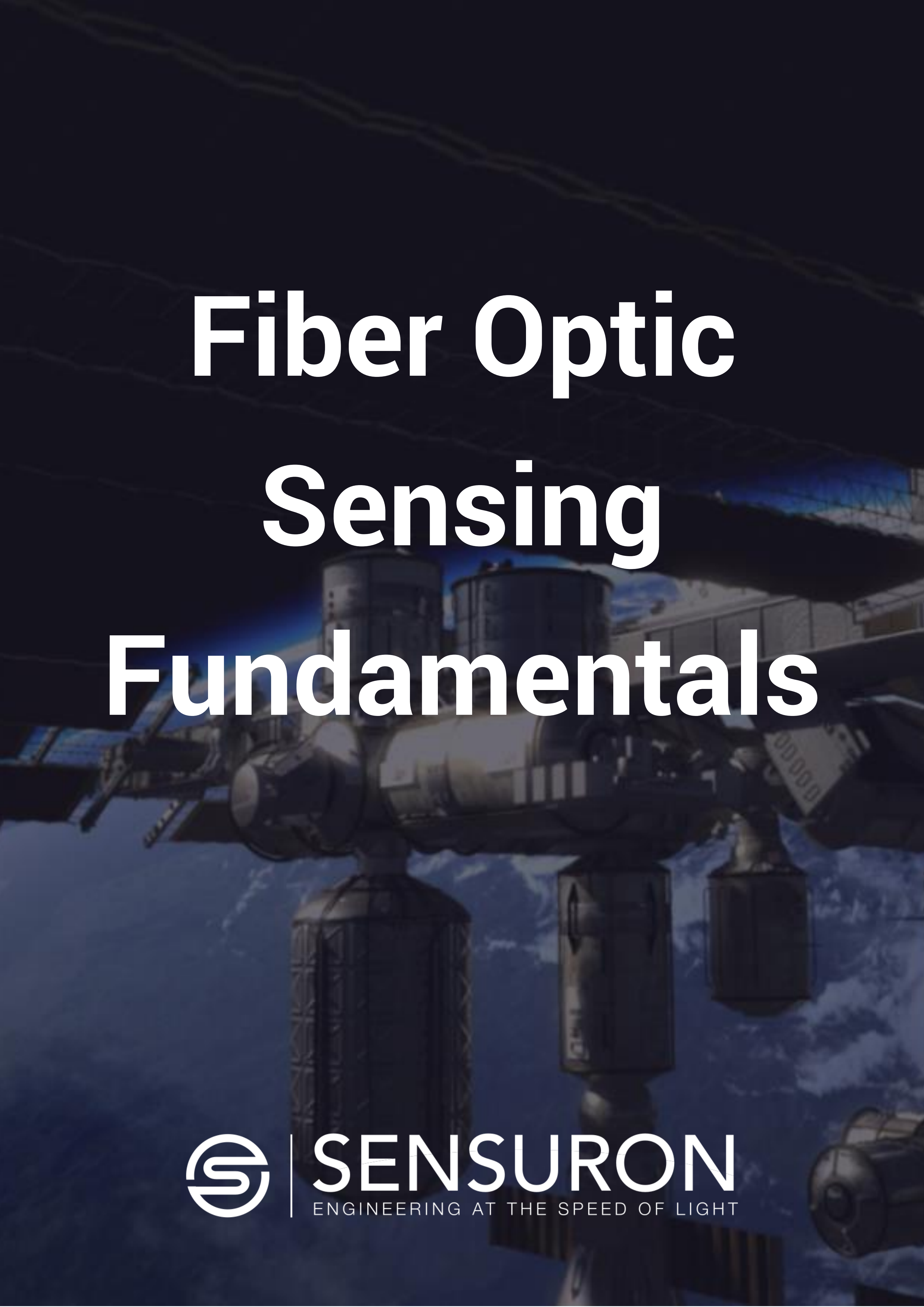
Fiber Optic Sensing Fundamentals



SENSURON
ENGINEERING AT THE SPEED OF LIGHT

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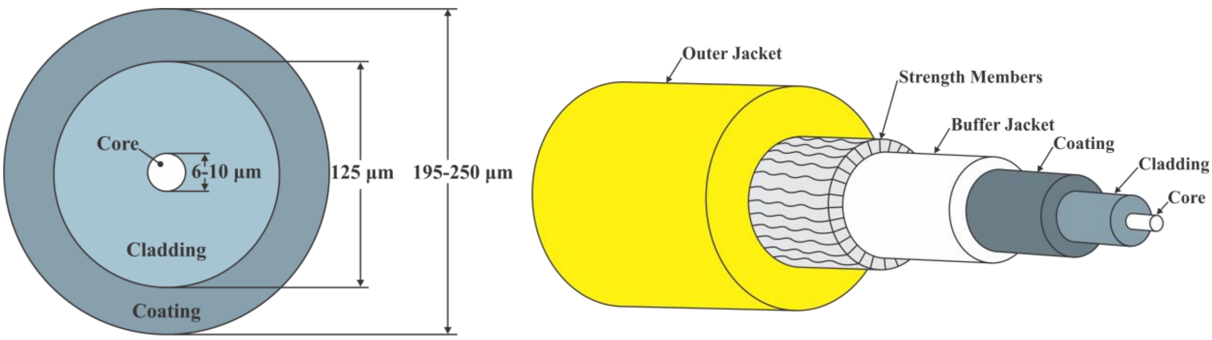
1 Introduction

Fiber optic sensors offer several unique advantages over conventional electrical based sensors. These advantages include immunity to electromagnetic interference, being extremely lightweight and small, embeddability, and excellent fatigue life. The most significant advantage of the Sensuron technology is the ability to acquire spatially continuous information along the entire length of an optical fiber with only a single lead cable. Single point measurement devices, such as a strain gauge, only capture information at a discrete point while requiring multiple lead cables and hours to perform an installation. A single fiber spanning upwards of 10 m, in contrast, can act akin to thousands of strain gauges or thermocouples installed adjacent to one another without the cumbersome associated wire bundles. For these reasons, fiber optic sensors are employed in wide variety of industries including civil, mechanical, aerospace, medical, nuclear, oil, wind energy, and automotive.

2 Structure of an Optical Fiber

An optical fiber is comprised of three primary components: the core, cladding, and coating. The core and cladding are both made from silica glass, however, the optical properties of each differ. Specifically, the refractive index (n) of the core, which describes the speed at which light travels through a material, is slightly increased during the manufacturing process. This refractive index profile is fundamentally what forms the waveguide, enabling light to be transmitted over long distances in the core with very low attenuation. The outermost layer, the coating, is applied to the outside of the cladding to increase the robustness of the fiber while protecting the glass from contaminants such as dirt and moisture. For strain sensing applications, this coating is extremely stiff to provide a load path for strain to transfer from the substrate into the core. These three primary layers of the optical fiber structure are depicted in Figure 1(a), as well as the typical dimensions of each for single-mode fiber.



(a) (b)

Figure 1: (a) The typical cross-section of single-mode fiber. Lead fiber is often packaged with additional protective layers to form a fiber optic cable, as shown in (b).

For additional environmental protection, fiber is often encased within auxiliary buffer tubes or jackets to form a fiber optic cable, otherwise known as a patch cord. As shown in Figure 1(b), fiber is commonly packaged in a tight buffer jacket and loosely incorporated into an outer jacket filled with strength members such as Kevlar strands. For the Sensuron technology these patch cords serve as standoff cables between the sensor and the interrogator.

3 The Fiber Bragg Grating

Due to its high signal to noise ratio, the fundamental component that most fiber optic sensing is based on is called a Fiber Bragg Grating (FBG). The optical equivalent of a foil strain gage or thermocouple, an FBG is a sensor inscribed into the core of the optical fiber by periodically modulating the refractive index of the core, as shown in Figure 2.

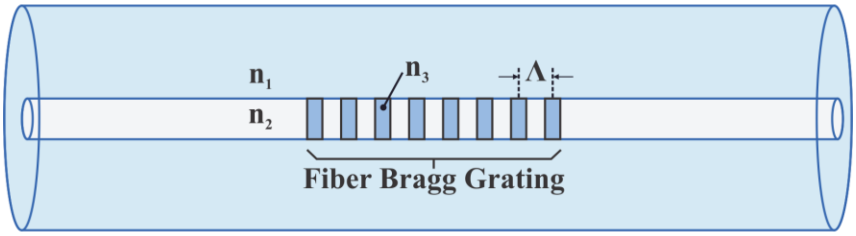


Figure 2: The Fiber Bragg Grating is formed in the core by a series of refractive index modulations with period Λ. A single grating is composed of thousands of modulations, but only a handful are shown for clarity.

The resulting grating structure acts as a wavelength selective mirror for light propagating through the fiber. Most wavelengths of light will travel through the grating uninterrupted. However, constructive interference occurs at one specific wavelength and light is partially reflected back down the fiber. This phenomenon is illustrated in Figure 3, where a broad spectrum light beam is passed through the fiber.

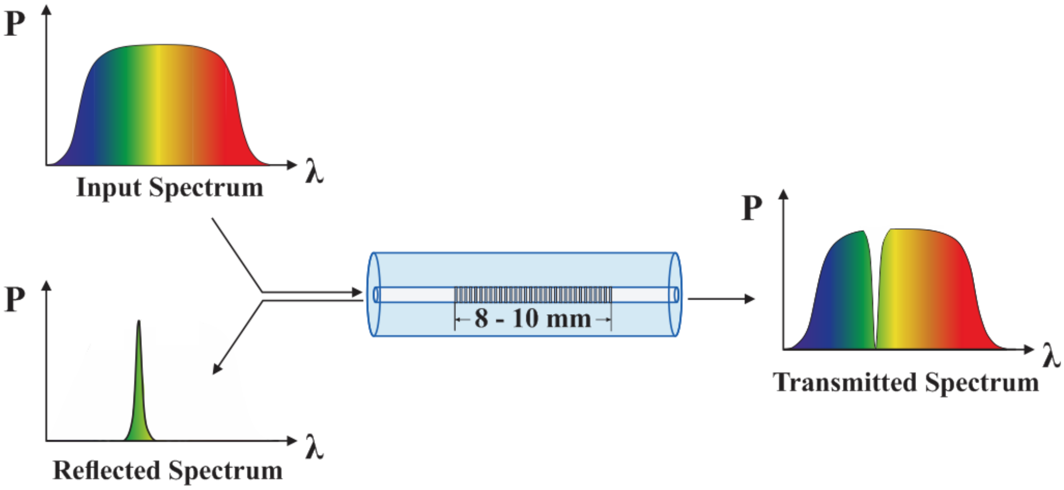


Figure 3: The working principle of a Fiber Bragg Grating

The wavelength which an FBG will reflect is called the Bragg wavelength λ_b, defined as:

$$\lambda_b = 2n_{eff}\Lambda \quad (1)$$
$$\text{where } n(\epsilon, T), \Lambda(\epsilon, T)$$

In equation (1), n_{eff} is the effective refractive index of the core and Λ is the grating period, quantities that both depend on mechanical strain (ϵ) and temperature (T). Thus, the reflected FBG wavelength can be used to determine strain or temperature at that location along the fiber.

$$\lambda_b(\epsilon, \Delta T) = 2n_{eff}\Lambda \quad (2)$$

4 Optical Transduction

Optical transduction involves monitoring the reflected FBG wavelength and correlating that information to either strain or temperature. Starting at equation (2), the sensitivity of the Bragg wavelength to strain and temperature is derived independently. Consider the first derivative of eq. (2) with respect to changes in the grating length (L).

$$\frac{d\lambda_B}{dL} = 2n_{eff}\left(\frac{d\Lambda}{dL}\right) + 2\Lambda\left(\frac{dn_{eff}}{dL}\right)$$

$$\frac{\Delta\lambda_B}{\Delta L} = \frac{1}{\Lambda}\frac{d\Lambda}{\mathrm{dL}}\lambda_B + \frac{1}{\mathrm{n_{eff}}}\frac{d\mathrm{n_{eff}}}{\mathrm{dL}}\lambda_B$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \Delta L\left(\frac{1}{\Lambda}\frac{d\Lambda}{\mathrm{dL}} + \frac{1}{\mathrm{n_{eff}}}\frac{d\mathrm{n_{eff}}}{\mathrm{dL}}\right)$$

$$\Rightarrow \frac{\Delta\lambda_B}{\lambda_B} = (1-\rho_e)\epsilon \quad (3)$$

ϵ is the axial strain along the fiber and ρ_e is the photo-elastic coefficient. The photo-elastic (or strain-optic) coefficient characterizes the change in refractive index due to changes in material density as the fiber compresses or elongates. Next, consider the first derivative of eq. (2) with respect to temperature.

$$\frac{d\lambda_B}{dT} = 2n_{eff}\left(\frac{d\Lambda}{dT}\right) + 2\Lambda\left(\frac{dn_{eff}}{dT}\right)$$

$$\frac{\Delta\lambda_B}{\Delta T} = \frac{1}{\Lambda}\frac{d\Lambda}{\mathrm{dT}}\lambda_B + \frac{1}{\mathrm{n_{eff}}}\frac{d\mathrm{n_{eff}}}{\mathrm{dT}}\lambda_B$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \Delta T\left(\frac{1}{\Lambda}\frac{d\Lambda}{\mathrm{dT}} + \frac{1}{\mathrm{n_{eff}}}\frac{d\mathrm{n_{eff}}}{\mathrm{dT}}\right)$$

$$\Rightarrow \frac{\Delta\lambda_B}{\lambda_B} = \Delta T(\alpha + \eta) \quad (4)$$

α is the coefficient of thermal expansion of silica and η is the so called thermo-optic coefficient. α relates the expansion/contraction of the fiber and associated change in grating period (Λ) to changes in temperature. η describes the temperature dependency of the refractive index (n). Combining equations (3) and (4) yields an equation that fully describes the sensitivity of the Bragg wavelength to strain and temperature.

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\epsilon + \Delta T(\alpha + \eta) \quad (5)$$

Equation (5) is often rewritten in terms of the gage factor, κ.

$$\frac{\Delta\lambda_B}{\lambda_B} = \kappa\epsilon + \Delta T(\alpha + \eta) \quad (6)$$

Mechanical strain and temperature are the two quantities that the Sensuron technology measures directly. Various installation and temperature compensation techniques are employed to decouple the measurement. Note that equation (6) only describes the first-order sensitivity of the Bragg wavelength to strain and temperature. Coating and other effects typically dictate that the temperature sensitivity becomes nonlinear over an extended range.