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Strain-Temperature Discrimination Using a Single FBG at Cryogenic Region

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Abstract: A simple technique is presented to discriminate the Strain and Temperature with a single Fiber Bragg Grating (FBG) at cryogenic regime. The single FBG is divided into two parts, one half is without coating (FBG1) and other half is coated with Cyno-Acrylic Adhesive (FBG2). The measured temperature and strain sensitivities of the FBG1 are 4.05×10^{-6} /K and 2.13×10^{-6} /$\mu\varepsilon$ and FBG2 are 1.39×10^{-5} /K and 1.72×10^{-6} /$\mu\varepsilon$ respectively. FBG2 is more sensitive to low temperature and FBG1 is more sensitive to axial strain. *Copyright © 2011 IFSA.*

Keywords: Fiber Bragg grating, Coating, Strain, Temperature.

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1. Introduction

The Optical fiber sensors that are based on Fiber Bragg Gratings (FBG's) have emerged as promising sensing devices to measure parameters like displacement, strain and temperature. Compared with electric sensors, FBG sensors offer numerous advantages such as the EMI immunity, compact size, high sensitivity and multiplexing capability. The success of FBG sensors in simultaneous measurement of strain and temperature has facilitated strain-temperature discrimination at cryogenic regime. In addition, they have an inherent self-referencing and are easily multiplexed in a serial fashion along a single fiber. Recently, several techniques have been proposed to discriminate the strain and temperature, such as Dual-wavelength superimposed FBGs [1], Fabry–Perot Cavity [2], Tilted FBG [3, 4], Birefringence effect [5], Superstructure FBG [6], Hybrid FBG Long Period Fiber Grating [7], step spectrum profile FBG arrangement [8] and Single FBG[9, 10]. The discrimination of the temperature and strain were carried out at room temperature and above.

In this paper, the performance of a half coated single FBG sensor for discrimination between the strain and temperature at cryogenic temperatures is studied. Half of an FBG is uncoated (FBG1) and another half is coated with Cyno-Acrylic Adhesive (FBG2). The FBG1 has much larger strain response than FBG2, and a smaller temperature response, which gives the potential for strain-temperature discrimination.

2. Theory

The principle of operation relies on the use of a single uniform FBG, where half part of it is coated with a material having large thermal expansion coefficient like Cyno-Acrylic Adhesive (FBG2) and other half is uncoated (FBG1). These two parts posses different sensitivities for strain and temperature.

The schematic diagram of the FBG structure under investigation is shown in Fig. 1 [11, 12]. When the FBG is stretched, the average strain experienced by the FBG, ε, is given by

$$\varepsilon = \frac{\Delta l_1 + \Delta l_2}{l} \tag{1}$$

where l is the length of the whole grating region and Δl_1 and Δl_2 are the elongations of FBG1 and FBG2 portions respectively. The strain in FBG1 and FBG2 are given by

$$\varepsilon_1 = \frac{2}{1 + \frac{A_1 E_1}{A_2 E_2}} \varepsilon \tag{2}$$

and

$$\varepsilon_2 = \frac{2}{1 + \frac{A_2 E_2}{A_1 E_1}} \varepsilon \, , \tag{3}$$

where A_1, A_2, E_1 and E_2 are the area of cross-section and Young's modulus of FBG1 and FBG2 respectively.

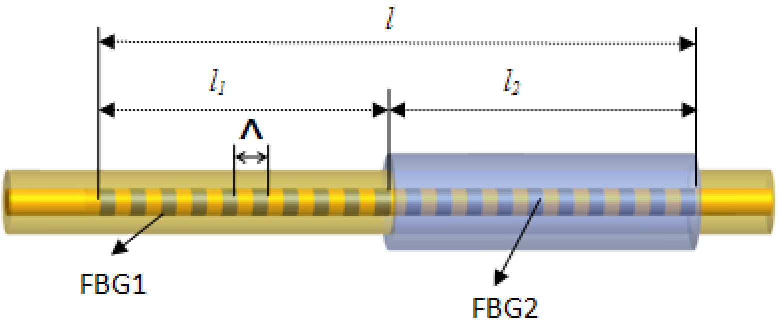


Fig. 1. The schematic of the half coated FBG.

In general, the change in Bragg wavelength of the grating $\Delta\lambda_{\mathbf{B}}$, due to the combination of strain and temperature is given as

$$\Delta\lambda_B(\varepsilon, T) = m_\varepsilon \Delta\varepsilon + m_T \Delta T \tag{4}$$

where $\Delta\varepsilon$ and ΔT are the change in strain and temperature respectively, and the coefficients m_ε and m_T are strain and temperature sensitivities respectively.

Thus change in Bragg wavelength of the FBG1 and FBG2 are as given below equation 5 and 6 respectively.

$$\Delta\lambda_{B1}(\varepsilon, T) = m_{\varepsilon 1} \Delta\varepsilon + m_{T1} \Delta T \tag{5}$$

$$\Delta\lambda_{B2}(\varepsilon, T) = m_{\varepsilon 2} \Delta\varepsilon + m_{T2} \Delta T \,, \tag{6}$$

where

$$m_{\varepsilon 1} = \frac{2}{1 + \dfrac{A_1 E_1}{A_2 E_2}} m_\varepsilon \text{ and } m_{\varepsilon 2} = \frac{2}{1 + \dfrac{A_2 E_2}{A_1 E_1}} m_\varepsilon .$$

From the above equations, it can be seen that two grating halves respond differently to the applied strain and temperature changes, so that the reflection peak will split into two when strain and/or temperature change occur. As a result, the change of the resonance wavelength with strain and temperature can be represented by

$$\begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} = \begin{bmatrix} m_{T1} & m_{\varepsilon 1} \\ m_{T2} & m_{\varepsilon 2} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \tag{8}$$

The inverse of which would be used to determine the change in temperature and strain and it is can be expressed as

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} -m_{\varepsilon 2} & m_{\varepsilon 1} \\ m_{T2} & -m_{T1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{9}$$

where $\Delta = m_{T1} m_{\varepsilon 2} - m_{\varepsilon 1} m_{T2}$.

3. Experiment

The FBGs used were written in a photosensitive fiber (9/125 µm) by the phase-mask technique, using a KrF excimer laser (248 nm) as a writing laser, at CSIO, Chandigarh, India. The Bragg wavelength at room temperature was about 1545.64 nm. The length of the FBG was 3 cm. Before depositing the Cyno-Acrylic Adhesive coating on one half of the fiber Bragg grating region, the fibre surface is cleaned to remove impurities by applying 2 M nitric acid and isopropyl alcohol is used to remove organic materials. The FBG half region was then coated with Cyno-Acrylic Adhesive is treated as FBG2 and uncoated half region is treated as FBG1. The FBG was cured at room temperature for 8 hrs.

The schematic of the experimental setup is shown in Fig. 2. A ‘K’ type thermocouple with temperature range -200 ^{0}C to 1250 ^{0}C was used as the standard against which the response of the FBG temperature sensor was compared. The FBG and the thermocouple were inserted in the Cryocan containing Liquid Nitrogen (LN_2) and the tip of the thermocouple is adjusted very close to FBG for making the temperature measurements accurate. A small weight of 0.5 gm was attached to the FBG to keep it at constant load. The temperature at the sensing element region was varied by the application of a variable AC voltage to a heating element kept in the LN_2. The temperature of the FBG as measured by the thermocouple was logged. A broadband source of 1.55 µm central wavelength, 50 nm spectral bandwidth was connected to one port of the circulator. The spectral measurement was performed with a reflection scheme using a circulator. The reflection spectrum was observed with an optical spectrum analyzer (Agilent 86142B). The resolution of the optical spectrum analyzer is 0.1 nm, and the peak wavelength displayed to the order of 0.01 nm. The FBG was placed near to the neck of the vessel along with thermocouple for temperature measurement, by applying the constant strain the peak wavelength of the FBG1 and FBG2 are noted. The strain response of both FBG1 and FBG2 are noted by loading different weights at the end of the FBG at constant temperature.

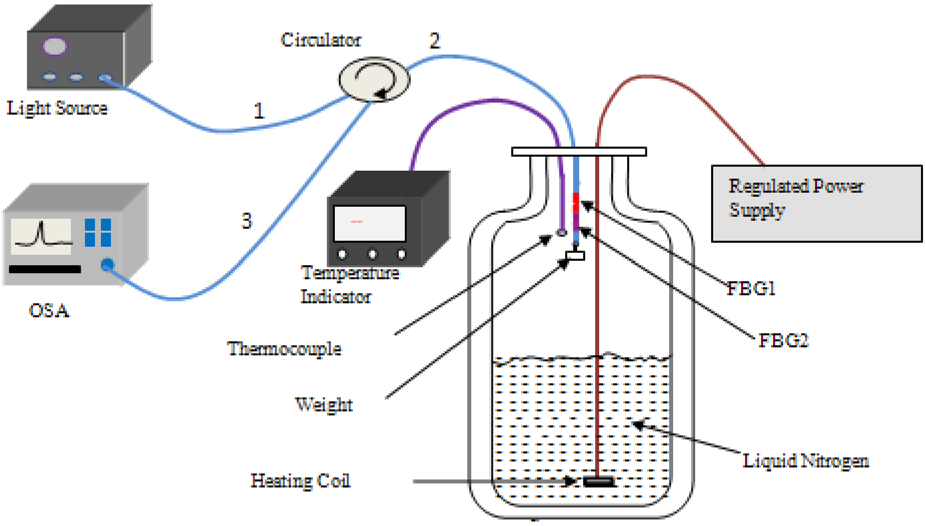


Fig. 2. Schematic experimental setup for stain-temperature discrimination.

4. Results and Discussion

Strain and Temperature response of the FBG1 and FBG2 were measured by applying strain and temperature to the sensor independently.

Fig. 3 shows the experiment results between temperature and shift in Bragg Wavelength. The Bragg wavelength shift is linear up to 150 K and later shows non linearity in both FBG1 and FBG2. This is due to thermal expansion of silica is very less at low temperature. The linear fitting of the graphs in Fig. 3 gives

$$\Delta\lambda_{B1} = 1543.81358 + 0.00626T \tag{10}$$

$$\Delta\lambda_{B2} = 1538.93722 + 0.02149T \tag{11}$$

The shift of the Bragg wavelength in response to the applied temperature of FBG1 and FBG2 are 6.26×10^{-3} nm/K and 21.49×10^{-3} nm/K respectively, and corresponding temperature sensitivities are 4.05×10^{-6} /K and 1.39×10^{-5} /K.

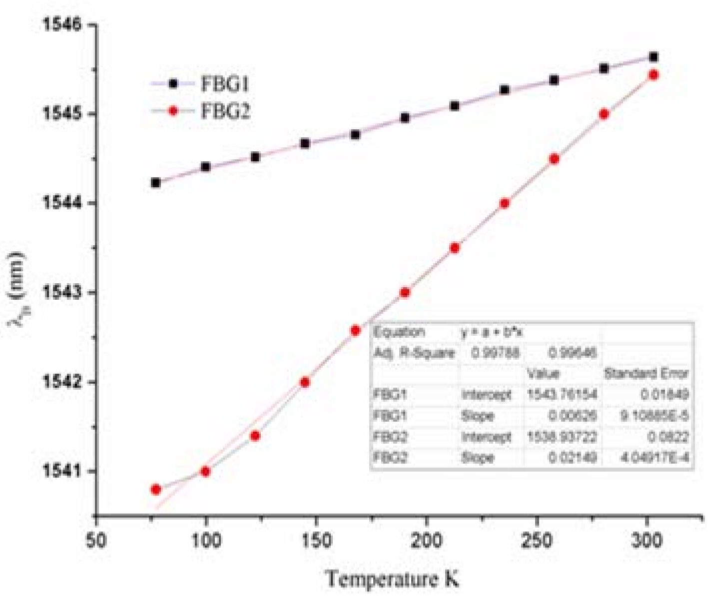


Fig. 3. Bragg wavelength Response of the FBG1 and FBG2 with temperature.

The reflected spectrum of the FBG is at 303 K is shown in Fig. 4 (a). A new peak was appeared along the left side of the spectrum due to effect of cynoacryolate adhesive on the half part of the FBG. As the temperature decreases the single peak split into two and the separation between the two peaks increases and shifted to shorter wavelength Fig. 4 (b). The thermal expansion of cynoacryolate adhesive is more and at low temperature it compresses the FBG, this causes more strain in FBG.

Fig. 5 shows the experimental results of FBG strain response. In this case, the temperature was kept constant at cryogenic level (150 K), while the strain applied was varied from 0 to 278 $\mu\varepsilon$. The linear fitting of the graphs in Fig. 5 gives

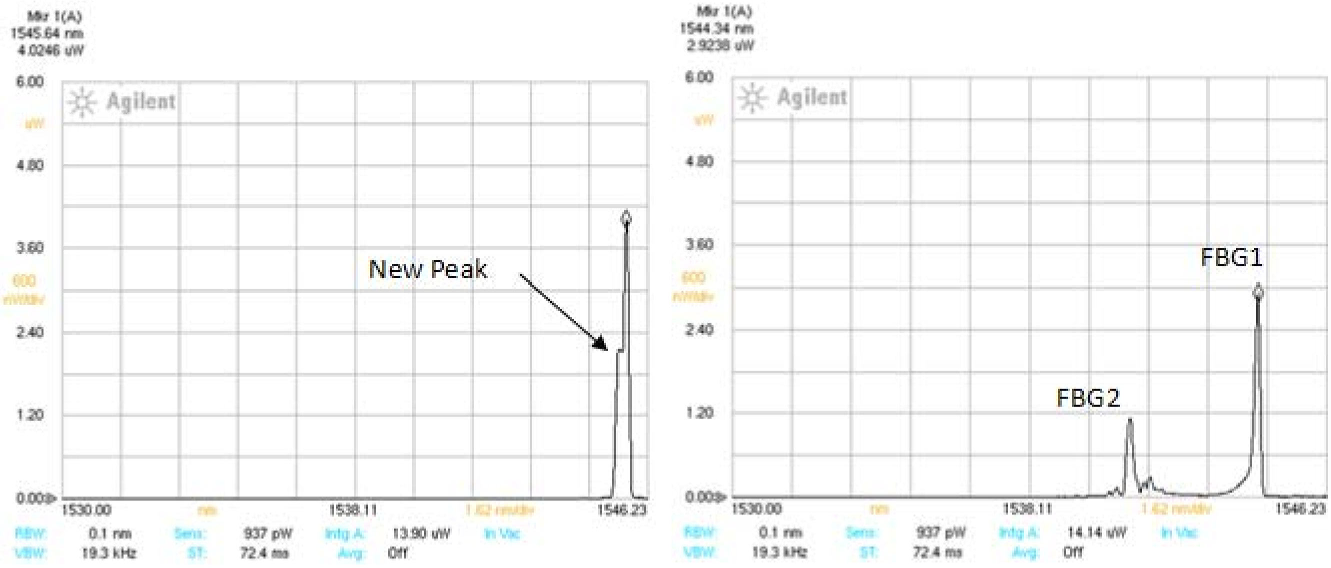
$$\Delta\lambda_{\mathbf{B}1} = 1544.27516 + 0.00329\varepsilon \tag{12}$$

$$\Delta\lambda_{\mathbf{B}2} = 1543.95439 + 0.00266\varepsilon \tag{13}$$

The measured shift of the wavelength in response to the applied strain of FBG1 and FBG2 are 3.29×10^{-3}nm/ $\mu\varepsilon$ and 2.6603×10^{-3}nm/ $\mu\varepsilon$ respectively, corresponding strain sensitivities are $2.13\times10^{-6}/\mu\varepsilon$ and $1.72\times10^{-6}/\mu\varepsilon$. This shows that strain sensitivity is more at low temperature then high temperature.

Experimental results also show that, the FBG1 is more sensitive to strain and less sensitive to temperature than FBG2. This is good for strain and temperature discrimination. From the slopes of equations (10)-(13) gives the simultaneous measurement of the strain and temperature and is represented in a matrix form

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = 49.2132 \begin{bmatrix} -1 & 1.2368 \\ 8.079 & -2.3534 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{14}$$



(a) (b)

Fig. 4. Reflection spectrum of FBG at a) 303K and b) 77k.

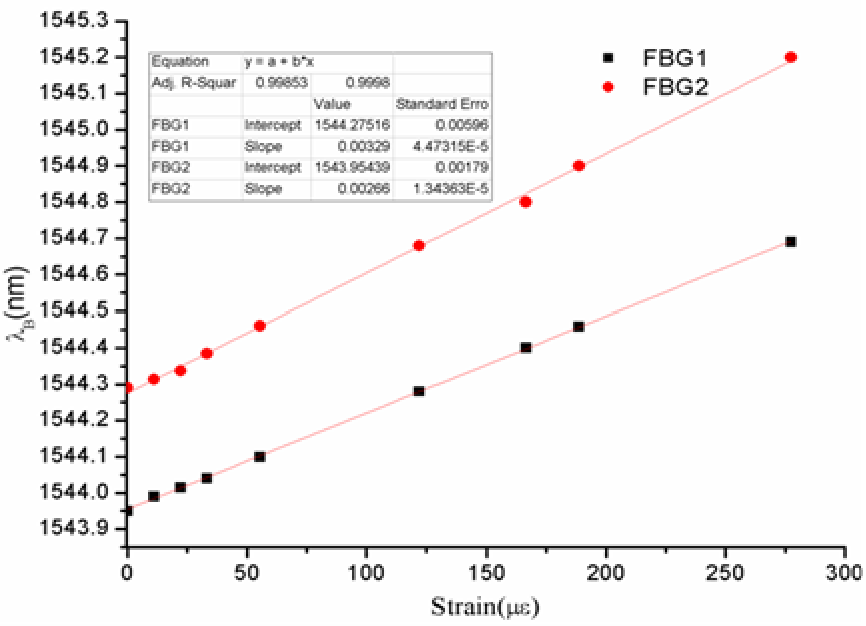


Fig. 5. Response of the FBG1 and FBG2 with strain.

5. Conclusion

We have demonstrated the feasibility of discriminating the strain and temperature using a single FBG coated by Cyno-Acrylic Adhesive to the half of its length. As the temperature decreased from 303 K to 77K the structural transition of the FBG was found. This transition caused splitting of the waveforms characterizing the Bragg gratings. The strain response of the sensor was measured at 100 K by varying the applied strain from 0 to 278 $\mu\varepsilon$. The experimental results show that the FBG2 is more sensitive to temperature and FBG1 is more sensitive to strain. The temperature and strain sensitivities of the FBG1 are 4.05×10^{-6}/K and $2.13\text{x}10^{-6}/\mu\varepsilon$ and FBG2 are 1.39×10^{-5}/K and $1.72\times10^{-6}/\mu\varepsilon$ respectively.

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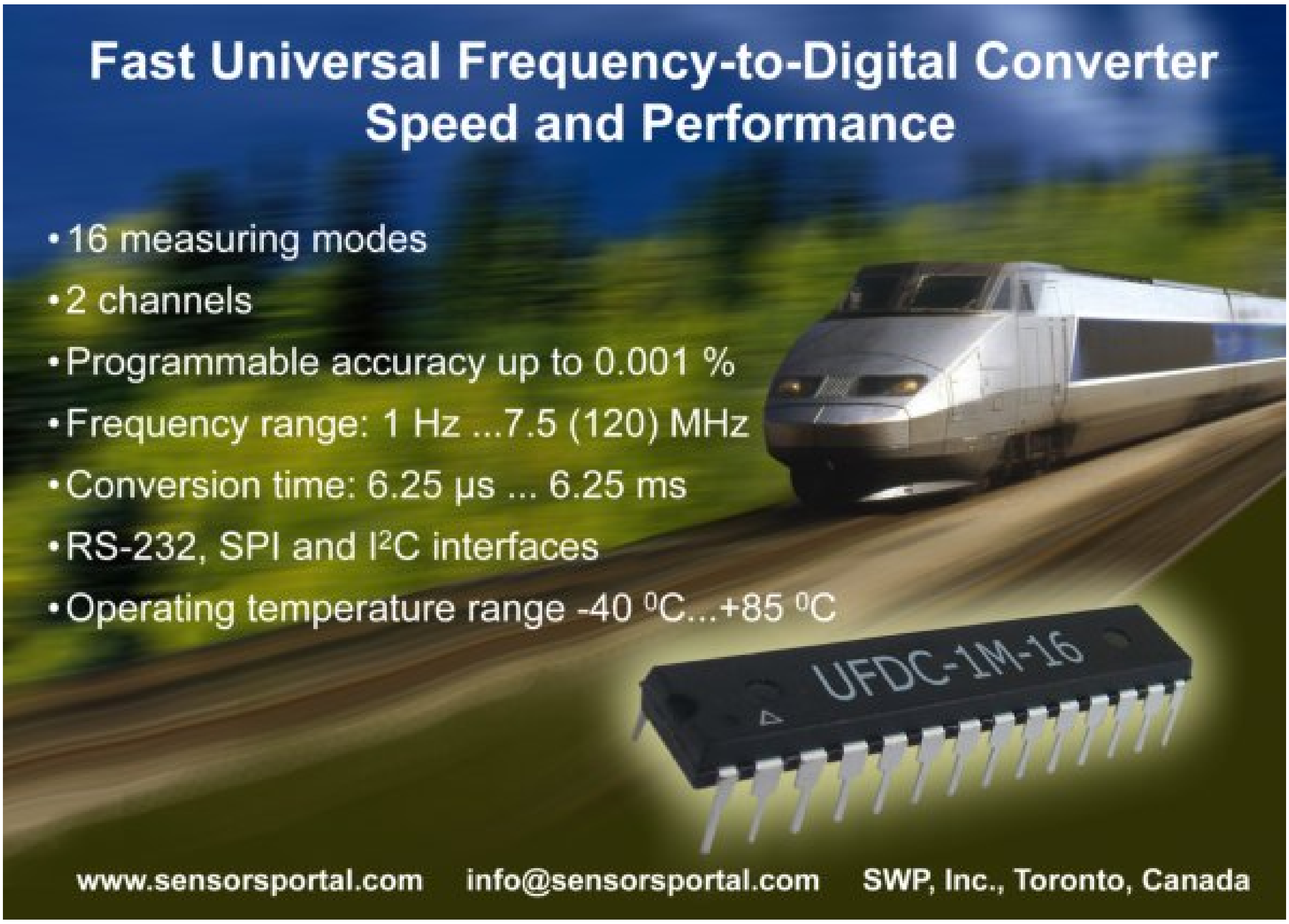
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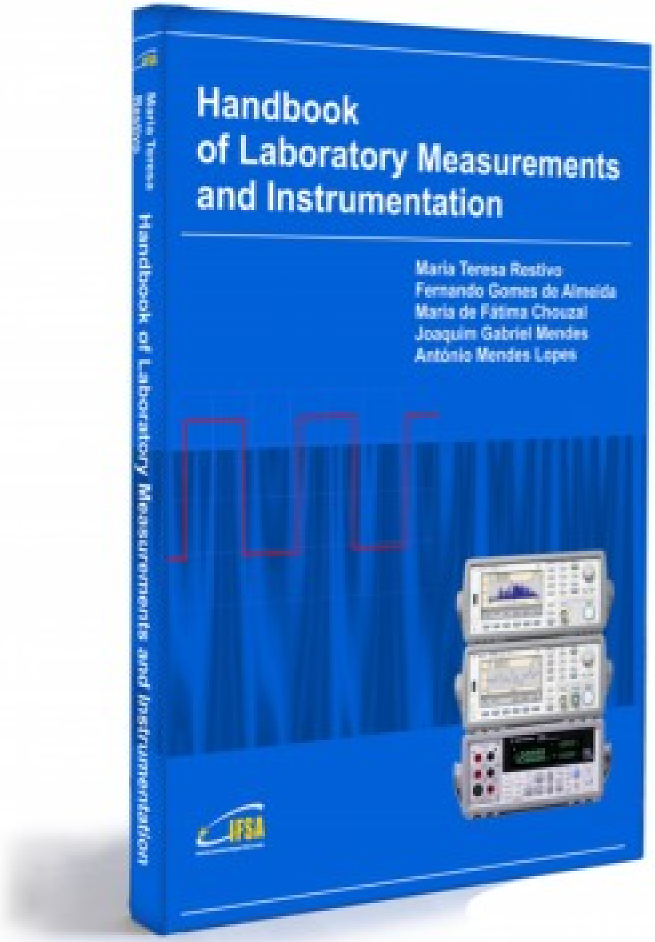

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