FIBER OPTIC SENSORS

FUNDAMENTALS AND APPLICATIONS

Fourth Edition

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To my grandson, Matthew Trotta, who at a very young age is showing a keen interest in science and engineering; and who has already made contributions to fiber optic sensor design.

D.K.

Many things must come together for one to have the opportunity to contribute towards the writing of a book. I have been very fortunate to find myself in such a position. Thanks are owed to my parents for their unselfish sacrifice, to my wife, Laurie, for always being everything to me, and to my three children, Kristin, Jesse, and Robyn, who always provide endless happiness and inspiration.

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T.M.

To my daughter Ariane—my little angel, with all my love.

A.M.

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Preface

Fiber optic sensor technology is not new, but is continuing to evolve after over 60 years of development and commercialization. The sensing designs are not based on a single concept but on a variety of optical phenomena that can be used to measure a broad range of physical and chemical parameters.

In early industrial applications, single point fiber optic sensors were used as an alarm to indicate the absence or presence of an object. As the technology evolved, the functionality increased to accurately determine the position of an object. Many of the sensing concepts that will be discussed throughout this book will be for single point sensors, which operate by detecting changes in the intensity of light (see Chapters 3, 8, and 9). They operate by altering the transmitted or reflected light intensity in a manner proportional to the parameter being sensed such as temperature, strain, or displacement (position). The sensing functionality can be expanded to monitor electric and magnetic field measurements using polarization concepts. As an example, certain materials exhibit Faraday rotation, which alters the plane of polarization and the resulting transmitted light intensity in the presence of a magnetic field. Polarization-based sensors are discussed in Chapter 7.

Interferometric sensors compare the phase of light in a sensing fiber to a reference fiber. Small phase shifts can be detected with extreme accuracy. The phase shifts are generated by changes in strain and/or temperature in the sensing fiber. This family of sensors has been especially useful in monitoring dynamic strain (vibration) (see Chapter 4). Also, a Sagnac interferometer is an interferometric sensor configured to be sensitive to rotation (Chapter 17). Two examples of successful commercialization of interfermetric-based sensors are hydrophones for submarine detection and fiber optic gyroscopes for advanced navigation systems. Both are for military applications primarily and have performed well for over 30 years with thousands of systems deployed.

A wavelength or spectral shift is another sensing approach. By introducing coatings on the fiber or a target that fluoresces, under certain conditions (usually related to chemical interaction or temperature fluctuation), a chemical reagent can be detected or temperature can be monitored. A more widely used spectral shift approach uses Bragg gratings, which are reviewed in detail in Chapter 5. A Bragg grating is characterized by having a resonant wavelength that is reflected as light is transmitted through the grating. The reflected light is very sensitive to the grating spacing and the index of refraction of the grating material. Temperature and strain alter both of these parameters. As a result, Bragg gratings can function as temperature or strain sensors. While Bragg gratings have been used as single point sensors, they have had great utility as quasi-distributed sensors in which multiple sensors are located along a single fiber.

Bragg gratings, which have been in development for over 25 years are in wide commercial use. They have been especially effective in enabling smart civil structures and as pressure and temperature sensors in smart oil wells. Bragg gratings have evolved to handle the very harsh environment associated with energy applications.

Light-scattering phenomena have emerged in the last 10 years to be a key family of technologies to enable fully distributed fiber optic sensing systems. Distributed sensing systems allow any point along a fiber to function as a sensor, with virtually thousands of sensing points along a single fiber that may exceed 30 km in length. The basic sensing mechanisms are Raman scattering, Rayleigh scattering, and Brilloiun scattering. Detailed descriptions of how these sensors work are given in Chapters 6 and 18. Briefly, Raman scattering is sensitive to temperature but not strain, and makes an excellent distributed temperature sensor referred to as DTS. Brillioun scattering is sensitive to temperature and strain and is the basis for distributed temperature and strain sensors referred to as DTSS. Rayleigh scattering is sensitive to acoustic vibrations and is used a distributed acoustic sensor referred to as DAS. DTS and DAS approaches have been especially effective for oil and gas applications.

A very important point that is understated is that fiber optic sensing systems have enabled smart oil and gas wells that are allowing North America to gain energy independence. Fiber optic sensor technology has a long history of development and commercialization successes. The technology has not yet reached maturity and will likely expand and create many new applications and commercialization opportunities.