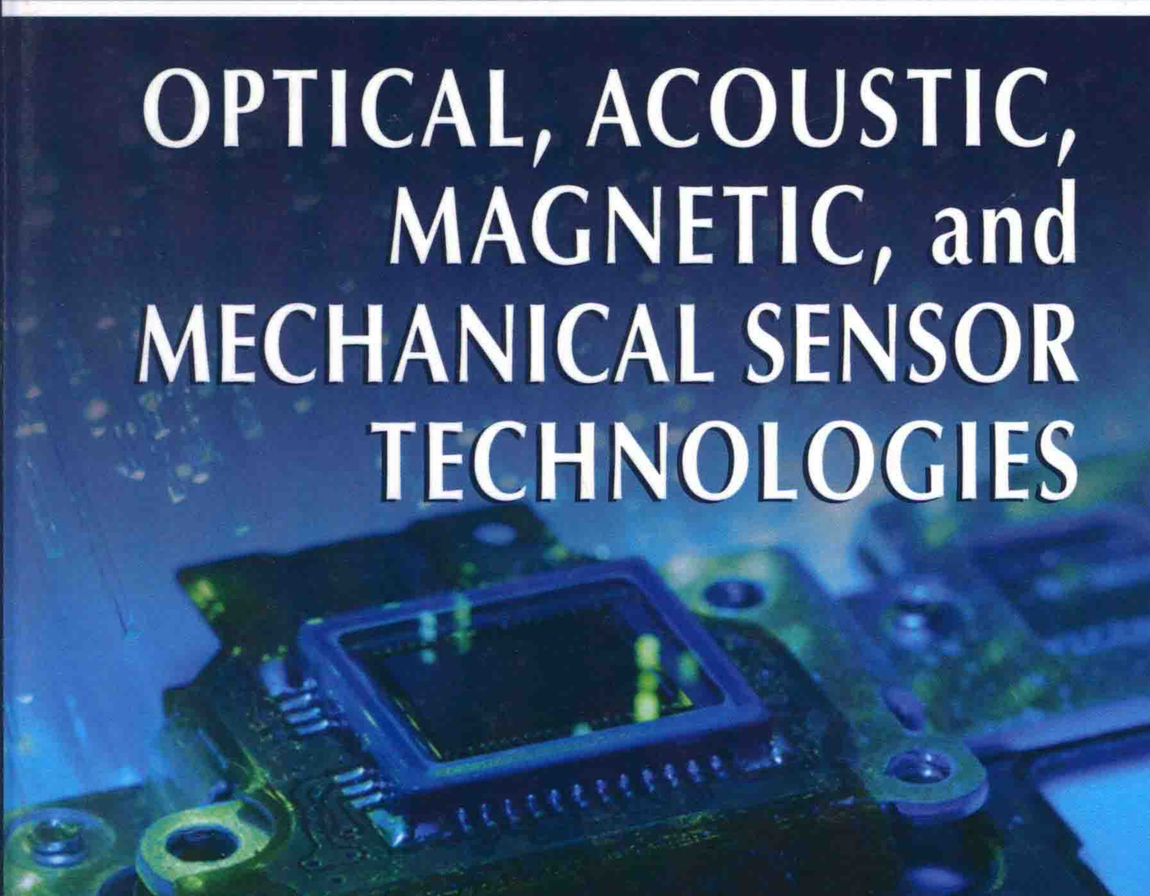
OPTICAL, ACOUSTIC, MAGNETIC, and MECHANICAL SENSOR TECHNOLOGIES



Edited by
Krzysztof Iniewski

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OPTICAL, ACOUSTIC, MAGNETIC, and MECHANICAL SENSOR TECHNOLOGIES

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Preface

Sensor technologies are a rapidly growing topic in science and product design, embracing developments in electronics, photonics, mechanics, chemistry, and biology. Their presence is widespread in everyday life; they sense sound, movement, optical, or magnetic signals. The demand for portable and lightweight sensors is relentless, filling various needs in consumer electronics, biomedical engineering, or military applications.

The book is divided into two parts. The first part deals with optical and acoustic sensors. Rogério Nogueira starts with optical fiber sensors while Christian-Alexander Bunge and Hans Poisel discuss sensors based on polymer optical fibers. Jeff Chamberlain and Daniel M. Ratner, from the University of Washington, discuss the potential of integrated optical biosensors and silicon photonics. This is followed by chapters by Joey Talghader and Merlin L. Mah on luminescent thermometry and by Andreas Stadler on solar cell analyses. The first part ends with Ellen Holthoff and Paul Pellegrino from the United States Army Research Laboratory describing sensing applications using photoacoustic spectroscopy while Bridget Benson and Ryan Kastner cover the design of underwater acoustic modems.

The second part of the book deals with magnetic and mechanical sensors. Hendrik Husstedt starts with the topic of magnetic field scanning. Researchers from Université Catholique de Louvain describe artificial microsystems for sensing airflow, temperature, and humidity that they accomplished by combining MEMS and CMOS technologies. Jürgen Hildenbrand, Andreas Greiner, and Jan Korvink present MEMS-based micro hot-plate devices while Marcin Marzencki and Skandar Basrour discusses vibration energy harvesting with piezoelectric MEMS. The second part concludes with Anurag Kasyap and Alexander Edrington describing self-powered wireless sensing.

With such a wide variety of topics covered, I am hoping that the reader will find something stimulating to read and discover that the field of sensor technologies is both exciting and useful in science and everyday life. Books like this one would not have been possible without many creative individuals meeting together in one place to exchange thoughts and ideas in a relaxed atmosphere. I would like to invite you to attend CMOS Emerging Technologies events that are held annually in beautiful British Columbia, Canada, where many topics covered in this book are discussed. See http://www.cmoset.com for presentation slides from the previous meeting and announcements about future ones. If you have any suggestions or comments about the book, please email me at kris.iniewski@gmail.com.

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Editor

Krzysztof (Kris) Iniewski manages R&D at Redlen Technologies Inc., a start-up company in Vancouver, Canada. Redlen's revolutionary production process for advanced semiconductor materials enables a new generation of more accurate, all-digital, radiation-based imaging solutions. Kris is also a president of CMOS Emerging Technologies (www.cmoset.com), an organization of high-tech events covering communications, microsystems, optoelectronics, and sensors.

Dr. Iniewski has held numerous faculty and management positions at the University of Toronto, the University of Alberta, SFU, and PMC-Sierra Inc. He has published over 100 research papers in international journals and conferences. He holds 18 international patents granted in the United States, Canada, France, Germany, and Japan. He is a frequent invited speaker and has consulted for several organizations internationally. He has written and edited several books for IEEE Press, Wiley, CRC Press, McGraw-Hill, Artech House, and Springer. His personal goal is to contribute to healthy living and sustainability through innovative engineering solutions. In his leisure time, Kris can be found hiking, sailing, skiing, or biking in beautiful British Columbia, Canada. He can be reached at kris.iniewski@gmail.com.

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Part 1

Optical and Acoustic Sensors

1 Optical Fiber Sensors

Rogério Nogueira, Lúcia Bilro, Nélia Alberto, Hugo Lima, and João Lemos Pinto

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INTRODUCTION

The laser invention in the 1960s and the advances toward low-loss optical fiber in the 1970s stimulated further scientific advances, both in telecommunications and in optical fiber sensors. With the first sensing applications of optical fibers the interest of the scientific community quickly grew for this new technology, and the number of research groups in optical fiber sensing rapidly increased.

The research on optical fiber sensors produced and continues to give life to a variety of measurement techniques for different applications, competing with traditional sensing methods, mainly in niche areas, from the airspace to the medical industry. The success of this technology relies on the intrinsic flexibility, low weight, immunity to electromagnetic interference, passive operation, and high dynamic range, associated with remote monitoring and multiplexing capabilities, which allows optical fiber sensors to succeed in difficult measurement situations where conventional sensors fail.

The technology is now in a mature state, with different applications already using commercial optical fiber sensors as a standard. This includes not only massive deployment for real-time structural health monitoring in airspace, civil and oil industry but also more specific applications such as environment monitoring, biochemical analyses, or gas leak monitoring in hazardous environments.

Optical fiber sensors operate by modifying one or more properties of the light passing through the sensor, when the parameter to be measured changes. An interrogation scheme is then used to evaluate the changes in the optical signal by converting them to a signal that can be interpreted. In this way, depending on the light property that is modified, optical fiber sensors can be divided into three main categories: intensity-, phase-, and wavelength-based sensors.

INTENSITY-BASED SENSORS

Of the range of optical fiber sensors reported in the literature, intensity-based sensors represent one of the earliest and perhaps the simplest type of optical fiber sensors. In applications where the precise signal intensity measurement is not critical or required, it has been shown that intensity-based systems are a valid solution for biomedical, structural health, and environmental applications. Generally, the system is based on a light source, an optical fiber, and a photodetector (or optical spectrum analyzer—OSA). Miniature solid-state light sources and photodetectors are available commercially, allowing the construction of rugged and portable hardware acquisition systems.

Intensity-based sensors offer the advantages of ease of fabrication, low price–performance ratio, and the simplicity of signal processing. These make them highly attractive, particularly in applications where the cost of implementation frequently excludes the use of other significantly more expensive optical fiber systems. Although high resolution and refined measurement capability are achievable using grating sensors and interferometric fiber sensors, it is not always necessary and, as such, less costly intensity-based sensing methods may offer an option in industry.

A wide number of intensity-based sensors are being presented and developed using different schemes; they can be grouped into two major classes: intrinsic- and extrinsic-type sensors. In the extrinsic type, the optical fiber is used as a means of transporting light to an external sensing system. In the intrinsic scheme, the light does not have to leave the optical fiber to perform the sensing function. In this class of sensors, the fiber itself plays an active role in the sensing function and this may involve the modification of the optical fiber structure.

TRANSMISSION AND REFLECTION SCHEMES

An additional classification scheme usually used is related to the way the optical signal is collected. If the receiver and emitter are at opposite ends of the fiber or fibers, the sensor is of a transmission kind, otherwise it is of reflection.

A straightforward example of the first situation is the intensity modulation based on the dependence of the power transmitted from one fiber to another on their separation. This basic sensing principle was used for structural health monitoring purposes by Kuang et al. [1]. The authors presented a comprehensive study where the performance of this sensor was evaluated in quasistatic tensile tests. The optical fiber sensor was surface-attached to an aluminum alloy specimen and revealed a high degree of strain linearity. Free vibration tests based on a cantilever beam configuration were also conducted to assess the dynamic response of the sensor. An impulse-type loading test was also performed to evaluate the ability to detect the various modes of vibration.

With respect to reflection methods, there are some variations, but most of them use reflecting surfaces to couple the light in the fiber, as presented by Binu et al. [2] for their fiber optic glucose sensor based on the changes in the refractive index (RI) with glucose concentration. Other sensors are based on Fresnel reflection mechanisms [3,4] or special geometries of the fiber tip [5]. One interesting application is described by Baldini et al. [6] with their optical fiber sensor for dew detection inside organ pipes. The working principle is based on the change in the reflectivity observed on the surface of the fiber tip when a water layer is formed on its distal end. Intensity changes around 35% were measured.

Macrobending or Microbending Sensors

Several mechanisms in an optical fiber weaken the propagated signal, such as absorption and diffusion by impurities, Rayleigh scattering, ultraviolet and infrared absorption, and microbending and macrobending. Despite many efforts to minimize the power losses in an optical fiber, its dependence on environmental physical parameters is strongly exploited by optical sensing technology.

Modulation due to an environmental effect can be transduced in the form of microbend or macrobend loss. Generally, a microbend is defined as a sharper bend in the optical fiber whose radius of curvature is smaller than the fiber radius and a macrobend is one with a bending radius much larger than the fiber radius. If the bending radius is reduced below a critical value, the loss in transmitted signal increases very rapidly, allowing the construction of a relatively sensitive macrobending fiber optic sensor. Large bending loss occurs at and below a critical bending radius, r_c, given by

$$r_c = \frac{3n_{\text{core}}^2\lambda}{4\pi(n_{\text{core}}^2 - n_{\text{clad}}^2)^{3/2}} \tag{1.1}$$

where n_{core} and n_{clad} are the refractive indices of the core and cladding, respectively, and λ is the operating wavelength [7]. Macrobending sensors are relatively few and measure parameters such as deformation [7], pressure [8], and temperature [9].

Rajan et al. [9] presented an all-fiber temperature sensor based on a macrobending single-mode fiber loop exploiting the thermo-optic coefficient of the cladding and core. Since the cladding and core are made of silica material and have a positive thermo-optic coefficient, the thermally induced change in RI of the core and cladding is linear, resulting in a linear variation of bend loss with temperature. The temperature sensitivity of the sensor can be varied by changing the bending radius or the operating wavelength. An absorption layer is applied over the cladding to absorb the radiation modes and to reduce the reflections from the air-cladding boundary. In this way, the fiber structure is approximately equivalent to a core-infinite cladding structure. The temperature information is extracted using a simple ratiometric power measurement system.

Among the innumerous transmission and reflection systems reported, there are several transduction mechanisms, namely spectrally based sensors and evanescent wave sensors.

Spectrally Based Sensors

For many applications, spectroscopic detection has been a reliable method for the design of fiber optic sensors and is popularly used for chemical, biological, and biochemical sensing [10]. This method examines the optical signal obtained and the related absorption, fluorescence measurements, or RI to the concentration of the target analyte. When a properly designed sensor reacts to changes in a physical quantity like RI or fluorescence intensity, a simple change of light intensity can possibly be correlated to the concentration of a measurand, which can be a biological or chemical species [11].

Generally, as shown in Figure 1.1, the design of the sensors can simply comprise optical fibers with a sample cell, for direct spectroscopic measurements, or be configured as fiber optrodes, where a chemical selective layer comprising chemical reagents in suitable immobilizing matrices is deposited onto the optical fiber.

In its simplest form, the technique involves confining a sample between two fibers and the quantification of the light transmitted through the sample. The attenuation in the optical path is related to the absorption or scattering properties of the medium. This detection procedure was applied for the purpose of environmental monitoring. A low-cost water turbidity sensor was presented by Bilro et al. [12,13], where the concentration of the total suspended solids in a liquid was determined by the attenuation of the light beam caused by the suspended particles (clay, ashes, and flour). A similar system configuration was used by Yokota et al. [14], but with a multi-wavelength approach for the analysis of soil nutrients. The wavelength of the light-emitting diodes (LEDs) was chosen to fit the absorption band of chemical reagents whose color develops by reaction with soil nutrients. The sensor is applied to detect six soil nutrients including ammonia nitrogen, nitrate nitrogen, and available phosphorus.

The fiber itself can play an active role acting as a sensing probe. The activation can be accomplished replacing the original cladding material, on a small section or end of the fiber, with a chemical agent or an environmentally sensitive material, in order to cause attenuation of the propagated light when the material is exposed to different chemicals or environments. A wide number of sensors reported in the literature make use of this technique. Goicoechea et al. [15], using the reflection method, developed an optical fiber pH sensor based on the indicator Neutral Red. Different strategies for the fabrication of the nanostructured pH-sensitive overlays