/(μm/m)	6.2 pm/K
ORMOCER®	0.66 pm/(μm/m)	7.5 pm/K

3.1. Temperature compensation

Two methods of temperature compensation of FBG sensors are commonly used. The first method is based on strain measurement on two identical specimens, both with installed FBG sensors. The first specimen is loaded in a testing machine, the second specimen is unloaded (influenced only by changes in ambient temperature). Pure strain readings are obtained by subtracting temperature readings (unloaded specimen) from the strain/temperature readings (loaded specimen).

The second compensation method is based on calibration of strain response to temperature change. FBG sensor is temperature-calibrated after the installation on the specimen surface (or integration into the structure). Specimen with FBG sensor is than placed in a laboratory furnace, and temperature is gradually increased. The calibration curve is evaluated from a free strain of the specimen. Temperature is measured during the experiment and compensation is done off-line, by calculation.

3.2. Sensitivity to non-axial and non-uniform loading conditions

FBG sensors are sensitive to various influences. When the uniform and uniaxial deformation is measured, spectrum peak shifts to the left (compressive stress) or to the right (tensile stress), see Fig. 3. It is proper behaviour of the FBG sensor. Non-uniform uniaxial strain field causes splitting of spectrum peak (see Fig. 4). This behaviour is typical for gratings which are only partly embedded. Grating period then changes along the sensor. FBG sensors integrated in composite are exposed to complex non-uniform stress field because of anisotropy and microbends, which can lead to a distortion of the spectrum (see Fig. 5). Influence of curvature (macrobends) on FBG sensor is pictured in the Fig. 6. Linear dependence of wavelength change on curvature was measured, with slope of -0.56 nm/(1/mm).

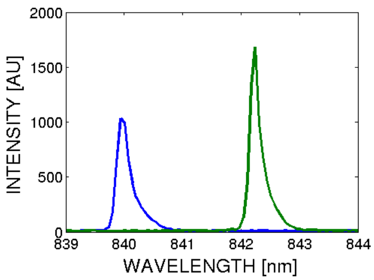

Fig. 3. Typical response of FBG sensor to uniform uniaxial strain (unloaded – left, loaded - right).

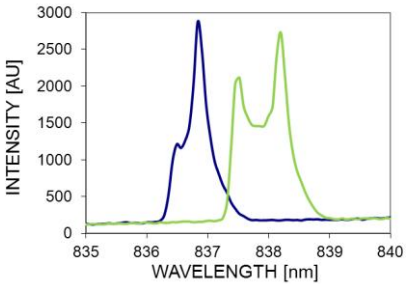

Fig. 4. Response of FBG sensor to non-uniform uniaxial strain field, causing uneven changes of grating period (unloaded – left, loaded - right).

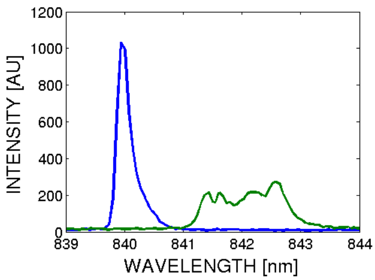

Fig. 5. Distortion of the spectrum reflected from the integrated FBG sensor caused by the complex non-uniform stress field during the tensile test of the C/E specimen.

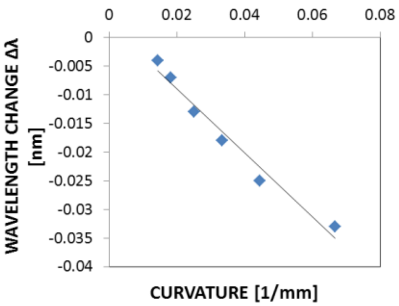

Fig. 6. Wavelength change versus curvature of the FBG sensing area.

3.3. Manufacturing of FBG sensors

Manufacturing methods for Fiber Bragg Gratings can be roughly divided into two groups (for more details see [1]): *Holographic* techniques, which use UV laser beam, split into two beams, to induce grating in the core of the fiber by their interference. *Noninterferometric* techniques, which use periodic amplitude phase mask or periodic exposure of optical fiber to pulsed light to create the grating.

In practice, there are two methods of manufacturing Bragg gratings for sensing purposes (FBG sensor) [5]. Standard procedure is to remove primary coating (usually polyacrylate) from the common telecommunication optical fiber. Then the grating is made using the UV laser and the phase mask (Fig. 7). Fiber is recoated again to restore its protection. Resulting sensor has maximum elongation at break about 1% and reflectivity more than 90%. FBG sensors with higher possible elongation (up to 5%, coated by polyimide or ORMOCER®) are produced by combined process of simultaneous drawing of the fiber and writing of the grating (Fig. 8). Because inscription to the core is done through the primary coating and the energy of the laser is low, the final FBG sensor has lower reflectivity (up to about 30%), but better mechanical properties.

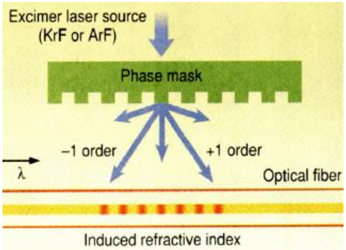

Fig. 7. Scheme of principle of the phase mask method [5].

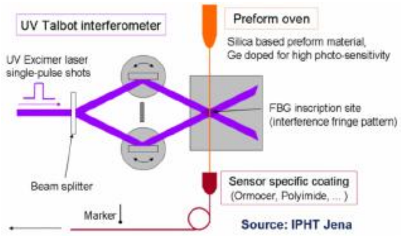

Fig. 8. Scheme of principle of the drawing method [5].

3.4. Multiplexing of FBG sensors

Optical sensors are convenient solution for multiplexing (joining of multiple signals to one conductor), because they are both sensors and conductors of signal. The most common multiplexing methods are, for example, Time Division Multiplexing (TDM) or Wavelength Division Multiplexing (WDM). For more details see [6].

In case of the FBG sensors, two basic multiplexing schemes are used. *Parallel*, in which optical devices are used to combine signals from particular optical fibers with gratings. Each sensor can use full width of the spectrum from the optical source, but scanning speed is limited by the speed of the electronics. In case of the *serial* scheme, so-called “FBG chain” is created from the particular FBG sensors in one optical fiber. Sensing speed is then not limited by the speed of the switching between the fibers. Main drawback is limitation of the spectrum width of the FBGs. When the one FBG from the chain is stretched and the adjacent FBG is compressed, their spectra could interfere, which would lead to measurement errors.

4. Examples of measurements

4.1. Monitoring of composite repair patches

Skin Doubler Specimen (SDS) type was used to model repair patch, which consists of aluminium body and two composite patches, bonded with film adhesive (see Fig. 9). Specimens were periodically loaded on increasing load levels. Changes of the strain amplitude were detected by strain gages, installed on the edges of patches and by FBG sensor, which was integrated in the film adhesive layer, see Fig 10.

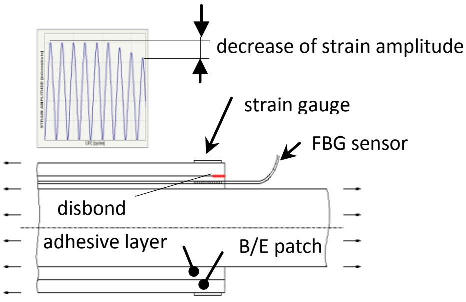

Fig.9. Principle of detection of disbonding during tensile fatigue loading of Skin Double Specimen [7].

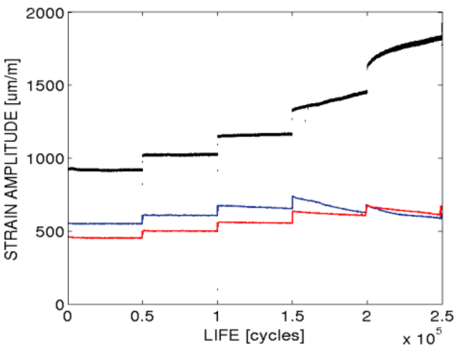

Fig. 10. Changes in strain amplitudes detected by the FBG sensors and strain gages during the fatigue tests[7].

Specimens were loaded by force-controlled periodic tensile load (R=0), at the load levels from 4.4 kN to 9.0 kN. Each load level lasted 50,000 cycles and specimens were loaded to the final fracture. Loading frequency was about 2.2 Hz. Time of the disbonding initiation was defined as a life cycle count, at which strain amplitude decreased by more than 10%. All FBG sensors remained functional even after the specimen fracture. Strain gages and FBG sensors showed good agreement in the determination of the beginning of the patch disbonding. Integrated FBG sensors gave better response to strain, compared to the strain gages. Moreover, they provide possibility of a disbond monitoring using the analysis of reflected optical spectra. For more details see [7].

4.2. Measurement of elastic-plastic deformation

A large elastic-plastic strain measuring capabilities of FBG sensors were researched using steel specimens of a tubular shape (see Fig. 11). Strain gages and FBG sensors were used to measure strains on tapered part of the specimen. Specimens were tested in cyclic alternating force loading mode at frequencies from 0.20 Hz to 0.25 Hz and load levels from 44 kN to 60 kN.

High levels of strains (about 1.2 % in compressive and tensile deformation) were reached by both the strain gages and the FBG sensors (see Fig 12). Differences in measured strain ranges were up to 6.4 %, which is within the common range of measurement error. This could be caused by the sensor misalignment or by the unsymmetrical fixture of specimen in the testing machine. All strain gages remained functional during strain levels, on which FBG sensors were damaged. Nevertheless, FBG sensors can be used for measurement of elastic-plastic low-cycle fatigue strain. For a more detailed description of experiment see [8].

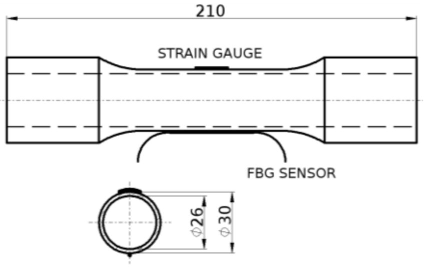

Fig. 11. Specimen dimensions with configuration of the sensors. [8].

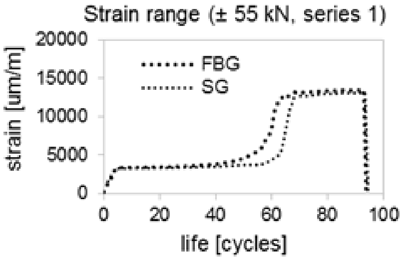

Fig. 12. Comparison of strain ranges, as determined from strain gauges and FBG sensors [8].

5. Conclusions

The experimental investigation of properties of FBG sensors has shown, that they can be successfully used for local as well as for global strain changes monitoring. Adverse effect can be compensated. Deformation and lifetime limits are comparable with the classical resistance strain gauges. Main advantages are the possibility of integration of fibers into composite structures and their insensitivity to electromagnetic fields.

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