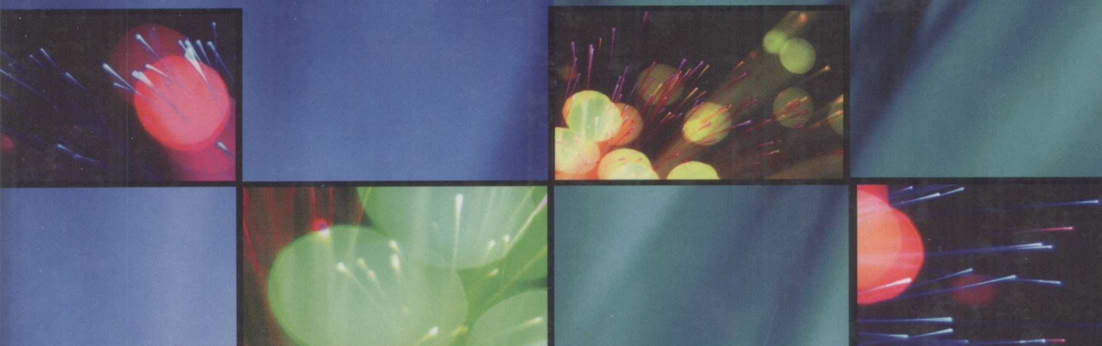
# Fiber Optic Measurement Techniques



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# Fiber Optic Measurement Techniques

To Erica and Andy, with Love

# Preface

Modern fiber-optic communications date back to the early 1960s when Charles Kao theoretically predicted that high-speed messages could be transmited long distances over a narrow glass waveguide, which is now commonly referred to as an optical fiber. In 1970, a team of researchers at Corning successfully fabricated optical fibers using fused-silica with a loss of less than 20dB/km at 633nm wavelength. The Corning breakthrough was the most significant step toward the practical application of fiber-optic communications. Over the following several years, fiber losses dropped dramatically, aided both by improved fabrication methods and the shift to longer wavelengths, where fibers have inherently lower attenuation.

Meanwhile, the prospect of long distance fiber-optic communication intensified research and development efforts in semiconductor lasers and other related optical devices. Near-infrared semiconductor lasers and LEDs operating at 810nm, 1320nm and 1550nm wavelengths were developed to fit into the low loss windows of silica optical fibers. The bandwidth in the 1550nm wavelength window alone can be as wide as 80nm, which is approximately 10THz. In order to make full and efficient use of this vast bandwidth, many innovative technologies have been developed, such as single frequency and wavelength tunable semiconductor lasers, dispersion shifted optical fibers, optical amplifiers, wavelength division multiplexing as well as various modulation formats and signal processing techniques.

In addition to optical communications, fiber-optics and photonic technologies have found a variety of other applications ranging from precision metrology, to imaging, to photonic sensors. Various optical measurement techniques have been proposed and demonstrated in research, development, maintenance and trouble-shooting of optical systems. Different optical systems demand different measurement and testing techniques based on the specific application and the key requirements of each system. Over the years, fiber-optic measurement has become a stand-alone research discipline, which is both interesting and challenging.

In general, optical measurements can be categorized into instrumentation and measurement methodology. In many cases, the measurement capability and accuracy are limited by the instruments used. Therefore, a good understanding of operation principles and performance limitations of basic optical instruments is essential in the design of experimental setups and to achieve the desired measurement speed and accuracy. From methodology point of view, a familiarity with various basic measurement system configurations and topologies is necessary, which helps in determining how to make the most efficient use of the available instrumentations, how to extract useful signals, and how to interpret and process the results.

The focus of this book is the measurement techniques related to fiber-optic systems, subsystems and devices. Since both optical systems and optical instruments are built upon various optical components, basic optical devices are discussed in chapter 1, which includes semiconductor lasers and LEDs, photodetectors, fundamental properties of optical fibers, optical amplifiers and optical modulators. Familiarity with the characteristics of these individual building blocks is essential for the understanding of optical measurement setups and optical instrumentation. Chapter 2 introduces basic optical instrumentation, such as optical spectrum analyzers, optical wavelength meters, Fabry-Perot, Mach-zehnder and Michelson interferometers, optical polarimeters, high-speed optical and RF oscilloscopes and network analyzers. Since coherent optical detection is a foundation for an entire new category of optical instrumentation, the fundamental principle of coherent detection is also discussed in this chapter, which helps in the understanding of linear optical sampling and vectorial optical network analyzer. In chapter 3, we discuss techniques of characterizing optical devices such as semiconductor lasers, optical receivers, optical amplifiers and various passive optical devices. Optical and optoelectronic transfer functions, intensity and phase noises and modulation characteristics are important parameters to investigate. Chapter 4 discusses measurement of optical fibers, including attenuation, chromatic dispersion, polarization mode dispersion and optical nonlinearity. Finally, chapter 5 is dedicated to the discussion of measurement issues related to optical communication systems.

Instead of describing performance and specification of specific instruments, the major purpose of this book is to outline the fundamental principles behind each individual measurement technique. Most of them described here can be applied to various different application fields. A good understanding of fundamental principles behind these measurement techniques is a key to making the best use of available instrumentation, to obtain the best possible results and to develop new and innovative measurement techniques and instruments.

## ACKNOWLEDGEMENTS

First, I would like to thank Mr. Tim Pitts of Academic Press. The idea of developing this book began in early 2006 when Tim and I met at the Optical Fiber Communications Conference (OFC) where he asked if I would consider writing a book in fiber-optic measurements. I particularly like this topic because

I have taught a graduate course in this subject for a few years and always have a great interest in this research area.

I would also like to thank my coauthor, Dr. Maurice O'Sullivan, who contributed materials for a number of sections in Chapter 5, where his expertise in fiber-optic communication systems research and development has proven to be a great asset.

My colleague professor Chris Allen at the University of Kansas carefully read through the entire manuscript and provided invaluable corrections. My research associate Dr. Jianfeng Jiang has provided many useful suggestions in in-situ polarization measurements in fiber-optic systems.

Finally, I would like to thank my wife Jian. Without her support and tolerance it would not be possible for me to accomplish this task.

Rongqing Hui

# About the Author

**Rongqing Hui** is a Professor of Electrical Engineering & Computer Science at the University of Kansas. He received B.S. and M.S. degrees from Beijing University of Posts & Telecommunications in China, and Ph.D degree from Politecnico di Torino in Italy, all in Electrical Engineering. Before joining the faculty of the University of Kansas in 1997, Dr. Hui was a Member of Scientific Staff at Bell-Northern Research and then Nortel, where he worked in research and development of high-speed optical transport networks. He served as a Program Director at the National Science Foundation for two years from 2006 to 2007, where he was in charge of research programs in photonics and optoelectronics. As an author or co-author, Dr. Hui has published widely in the area of fiber-optic systems and devices and holds 12 US patents. He served as a topic editor for *IEEE Transactions on Communications* from 2001 to 2007 and is currently serving as an associate editor for *IEEE Journal of Quantum Electronics* since 2006.

**Maurice O'Sullivan** has worked for Nortel for a score of years, at first in the optical cable business, developing factory-tailored metrology for optical fiber, but, in the main, in the optical transmission business developing, modeling and verifying physical layer designs & performance of Nortel's line and highest rate transmission product including OC-192, MOR, MOR+, LH1600G, eDCO and eDC40G. He holds a Ph.D. in physics (high resolution spectroscopy) from the University of Toronto, is a Nortel Fellow and has been granted more than 30 patents.

# Constants

**Physics Constants**

| Constant | Name | Value | Unit |
|---|---|---|---|
| $\kappa$ | Boltzmann's constant | $1.28 \times 10^{-23}$ | $J\text{-}K^{-1}$ |
| $h$ | Planck's constant | $6.626 \times 10^{-34}$ | J-s |
| $q$ | Electron charge | $1.6023 \times 10^{-19}$ | Coulomb |
| $c$ | Speed of light in free space | $2.99792 \times 10^{8}$ | m/s |
| $T$ | Absolute temperature | 273 K = 0 °C | Kelvin |
| $\varepsilon_0$ | Permittivity in free space | $8.854 \times 10^{-12}$ | F/m |
| $\mu_0$ | Permeability in free space | $12.566 \times 10^{-7}$ | $N/A^2$ |

**Conversion table**

| Symbol [unit] | Parameter 1 | Symbol [unit] | Parameter 2 | Conversion |
|---|---|---|---|---|
| $\lambda$ [nm] | Vacuum wavelength | $f$ (Hz) | Frequency | $f = c/\lambda$ |
| $\Delta\lambda$ [nm] | Wavelength difference | $\Delta f$ (Hz) | Frequency difference | $\Delta f = -\frac{c}{\lambda^2}\Delta\lambda$ |
| $\alpha$ [Neper/km] | Attenuation | $\alpha_{dB}$ [dB/km] | Attenuation | $\alpha_{dB} = 4.343\alpha$ |
| $D$ [ps/nm/km] | Dispersion parameter | $\beta_2$ [$ps^2$/nm] | Dispersion parameter | $D = -\frac{2\pi c}{\lambda^2}\beta_2$ |
| $E_g$ [eV] | Photon energy | $\lambda$ [nm] | Wavelength | $\lambda = hc/E_g$ |
| $\Lambda$ [$cm^{-1}$] | Wave number | $\lambda$ [nm] | Wavelength | $\Lambda = 10^7/\lambda$ |
| $T_C$ [°C] | Temperature | $T_F$ [°F] | Temperature | $T_C = \frac{5}{9}(T_F - 32)$ |
| Meter | Length | Inch | Length | 1 meter = 39.37 inch |

# Contents

## Chapter 1

# Fundamentals of Optical Devices