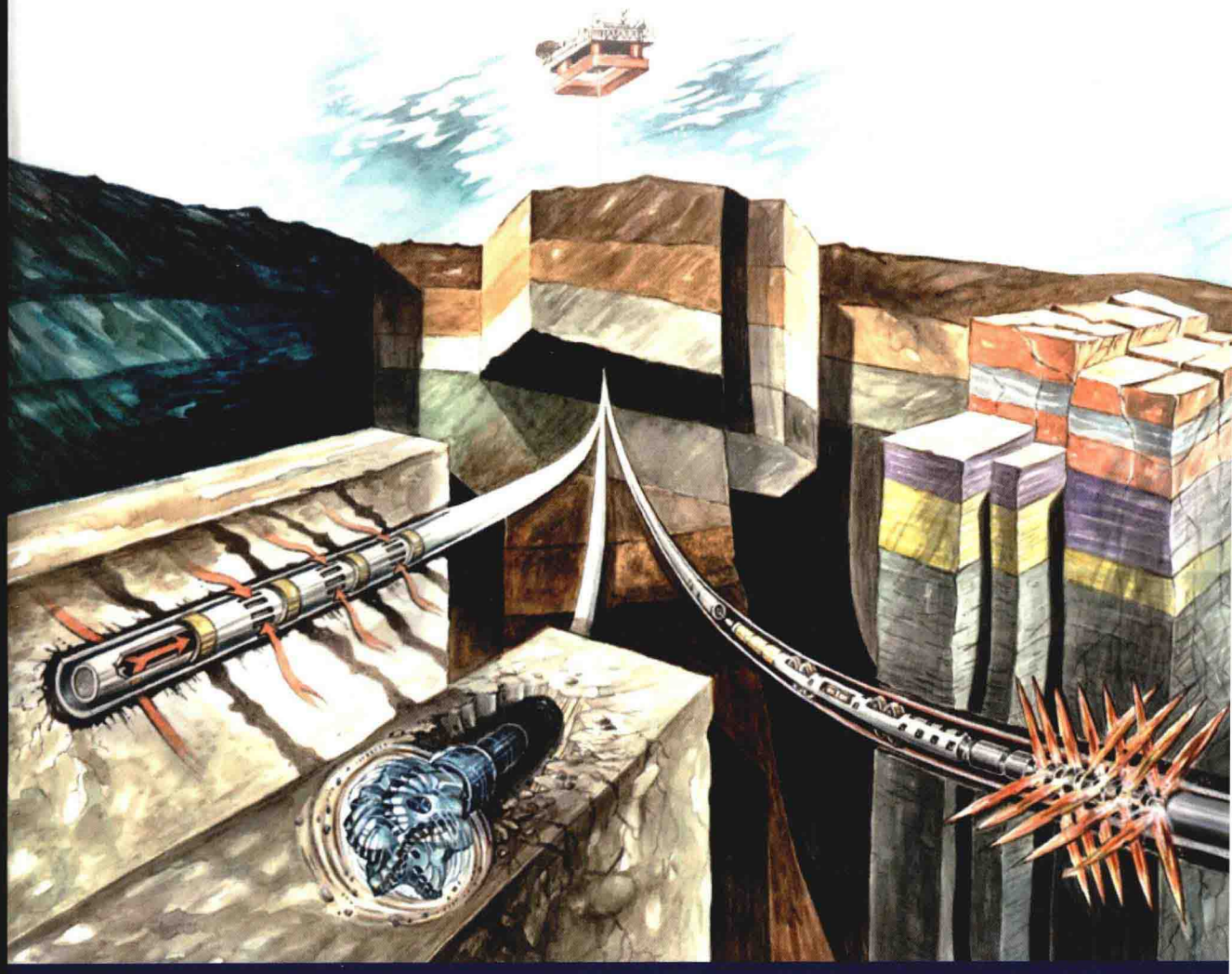
Arthur H. Hartog

AN INTRODUCTION TO DISTRIBUTED OPTICAL FIBRE SENSORS



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An Introduction to Distributed Optical Fibre Sensors

Arthur H. Hartog

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An Introduction to Distributed Optical Fibre Sensors

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An Introduction to Distributed Optical Fibre Sensors
Arthur H. Hartog

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To the memory of my parents, Dolf Hartog and Joyce Whitney.

Arthur H. Hartog

Series Preface

Optical fibers are considered among the top innovations of the twentieth century, and Sir Charles Kao, a visionary proponent who championed their use as a medium for communication, received the 2009 Nobel Prize in Physics. Optical fiber communications have become an essential backbone of today's digital world and internet infrastructure, making it possible to transmit vast amounts of data over long distances with high integrity and low loss. In effect, most of the world's data flows nowadays as light photons in a global mesh of optical fiber conduits. As the optical fiber industry turns fifty in 2016, the field might be middle aged, but many more advances and societal benefits are expected of it.

What has made optical fibers and fiber-based telecommunications so effective and pervasive in the modern world? It is its intrinsic features and capabilities make it so versatile and very powerful as an enabling and transformative technology. Among their characteristics we have their electromagnetic (EM) immunity, intrinsic safety, small size and weight, capability to perform multi-point and multi-parameter sensing remotely, and so on. Optical fiber sensors stem from these same characteristics. Initially, fiber sensors were lab curiosities and simple proof-of-concept demonstrations. Nowadays, however, optical fiber sensors are making an impact and serious commercial inroads in industrial sensing, biomedical applications, as well as in military and defense systems, and have spanned applications as diverse as oil well downhole pressure sensors to intra-aortic catheters.

This transition has taken the better part of thirty years and has now reached the point where fiber sensor operation and instrumentation are well understood and developed, and a variety of diverse variety of commercial sensors and instruments are readily available. However, fiber sensor technology is not as widely known or deeply understood today as other more conventional sensors and sensing technologies such as electronic, piezoelectric, and MEMS devices. In part this is due to the broad set of different types of fiber sensors and techniques available. On the other hand, although there are several excellent textbooks reviewing optical fiber sensors, their coverage tends to be limited and do not provide sufficiently in-depth review of each sensor technology type. Our book series aims to remedy this by providing a collection of individual tomes, each focused exclusively on a specific type of optical fiber sensor.

The goal of this series has been from the onset to develop a set of titles that feature an important type of sensor, offering up-to-date advances as well as practical and concise information. The series encompasses the most relevant and popular fiber sensor types in common use in the field, including fiber Bragg grating sensors, Fabry-Perot sensors, interferometric sensors, distributed fiber sensors, polarimetric sensors, polymer fiber sensors, structural health monitoring (SHM) using fiber sensors, biomedical fiber sensors, and several others.

This series is directed at a broad readership of scientists, engineers, technicians, and students involved in relevant areas of research and study of fiber sensors, specialty optical fibers, instrumentation, optics and photonics. Together, these titles will fill the need for concise, widely accessible introductory overviews of the core technologies, fundamental design principles, and challenges to implementation of optical fiber-based sensors and sensing techniques.

This series has been made possible due to the tenacity and enthusiasm of the series manager, Ms. Luna Han, to whom I owe a debt of gratitude for her passion, encouragement and strong support – from the initial formulation of the book project and throughout the full series development. Luna has been a tremendous resource and facilitator, and a delight to work with in the various stages of development for each of the series volumes.

Information, as the saying goes, is knowledge. And thanks to the dedication and hard work of the individual volume authors as well as chapter co-authors, the readers have enriched their knowledge on the

subject of fiber optic sensors. I thank all the authors and extend my deep appreciation for their interest and support for this series and for all the time and effort they poured into its writing.

To the reader, I hope that this series is informative, fresh and of aid in his/her ongoing research, and wish much enjoyment and success!

Alexis Méndez, PhD
Series Editor
President
MCH Engineering, LLC
Alameda, California

Foreword

Fibre optic sensor technology was initially suggested about half a century ago. By the early 1980s, the thought that this basic principle could be used in a so-called distributed architecture began to emerge. It is an exciting idea – lay out a perfectly normal fibre and look out for the way the environment changes the detail of the fibre transmission characteristics. Detect these changes by using a variant on optical radar – the optical time-domain reflectometer (OTDR) – and relate the detected changes to changes in the environment located around the fibre at the point to which the OTDR is tuned. Thence appears a map of what is happening as function of position along the fibre itself! It all seems too good to be true!

Indeed, whilst the system designers were convinced, the prospective users of this magical device were initially far from convinced. It took until the late 1990s for the quite amazing capabilities of this idea to become appreciated, and since then, distributed optical fibre sensing has emerged as the preferred approach to sensing events along long, thin structures like tunnels, pipelines and oil wells. The system has also become progressively more versatile, both in performance capability and in parameters that can be addressed.

Arthur Hartog is most certainly amongst the very best placed to record this history, to enlighten readers on the principles and limitations of the technique and to shed insight on the ever-expanding portfolio of applications. Arthur has been closely involved from the very beginning as both an active researcher and as a very successful industrial protagonist, improving on the basics, appreciating the many faceted needs in the practical environment and ensuring that these diverse needs are effectively satisfied.

This book reflects this wealth of experience and expertise, giving the most authoritative account available of an important and ever expanding technology. The text encompasses basic principles and established and emerging applications and insights into ongoing development. It will appeal to the student as well as the practising engineer and also presents insight into current and prospective applications.

Distributed systems are the predominant success story in fibre-optic sensing. This book presents an authoritative account of this important topic benefitting from the author's unique experiences and insights. It is an invaluable addition to the technical literature and promises to become the essential reference text for many, many years to come!

Brian Culshaw
Glasgow

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Preface

The field of distributed optical fibre sensors (DOFSs) has grown from an intriguing concept in the early 1980s to a technology that has widespread usage today, and it continues to be the subject of very active research. Distributed sensors have become a *de facto* standard way of operating, for example, in the monitoring of high-voltage transmission cables, certain fire detection applications and, increasingly, in the monitoring of boreholes in geothermal and hydrocarbon production. These practical applications have, in turn, led to the development of a number of industrial teams dedicated to the supply of distributed fibre sensors and the interpretation of the results.

The research into DOFS is documented in a large, and growing, set of scientific papers, conference presentations and patent applications. DOFSs are also described in single chapters in books on the more general subject of optical fibre sensors. However, there is no single volume dedicated to the subject of DOFS that provides the detail that students or engineers wishing to enter the field need to become effective contributors. I am frequently asked by new engineers or interns for background reading on DOFS and I have usually provided them with references to review articles. However, I usually feel that the available documents are unsatisfactory because they cover only selected parts of the field whilst assuming too much prior knowledge on the part of the reader.

The aim of this book is therefore to provide, in a single volume, sufficient background on the technology and applications to allow people new to the field to gain rapidly a view of the entire subject; I hope it will also be a useful reference for those of us who have worked on this topic for some time.

On a personal note, the field of distributed sensing has held my interest, in one way or another, for most of my professional life, with ever more fascinating science to explore whilst refining the design of interrogation systems and discussing applications with clients and partners. The many applications of the technology have also opened doors into vast swathes of engineering that can benefit from DOFS technology. This has led me to electrical substations and transformer manufacturing sites, down coal mines, onto dam construction sites, oil production rigs and many more. As someone with a keen interest in science and technology, DOFS has provided me with a wonderful insight into many fields of science and engineering.

The writing of this book was prompted by an invitation of the Series Editor Alexis Méndez (MCH Engineering LLC) and Luna Han, Senior Publishing Editor at Taylor & Francis, and I am grateful to them for their initial comments on the proposal, and to Luna for her suggestions and support throughout this project. I am also grateful to Adel Rosario at the Manila Typesetting Company (MTC) who oversaw the production phase of the publication process most effectively and to Anna Grace de Castro, Lisa Monette and Mamta Jha at MTC for their careful copyediting, proofreading and indexing.

The outline of this work was reviewed by several anonymous reviewers. I am grateful to all of them for their supportive and constructive comments that have helped shape the way in which the material is presented.

I thank Brian Culshaw (University of Strathclyde) for kindly writing a foreword to this volume.

The first demonstration of a distributed temperature sensor with my co-inventor, David Payne, would not have occurred without the doctoral training that he, Mike Adams and Alec Gambling provided within the Optical Fibre Research Group at Southampton University and the support of members of that group, including Alan Conduit, Frédérique de Fornel, Martin Gold, Bob Mansfield, Steve Norman, Cathy Ragdale, Francis Sladen and Eleanor Tarbox.

This book is heavily influenced by my interaction with friends and colleagues at York Sensors over the time that this distributed sensing technology has developed, whether on the technology or the commercial aspects. I would like to thank Glen Fowler, Roger Hampson, Richard Kimish, Adrian Leach, Darryl Marcus-Hanks, Richard Marsh, Iain Robertson, Pat Ross, Jane Rowsell, Robert Theobald,

Peter Travis, Peter Wait and Val Williams amongst those who contributed in one way or another to the success of this technology. As the ownership of York Sensors moved to Sensor Highway, George Brown, Nigel Leggett and Glyn Williams were instrumental in moving the technology to the oilfield, ultimately within Schlumberger. In more recent years, I have also had the pleasure of working at the Schlumberger Fibre-Optic Technology Centre with a number of colleagues, including Dom Brady, Yuehua Chen, Alexis Constantinou, Matt Craig, Theo Cuny, Tim Dean, Florian Englich, Alireza Farahani, Max Hadley, Will Hawthorne, Graeme Hilton, Ian Hilton, Kamal Kader, Gareth Lees, Adam Stanbridge, Paul Stopford and many others (some of whom were previously at York Sensors). The initial demonstrations of oilfield applications of distributed vibration sensors were greatly facilitated by collaboration with colleagues within Schlumberger, including William Allard, Mike Clarke, Richard Coates, Bernard Frignet, Duncan Mackie, Doug Miller and Merrick Walford and many colleagues at the Schlumberger Gould Research Centre (Cambridge, United Kingdom), Schlumberger Doll Research Centre (Cambridge, Massachusetts, USA) and the Schlumberger Moscow Research Centre.

The development of distributed temperature sensor (DTS) technology at York Sensors was considerably assisted by the close collaboration with our then Japanese partners, initially part of Nippon Mining and later becoming Y.O. Systems and now YK Gikken. The support and friendship of their founder Osamu Yasuda (now deceased) and of Shunsuke Kubota is an enduring contribution to the field.

I have the great pleasure of working with a team at the Peter the Great St. Petersburg Polytechnical University led initially by Oleg I. Kotov and now by Leonid Liokumovich together with their colleagues Andrey Medvedvev, Nikolai Ushakov, Artem Khlybov and (at St Petersburg State University) Mikhail Bisyarin. Their contributions, spanning more than 10 years, to Raman distributed sensing and more recently to distributed vibration sensing are greatly appreciated as is their continuing collaboration on new topics. Other aspects of my understanding of the subject were enhanced by collaborations with Trevor Newson and his students at Southampton University, particularly Yuh Tat Cho, Mohammad Belal and Mohamed Alahbabi. More recently, I have appreciated the support of Dimitris Syvridis and his colleagues at the National and Kapodistrian University of Athens, Greece, and I have also enjoyed a fruitful collaboration with Daniela Donna (Ecole des Mines – Paritech) and James Martin (then at the Institut de Physique du Globe de Paris).

Although this work is a personal project, I am happy to acknowledge the support and encouragement of Simon Bittleston (Schlumberger Vice President, Research) and Frédérique Kalb (then Centre Manager at the Schlumberger Fibre-Optic Technology Centre). I am also keen to recognise the assistance of the Schlumberger librarians, particularly Clare Aitken and Jacqui Wright, in finding a number of obscure references.

A special word of thanks is due to my friends and colleagues Will Hawthorne, Dom Brady, George Brown, Alexis Constantinou and Paul Dickenson, as well as to Jennifer Hartog, for their comments on various parts of the manuscript.

Finally, and most importantly, I want to thank my wife, Christine Maltby, in addition to her careful proofreading of the manuscript, for her unwavering and unquestioning support, love and patience for the several years that I have hidden away working on this project and for our many happy years together.

Arthur H. Hartog
Martyr Worthy, Winchester, United Kingdom

Author

Arthur H. Hartog earned a BSc in Electronics at the University of Southampton, where he was first exposed to the world of optical fibres. He followed up with a PhD in the Optical Fibre Research Group in a team led by Prof. W.A. Gambling at the same university. In his doctoral and post-doctoral research, he focused on measurements of light propagation in optical fibres, including research in optical time-domain reflectometry. This work led to the first demonstration of a distributed optical fibre sensor in 1982.

In 1984, Arthur moved to York Ltd., a start-up providing instrumentation for manufacturers of optical fibre preforms, fibres and cables as well as speciality optical fibres (these businesses still continue as part of Photon Kinetics, Inc for the instrumentation and as Fibercore Ltd. for the speciality fibre). After initial work on optical time-domain reflectometers (OTDRs) and other measurements at York Ltd., he set up a team to design and commercialise the first Raman distributed temperature sensor, a business that was eventually separated as York Sensors Ltd. During his time at York and York Sensors, he dealt with most aspects of the product life, from research to manufacturing, including applications development and working with strategic overseas partners.

After several changes of ownership, York Sensors became part of Schlumberger, the leading oilfield services company. As a Schlumberger Fellow, Arthur continues to research optical fibre sensors and their applications to the oilfield whilst providing advice on wider matters within the company.

Arthur Hartog is a senior member of the Institute of Electrical and Electronics Engineers and of the Optical Society of America and a member of the European Association of Geoscientists & Engineers.

List of Symbols

a	core radius
a_e	amplitude of element electric field (in model of coherent scattering)
A_e	amplitude of electric field summation (in model of coherent scattering)
A_{eff}	effective area of a mode
A_V	forward gain of a voltage amplifier
B	backscatter capture fraction
B'	normalised backscatter capture fraction
$B_{as,s}$	backscatter capture fraction for the anti-Stokes and Stokes Raman signals
B_T	isothermal compressibility
B_w	noise bandwidth of a receiver
c	speed of light in vacuum
$C_{\nu_B\varepsilon}$, $C_{\nu_B T}$	coeffecient of the Brillouin frequency shift due to strain and temperature, respectively
$C_{I_B\varepsilon}$, $C_{I_B T}$	coeffecient of the Brillouin intensity due to strain and temperature, respectively
C_T	total capacitance at the input node of an optical receiver
D_a	peak displacement due to a seismic wave
e	electron charge
E_b	electric field of backscatter signal
E_{LO}	electric field of local oscillator
E_m	electric field distribution of mode m
E_p	probe energy
E_{ph}	photon energy
E_s	electric field summation in modelling of coherent backscatter
E_{tot}	sum of local oscillator and backscatter field in coherent-detection OTDR
E_Y	Young's modulus
f_b	beat frequency relating to a location in OFDR
$f_{b_{max}}$	maximum value of the beat frequency in OFDR
f_d	sampling frequency
f_m	modulation frequency (in BOCDA)
$f_p(r)$	refractive index profile function
f_R	pulse repetition frequency
$\mathcal{F}$	finesse (of a Fabry-Pérot interferometer)
$F(M_G)$	excess noise multiplication factor for an APD
g_B	Brillouin gain
g_m	transconductance of a field-effect transistor
h	Planck's constant
H_{SBS}	transfer function of the Brillouin gain process
i_{fe}	channel thermal noise of an FET
i_{het}	heterodyne signal term in the output of a coherent OTDR
i_n	receiver current noise spectral density
i_{RF}	Johnson noise current density
I_{as}	intensity of the anti-Stokes Raman backscatter signal
I_{du}, I_{dm}	unmultiplied and multiplied (respectively) detector dark current
I_G	gate leakage current of an FET

I_s	intensity of the Stokes Raman backscatter signal
k_A	acoustic wavenumber
K_{as}, K_s	constants used in the expressions for the anti-Stokes Raman and Stokes Raman intensities (respectively) to account for losses in the optical system
k_B	Boltzmann's constant
L	fibre length
L_{eff}	effective fibre length for non-linear interactions
L_G	gauge length
m_d	modulation depth (in BOCDA)
M	code length in pulse-compression OTDR
M_{DTS}	figure of merit for DTS systems
M_f	number of degrees of freedom for coherent Rayleigh backscatter statistics
M_G	gain of an avalanche photodiode
n_1, n_2	refractive index in core and cladding, respectively
n_{eff}	effective index for a mode
n_x, n_y	effective index for the principal modes of a birefringent optical fibre
N_g	group refractive index
N_s	number of independently sampled points
NA	numerical aperture
p_{11}, p_{12}	photoelastic constants
$P_{BS}(t)$	backscatter power vs time; suffices $BS1$ and $BS2$ are used to distinguish power measured from End 1 and End 2 of a fibre loop
P_d	probability that one photon will be detected in photon counting DTS
P_{LO}	local oscillator power (coherent detection)
P_p	probe pulse power
$P_s(z)$	signal power reaching an optical receiver
$\mathbf{Pr}(P_{BS}(z))$	probability distribution for coherent Rayleigh backscatter power
q	electron charge
Q	detector quantum efficiency
R_d	detector responsivity
R_F	feedback resistor value (Transimpedance amplifier)
$R(T(z))$	anti-Stokes/Stokes Raman ratio; suffices $E1$ and $E2$ are used to distinguish power ratios measured from End 1 and End 2 of a fibre loop
$\bar{R}(T(z))$	normalised anti-Stokes/Stokes Raman ratio
$\mathbf{S}_{\mathrm{LE}}$	temperature sensitivity coefficient of the natural logarithm of the anti-Stokes/Stokes Raman ratio
T	temperature
T_A	ambient temperature
T_C	temperature of the channel of an FET
T_f	fictive temperature (of a glass)
T_r	sweep duration in OFDR
T_{ref}	temperature of the reference coil
v_g	group velocity
V	normalised frequency
V_A	acoustic velocity
V_{sw}	voltage swing available at the output of a transimpedance preamplifier
z	distance variable along an optical fibre
z_{sc}^m	distance to the mth scatterer in coherent backscatter model
α	fibre attenuation per unit length
α_p, α_{as}, α_s	attenuation at the probe, anti-Stokes and Stokes Raman wavelengths, respectively

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