Fiber Bragg grating sensors

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A brief overview of fiber Bragg grating based sensor technology from sensor head, read out unit and commercial applications is given. Fiber Bragg grating based sensor systems are becoming mature rapidly. Components for commercial pressure sensors and temperature sensors are available and slowly getting accepted. However, many advantages of the fiber Bragg grating as sensor are still not fully recognized by a wider audience. Properties such as the ability for distributed sensing, small size, light weight, immune for electromagnetic interference and resistance to harsh environments are examples of the advantages of fiber Bragg grating based sensors.

Introduction

A Fiber Bragg Grating (FBG) is a periodic perturbation of the refractive index along a couple of millimetres of fiber length which is formed by exposure of the core using ultraviolet light and a phase mask [1]. The index perturbation within the core of the monomode fiber acts as a filter, which reflects an incident optical field. Reflection of the incident field is maximized if the wavelength of the incident field matches the periodic index perturbation by,

$$\lambda_B = 2 n_{eff} \Lambda \qquad (1)$$

in which λ_B is the Bragg wavelength, n_{eff} the effective refractive index of the fiber and Λ the grating period. See Figure 1.

Any change in the grating period or effective index, either by temperature or strain will vary the grating period and/or the effective refractive index and therefore shift the central reflectance wavelength λ_B. These properties can be used for sensor purposes.

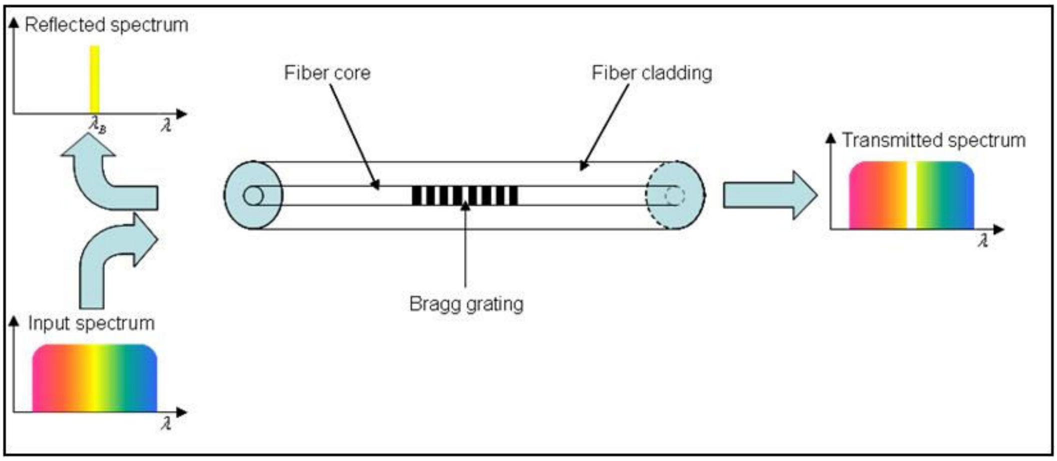

Figure 1: schematic representation of the Fiber Bragg grating principle

FBG strain and temperature sensor

To illustrate the FBG as sensor first a simple FBG based temperature sensor is discussed. The temperature dependence of the grating period and effective refractive index on temperature can described as [2],

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \tag{2}$$

In which α and ξ represent the thermal expansion coefficient and thermo optic coefficient respectively. For the temperature response of the sensor the latter is the dominant effect ($\alpha = 0.55 \cdot 10^{-6}$ and $\xi = 6.7 \cdot 10^{-6}$). Typical temperature coefficient of a FBG with central wavelength of 1550 nm is ~11 pm/K.
Alternatively, a wavelength shift of the FBG can be induced by elongation of the fiber. Stretching the fiber will change the grating pitch and in turn the reflective wavelength will shift. Fiber elongation is normally expressed in terms of strain ε which represents the normalized length change, i.e. 1 με represents 1 μm elongation of 1 m fiber length. The wavelength dependency on strain for a FBG with central wavelength of 1550 nm is ~1.2 pm/με.
To illustrate a practical example of strain sensing consider a beam of a certain length, l_0 and thickness, d. The beam will bent if supported on both edges and a force, F is applied to the beam centre, see Figure 2.

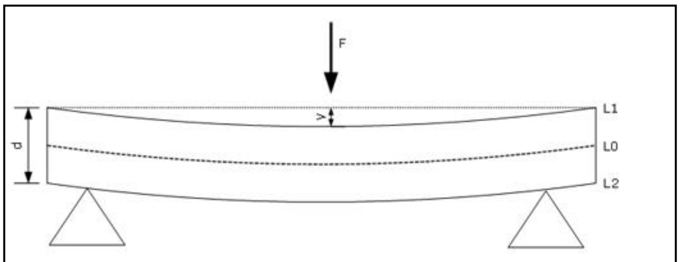

Figure 2: illustrative image of a 2d beam bent by a force F.

Due to the applied force the length of the beam will change both at the bottom (l_2) and top (l_1) side of the beam, while at the centre of the beam the length, (l_0) remains unchanged. The positive length change of l_2 with respect to l_0 can be approximated by considering the shape of l_0 as a part, ϕ of a circle with radius, R. Thus, $l_0 = \phi R$, which implies that $l_2 = \phi\left(R + \frac{d}{2}\right)$. The strain at the bottom side of the beam can be rewritten to $\varepsilon = \frac{d}{2R}$. Using straightforward goniometric functions the radius of the circle, R can be rewritten as a function of the beam original length and beam deflection, y resulting into

$$\varepsilon = \frac{1}{2} \cdot \frac{d \cdot y}{\left(\frac{l_0}{2}\right)^2 \cdot \sqrt{1 + \frac{y^2}{\left(\frac{l_0}{2}\right)^2}}} \tag{3}$$

For a beam width of 1 mm and beam length of 50 mm, deflected by 100 μm the strain at the surface is around 80 με (the difference in strain between the top and bottom side of the beam is the sign). If a FBG is attached to a side of the beam, the wavelength shift due to the deflection is around 96 pm (using the strain to wavelength dependence given earlier).

FBG readout unit a.k.a. interrogator

From the previous paragraph, a FBG wavelength shift in the order of a picometer has to be detected for a high resolution sensor system. The resolution of the most dedicated commercial optical spectrum analyzer is often limited to about 20 picometers while the measurement time is seconds. Therefore dedicated FBG interrogators have to be developed for sensing application.
Several commercial interrogator systems are currently on the market. Most of these systems are based on a tuneable filter/source, which sweeps a narrow wavelength band across a certain span over time. See Figure 3 for a simplistic overview.

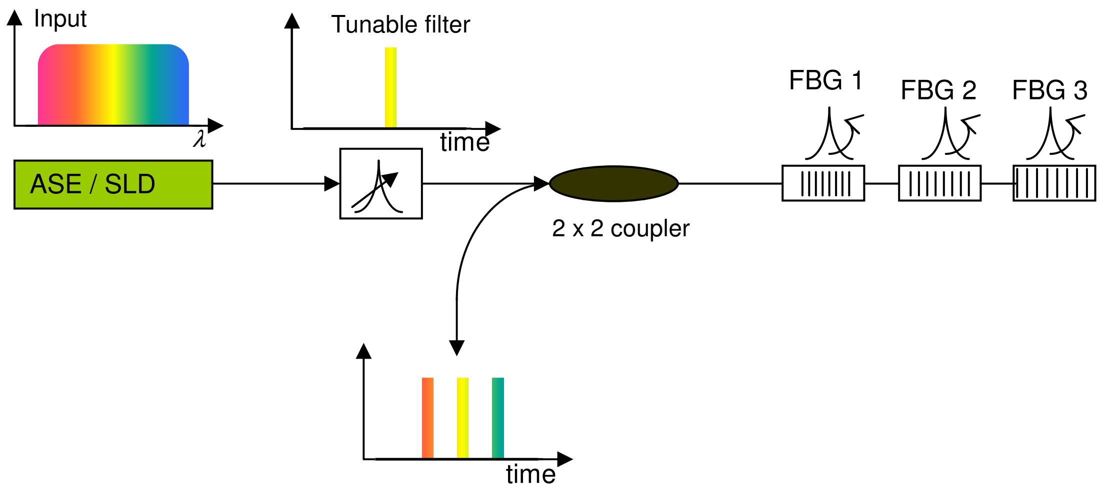

Figure 3: Schematic representation of a common fiber Bragg interrogator

An important notice illustrated in Figure 3 is the number of FBG sensors attached to a single fiber fed from the interrogator unit. By choosing the reflective wavelength of each sensor such that there is no spectral overlap between other sensors, multiple sensors can be read simultaneously utilizing only a single fiber.

Advantages of Fiber Bragg based sensors and application examples

An increasing demand is observed for sensing solutions in all kind of applications and environments. For each application, fiber Bragg grating based sensor technology has the potential to provide a dedicated solution. E.g. the advantage of distributed sensing as described in Figure 3 can be exploited even further by changing the sensitivity parameter for each FBG sensor by combining both temperature and pressure sensors on a single fiber. This multi parameter sensing principle has been demonstrated in [3]. In addition, [3] and [4] also shows an impressive operational temperature range of -200°C up to 300 °C.

Operations under harsh environments like space or in the oil- and gas industry are markets which are starting to accept and more importantly appreciate the fiber Bragg grating based technology. Each market tries to exploit the technology differently, and often very successfully. An example of a recent innovation for the oil and gas industry is a fiber Bragg grating based flowmeter which can be used in the harsh surface- and downhole conditions, i.e. temperatures exceeding 300°C and pressures up to 100 bar [4].

Another market in which fiber Bragg grating technology has already been accepted for some years is structural health monitoring. Buildings, bridges and other kinds of large structures are being continuously monitored by fiber Bragg grating sensors to verify their structural integrity, see for example [5].

By listing these examples, we demonstrate that each market and application has its individual benefits from using fiber Bragg grating based sensors. Note however, that the sensor system optimization does not end at the sensor part. In fact the complete system must be taken into account. Optimization of the interrogator in terms of Cost of Goods, wavelength span, resolution and sweep frequency are among the parameters to tweak to obtain the optimal fiber Bragg grating sensor system for each specific application.

References

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