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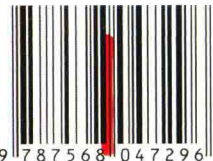
Optical Fiber Sensing and Structural Health Monitoring Technology

Yanliang Du · Baochen Sun · Jianzhi Li · Wentao Zhang

Optical Fiber Sensing and Structural Health Monitoring Technology

This book focuses on optical fiber sensing and structural health monitoring technologies. It provides detailed information on the basic theory of F-P optical fiber sensors, fiber Bragg grating sensors, fiber laser grating sensors and fully distributed optical fiber sensors. Drawing on the authors' research achievements and many years of practical experience in the field of engineering structure health monitoring, the book elaborates on the structural principle, design and manufacture of optical fiber sensors and monitoring technologies, and briefly describes advances made with regard to multiple engineering structures.

ISBN 978-7-5680-4729-6



9 787568 047296 >

定价: 198.00元

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Optical Fiber Sensing and Structural Health Monitoring Technology

 华中科技大学出版社
<http://www.hustp.com>
中国·武汉

 Springer

图书在版编目(CIP)数据

光纤传感与结构健康监测技术=Optical Fiber Sensing and Structural Health Monitoring Technology:英文/杜彦良等著. —武汉:华中科技大学出版社,2019.3
ISBN 978-7-5680-4729-6

I. ①光… II. ①杜… III. ①光纤传感器-智能材料-结构-监测-研究-英文
IV. ①TP212.4

中国版本图书馆 CIP 数据核字(2019)第 038465 号

Sales in Mainland China Only

本书仅限在中国大陆地区发行销售

光纤传感与结构健康监测技术

GUANGXIAN CHUANGAN YU JIEGOU JIANKANG JIANCE JISHU

杜彦良 等著

策划编辑:俞道凯

责任监印:周治超

出版发行:华中科技大学出版社(中国·武汉)

电话:(027)81321913

武汉市东湖新技术开发区华工科技园

邮编:430223

录 排:武汉三月禾文化传播有限公司

印 刷:湖北恒泰印务有限公司

开 本:710mm×1000mm 1/16

印 张:23

字 数:490千字

版 次:2019年3月第1版第1次印刷

定 价:198.00元



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Preface

The international academic and engineering community have reached a broad consensus to monitor the health of civil engineering structure, study the health state of structure in real time, discover and eliminate the potential safety hazard in time, and guarantee the long-term safe service of various civil engineering structures. The health monitoring technology based on optical fiber sensing has unique advantages such as small volume, lightweight, high sensitivity, anti-electromagnetic interference capability, integrated transmission and sensing functions, easy networking, and distributed measurement. Therefore, it made rapid development and considerable progress in the recent 20 years. Its role in the health monitoring of engineering structure is increasingly important.

The authors and their research team have dedicated themselves to the research on the development and application of health monitoring technology based on optical fiber sensing for a long time. They have rich research achievements and engineering practice experience. The book introduces the basic theory and method of optical fiber sensing technology as well as the structural design, manufacture, and practical application of sensors from the point of structural health monitoring. The book is divided into 10 chapters. Chapter 1 is Introduction. It mainly introduces the basic concept, type, and feature of optical fiber sensing technology as well as its application and development trend in the structural health monitoring field. Chapters 2–5 mainly focus on the demand for engineering structure health monitoring. They describe various optical fiber sensors, including F-P optical fiber sensor, optical fiber laser sensor, fiber Bragg grating sensor, and fully distributed optical fiber sensor, from the aspects of sensor working principle, structure design, manufacture process, and sensing characteristics. Chapters 6–9 emphasize the health monitoring technologies of different engineering structures such as prestressed tendon, cable, and concrete. Chapter 10 focuses on the engineering application of optical fiber sensing technology. It mainly introduces the long-term health monitoring, security evaluation, and alarm system of several projects with optical fiber sensors, including Wuhu Yangtze River Bridge, Liaohe Grand Bridge on Qinhuangdao-Shenyang Passenger Dedicated Line, Hemaxi Grand Bridge, Xiaogou Grand Bridge on Shanxi Xinyuan Highway, and the high and steep slope of Shuohuang Railway.

The book summarizes and integrates the research achievements and engineering applications of the author and his research team in over 20 years. Sincerely thank the research team members for their dedicated cooperation and hard work for many years, including Sun Baochen, Su Mubiao, Wang Xinmin, Zhao Weigang, Liu Yongqian, Chen Baoping, Li Jianzhi, Chen Shuli, Li Yiqiang, etc. In addition, Zhang Xushe, Jin Xiumei, Wei Bin, Zhang Wentao, Li Feng, Xu Hongbin, Li Xiaoyang, Liu Chenxi, Shao Lin, Yang Yaoen, Yang Liping, Dai Jingyun, Xu Hua, Hao Gengjie, Han Jing, and Hou Yuemin devoted their wisdom and painstaking efforts to the research contents in the book when they were studying for doctoral or master's degree. When the book was drafted and compiled, Liu Bo, Li Feng, Xu Hongbin, Sun Xu, Zheng Xinyu, Ren Zexu, Li Zhendong, Wang Qingyou, Sun Haokai, Wang Haiyong, and other doctoral or master students made great efforts to the literature arrangement, translation, and review. The authors are hereby deeply grateful to all of them.

The book was funded by China High Technology Research and Development Projects "Inspection and Reinforcement Technology of the Bridge and Subgrade for Heavy-haul Railway" (2009AA11Z102) and "Monitoring Technology of Heavy-haul Train Operation Danger State Based on Optical Fiber Sensing" (2009AA11Z212); National Natural Science Foundation of China "Critical State Evaluation and Critical Technology Research on Cable-stayed Bridge Structure Based on Smart Stay Cable" (50778116), "Monitoring Technology and Method Research on Critical Bearing Component State of Prestressed Reinforced Concrete Structure" (50278058), "New Method of Long-term Composite Monitoring for Prestressed Anchor Cable Corrosion Damage" (51778379) and "New Method of Long-term Monitoring for Geotechnical Anchor Cable with Fully Distributed Stress and Damage Positioning Function" (51508349); Natural Science Foundation of Hebei Province "Research on the Real-time Monitoring and Security Evaluation System of Stayed Cable Based on Fiber Bragg Grating" (E2004000417), "Critical Technology Research on Carbon Fiber Composite Reinforcement with Automatic Monitoring Function" (E2006000389), "Dynamic Stress Analysis and Property of Intelligent Composite Material for Fiber Bragg Grating" (E2015210094); Scientific Research Project of Hebei Province "Research and Development of Optical Fiber Strain Sensor and Its Signal Acquisition System" (03213539D); Science and Technology Research and Development Projects of Ministry of Railways "Long-term Monitoring and Security Evaluation System of Wuhu Yangtze River Bridge" (2000G19-B) and "Application Research on Optical Fiber Testing Technology of Liaohe Grand Bridge on Qinhuangdao-Shenyang Passenger Dedicated Line" (2001G018-B). The authors hereby express their sincere thanks to the Ministry of Science and Technology, National Natural Science Foundation of China, Hebei Province, Ministry of Railways and other science and technology administration departments for their full support and project grant.

It is expected that the book is helpful for scientific researchers and engineering technicians in the field of structural health monitoring and optical fiber sensing technology, as well as the teachers and students in related majors of colleges and universities. The research contents in this book involve civil engineering,

mechanics, photology, machinery, material, measurement and control, featuring multidisciplinary interpenetration, large span, and high difficulty. Given the limited level of the author, it is unavoidable to have omissions and improperness in the book. Please kindly offer advice and correct them.

Shijiazhuang, China
Spring 2018

Yanliang Du

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Chapter 1

Introduction

1.1 Optical Fiber and Optical Fiber Sensor

Sensor is a tool to measure the parameters of various structural systems and obtain the information of structure. It is not only one of the three pillars in the information technology field (sensing and control technology, communication technology, and computer technology) but also an indispensable component of production automation, scientific testing, calculation and accounting, monitoring and diagnosing, and other systems. Therefore, the research and development of advanced sensing and testing technology have great significance to increase the safety and reliability of structure and equipment, promote the scientific and technological progress, and improve the economic and social benefits.

In recent years, with the rapid development of science and technology, the common sensing technology is also brewing new changes. In current research and development boom of sensing technology, the optical fiber sensing and testing technology has drawn high attention from various countries in the world because of its unique advantages. The optical fiber sensing technology can integrate optical waveguide technology and optical fiber technology with distinct characteristic of unifying “transmission” and “sensing” into one. The light that works for sensing and transmission has dominant advantages such as great transmission capacity and strong anti-electromagnetic interference capability. The optical fiber that works as light-wave carrier features chemical inertness and flexibility. Thus, the optical fiber sensing technology has incomparable competitive advantages in the aspects of intelligent material and structure, large structural safety monitoring, high voltage, and intense magnetic field.

This chapter mainly introduces the basic concept, type, and feature of optical fiber sensing technology as well as its application and development trend in the structural health monitoring field.

1.1.1 Optical Fiber

Optical fiber, also called as light-guide fiber, is a light transmission structure with the total reflection principle of light in the glass or plastic fiber. Gao Kun and G.A. Hockham first proposed the scientific idea of applying optical fiber in the communication transformation field. Hence, Gao Kun was granted with Nobel Prize in Physics in 2009. In general, optical fiber is the long and thin fibrous cylinder where the high-purity silica glass is mixed with a little germanium, boron, phosphorus, and other impurities.

The main structure of ordinary communication optical fiber is composed of fiber core and cladding. The cladding is covered by a coating layer, as shown in Fig. 1.1. The cladding is used to seal the optical wave in the optical fiber to realize transmission.

To transmit the optical wave, the refractive index n_1 of fiber core must be slightly greater than refractive index n_2 of cladding. The maximum relative refractive index difference Δ of optical fiber is shown in Formula (1.1) (Sun et al. 2000).

$$\Delta = \frac{n_1^2 - n_2^2}{n_1^2} \approx \frac{n_1 - n_2}{n_1} \quad (1.1)$$

The fiber core and cladding must be made of different materials in order to make their refractive indexes different. Currently, for the common quartz fiber, the refractive index will be increased if the fiber core is provided with GeO_2 , TiO_2 , Al_2O_3 , or P_2O_5 , while it will be decreased if the quartz is provided with B_2O_3 . Therefore, these materials can be used as dopants of cladding. In addition, plastic optical fiber, photonic crystal fiber, and other types of optical fibers emerge in recent years.

Optical fiber is mainly used in the communication field first and develops rapidly in the sensing field in recent years. Various optical fiber sensors now are widely used in many fields. Particularly in 1978, Hill et al. (1978), Kawasaki et al. (1978) discovered the light sensitivity of optical fiber and fabricated the world's first fiber grating, which causes a new revolution in the optical fiber sensing field.

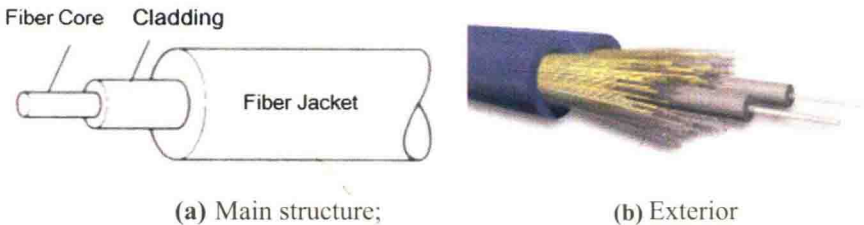


Fig. 1.1 Fiber structure

1.1.2 Optical Fiber Sensor

With the continuous development of optical communication technology, optical fiber sensor (Fig. 1.2) has become a new type of sensor since 1970s. Basic working principle of optical fiber sensor: transmit the light from light source to modulator through optical fiber, interact the parameters to be tested and the light in the modulation area, change the optical property (e.g., intensity, wavelength, frequency, phase, and polarization state) and call as modulated signal light, transmit it to optical detector through optical fiber, and obtain the parameters to be tested after modulation. According to the working principle, the optical fiber sensing system is mainly composed of light source, transmission optical fiber, sensing element, photoelectric detector, and signal processing unit. With the development in the over forty years, the optical fiber sensor has been widely used in the national defense and military, space flight and aviation, industry, mining, agriculture, energy conservation, biomedicine, metrology testing, automatic control, domestic appliance, and many other fields because of its advantages such as high precision, corrosion resistance, small size, light weight, flexibility, and anti-electromagnetic interference.

In recent years, various countries have applied the optical fiber sensing technology in the civil engineering structures. For example, the optical fiber sensor is used to monitor several physical quantities such as strain, damage, crack, and displacement. It plays an important role in the health monitoring of dam, bridge, and other civil engineering structures. Moreover, it gradually introduces a new trend of combining advanced monitoring technology and traditional civil engineering structures.

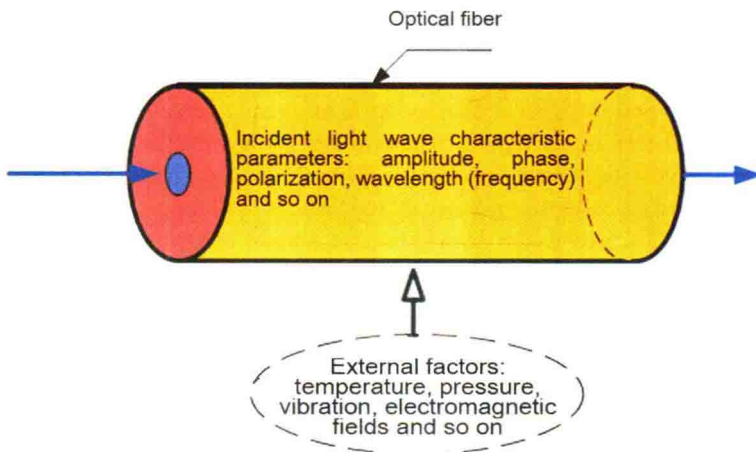


Fig. 1.2 Optical fiber sensor

1.2 Classification and Characteristics of Optical Fiber Sensor

1.2.1 Classification of Optical Fiber Sensor

There are various optical fiber sensors. Based on different classification standards, the common classification methods are shown below:

1. By the Principle of Light Modulation in the Optical Fiber

It is a key technology of optical fiber sensor to detect the light modulation by external parameters. According to the principle of light modulation in the optical fiber sensor, the optical fiber sensor is classified into five types: strength intensity, phase modulation, frequency modulation, wavelength modulation, and polarization modulation.

(1) Intensity-modulated optical fiber sensor

Intensity-modulated optical fiber sensor is to sense the parameters by measuring the change of light intensity in the optical fiber due to external factors. It is mainly composed of reflection type intensity-modulated optical fiber sensor, transmission type intensity-modulated optical fiber sensor, evanescent field coupling type intensity-modulated optical fiber sensor and physical effect type intensity-modulated optical fiber sensor.

(2) Phase-modulated optical fiber sensor

Phase-modulated optical fiber sensor changes the phase of optical wave transmitted in the optical fiber with the effect of energy field tested and then converts the phase change to light intensity change through interferometry technology. Thus, parameters are detected. At present, optical detectors cannot directly sense the phase change of optical wave. Therefore, the light interference technology must be applied to convert the phase change to light intensity change. Then, the external parameters are sensed. Common optical fiber interferometers include Michelson optical fiber interferometer, Mach-Zehnder optical fiber interferometer, Sagnac optical fiber interferometer, and Fabry-Perot optical fiber interferometer.

(3) Frequency-modulated optical fiber sensor

Frequency-modulated optical fiber sensor is to sense the external parameters by measuring the light frequency change due to external factors with Doppler effect.

(4) Wavelength-modulated optical fiber sensor

The wavelength or spectrum distribution of light energy in the optical fiber is changed due to external factors. Wavelength-modulated optical fiber sensor measures the parameters by monitoring the spectrum distribution. The wavelength modulation is also called color modulation because the wavelength is directly related to color.