

Fibre Optics

Principles and Practices

Abdul Al-Azzawi



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

This material was previously published in *Photonics: Principles and Practices* © 2007 by Taylor & Francis Group, LLC.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2007 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-8295-5 (Hardcover)
International Standard Book Number-13: 978-0-8493-8295-6 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

No part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

LUMENTUM HOLDINGS, INC.

Table of Contents

Chapter 1

Fibre Optic Cables.....	1
1.1 Introduction.....	1
1.2 The Evolution of Fibre Optic Cables.....	1
1.3 Fibre Optic Cables.....	5
1.4 Plastic Fibre Cables.....	6
1.5 Light Propagation in Fibre Optic Cables.....	7
1.6 Refractive-Index Profile.....	8
1.7 Types of Fibre Optic Cables.....	8
1.7.1 Single-Mode Step-Index Fibre Cable.....	9
1.7.2 Multimode Step-Index Fibre Cable (Multimode Fibre Cable).....	9
1.7.3 Multimode Graded-Index Fibre (Graded-Index Fibre Cable).....	10
1.8 Polarization Maintaining Fibre Cables.....	10
1.9 Specialty Fibre Cables.....	11
1.10 Fibre Cable Fabrication Techniques.....	11
1.10.1 Double Crucible Method.....	12
1.10.2 Chemical Vapour Deposition Processes.....	13
1.10.3 Outside Vapour Deposition.....	14
1.10.4 Vapour Axial Deposition.....	14
1.10.5 Modified Chemical Vapour Deposition.....	15
1.10.6 Plasma Chemical Vapour Deposition.....	16
1.11 Fibre Drawing.....	17
1.12 Numerical Aperture.....	17
1.13 Modes in a Fibre Optic Cable.....	19
1.14 Light Source Coupling to a Fibre Cable.....	20
1.15 Launching Light Conditions into Fibre Cables.....	22
1.16 Fibre Tube Assembly.....	23
1.17 Fibre Optic Cables versus Copper Cables.....	23
1.18 Applications of Fibre Optic Cables.....	25
1.19 Experimental Work.....	26
1.19.1 Case (a): Fibre Cable Inspection and Handling.....	26
1.19.2 Case (b): Fibre Cable Ends Preparation.....	26
1.19.3 Case (c): NA and Acceptance Angles Calculation.....	26
1.19.4 Case (d): Fibre Cable Power Output Intensity.....	27
1.19.5 Technique And Apparatus.....	27
1.19.6 Procedure.....	29
1.19.7 Safety Procedure.....	29
1.19.8 Apparatus Set-Up.....	29
1.19.8.1 Case (a): Fibre Cable Inspection and Handling.....	29
1.19.8.2 Case (b): Fibre Cable Ends Preparation.....	31
1.19.8.3 Case (c): NA and Acceptance Angles Calculation.....	34
1.19.8.4 Case (d) Fibre Cable Power Output Intensity.....	35
1.19.9 Data Collection.....	37
1.19.9.1 Case (a): Fibre Cable Inspection and Handling.....	37
1.19.9.2 Case (b): Fibre Cable Ends Preparation.....	37
1.19.9.3 Case (c): NA and Acceptance Angles Calculation.....	37
1.19.9.4 Case (d): Fibre Cable Power Output Intensity.....	37

LUMENTUM HOLDINGS INC

1.19.10	Calculations and Analysis	38
1.19.10.1	Case (a): Fibre Cable Inspection and Handling	38
1.19.10.2	Case (b): Fibre Cable Ends Preparation	38
1.19.10.3	Case (c): NA and Acceptance Angles Calculation.....	38
1.19.10.4	Case (d): Fibre Cable Power Output Intensity	38
1.19.11	Results and Discussions	38
1.19.11.1	Case (a): Fibre Cable Inspection and Handling	38
1.19.11.2	Case (b): Fibre Cable Ends Preparation	38
1.19.11.3	Case (c): NA and Acceptance Angles Calculation.....	39
1.19.11.4	Case (d): Fibre Cable Power Output Intensity	39
1.19.12	Conclusion	39
1.19.13	Suggestions for Future Lab Work	39
1.20	List of References.....	39
1.21	Appendix.....	39
	Further Reading	39

Chapter 2

	Advanced Fibre Optic Cables	41
2.1	Introduction.....	41
2.2	Advanced Types of Fibre Optic Cables.....	41
2.2.1	Dual-Core Fibre for High-Power Laser	42
2.2.2	Fibre Bragg Gratings	42
2.2.2.1	Manufacturing Method	43
2.2.3	Chirped Fibre Bragg Gratings	44
2.2.3.1	Manufacturing Method	45
2.2.4	Blazed Fibre Bragg Gratings	46
2.2.5	Nonzero-Dispersion Fibre-Optic Cables	46
2.2.6	Photonic Crystal Fibre Cables	46
2.2.7	Microstructure Fibre Cables.....	49
2.2.8	Polymer Holey-Fibre Cables	49
2.2.9	Image Fibre Cables.....	50
2.2.10	Liquid Crystal Photonic Bandgap Fibre Cables	51
2.2.11	Lensed and Tapered Fibre Cables	51
2.2.11.1	Advantages of Lensing Technology	52
2.2.11.2	Manufacturing Technologies.....	53
2.2.12	Bend-Insensitive Fibre Cables	54
2.2.13	Nanoribbon Fibre Optic Cables	55
2.3	Applications of Advanced Fibre Cables	55
2.4	Experimental Work.....	57
2.4.1	Conclusion	57
2.4.2	Suggestions for Future Lab Work	57
2.5	List of References.....	57
2.6	Appendix.....	57
	Further Reading	57

Chapter 3

	Light Attenuation in Optical Components.....	59
3.1	Introduction.....	59
3.2	Light Losses in an Optical Material.....	59
3.2.1	Absorption.....	60
3.2.2	Dispersion	60

3.2.3	Scattering	60
3.2.4	Light Loss in Parallel Optical Surfaces	61
3.2.5	Light Loss in an Epoxy Layer	61
3.2.6	Bending and Micro-Bending	62
3.3	Attenuation Calculations	63
3.4	Experimental Work.....	65
3.4.1	Technique and Apparatus.....	65
3.4.2	Procedure	66
3.4.3	Safety Procedure.....	66
3.4.4	Apparatus Setup	66
3.4.4.1	Laser Light Power Loss through One to Five Microscope Slides	66
3.4.4.2	Laser Light Power Loss through a Single Slide Inclined at Different Angles	67
3.4.4.3	Laser Light Power Loss through an Epoxy Layer Between Two Slides	68
3.4.4.4	Laser Light Power Loss through a Fibre Optic Cable	70
3.4.4.5	Laser Light Power Loss through a Fibre-Optic Cable Due to Micro-Bending	71
3.4.4.6	Laser Light Power Loss through a Fibre-Optic Cable Coupled to a Grin Lens at the Input and/or Output	72
3.4.5	Data Collection.....	73
3.4.5.1	Laser Light Power Loss through One to Five Microscope Slides	73
3.4.5.2	Laser Light Power Loss through a Single Slide Inclined at Different Angles	73
3.4.5.3	Laser Light Power Loss through an Epoxy Layer between Two Slides	74
3.4.5.4	Laser Light Power Loss through a Fibre-Optic Cable	74
3.4.5.5	Laser Light Power Loss through a Fibre-Optic Cable Due to Micro-Bending	74
3.4.5.6	Laser Light Power Loss through a Fibre-Optic Cable Coupled to a Grin Lens at the Input and/or Output	75
3.4.6	Calculations and Analysis	75
3.4.6.1	Laser Light Power Loss through One to Five Microscope Slides	75
3.4.6.2	Laser Light Power Loss through a Single Slide Inclined at Different Angles	75
3.4.6.3	Laser Light Power Loss through an Epoxy Layer between Two Slides	75
3.4.6.4	Laser Light Power Loss through a Fibre-Optic Cable	76
3.4.6.5	Laser Light Power Loss through a Fibre-Optic Cable Due to Micro-Bending.....	76
3.4.6.6	Laser Light Power Loss through a Fibre-Optic Cable Coupled to a Grin Lens at the Input and/or Output	76
3.4.7	Results and Discussions	76
3.4.7.1	Laser Light Power Loss through One to Five Microscope Slides	76
3.4.7.2	Laser Light Power Loss through a Single Slide Inclined at Different Angles.....	76

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts



Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research



With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips



Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.