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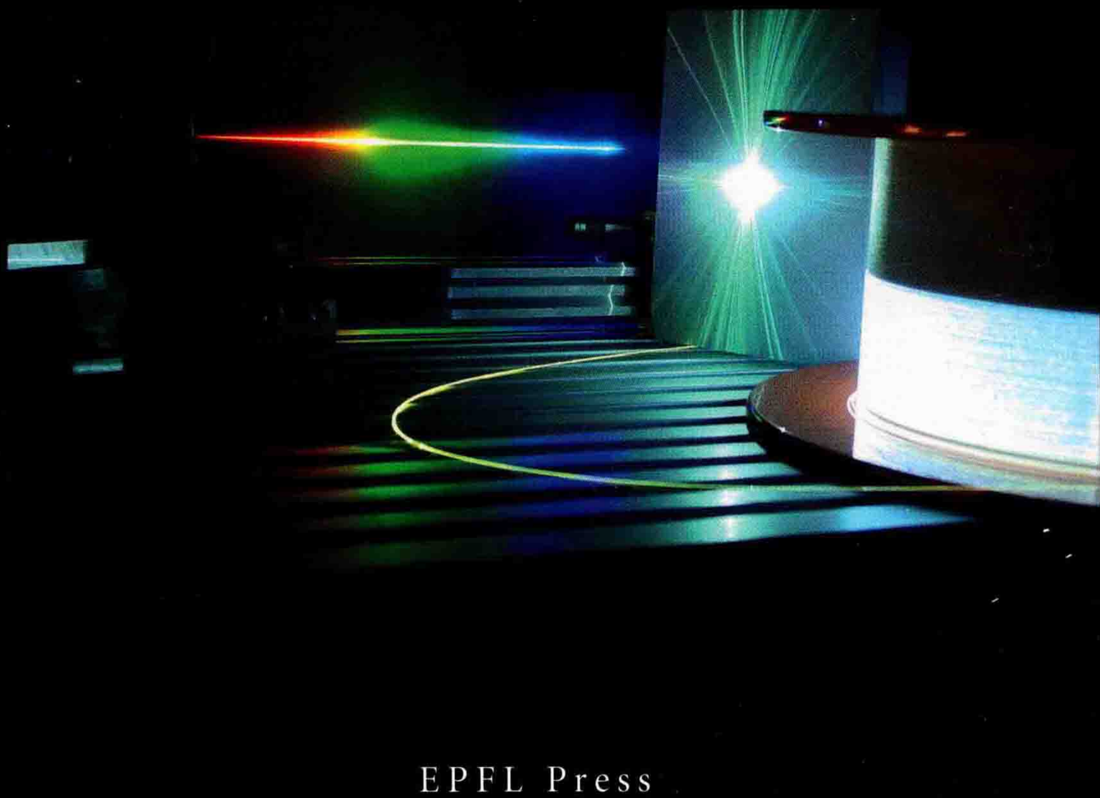
# ADVANCED FIBER OPTICS

## CONCEPTS AND TECHNOLOGY

Luc Thévenaz, Editor



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With contributions by Francis Berghmans, John Dudley, Sébastien Février, Thomas Geernaert, Goery Gentry, Miguel González-Herráez, Mircea Hotoleanu, Kyriacos Kalli, Michel M. Marhic, Thibaut Sylvestre, Luc Thévenaz, Moshe Tur, David J. Webb, and Marc Wuilpart.





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# ADVANCED FIBER OPTICS

# PREFACE

Few techniques have had an impact on society that can compare to that of fiber optics. These tiny hair-sized glass wires have deeply transformed, at the dawn of this third millennium, access to information, modes of communicate, and even the behavior of consumers. This tremendous impact was rightfully honored by the presentation of the 2009 Nobel Prize in Physics to Charles K. Kao, who predicted in 1966, by careful calculations, that optical fibers could transmit a broadband signal over distances outperforming any existing transmission line. Since then, optical fibers have gradually occupied a more and more predominant place in the world of telecommunications, while deeply revolutionizing the field of optics by confining light in these small silica waveguides, transforming classical free-beam optics into a novel concept of wired optical circuits.

Today optical fibers are omnipresent in modern optical systems, so that a solid background in fiber optics is absolutely required by any engineer or scientist who has the ambition to become specialist in the design and the understanding of systems based on light signals. The tremendous development of optical communication has convinced a wide public that optical fibers can do much more than passively transmit a light signal. The objective of this book is to provide, to advanced students and early-career researchers, an extensive knowledge about novel applications and optical functions that can be realized using optical fibers. The research in this field remains extremely active as a consequence of the extraordinary properties of optical fibers, which allow them to confine light within a microscopic-sized surface over kilometric distances. This converts a minute effect into a large interaction that can lead to fantastic transformations on the light. The constant search for new functions entirely carried out within optical fibers has gradually led to the development of special fibers with specific properties, such as rare earth-doped fibers for amplification and laser emission, or photonic crystal fibers offering a larger control of the light confinement and dispersion properties.

This book is an enlarged collection of lectures given during a training school for young researchers, organized in the framework of an action of the European Scientific and Technical Cooperation (COST Action 299 "FIDES: Optical Fibers for New Challenges facing the Information Society") and held in Larnaca, Cyprus, from March 30 to April 1, 2009. The lectures were given by eminent European specialists in fiber optics with a long experience in research and education. This resulted in a unique collection of high quality teaching on this particular topic and, as a response to the enthusiastic interest of the participants, teachers decided to collect the content of the teaching material in a book with the ambition to disseminate the knowledge to a broader community.

The level of the contributions here allow a scientist or engineer to acquire the solid theoretical knowledge that will provide them an entry into the latest technology of fiber optics, requiring only as a prerequisite a background at the bachelor level in physics or electrical engineering. The book is self-contained, and each chapter gives a list of references to deepen the knowledge on a particular topic. After an initial chapter, which summarizes the basic properties of optical fibers, as well as their light guiding mechanism and their fabrication procedure by a glass-drawing process, each subsequent chapter addresses an advanced feature of fiber optics. For instance the behavior of light polarization – a fairly complex topic in optical fibers – is described in Chapter 2, while the amplification and the emission of light by fibers are addressed in Chapter 6. The interaction processes required for light amplification are better realized using specific atoms not present in silica, such as erbium, requiring the fabrication of fibers with a doped core (Chap. 4). Amplification and light conversion can also be achieved using a set of nonlinear optical interactions, presented in Chapter 5, that are the key mechanisms to achieve novel and creative functions. The best conditions for the generation of important nonlinear interactions are often realized by properly modeling the guiding and propagation in the fiber and, more recently, in photonic crystal fibers, a subject presented in Chapter 3, where these are seen to be an essential tool for creating flexible propagation conditions that are simply impossible to obtain in standard fibers. One of the most striking achievements based on the combination of nonlinear interactions and modified propagation conditions in photonic crystal fibers is the generation of a light supercontinuum, in which the single color light from a laser is spread over a very broad spectrum, giving a white light source that is more radiatively dense, by orders of magnitude, than the sun (Chap. 7).

An important field of applications of optical fibers is the domain of sensing that is currently experiencing economic growth that is proportionally larger than optical telecommunications. As a consequence of this new importance, the different aspects of fiber sensing are addressed in detail with three distinct chapters. One of the main assets of fiber sensing is its capability to realize distributed sensing, for which the measure of a quantity, such as temperature or strain, can be independently carried out at any point along the fiber. This offers the possibility of instantaneously obtaining a map of the distribution of the measured quantity along the fiber and to advantageously substitute a fiber for thousands of point sensors. Natural scattering processes in the fiber material are judiciously used for this purpose, and Chapter 8 describes the most intense and most widely used type of scattering in fibers: Rayleigh scattering. More advanced configurations use a weaker inelastic scattering (Brillouin and Raman) that turn out to be more sensitive to the environmental quantities and thus more favorable for sensing. Chapter 9 is entirely dedicated to the study of inelastic scattering and their numerous applications ranging from sensing to amplification and the active control of the speed of a light signal (slow light). The possibility to realize sequential changes of the refractive index directly in the fiber core by high-energy illumination, with a periodicity in the range of the light wavelength, has offered a novel class of all-fiber optical devices to the community, designated as fiber Bragg gratings. These important devices are described in Chapter 10 and offer a wavelength-selective function that makes excellent filters and very efficient miniature point sensors.

Finally there is a constant search for alternative materials to draw fibers from, which can potentially offer a better susceptibility to nonlinear optical interactions, in order to obtain certain advanced functions more efficiently; or a better sensitivity to the environment for more accurate sensing; or other advantages related to the economics and ease of implementation for particular applications. Among these alternative materials, particular attention is currently paid to organic polymers, and Chapter 11 addresses all recent progress and potential future applications using polymer optical fibers. Chalcogenide and soft glasses are other types of materials that may lead to nonlinear optical effects enhanced by two or three orders of magnitude, while offering a better transparency in the infrared. Although presenting their own limitations in terms of optical-power density, and despite difficulties in handling and coupling to standard fibers, these new materials have a promising future to turn optical fibers into an even more efficient and omnipresent tool for advanced photonics.

*Luc Thévenaz*

*Chairman of COST Action 299*

*Lausanne, January 2011*

Group picture of the specialists teaching at the Larnaca training school and co-authoring this book. Front, from left to right: Michel Marhic, John Dudley, Michael Komodromos (Local Organizer, not authoring), Marc Wuilpart, Francis Berghmans, Miguel González Herráez, Mircea Hotoleanu. Back, from left to right: Roy Taylor (not authoring), Kyriacos Kalli, Sébastien Février, Thibaut Sylvestre, Luc Thévenaz. Absent from the picture: Moshe Tur.

Group picture of the 72 students and the 12 teachers participating to the COST299 Training School on Advanced Fiber Optics in Larnaca, Cyprus, during Spring 2009.

# ABOUT THE AUTHORS

## FRANCIS BERGHMANS

Francis Berghmans graduated as electrotechnical engineer with majors in applied physics in 1992 and received the Ph.D. degree in applied sciences in 1998, both from the Vrije Universiteit Brussel (VUB), Belgium. After a 13 year career at the Belgian Nuclear Research Centre SCK·CEN, where he coordinated applied research activities in the field of photonics, he took a Professor position at VUB, in the Department of Applied Physics and Photonics. There he is a member of the Brussels Photonics team B-PHOT and leads the research on photonic crystal fibers and micro-optical sensors. He served as vice-chair of the COST 299 action on "Optical Fibers for New Challenges Facing the Information Society". He has (co-)authored 75 journal papers and more than 130 publications in international conference proceedings. Prof. Berghmans is general chair of the SPIE Photonics Europe symposia in Brussels (Belgium) and has served on many other conference committees. He is a fellow of SPIE, and member of IEEE-Photonics Society, IEEE-Nuclear and Plasma Sciences Society, SFO, EOS and OSA.

## JOHN DUDLEY

John Dudley received B.Sc and Ph.D. degrees from the University of Auckland in 1987 and 1992 respectively. In 1992 and 1993, he carried out postdoctoral research at the University of St Andrews in Scotland before taking a lecturing position in in 1994 at the University of Auckland. In 2000, he was appointed Professor at the University of Franche-Comte in Besancon, France, where he heads the Optoelectronics, Photonics and Optical Telecommunications research group. He was named a member of the Institut Universitaire de France in 2005 and elected a fellow of the Optical Society of America in 2007 and a fellow of the IEEE in 2011.

## SÉBASTIEN FÉVRIER

Sébastien Février defended his Ph.D. thesis in 2002. Since 2003 he has been a reader at the University of Limoges, France and belongs to Xlim Research Institute. He has been engaged in research and development of optical fibers in the fields of fiber amplifiers, gain-flattening filters and dispersion-compensating fibers for telecommunication purposes. His research activities currently cover photonic bandgap fibers for high-power generation or delivery and management of nonlinear effects and dispersion properties. He is also developing specialty fibers for the mid-infrared domain. He has published six patents and over 90 publications in peer-review journals and conference proceedings.

**THOMAS GEERNAERT**

Thomas Geernaert graduated as electrotechnical engineer with majors in photonics in 2006 and received the Ph.D. degree in engineering in 2011, both from the Vrije Universiteit Brussel (VUB), Belgium. He is a member of the Brussels Photonics team B-PHOT and his research is focused on theoretical and experimental work of photonic crystal fibers for sensing applications, based on fiber bragg gratings. He was an active participant in the European COST 299 action on "Optical Fibers for New Challenges Facing the Information Society" and was visiting scientist at the Institute of Photonic Technology (Jena, Germany) and at the Cyprus University of Technology (Nicosia, Cyprus). Dr. Geernaert has (co-)authored six journal papers and 14 publications in international conference proceedings. He is a member of SPIE and OSA.

**MIGUEL GONZÁLEZ-HERRÁEZ**

Miguel González-Herráez received the M.Eng. and D.Eng. degrees from the Polytechnic University of Madrid, Madrid, Spain, in 2000 and 2004, respectively. In October 2004, he was appointed Assistant Professor in the Department of Electronics, University of Alcalá, Madrid, Spain, where he was promoted to Associate Professor in June 2006. He has made recognized contributions in the field of nonlinear optical fibers, in particular in slow light and continuous-wave supercontinuum generation. He is the author or coauthor of over 50 papers in international refereed journals and over 70 conference contributions. He has also given several invited or plenary talks at international conferences, and has earned several early career recognitions and prizes. His research interests cover the wide field of nonlinear interactions in optical fibers and semiconductor waveguides.

**MIRCEA HOTOLEANU**

Mircea Hotoleanu entered the Technical University of Cluj-Napoca from which he received in 1989 a master degree in Electronics and Telecommunications. After a short period when he worked as computer service engineer, he joined Technical University of Cluj-Napoca in 1991 as assistant professor, later as lecturer in electronics, optoelectronics and optical communications. In 2007 he received the Ph.D. degree in telecommunications. In 2001 he joined a fresh start-up in Finland, Liekki Oy – specialty optical fiber manufacturer – where he stayed for almost eight years. During this period he held various positions: research scientist, measurement manager and vice president for operations. Later he was named Director, Fiber and Simulation Development at nLIGHT Corp. For more than 15 years he has been involved in the activities and management of several European Union sponsored research projects. He also worked as consultant for several companies in Finland and US in the field of design and development of specialty optical fibers and various software products. Currently he is the Director of Emerson Romania Shared Services in Cluj-Napoca Romania.

**KYRIACOS KALLI**

Kyriacos Kalli received the B.Sc. (Hons) in Theoretical Physics (1988) and Ph.D. in Physics (1992) from the University of Kent at Canterbury. After a year at the Fiber and Electro-Optics Research Center, Virginia Tech and three more years back at the University of Kent, he joined the Photonics Research Group, University of Cyprus in 1997. From 2001 he was a permanent academic at the Higher Technical Institute in Cyprus, He has been an Assistant Professor in the Department of Electrical Engineering and Information Technology at the Cyprus University of Technology since 2008. His research interests are in Bragg grating and optical fiber sensors, photonic switching devices, laser material interactions and photosensitivity. Dr. Kalli has more than 150 journal and conference publications, is co-author of "Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing." He is a member of the Institute of Physics, Optical Society of America and Institute of Electrical and Electronics Engineers.

**MICHEL E. MARHIC**

Michel E. Marhic received the Diplôme D'Ingénieur from Ecole Supérieure D'Electricité, France, the M.S. degree from Case Western Reserve University, and the Ph.D. degree from UCLA, all in electrical engineering. He was on the faculty of the Department of Electrical Engineering at Northwestern University (1974–1998), and on sabbatical leaves at USC (1979–80) and Stanford University (1984–1985, and 1993–1994). He was Consulting Professor in the Department of Electrical Engineering at Stanford University from 1998 to 2006. He is currently Chair Professor at the Institute of Advanced Telecommunications, School of Engineering, Swansea University, Wales, U.K. In addition, he (co)-founded Holicon, Holographic Industries, and OPAL Laboratories. Over the past 15 years, his work has emphasized optical communication systems, and nonlinear optical interactions in fibers. He has written the first book on fiber optical parametric amplifiers. He is the author or coauthor of over 300 journal and conference papers, and has 9 patents awarded. He is a fellow of OSA, and a senior member of IEEE.

**THIBAUT SYLVESTRE**

Thibaut Sylvestre received the diploma of advanced studies and the doctorate of sciences in engineering from the Université de Besançon in 1995 and 1999, respectively. He then worked as a postdoctoral research associate at the Université Libre de Bruxelles, Belgium. In 2001, He was appointed senior researcher at the Centre National de la Recherche Scientifique (CNRS) in the FEMTO-ST Institute in Besançon. In 2006, he received the French post-doctoral degree allowing its holder to supervise Ph. D. students. He is involved with theoretical and experimental studies of fundamental nonlinear optical phenomena with the aim of investigating potential applications to telecommunications and other domains. He has authored more than 140 journal and conference papers in the field of nonlinear optics and holds two patents. He is a member of the Optical Society of America (OSA), of the Institute of Electrical and Electronics Engineers (IEEE), and the French society of optics (SFO).

**LUC THÉVENAZ**

Luc Thévenaz received the M.Sc. degree in astrophysics from the Observatory of Geneva in 1982, and the Ph.D. degree in physics in 1988 from the University of Geneva, Switzerland. In 1988 he joined the Swiss Federal Institute of Technology of Lausanne (EPFL). Research topics include Brillouin-scattering fiber sensors, nonlinear fiber optics, slow & fast light and laser spectroscopy in gases. He has been visiting scientist to the PUC University, Brazil (1991); Stanford University USA; Korea Advanced Institute of Science and Technology, South Korea (1998-99); Tel Aviv University, Israel (2007); and University of Sydney, Australia (2010). In 1998, he became Expert Scientist to the company Orbisphere Laboratories SA in Neuchâtel, Switzerland, and in 2000 he co-founded Omnisens, a company that develops photonic instrumentation. He is Chairman of the European COST Action 299 "FIDES: Optical Fibers for New Challenges Facing the Information Society", member of the Consortium in the FP7 European Project GOSPEL "Governing the speed of light" and author or co-author of some 300 publications and 5 patents. He is also Fellow of the Optical Society of America.

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Moshe Tur received the B.Sc. in Mathematics and Physics, from the Hebrew University, Jerusalem, Israel (1969), the M.Sc. degree in Applied Physics from the Weizmann Institute of Science, Rehovot, Israel (1972), and his Ph.D. from Tel-Aviv University, Tel-Aviv, Israel (1981). He is presently the Gordon Professor of Electrical Engineering at the School of Electrical Engineering of Tel-Aviv University, Tel-Aviv, Israel, where he has established a fiber-optic sensing and communication laboratory. He authored or co-authored more than 300 journal and conference technical papers with emphasis on fiber-optic sensing (with current emphasis on structural health monitoring, using fiber Bragg gratings and the Brillouin effect), polarization mode dispersion, microwave photonics, and advanced fiber-optic communication systems. He was chairman of the "New challenges in Fiber sensors" working group of the COST 299 Action FIDES. Dr. Tur is a Fellow of both the IEEE and the Optical Society of America.

**DAVID J. WEBB**

David J. Webb received a B.A. in Physics (University of Oxford) and a Ph.D. in physics (University of Kent), where he subsequently spent ten years as a Lecturer, then Senior Lecturer. He joined Aston University as Reader in Photonics in May

2001. A member of the Photonics Research Group, he has 25 years' research experience in the field of photonics, working in the areas of non-linear optics and optical fiber sensors and devices. He is involved in more than a dozen collaborative projects with industry, including both SMEs and major companies (e.g. Airbus, BAeSystems, Taylor Woodrow). He is also founding director in March 2007 of Astasense – a commercial vehicle to exploit sensing expertise at Aston University. He has published over 300 journal and conference papers on these subjects, as well as a research text book on photorefractive nonlinear optics. He is member of the IoP, OSA, and IEEE.

**MARC WUILPART**

Marc Wuilpart received the degree of Electrical Engineering from the *Faculté Polytechnique de Mons*, Mons, Belgium in 1999 and the Ph.D. in applied science in the same university in 2003. He is currently an associate professor at the University of Mons (Electromagnetism and Telecommunication Department) where he is teaching in the fields of electromagnetism, telecommunication and optical communication. His research activities concern optical fiber metrology. It consists in developing measurement techniques to determine the fundamental parameters characterizing optical fibers in the frame of telecommunications and sensing applications. In particular, he is interested in distributed measurement systems (OTDR, OFDR, POTDR, etc.) and in the characterization of polarization effects in optical fibers and fiber Bragg gratings. His research activities lead him to be author and co-author of four book chapters, about 100 journal and conference papers and 3 patent applications. He was chairman of a working group of the COST 299 Action FIDES and is a board member of the IEEE Photonics Society Benelux Chapter.

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