

BUILDING ELECTRO-OPTICAL SYSTEMS

Physical Constants and Rules of Thumb

Solar constant (at zenith, above atmosphere)	1.36 kW/m ² , 20 MW/m ² /sr, 136 klx
Transmittance of clear atmosphere	0.8
Minimum luminance for easy reading	5 lx
Bright room lights	400 lx
Bright desk lamp for close work	7000 lx
Peak luminous efficiency of light-adapted eye	683 lm/W @552 nm, -3 dB @510&610
Brightest stars ($m_v = 0$)	2.0 μ lx at ground
Faintest naked-eye star ($m_v = 6$)	$8 \cdot 10^{-9}$ lx at ground
Black body radiation	56.7 kW/m ² at 1000 K
Earth's magnetic field B	0.3 to 0.6 gauss
Circular cone of half-angle θ	$NA = n \sin \theta$, $\Omega' = \pi(NA)^2$
Airy disc radius of circular aperture of radius a	$0.61\lambda/a$ radians ($a \gg \lambda$)
Étendue of Gaussian beam	$(\pi\lambda/4)^2$
Waist radius of Gaussian beam	$w = \lambda/(\pi NA)$
Airy disc diameter in the visible	$a \approx f\# = 0.5/NA$ (a in microns)
Defocus Tolerance	$ \Delta Z < 0.5\lambda/(NA)^2$
Peak efficiency of an optical system + photodiode	0.4 to 0.8 depending on coatings
Image flux density at $f/8$ (0.063 NA), distant object	1% of object flux density (Lambertian)
Strehl ratio with RMS wavefront error E waves	$S \approx \exp(-E^2/2)$
Diffraction limit	$\lambda/4$ RMS wavefront error \rightarrow 0.8 Strehl
Hyperfocal distance of lens of diameter D	D^2/λ
Aberration scaling with NA and field angle	Spherical $\propto (NA)^3$, Coma $\propto (NA)^2\theta$, Astigmatism & Field Curvature $\propto (NA)\theta^2$, Distortion (barrel or pincushion) $\propto \theta^3$
Things invariant under magnification:	radiance, $n^2 A\Omega'$, # resolvable spots, phase shift, total power
Fibre Étendue: $n^2 A\Omega'$ (cm ² ·sr)	$\sim 3 \cdot 10^{-6}$ (SM), $3 \times 10^5 \cdot 10^{-3}$ (step MM)
Responsivity of photodiode ($\eta = 1$)	$\mathcal{R}_{\max} = \lambda/1.240 \mu\text{m A/W}$
1 dB increase	26% power, 12% voltage
Additional noise producing 1 dB SNR reduction	5.87 dB below noise floor
Shot Noise limit	$i_{\text{photo}} R_L > 2kT/e$ (50 mV at 300 K)
Shot Noise Rule of One	1 σ AC shift with 1 photon/s in 1 Hz coherently added
Shot Noise of 1 mA	17.90 pA/ $\sqrt{\text{Hz}}$
Resistor with Johnson noise of 1 nV/ $\sqrt{\text{Hz}}$ (300 K)	60.4 Ω
Resistor with Johnson noise of 1 pA/ $\sqrt{\text{Hz}}$ (300 K)	16.56 k Ω
Noise power with matched source (NF = 0 dB for pure Johnson noise)	$P_J(\text{dBm}) = -173.8 + \text{NF} + 10 \log \left(\frac{T}{300\text{K}} \right) + 10 \log \text{BW}$
Quantization noise	$1/\sqrt{12}$ ADU
Sine wave power (50 Ω)	$P(\text{dBm}) = 4 + 20 \log_{10} V_{\text{pp}}$
Transconductance of bipolar transistor	$g_m = i_C/(kT) = i_C/25.7 \text{ mV}$ (300 K)
Sheet resistance of 0.5-oz copper (0.017 mm)	1.0 m Ω/\square at 25°C
Inductance of 1 inch component lead	$L \approx 20 \text{ nH}$
Capacitance of 1mm ² pad on 4-layer card	0.08 - 0.2 pF (1 & 3 layers from ground)
Low frequency capacitance of RG-58 cable	100 pF/m

BUILDING ELECTRO-OPTICAL SYSTEMS

MAKING IT ALL WORK

SECOND EDITION

Philip C. D. Hobbs
Principal,
ElectroOptical Innovations
Briarcliff Manor, NY

 **WILEY-
INTERSCIENCE**

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright ©2008 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services please contact our Customer Care Department with the U.S. at 877-762-2974, outside the U.S. at 317-572-3993 or fax 317-572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print, however, may not be available in electronic format.

Library of Congress Cataloging-in-Publication Data:

Building Electro-Optical Systems:making it all work/ Philip C. D. Hobbs.

p. cm.—(Wiley series in pure and applied optics)

“A Wiley-Interscience publication.”

Includes index.

ISBN 0-471-24681-6 (cloth : alk. paper)

I. Electrooptical devices—Design and construction.

I. Title

II. Series.

TA1750.H63 2008

t21.381'045—dc21

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

*In memory of my father,
Gerald H. D. Hobbs
John 6:40*



We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover up all the tracks, to not worry about the blind alleys or describe how you had the wrong idea first, and so on. So there isn't any place to publish, in a dignified manner, what you actually *did* in order to get to do the work.

—Richard P. Feynman, Nobel lecture 1966.

CONTENTS

Preface	xxxix
Acknowledgments	xliii
1 Basic Optical Calculations	1
1.1 Introduction	1
1.2 Wave Propagation	3
1.2.1 Maxwell's Equations and Plane Waves	3
1.2.2 Plane Waves in Material Media	3
1.2.3 Phase Matching	4
1.2.4 Refraction, Snell's Law, and the Fresnel Coefficients	5
1.2.5 Brewster's Angle	6
1.2.6 Total Internal Reflection	7
1.2.7 Goos-Hänchen Shift	7
1.2.8 Circular and Elliptical Polarization	8
1.2.9 Optical Loss	8
1.3 Calculating Wave Propagation In Real Life	8
1.3.1 Scalar Optics	9
1.3.2 Paraxial Propagation	10
1.3.3 Gaussian Beams	11
1.3.4 The Debye Approximation, Fresnel Zones and The Fresnel Number	13
1.3.5 Ray Optics	15
	vii

1.3.6	Lenses	16
1.3.7	Aperture, Field Angle, and Stops	17
1.3.8	Fourier Transform Relations	18
1.3.9	Fourier Imaging	22
1.3.10	The Pupil	23
1.3.11	Connecting Wave and Ray Optics: <i>ABCD</i> Matrices	24
1.3.12	Source Angular Distribution: Isotropic and Lambertian Sources	28
1.3.13	Solid Angle	29
1.3.14	Étendue: How Much Light Can I Get?	29
1.3.15	What Is ‘Resolution’?	31
1.4	Detection	31
1.5	Coherent Detection	32
1.5.1	Interference	32
1.5.2	Coherent Detection and Shot Noise: the Rule of One	33
1.5.3	Spatial Selectivity of Coherent Detection	34
1.6	Interferometers	35
1.6.1	Two-Beam Interferometers	35
1.6.2	Multiple-Beam Interferometers: Fabry Perots	35
1.6.3	Focused-Beam Resonators	36
1.7	Photon Budgets and Operating Specifications	36
1.7.1	Basis	36
1.8	Signal Processing Strategy	42
1.8.1	Analogue Signal Processing	42
1.8.2	Post-Processing Strategy	43
1.8.3	Putting It All Together	44
2	Sources And Illuminators	49
2.1	Introduction	49
2.2	The Spectrum	50
2.2.1	Visible Light	50
2.2.2	Ultraviolet	50
2.2.3	Infrared	51
2.3	Radiometry	51
2.4	Continuum Sources:	52
2.4.1	Black Body Radiators	53
2.4.2	Radiance Conservation and the Second Law of Thermodynamics	54
2.4.3	Tungsten Bulbs	54
2.4.4	Glow bulbs and Globars	55
2.5	Interlude: Coherence	56
2.5.1	Speckle	57
2.5.2	Imaging Calculations with Partially Coherent Light	58

2.5.3 Gotcha: Coherence Fluctuations At Finite Bandwidth	58
2.5.4 Measuring Laser Noise In Practice	59
2.6 More Sources	60
2.6.1 LEDs	60
2.6.2 Superluminescent Diodes	61
2.6.3 Amplified Spontaneous Emission (ASE) Devices	62
2.6.4 High pressure arc lamps	62
2.6.5 Flashlamps	63
2.6.6 Spark and Avalanche Sources	64
2.7 Incoherent Line Sources	64
2.7.1 Low pressure discharges	64
2.8 Using Low-Coherence Sources: Condensers	65
2.8.1 Radiometry of Imaging Systems	65
2.8.2 The Condenser Problem	65
2.9 Lasers	67
2.9.1 Mode structure	67
2.9.2 Relaxation oscillation	68
2.10 Gas Lasers	68
2.11 Solid-State Lasers	69
2.11.1 Modelocked Lasers, Optical Parametric Oscillators, and Other Exotica	71
2.12 Diode Lasers	71
2.12.1 Visible laser diodes	73
2.12.2 Distributed feedback and distributed Bragg reflector	73
2.12.3 Tuning properties	74
2.12.4 Mode Jumps	74
2.12.5 Regions of Stability	75
2.12.6 Checking The Mode Structure	75
2.12.7 Vertical-cavity surface-emitting lasers	75
2.12.8 Modulation behaviour	76
2.12.9 ESD sensitivity	77
2.12.10 Difficulty in collimating	77
2.12.11 Other diode laser foibles	78
2.13 Laser Noise	78
2.13.1 Intensity noise	78
2.13.2 Frequency Noise	79
2.13.3 Mode Hopping	79
2.13.4 Mode-Partition Noise	80
2.13.5 Gotcha: Surface Near A Focus	80
2.13.6 Pulling	80
2.13.7 Mode Beats	81
2.13.8 Power supply ripple and Pump Noise	81
2.13.9 Microphonics	82

2.13.1	Frequency noise	82
2.13.1	Spatial and polarization dependence of noise, wiggle noise	82
2.14	Diode Laser coherence control	83
2.14.1	External cavity diode lasers	83
2.14.2	Injection locking and MOPA	83
2.14.3	Strong UHF modulation	84
3	Optical Detection	85
3.1	Introduction	85
3.2	Photodetection In Semiconductors	86
3.3	Signal to Noise Ratios	87
3.3.1	Square Law Detectors	87
3.3.2	Photons	88
3.4	Detector figures of merit	89
3.4.1	Quantum Efficiency	89
3.4.2	Responsivity	89
3.4.3	Noise-Equivalent Power (NEP)	90
3.4.4	D^*	91
3.4.5	Capacitance	93
3.4.6	Spectral Response	93
3.4.7	Spatial Uniformity	94
3.5	Quantum detectors	94
3.5.1	Photodiodes and Their Relatives.	94
3.5.2	Shunt Resistance	96
3.5.3	Speed	96
3.5.4	Photodiodes and Pulses	97
3.5.5	Phototransistors	97
3.5.6	Prepackaged Combinations of photodiodes with amplifiers and digitizers	97
3.5.7	Split Detectors	98
3.5.8	Lateral effect cells	98
3.5.9	Position-sensing detector pathologies	99
3.5.10	Other position sensing detectors	99
3.5.11	Infrared Photodiodes	101
3.5.12	Quantum Well Infrared Photodiodes	102
3.6	Quantum Detectors With Gain	103
3.6.1	Photomultipliers	103
3.6.2	PMT Circuit Considerations	103
3.6.3	Avalanche photodiodes (APDs)	106
3.6.4	Photon Counting with APDs	108
3.6.5	Vacuum APDs	109
3.6.6	Photoconductors	110
3.7	Thermal Detectors	111

3.8	Image intensifiers	112
3.8.1	Image Tubes	112
3.8.2	Microchannel Plates	112
3.8.3	Streak Tubes	113
3.9	Silicon Array Sensors	113
3.9.1	Charge-Coupled Devices	113
3.9.2	Types of CCD	114
3.9.3	Efficiency And Spectral Response	114
3.9.4	Noise and Dark Current	115
3.9.5	Bloom, Bleed, and Fringing	115
3.9.6	Spatial Pattern	116
3.9.7	Linearity	116
3.9.8	Driving CCDs	117
3.9.9	Time Delay Integration (TDI) CCDs	117
3.9.10	Charge-Multiplying CCDs	117
3.9.11	Charge Injection Devices (CIDs)	118
3.9.12	Photodiode Arrays	119
3.9.13	CMOS Imagers	119
3.9.14	Video Cameras	119
3.9.15	Extending the Wavelength Range: CCDs + fluors	120
3.9.16	Electron storage materials	120
3.9.17	Infrared Array Detectors	121
3.9.18	Intensified cameras	121
3.9.19	Calibrating Image Sensors	122
3.9.20	Linearity Calibration	123
3.10	How do I know which noise source dominates?	124
3.10.1	Source noise	124
3.10.2	Shot noise	125
3.10.3	Background fluctuations	126
3.10.4	Thermal emission	126
3.10.5	Lattice Generation-Recombination noise	126
3.10.6	Multiplication noise	127
3.10.7	Temperature Fluctuations	127
3.10.8	Electronic Noise	128
3.10.9	Noise Statistics	128
3.11	Hacks	128
3.11.1	Use an optical filter	128
3.11.2	Reduce the field of view	128
3.11.3	Reduce the detector size	129
3.11.4	Tile with detectors	130
3.11.5	Cool the detector	130
3.11.6	Reduce the duty cycle	131

3.11.7	Use coherent detection	131
3.11.8	Catch the front surface reflection	132
3.11.9	Watch Background Temperature	132
3.11.10	Form linear combinations	133
3.11.11	Use solar cells at AC	133
3.11.12	Make windowed photodiodes into windowless ones	133
3.11.13	Use a LED as a photodetector	135
3.11.14	Use an Immersion Lens	135
3.11.15	Use a Non-imaging Concentrator	135
3.11.16	Think outside the box	135

4 Lenses, Prisms, and Mirrors 137

4.1	Introduction	137
4.2	Optical Materials	138
4.2.1	Glass	138
4.2.2	Temperature Coefficients of Optical Materials	139
4.2.3	Air and Other Gases	140
4.2.4	Optical Plastics	140
4.3	Light Transmission	141
4.3.1	UV Materials	141
4.3.2	IR materials	141
4.4	Surface Quality	142
4.5	Windows	143
4.5.1	Leading Order Optical Effects	143
4.5.2	Optical Flats	144
4.6	Pathologies of Optical Elements	144
4.6.1	Birefringence	144
4.7	Fringes	145
4.7.1	Surface Reflections	145
4.7.2	Etalon Fringes	146
4.7.3	Getting Rid of Fringes	147
4.7.4	Smearing Fringes Out	148
4.7.5	Advice	150
4.8	Mirrors	150
4.8.1	Plate Beamsplitters	150
4.8.2	Pellicles	150
4.8.3	Flat Mirrors	151
4.9	Glass Prisms	151
4.9.1	Right-angle and Porro Prisms	152
4.9.2	Dove Prisms	153
4.9.3	Equilateral, Brewster, and Littrow Prisms	153

4.9.4 Pentaprisms	154
4.9.5 Other Constant-Angle Prisms	154
4.9.6 Wedges	154
4.9.7 Roof prisms	155
4.9.8 Corner reflectors and cats' eyes	155
4.9.9 Beamsplitter Cubes	155
4.9.10 Fresnel Rhombs	156
4.10 Prism Pathologies	157
4.11 Lenses	157
4.11.1 Thin Lenses	158
4.11.2 Thick Lenses	158
4.11.3 Fast Lenses	161
4.11.4 Lens Bending	161
4.11.5 Dependence of aberrations on wavelength and refractive index	161
4.11.6 Aspheric lenses	162
4.11.7 Cylinder lenses	162
4.12 Complex Lenses	163
4.12.1 Achromats and Apochromats	163
4.12.2 Camera lenses	164
4.12.3 Microscope Objectives	164
4.12.4 Infinity correction	165
4.12.5 Focusing Mirrors	165
4.12.6 Anamorphic systems	166
4.12.7 Fringe Diagrams	166
4.13 Other Lenslike Devices	167
4.13.1 GRIN Lenses	167
4.13.2 Fresnel Zone Plates	168
4.13.3 Diffractive Lenses and Holographic Optical Elements	168
4.13.4 Fresnel lenses	169
4.13.5 Micro-Lens Arrays	169
4.13.6 Axicons	170
5 Coatings, Filters, and Surface Finishes	171
5.1 Introduction	171
5.1.1 Refraction and Reflection at an Interface	171
5.2 Metal Mirrors	172
5.2.1 Lossy Media	172
5.2.2 How thick does the metal have to be?	173
5.2.3 Designing Metal Films	174
5.3 Transmissive Optical Coatings	175
5.3.1 Dielectric Coating Materials	175

5.4	Simple Coating Theory	176
5.4.1	Multilayer Coating Theory	178
5.4.2	Lossless Coating Examples	178
5.4.3	Angle Tuning	180
5.4.4	Examples of Multilayer Coatings	180
5.4.5	Polarizing Beamsplitters	183
5.4.6	Interference Filters	185
5.4.7	Coating Problems	186
5.5	Absorptive Filters	186
5.5.1	Filter glass	186
5.5.2	Internal and External Transmittance	187
5.5.3	Holographic Filters	188
5.5.4	Colour Correcting Filters	188
5.6	Beam Dumps and Baffles	188
5.6.1	What is a black surface?	189
5.6.2	Black Paint	189
5.6.3	India Ink	190
5.6.4	Black Anodizing	190
5.6.5	Dendritic finishes	190
5.6.6	Black Appliques	190
5.6.7	Black Plastic	190
5.6.8	Black Wax	191
5.6.9	Black Glass	191
5.6.10	Designing Beam Dumps and Light Traps	191
5.6.11	Wood's Horn	191
5.6.12	Cone Dumps	192
5.6.13	Black Glass at Brewster's Angle	192
5.6.14	Shiny Baffles	193
5.6.15	Flat Black Baffles	193
5.6.16	Combinations	193
5.7	White Surfaces and Diffusers	193
5.7.1	Why Is It White?	194
5.7.2	Packed Powder Coatings	194
5.7.3	Barium Sulphate Paint	194
5.7.4	Spectralon	195
5.7.5	Opal glass	195
5.7.6	Magic Invisible Tape	195
5.7.7	Integrating Spheres	195
5.7.8	Ping-Pong Balls	196
5.7.9	Ground Glass	196
5.7.10	Holographic Diffusers	197
5.7.11	Diffusers and Speckle	197

6 Polarization	199
6.1 Introduction	199
6.2 Polarization of Light	200
6.2.1 Unpolarized Light	200
6.2.2 Highly Polarized Light	200
6.2.3 Circular Polarization	200
6.2.4 An Often-Ignored Effect: Pancharatnam's Topological Phase	201
6.2.5 Orthogonal Polarizations	201
6.3 Interaction of Polarization with Materials	202
6.3.1 Polarizers	202
6.3.2 Birefringence	202
6.3.3 Retardation	203
6.3.4 Double Refraction	204
6.3.5 Walkoff	204
6.3.6 Optical Activity	204
6.3.7 Faraday Effect	205
6.4 Absorption polarizers	205
6.4.1 Film Polarizers	206
6.4.2 Wire Grid Polarizers	206
6.4.3 Polarizing Glass	206
6.5 Brewster Polarizers	207
6.5.1 Pile-of-Plates Polarizers	207
6.5.2 Multilayer polarizers	207
6.5.3 Polarizing Cubes	207
6.6 Birefringent Polarizers	207
6.6.1 Walkoff Plates	208
6.6.2 Savart plates	209
6.7 Double-Refraction Polarizers	209
6.7.1 Wollaston Prisms	209
6.7.2 Rochon Prisms	210
6.7.3 Cobbling Wollastons	210
6.7.4 Nomarski wedges	211
6.7.5 Homemade polarizing prisms	212
6.8 TIR Polarizers	212
6.8.1 Refraction And Reflection At Birefringent Surfaces	213
6.8.2 Glan–Taylor	213
6.8.3 Glan–Thompson	214
6.9 Retarders	214
6.9.1 Wave Plates	214
6.9.2 Quarter Wave Plates	215
6.9.3 Half Wave Plates	215
6.9.4 Full Wave Plates	215

6.9.5 Multi-order Wave Plates	216
6.9.6 Zero-Order Wave Plates	216
6.9.7 Film and Mica	216
6.9.8 Circular polarizers	216
6.10 Polarization Control	217
6.10.1 Basis Sets for Fully Polarized Light	217
6.10.2 Partial Polarization and the Jones Matrix Calculus	217
6.10.3 Polarization States	218
6.10.4 Polarization Compensators	219
6.10.5 Circular Polarizing Film for Glare Control	219
6.10.6 Polarization rotators	219
6.10.7 Depolarizers	220
6.10.8 Faraday rotators and optical isolators	220
6.10.9 Beam separators	222
6.10.10 Lossless Interferometers	222
6.10.11 Faraday Rotator Mirrors and Polarization Insensitivity	222
7 Exotic Optical Components	225
7.1 Introduction	225
7.2 Gratings	225
7.2.1 Diffraction Orders	226
7.3 Grating Pathologies	229
7.3.1 Order Overlap	229
7.3.2 Ghosts and Stray Light	229
7.4 Types Of Gratings	229
7.4.1 Reflection and Transmission Gratings	230
7.4.2 Ruled Gratings	230
7.4.3 Holographic Gratings	231
7.4.4 Concave Gratings	231
7.4.5 Echelles	232
7.5 Resolution Of Grating Instruments	232
7.5.1 Spectral Selectivity And Slits	232
7.5.2 Angular Dispersion Factor	233
7.5.3 Diffraction Limit	233
7.5.4 Slit-Limited Resolution	234
7.5.5 Étendue	234
7.6 Fine Points of Gratings	234
7.6.1 Order Strengths	234
7.6.2 Polarization Dependence	235
7.6.3 Bragg gratings	235
7.7 Holographic optical elements	236
7.7.1 Combining Dispersing Elements	237

7.8	Retroreflective Materials	237
7.9	Scanners	239
7.9.1	Galvos	239
7.9.2	Rotating Scanners	240
7.9.3	Polygon Scanners	240
7.9.4	Polygon Drawbacks	241
7.9.5	Butterfly Scanners	241
7.9.6	Correcting Rasters	241
7.9.7	Descanning	242
7.9.8	Constant Linear Scan Speed	243
7.9.9	Hologons	244
7.9.10	Fast and cheap scanners	245
7.9.11	Dispersive Scanning	245
7.9.12	Raster Scanning	245
7.9.13	Mechanical Scanning	246
7.10	Modulators	246
7.10.1	Pockels And Kerr Cells	246
7.10.2	House-Trained Pockels Cells: Resonant And Longitudinal	249
7.10.3	Liquid Crystal	250
7.10.4	Acousto—Optic Cells	250
7.10.5	AO Deflectors	252
7.10.6	Photoelastic Modulators	253
7.10.7	Acousto-optic Laser Isolators	253
8	Fibre Optics	255
8.1	Introduction	255
8.2	Fibre Characteristics	256
8.2.1	Fibre Virtues	256
8.2.2	Ideal Properties Of Fibre	257
8.2.3	Fibre Vices	258
8.3	Fibre Theory	259
8.3.1	Modes	259
8.3.2	Degeneracy	261
8.3.3	Mode Coupling	261
8.3.4	Space-Variant Coupling	263
8.3.5	Dispersion	263
8.4	Fibre Types	264
8.4.1	Single Mode Optical Fibres	264
8.4.2	Multimode Optical Fibres	264
8.4.3	Few-Mode Fibre	265
8.4.4	Polarization-Maintaining (PM) Fibre	265
8.4.5	Chalcogenide Fibres For IR Power Transmission	266

8.4.6 Fibre Bundles	266
8.4.7 Split Bundles	267
8.4.8 Coupling Into Bundles	268
8.4.9 Liquid Light Guides	268
8.5 Other Fibre Properties	269
8.5.1 Leaky Modes	269
8.5.2 Cladding Modes	269
8.5.3 Bending	269
8.5.4 Bending and Mandrel Wrapping	269
8.5.5 Bend Birefringence and Polarization Compensators	269
8.5.6 Piezo-optical Effect and Pressure Birefringence	270
8.5.7 Twisting And Optical Activity	270
8.5.8 Fibre Loss Mechanisms	270
8.5.9 Mechanical Properties	271
8.5.10 Fabry-Perot Effects	271
8.5.11 Strain Effects	272
8.5.12 Temperature Coefficients	272
8.5.13 Bad Company: Fibres and Laser Noise	272
8.6 Working With Fibres	274
8.6.1 Getting Light In And Out	274
8.6.2 Launching Into Fibres In The Lab	275
8.6.3 Waveguide-To-Waveguide Coupling	277
8.6.4 Connecting Single-Mode to Multimode Fibre	277
8.6.5 Fibres and Pulses	277
8.6.6 Mounting Fibres In Instruments	277
8.6.7 Connectors	278
8.6.8 Splices	278
8.6.9 Expanded-Beam Connectors	279
8.6.10 Cleaving Fibres	279
8.7 Fibre Devices	279
8.7.1 Fibre Couplers	279
8.7.2 Fibre Gratings	280
8.7.3 Type II Gratings	281
8.7.4 Fibre Amplifiers	282
8.7.5 Fibre Lasers	282
8.7.6 Fibre Polarizers	282
8.7.7 Modulators	283
8.7.8 Switches	283
8.7.9 Isolators	283
8.8 Diode lasers and fibre optics	283
8.9 Fibre Optic Sensors	284
8.9.1 Sensitivity	284

8.9.2 Stabilization Strategy	284
8.9.3 Handling Excess Noise	285
8.9.4 Source Drift	285
8.10 Intensity Sensors	285
8.10.1 Microbend Sensors	286
8.10.2 Fibre Pyrometers	286
8.10.3 Fluorescence Sensors	286
8.10.4 Optical Time-Domain Reflectometry	286
8.11 Spectrally Encoded Sensors	286
8.11.1 Fibre Bragg Grating Sensors	286
8.11.2 Extrinsic Fabry-Perot Sensors	288
8.11.3 Other Strain Sensors	288
8.11.4 Fibre Bundle Spectrometers	288
8.11.5 Raman Thermometers	289
8.11.6 Band Edge Shift	289
8.11.7 Colorimetric Sensors	289
8.12 Polarimetric Sensors	289
8.12.1 Faraday Effect Ammeters	289
8.12.2 Birefringent Fibre	290
8.12.3 Photonic Crystal Fibre	290
8.13 Fibre Interferometers	290
8.13.1 Single Mode	291
8.13.2 Two-Mode	291
8.14 Two-Beam	291
8.14.1 Mach-Zehnder	292
8.14.2 Michelson	292
8.14.3 Sagnac	292
8.15 Multiple Beam Fibre Interferometers	292
8.15.1 Fabry-Perot	292
8.15.2 Ring Resonator	294
8.15.3 Motion sensors	294
8.15.4 Coherence-Domain Techniques	294
8.16 Phase and Polarization Stabilization	296
8.16.1 Passive Interrogation	296
8.16.2 Frequency Modulation	296
8.16.3 Fringe Surfing	296
8.16.4 Broadband Light	297
8.16.5 Ratiometric Operation	297
8.16.6 Polarization-Insensitive Sensors	297
8.16.7 Polarization Diversity	297
8.16.8 Temperature Compensation	297
8.16.9 Annealing	298

8.17 Multiplexing and Smart Structures	298
8.18 Fibre Sensor Hype	298
9 Optical Systems	301
9.1 Introduction	301
9.2 What, exactly, does a lens do?	301
9.2.1 Ray Optics	303
9.2.2 Connecting Rays And Waves: Wavefronts	303
9.2.3 Rays and the Eikonal Equation	305
9.2.4 Geometrical optics and electromagnetism	306
9.2.5 Variational Principles In Ray Optics	307
9.2.6 Schlieren effect	308
9.2.7 The Geometrical Theory of Diffraction	308
9.2.8 Pupils	310
9.2.9 Invariants	310
9.2.10 The Abbe Sine Condition	311
9.3 Diffraction	311
9.3.1 Plane Wave Representation	312
9.3.2 Green's Functions And Diffraction	312
9.3.3 The Kirchhoff Approximation	314
9.3.4 Plane Wave Spectrum Of Diffracted Light	314
9.3.5 Diffraction At High NA	315
9.3.6 Propagating From A Pupil To An Image	315
9.3.7 Telecentricity	319
9.3.8 Stereoscopy	319
9.3.9 The Importance of the pupil function	319
9.3.10 Coherent Transfer Functions	319
9.3.11 Optical Transfer Functions	324
9.3.12 Shortcomings of the OTF Concept	325
9.3.13 Modulation transfer function	326
9.3.14 Cascading Optical Systems	326
9.3.15 Which transfer function should I use?	326
9.4 Aberrations	326
9.4.1 Aberration Nomenclature	327
9.4.2 Aberrations of Windows	328
9.4.3 Broken Symmetry And Oblique Aberrations	330
9.4.4 Stop Position Dependence	330
9.5 Representing Aberrations	330
9.5.1 Seidel Aberrations	331
9.5.2 Aberrations Of Beams	331
9.5.3 Chromatic Aberrations	333
9.5.4 Strehl Ratio	333

9.6	Optical Design Advice	334
9.6.1	Keep Your Eye On The Final Output	335
9.6.2	Combining Aberration Contributions	335
9.7	Practical Applications	335
9.7.1	Spatial Filtering—how and why	335
9.7.2	How to Clean Up Beams	336
9.7.3	Dust Doughnuts	338
9.8	Illuminators	338
9.8.1	Flying-Spot Systems	339
9.8.2	Direction cosine space	339
9.8.3	Bright and Dark Field	340
9.8.4	Flashlight Illumination	340
9.8.5	Critical Illumination	340
9.8.6	Köhler illumination	340
9.8.7	Testing illuminators	341
9.8.8	Image Radiance Uniformity	341
9.8.9	Contrast and Illumination	341
9.8.10	Retroreflectors And Illumination	342
10	Optical Measurements	343
10.1	Introduction	343
10.2	Grass on the Empire State Building	344
10.2.1	Background, Noise, and Spurious Signals	344
10.2.2	Pedestal	345
10.2.3	Background Fluctuations	345
10.2.4	Noise statistics	345
10.2.5	Laser Noise	345
10.2.6	Lamp Noise	346
10.2.7	Media Noise	346
10.2.8	Electrical Interference	347
10.2.9	Electronic Noise	347
10.2.10	Quantization Noise	347
10.2.11	Baseband Isn't A Great Neighbourhood	347
10.3	Detection Issues: When Exactly Is Background Bad?	348
10.3.1	Dark Field	348
10.3.2	Bright Field: Amplitude Vs. Intensity Sensitivity	348
10.3.3	Coherent Background	349
10.3.4	Optical theorem	349
10.3.5	Dim Field Measurements	349
10.3.6	Bright and dark field are equivalent	350
10.3.7	Heterodyne Interferometry	351
10.3.8	SSB Interferometers	351

10.3.9	Shot-Noise Limited Measurements At Baseband	352
10.4	Measure The Right Thing	352
10.4.1	Phase measurements	353
10.4.2	Multiple-Scale Measurements Extend Dynamic Range	355
10.4.3	Fringes	355
10.5	Getting More Signal Photons	355
10.5.1	Don't Throw Photons Away	355
10.5.2	Optimize The Geometry	356
10.5.3	Use TDI	356
10.5.4	Consider OMA Spectroscopy	356
10.5.5	Consider Slitless Spectroscopy	356
10.5.6	Consider Fourier Transform Infrared (FTIR) Spectroscopy	357
10.5.7	Use Laser Scanning Measurements	357
10.5.8	Modify The Sample	358
10.5.9	Corral Those Photons	358
10.6	Reducing The Background Fluctuations	359
10.6.1	Beam Pointing Stabilization	359
10.6.2	Beam Intensity Stabilization	359
10.6.3	Photocurrent stabilization	360
10.6.4	Ratiometric Measurements	360
10.6.5	Changing The Physics	361
10.7	Optically Zero Background Measurements	361
10.7.1	Dark Field	361
10.7.2	Fringe-based devices	362
10.7.3	Monochromator-based measurements	362
10.7.4	Fluorescence and Photon counting	362
10.7.5	Nonlinear Measurements	363
10.7.6	Non-Optical Detection	363
10.7.7	Active Fringe Surfing	363
10.7.8	Polarization Tricks	364
10.7.9	Optical Time Gating	364
10.8	Electronically Zero Background Measurements	365
10.8.1	Polarization Flopping	365
10.8.2	Electronic Time Gating	365
10.8.3	Nulling Measurements	365
10.8.4	Differential Measurements	366
10.8.5	Other Linear Combinations	367
10.8.6	Laser Noise Cancellers	368
10.9	Labelling Signal Photons	368
10.9.1	Chopping	369
10.9.2	Scanning	370
10.9.3	AC Measurements	371

10.9.4	Modulation Mixing	371
10.9.5	AC interference	372
10.9.6	Labelling modulation phase	372
10.9.7	Labelling Arrival Time	372
10.9.8	Labelling Time Dependence	372
10.9.9	Labelling Wavelength	373
10.9.10	Labelling Coherence	373
10.9.11	Labelling Coincidence	373
10.9.12	Labelling Position	373
10.9.13	Labelling Polarization	373
10.10	Closure	374

11 Designing Electro–Optical Systems 375

11.1	Introduction	375
11.2	Do You Really Want To Do This?	376
11.2.1	Collegiality	376
11.2.2	Collegiality And Team Productivity	377
11.2.3	Choosing Projects	377
11.2.4	Procedural Advice	377
11.3	Very Basic Marketing	381
11.3.1	Who Or What Is Your Customer?	381
11.3.2	Making A Business Case: Internal	382
11.3.3	Making A Business Case: External	382
11.3.4	Figuring The Price	383
11.3.5	Budget For Market Creation	383
11.3.6	Budget for After-Sales Support	383
11.4	Classes Of Measurement	383
11.4.1	Know Your Measurement Physics	384
11.4.2	Crunchy Measurements	384
11.4.3	In-Between Measurements	384
11.4.4	Squishy Measurements	384
11.4.5	Pretty Pictures	385
11.4.6	Pretty Pictures Measurements	385
11.5	Technical Taste	386
11.6	Instrument Design	390
11.7	Guiding Principles	395
11.8	Design For Alignment	398
11.9	Turning A Prototype Into A Product	400
11.9.1	Be Very Careful Of ‘Minor’ Optical Design Changes	400
11.9.2	Don’t Design In Etalon Fringes	401
11.9.3	Handle Demo Karma Gracefully	401

12 Building Optical Systems	403
12.1 Introduction	403
12.2 Build What You Designed	404
12.3 Assembling Lab Systems	404
12.3.1 Build Horizontally	404
12.3.2 Use Metal	405
12.3.3 Scribble On The Optical Table	405
12.3.4 Mounts	405
12.3.5 Use Microbench for complicated systems	406
12.3.6 Machine A Base Plate	406
12.3.7 Use Irises	406
12.3.8 Getting The Right Height	406
12.3.9 Light-Tightness	407
12.3.10 Chop Up 35 mm SLR Cameras	407
12.3.11 Try to use at least one screw per component	407
12.3.12 Detector Alignment Needs Thought	407
12.3.13 Do-It-Yourself Spatial Filters	408
12.3.14 Field Lenses	409
12.4 Alignment and Testing	410
12.4.1 Things To Count On	410
12.4.2 Clamping	411
12.4.3 Soft lenses	411
12.4.4 Dimensional Stability	411
12.4.5 Beam Quality	412
12.4.6 Image Quality	412
12.5 Optical Assembly and Alignment Philosophy	413
12.5.1 Stability	413
12.5.2 Orthogonality	413
12.5.3 Use Serendipitous Information	414
12.6 Collimating Beams	414
12.6.1 Direct Collimation	414
12.6.2 Fizeau Wedges	415
12.6.3 Shear Plates	415
12.6.4 Collimeter	415
12.7 Focusing	415
12.7.1 Autocollimation	415
12.7.2 Direct Viewing	416
12.7.3 Foucault Knife Edge	417
12.7.4 Intensity-Based Chopping Tests	417
12.7.5 Diffraction Focusing	417
12.7.6 Speckle Focusing	417
12.7.7 Focusing Imagers	418

12.7.8 Standards	418
12.7.9 Sub-Apertures	418
12.8 Aligning beams with other beams	418
12.8.1 Co-Propagating Beams	419
12.8.2 Constrained beam-to-beam alignment	420
12.8.3 Counterpropagating Beams	420
12.9 Advanced Tweaking	421
12.9.1 Interferometers and Back-Reflections	421
12.9.2 Backlash and stick-slip	421
12.9.3 Adding Verniers	422
12.9.4 Cavities with Obstructions	422
12.9.5 Aligning Two-Beam Interferometers	422
12.9.6 Measuring Focal Lengths	423
12.9.7 Aligning Fabry-Perot Interferometers	423
12.9.8 Aligning Lasers	424
12.9.9 Aligning spatial filters	424
12.9.10 Use Corner Cubes And Pentaprisms	425
12.9.11 Use Quad Cells For XY alignment	426
12.9.12 Use Fringes For Angular Alignment	426
12.10 Aligning Laser Systems	426
12.10.1 Define An Axis	426
12.10.2 Adding Elements	427
12.10.3 Marking lens elements	427
12.10.4 Lenses are easier than mirrors, <i>especially</i> off-axis aspheres	428
12.10.5 Use an oscilloscope	428
12.11 Adhesives	428
12.11.1 Structural Adhesives	428
12.11.2 Optical Adhesives: UV Epoxy	429
12.11.3 Hydroxyl Bonding	430
12.11.4 Temporary Joints: Index Oil and Wax	430
12.12 Cleaning	430
12.12.1 What does a clean lens look like?	431
12.12.2 When To Clean	431
12.12.3 Cleaning lenses	431
12.12.4 Cleaning gratings	432
12.12.5 Opticlean polymer	433
12.13 Environmental Considerations	434
12.13.1 Fungus	434
12.13.2 Coating Drift	434
12.13.3 Lens Staining	434
12.13.4 Drift From Temperature and Humidity	434

13 Signal Processing	435
13.1 Introduction	435
13.2 Analogue Signal Processing Theory	436
13.2.1 Two Port Black Box	436
13.2.2 Linearity & Superposition	436
13.2.3 Time Invariance	437
13.2.4 Fourier Space Representation	437
13.2.5 Analytic Signals	438
13.3 Modulation and Demodulation	440
13.3.1 Terms	441
13.3.2 Phasors	445
13.3.3 Frequency Mixing	445
13.3.4 Amplitude Modulation (AM)	446
13.3.5 Double sideband (DSB)	446
13.3.6 Single sideband (SSB)	447
13.3.7 Phase Modulation (PM)	448
13.3.8 Frequency Modulation (FM)	449
13.4 Amplifiers	449
13.5 Departures From Linearity	449
13.5.1 Harmonics	450
13.5.2 Frequency Multipliers	451
13.5.3 Intermodulation	451
13.5.4 Saturation	452
13.5.5 Cross-Modulation	453
13.5.6 AM-PM conversion	453
13.5.7 Distortion in Angle-Modulated Systems	453
13.6 Noise and Interference	454
13.6.1 White Noise and $1/f$ noise	454
13.6.2 Johnson (Thermal) Noise	455
13.6.3 Shot Noise In Circuits	457
13.6.4 Other Circuit Noise	457
13.6.5 Noise Figure, Noise Temperature, and All That	457
13.6.6 Noise Models of Amplifiers	459
13.6.7 Combining Noise Contributions	460
13.6.8 Noise of Cascaded Stages	462
13.6.9 Interference: What does a spur do to my measurement, anyway?	462
13.6.10 AM noise and PM noise	462
13.6.11 Additive vs. multiplicative noise	464
13.6.12 Noise Statistics	464
13.6.13 Gaussian statistics	466
13.6.14 Shot Noise Statistics	467
13.6.15 Thresholding	467

13.6.1 Photon Counting Detection	468
13.7 Frequency Conversion	469
13.7.1 Mixers	470
13.7.2 Choosing an IF	470
13.7.3 Image Rejection	471
13.7.4 High Side vs. Low Side LO	472
13.7.5 Direct Conversion	473
13.7.6 Effects of LO noise	473
13.7.7 Gain Distribution	473
13.8 Filtering	473
13.8.1 Cascading Filters	474
13.8.2 Impulse response	475
13.8.3 Step response	475
13.8.4 Causality	475
13.8.5 Filter Design	477
13.8.6 Group delay	477
13.8.7 Hilbert transform filters	478
13.8.8 Linear Phase Bandpass and Highpass Filters	479
13.8.9 How To Choose A Filter	480
13.8.10 Matched filtering And Pulses	480
13.8.11 Pulsed Measurements And Shot Noise	483
13.9 Signal Detection	484
13.9.1 Phase sensitive detectors	484
13.9.2 AM Detectors	484
13.9.3 PLL Detectors	485
13.9.4 FM/PM Detectors	485
13.9.5 Phase-Locked Loops	486
13.9.6 I and Q Detection	487
13.9.7 Pulse Detection	487
13.10 Reducing Interference and noise	487
13.10.1 Lock-In Amplifiers	488
13.10.2 Filter Banks	488
13.10.3 Time-gated detection	488
13.10.4 Signal Averaging	489
13.10.5 Frequency Tracking	489
13.10.6 Modulation-Mixing Measurements	489
13.11 Data Acquisition and Control	490
13.11.1 Quantization	490
13.11.2 Choosing A Sampling Strategy	491
13.11.3 Designing with ADCs	491
13.11.4 Choosing The Resolution	492
13.11.5 Keep Zero On-Scale	492

14 Electronic Building Blocks	495
14.1 Introduction	495
14.2 Resistors	496
14.2.1 Resistor Arrays	496
14.2.2 Potentiometers	497
14.2.3 Trim Pots	497
14.2.4 Loaded Pots	498
14.3 Capacitors	498
14.3.1 Ceramic and Plastic Film Capacitors	500
14.3.2 Parasitic Inductance and Resistance	500
14.3.3 Dielectric Absorption	501
14.3.4 Electrolytic Capacitors	501
14.3.5 Variable Capacitors	502
14.3.6 Varactor Diodes	502
14.3.7 Inductors	503
14.3.8 Variable Inductors	505
14.3.9 Resonance	505
14.3.10 D -Networks and Q	505
14.3.11 Inductive Coupling	506
14.3.12 Loss In Resonant Circuits	507
14.3.13 Temperature Compensating Resonances	507
14.3.14 Transformers	507
14.3.15 Tank Circuits	508
14.4 Transmission Lines	508
14.4.1 Mismatch and Reflections	509
14.4.2 Quarter-Wave Series Sections	510
14.4.3 Coaxial Cable	511
14.4.4 Balanced lines	511
14.4.5 Twisted Pair	512
14.4.6 Microstrip	512
14.4.7 Termination Strategies	513
14.5 Transmission Line Devices	514
14.5.1 Attenuators	514
14.5.2 Shunt Stubs	514
14.5.3 Trombone lines	515
14.5.4 Transmission line transformers and chokes	515
14.5.5 Directional couplers	515
14.5.6 Splitters and Tees	516
14.6 Diodes and Transistors	516
14.6.1 Diode Switches	516
14.6.2 Bipolar Transistors	518
14.6.3 Temperature Dependence of I_S and V_{BE}	519

14.6.4	Speed	519
14.6.5	Biasing and Current Sources	519
14.6.6	Cutoff and Saturation	520
14.6.7	Amplifier Configurations	521
14.6.8	Differential Pairs	522
14.6.9	Current-Mode Circuitry	523
14.7	Signal Processing Components	524
14.7.1	Choosing Components	524
14.7.2	Read The Data Sheet Carefully	525
14.7.3	Don't Trust Typical Specs	525
14.7.4	Specsmanship	525
14.7.5	Watch For Gotchas	525
14.7.6	Mixers	526
14.7.7	LO Effects	526
14.7.8	Op Amps	527
14.7.9	Differential Amps	527
14.7.10	RF Amps	528
14.7.11	Isolation Amps	528
14.7.12	Radio ICs	529
14.7.13	Stability	529
14.7.14	Slew Rate	530
14.7.15	Settling Time	530
14.7.16	Limiting Amplifiers	531
14.7.17	Lock-In Amplifiers	532
14.8	Digitizers	533
14.8.1	Digital-to-Analogue Converters	533
14.8.2	Track/Hold amplifiers	534
14.8.3	Analogue-To-Digital Converters	536
14.8.4	DAC and ADC Pathologies	538
14.8.5	Differential Nonlinearity And Histograms	540
14.8.6	Dynamic Errors	541
14.8.7	Dynamic Range	541
14.8.8	ADC Noise	542
14.8.9	Ultrafast ADCs	542
14.9	Analogue Behaviour of Digital Circuits	542
14.9.1	Frequency Dividers	542
14.9.2	Phase Noise and Jitter of Logic	543
14.9.3	Analog uses of gates and inverters	543
15	Electronic Subsystem Design	545
15.1	Introduction	545
15.2	Design Approaches	546

15.2.1 Describe The Problem Carefully	546
15.2.2 Systems Engineers And Thermodynamics	547
15.2.3 Guess A Block Diagram	549
15.2.4 Getting The Gains Right	551
15.2.5 Error Budget	551
15.2.6 Judicious Gold-Plating	553
15.2.7 Interface Design	553
15.3 Perfection	554
15.4 Feedback Loops	556
15.4.1 Feedback Amplifier Theory And Frequency Compensation	557
15.4.2 Loop Gain	558
15.4.3 Adding Poles And Zeroes	558
15.4.4 Integrating Loops	560
15.4.5 Settling and Windup	561
15.4.6 Speedup Tricks	561
15.4.7 Output Loading	561
15.5 Signal Detectors	562
15.5.1 AM Detection	562
15.5.2 Emitter Detector	564
15.5.3 Synchronous Detectors	564
15.5.4 High performance envelope detection	564
15.5.5 Pulse Detection	565
15.5.6 Gated Integrators	567
15.5.7 Peak Track/Hold	567
15.5.8 Perfect Rectifiers	567
15.5.9 Logarithmic Detectors	568
15.5.10 Phase sensitive detectors	570
15.5.11 FM Detectors	571
15.5.12 Delay Discriminator	571
15.6 Phase-Locked Loops	572
15.6.1 Loop Design	573
15.6.2 More Complicated PLLs	574
15.6.3 Noise	574
15.6.4 Lock Detection	574
15.6.5 Acquisition Aids	575
15.7 Calibration	575
15.7.1 Calibrating Phase Detectors	576
15.7.2 Calibrating Amplitude Detectors	576
15.7.3 Calibrating a Limiter	577
15.8 Filters	577
15.8.1 LC Filters	577
15.8.2 Butterworth Filters	578

15.8.3	Chebyshev Filters	579
15.8.4	Filters With Good Group Delay	579
15.8.5	Filters With Good Skirts	579
15.8.6	Lowpass to Bandpass Transformation	579
15.8.7	Tuned Amplifiers	580
15.8.8	Use diplexers to control reflections and instability	580
15.9	Other Stuff	580
15.9.1	Diode Laser Controllers	580
15.9.2	Digitizing Other Stuff	581
15.9.3	Use sleazy approximations and circuit hacks	582
15.9.4	Oscillators	582
15.10	More Advanced Feedback Techniques	583
15.10.1	Put The Nonlinearity In The Loop	583
15.10.2	Feedback nulling	583
15.10.3	Auto-zeroing	584
15.10.4	Automatic Gain Control	584
15.10.5	Automatic Level Control	584
15.10.6	Feedback loops don't have to go to dc	584
15.11	Hints	585
15.12	Linearizing	586
15.12.1	Balanced circuits	587
15.12.2	Off-stage resonance:	587
15.12.3	Waveform Control	588
15.12.4	Breakpoint amplifiers	588
15.12.5	Feedback Using Matched N, nonlinearities	588
15.12.6	Inverting A Linear Control	589
15.12.7	Feedforward	589
15.12.8	Pre-distortion	589
15.13	Digital Control And Communication	589
15.13.1	Multiple serial DACS	590
15.13.2	Data Acquisition Cards	590
15.13.3	Nonsimultaneous sampling	590
15.13.4	Simultaneous Control and Acquisition	591
15.14	Miscellaneous Tricks	592
15.14.1	Avalanche Transistors	592
15.15	Bulletproofing	593
15.15.1	Hot Plugging	594
15.15.2	It works once, how do I make it work many times?	595
15.15.3	Centre Your Design	595
16	Electronic Construction Techniques	597
16.1	Introduction	597

16.2 Circuit Strays	598
16.2.1 Circuit Boards	598
16.2.2 Microstrip Line	599
16.2.3 Inductance and Capacitance of Traces	599
16.2.4 Stray Inductance	600
16.2.5 Stray Capacitance	601
16.2.6 Measuring Capacitance	602
16.3 Stray Coupling	602
16.3.1 Capacitive Coupling	602
16.3.2 Inductive Coupling	602
16.3.3 Transmission Line Coupling	603
16.3.4 Telling Them Apart	603
16.4 Ground Plane Construction	603
16.4.1 Ground currents	603
16.4.2 Ground Planes	604
16.4.3 Relieving The Ground Plane	605
16.4.4, Skin Depth	605
16.5 Technical Noise and Interference	606
16.5.1 What <i>is</i> ground, anyway?	606
16.5.2 Ground Loops	606
16.5.3 Floating Transducers	607
16.5.4 Mixed Signal Boards	608
16.5.5 High-Impedance Nodes And Layout	609
16.5.6 Connecting Coaxial Cables	609
16.5.7 Bypassing and Ground/supply inductance	610
16.5.8 Bypass Capacitor Self-Resonances	611
16.6 Product Construction	611
16.6.1 Cost vs Performance	611
16.6.2 Chassis Grounds	611
16.6.3 Magnetic Shielding	612
16.6.4 PC Boards	612
16.6.5 Design For Test	613
16.6.6 Connectors and Switches	613
16.6.7 Multi-Card Systems	613
16.6.8 Computer Plug-in Cards	614
16.7 Getting Ready	614
16.7.1 Buy A Stock Of Parts	614
16.7.2 Get The Right Equipment	614
16.7.3 Soldering	615
16.8 Prototyping	616
16.8.1 Dead Bug Method	616
16.8.2 Laying Out The Prototype	616

16.8.3	Adding Components	617
16.8.4	Hookup Wire	617
16.8.5	Wire It Correctly And Check It	618
16.8.6	Cobbling Copper Clad Board	618
16.8.7	Perforated Board	619
16.8.8	Perf board with pads	619
16.8.9	White solderless breadboards	619
16.8.10	Prototype Printed Circuit Boards	620
16.8.11	Blowing Up Prototypes	620
16.9	Surface Mount Prototypes	620
16.9.1	Stuffing Surface Mount PC Boards	620
16.9.2	Debugging SMT Boards	621
16.9.3	Probe Stations	621
16.9.4	Hacking SMTs	622
16.9.5	Board Leakage	622
16.10	Prototyping Filters	623
16.10.1	Standard Capacitors	623
16.10.2	Calibrating Inductors And Capacitors: A Hack	624
16.10.3	Filter Layout	625
16.10.4	Watch For Inductive Coupling	625
16.11	Tuning, or, You Can't Optimize What You Can't See	625
17	Digital Post-Processing	631
17.1	Introduction	631
17.2	Elementary Post-Processing	632
17.2.1	Gain and Offset	632
17.2.2	Background Correction And Calibration	633
17.2.3	Frame Subtraction	633
17.2.4	Baseline Restoration	634
17.2.5	Two Channel Correction	636
17.2.6	Plane Subtraction And Drift	636
17.2.7	More Aggressive Drift Correction	637
17.3	Dead Time Correction	637
17.4	Fourier Domain Techniques	637
17.4.1	Discrete Function Spaces	637
17.4.2	Finite Length Data	638
17.4.3	Sampled Data Systems	639
17.4.4	The Sampling Theorem and Aliasing	641
17.4.5	Discrete Convolution	643
17.4.6	Fourier Series Theorems	643
17.4.7	The Discrete Fourier Transform	644
17.4.8	Does the DFT give the right answer?	646

17.4.9 Leakage And Data Windowing	647
17.4.10 Data Windowing	648
17.4.11 Interpolation Of Spectra	652
17.5 Power spectrum estimation	653
17.5.1 DFT Power Spectrum Estimation: Periodograms	654
17.5.2 Maximum Entropy (All Poles) Method	655
17.6 Digital Filtering	657
17.6.1 Circular Convolution	659
17.6.2 Windowed Filter Design	659
17.6.3 Filtering In The Frequency Domain	660
17.6.4 Optimal Filter Design	661
17.7 Deconvolution	661
17.7.1 Inverse filters	661
17.7.2 Wiener filters	662
17.8 Resampling	663
17.8.1 Decimation	664
17.9 Fixing Space-Variant Instrument Functions	664
17.10 Finite Precision Effects	666
17.10.1 Quantization	666
17.10.2 Roundoff	666
17.10.3 Overflow	666
17.11 Pulling Data Out of Noise	666
17.11.1 Shannon's Theorem	667
17.11.2 Model Dependence	668
17.11.3 Correlation techniques	668
17.11.4 Numerical Experiments	669
17.11.5 Signal Averaging	669
17.11.6 Two-Point Correlation	670
17.12 Phase Recovery Techniques	671
17.12.1 Unwrapping	671
17.12.2 Phase Shifting Measurements	672
17.12.3 Fienup's Algorithm	672
18 Front Ends	673
18.1 Introduction	673
18.1.1 Noise Sources	674
18.1.2 Sanity Checking	674
18.2 Photodiode Front Ends	675
18.2.1 The Simplest Front End: A Resistor	675
18.2.2 Reducing the Load Resistance	677
18.3 Key Idea: Reduce the Swing Across C_d	677
18.4 Transimpedance Amplifiers	678

18.4.1	Frequency Compensation	680
18.4.2	Noise in the Transimpedance Amp	681
18.4.3	Choosing The Right Op Amp	683
18.4.4	No Such Amp Exists: Cascode Transimpedance Amplifiers	685
18.4.5	Noise In The Cascode	686
18.4.6	Externally Biased Cascode	688
18.4.7	Noise Considerations	688
18.4.8	Bootstrapping the Cascode	689
18.4.9	Circuit Considerations	691
18.4.10	One Small Problem...Obsolete Parts	692
18.4.11	Power Supply Noise	693
18.4.12	Beyond Transimpedance Amps: Cascode + , , Noninverting Buffer	693
18.4.13	Choosing Transistors	695
18.5	How to go faster	697
18.5.1	Series Peaking	699
18.5.2	Broader Band Networks	701
18.5.3	Matching Networks and Bode's Theorem	702
18.5.4	T-Coils	703
18.6	Advanced Photodiode Front Ends	704
18.6.1	Linear Combinations	704
18.6.2	Analogue Dividers	705
18.6.3	Noise Cancellers	705
18.6.4	Using Noise Cancellers	708
18.6.5	Noise Canceller Performance	708
18.6.6	Multiplicative Noise Rejection	709
18.6.7	Applications	709
18.6.8	Limitations	710
18.7	Other Types of Front End	710
18.7.1	Low Level Photodiode Amplifiers	710
18.7.2	Pyroelectric Front Ends	711
18.7.3	IR Photodiode Front Ends	713
18.7.4	Transformer Coupling	713
18.8	Hints	714
19	Bringing Up The System	719
19.1	Introduction	719
19.1.1	The Particle Counter That Wouldn't	720
19.2	Avoiding Catastrophe	722
19.2.1	Incremental Development	722
19.2.2	Greedy Optimization	722
19.2.3	Specifying the Interfaces	723
19.2.4	Talking to Each Other	723

19.2.5 Rigorous Subsystem Tests	723
19.2.6 Plan the Integration Phase Early	724
19.2.7 Don't Ship It Till It's Ready.	724
19.3 Debugging And Troubleshooting	725
19.4 Getting Ready	726
19.5 Indispensable Equipment	728
19.5.1 Oscilloscopes	728
19.5.2 Spectrum Analyzers	729
19.5.3 Probes	729
19.6 Analogue Electronic Troubleshooting	730
19.7 Oscillations	733
19.7.1 My op amp rings at 1 MHz when I put this cable on it	734
19.7.2 When I wave at it, it waves back	734
19.7.3 My circuit works until I let go of it	734
19.7.4 My transistor amplifier oscillates at 100 MHz.	734
19.7.5 Another kind of digital troubleshooting	735
19.8 Other Common Problems	735
19.9 Debugging and Troubleshooting Optical Subsystems	738
19.10 Localizing The Problem	742
19.10.1 Is It Optical Or Electronic?	742
19.10.2 Component Tests	743
19.10.3 Beam Quality Tests	743
19.10.4 Collimated Beam Problems	743
19.10.5 Focused Beam Problems	744
19.10.6 Viewing Techniques	744
19.10.7 Test Techniques for Imaging Systems	744
19.10.8 Test Techniques for Light Buckets	745
19.10.9 Invisible Light	745
19.10.10 Test Techniques for Fibre Systems	745
19.10.11 Test Techniques for Frequency-Selective Systems	746
19.10.12 Source Noise Problems	746
19.10.13 Pointing Instability Problems	746
19.10.14 Source Pulling	746
19.10.15 Misalignment	747
19.10.16 Etalon Fringes	747
19.10.17 Thermal Drift	747
19.10.18 Environmental Stuff	747
19.10.19 Take It Apart And Put It Together Again	747

Appendix A: Good Books**749**

Topic Index

759



PREFACE

You are fools, to say you learn from your mistakes. I learn from the mistakes of other men.

—Otto von Bismarck

This is a book of lore. *Lore* is an old word for wisdom and knowledge. While it often refers to magic and epic poetry, what I mean by it is altogether more homely: a mixture of rules of thumb, experience, bits of theory, and an indefinable feeling for the right way to do things, a sort of technical taste. It is what makes the difference between analyzing a design once completed and coming up with a good design to fit a particular purpose. Course work and textbooks have lots of analysis but most contain no lore whatsoever.

One of the odd things about lore is that it lives in the fingers more than in the brain, like piano playing. In writing this book, I have often run up against the difference between how I do something and how I *think* I do it, or how I remember having done it. Since it's the actual lore of doing that is useful, I have where possible written or revised each section when I was actually doing that task or consulting with someone who was. I hope that this gives those sections a sense of immediacy and authenticity.

Apologia

Lore is acquired slowly through experience and apprenticeship. Beginners pester experts, who help fairly willingly, mostly because they're kept humble by stepping in potholes themselves. This mutual aid system works but is slow and unsystematic. As a beginner, I once spent nearly six months trying to get a fancy laser interferometer to work properly, a task that would now take about a week. The reason was a breakdown in the apprenticeship system—everyone consulted said 'Oh, that comes with practice'—perfectly true, and by no means unsympathetic, but not too helpful. Conversations with many others in the field

indicate that this sort of thing is the rule and not the exception. Time, enthusiasm and confidence are far too precious to go wasting them like that.

This book is an attempt to provide a systematic and accessible presentation of the practical lore of electro-optical instrument design and construction—to be the book I needed as a graduate student. It is intended for graduate students at all levels, as well as practicing scientists and engineers: anyone who has electro-optical systems to build and could use some advice. Its applicability ranges from experimental apparatus to optical disc players.

The range of topics covered here is enormously broad, and I wish I were master of it all. Most of it was invented by others whose names I don't know; it's the lore of a whole field, as filtered through one designer's head. It's mostly been learned by watching and doing, or worked out with colleagues at a white board, rather than reading journal articles, so there aren't many references. For further reading, there is a list of 100 or so good books in the Appendix that should fill in the gaps.

I hope that a book like this can erect bridges between subdisciplines, prevent common mistakes and help all those working on an instrument project to see it as a whole. So much good stuff gets lost in the cracks between physics, electrical engineering, optical engineering, and computer science, that a salvage attempt seemed justified. I apologize to those whose work has been acknowledged inadequately or whose priority has been overlooked, and hope that they can remember once needing a book like this.

Mission

Designing and constructing electro-optical instruments is without a doubt one of the most interdisciplinary activities in engineering. It makes an absorbing and rewarding career, with little danger of growing stale. On the other hand, the same interdisciplinary quality means that instrument building is a bit scary and keeps us on our toes. The very broad range of technologies involved means that at least one vital subsystem lies outside the designer's expertise, presenting a very real danger of major schedule slippage or outright failure, which may not become apparent until very late in the project.

We in electro-optics rely on whatever subset of these technologies we are familiar with, together with a combination of outside advice, collaboration, and purchased parts. Often, there are many ways of reaching the goal of a robust, working system; then the problem is where to start among a range of unfamiliar alternatives. It's like the classic computer game ADVENT: 'You are in a maze of twisty little passages, all different.' Some judicious advice (and perhaps a map left by a previous adventurer) is welcome at such times, and that's what this book is about, the lore of designing and building electro-optical instruments that work.

To have confidence in an instrument design, we really need to be able to calculate its performance ahead of time, without constructing an elaborate simulation. It is a nontrivial matter, given the current fragmented state of the literature, to calculate what the resolution and SNR of a measurement system will be before it is built. It's not that there isn't lots of information on how to calculate the performance of each lens, circuit, or computer program, but rather the complexity of the task and the very different ways in which the results are expressed in the different fields encountered. For example, what is the effect of fourth-order spherical aberration in the objective lens on the optimal band-setting filter in the analogue signal processor, and then on the signal-to-noise ratio of the ultimate digital data set? Somebody on the project had better know that, and my aim is to make you that somebody.

The book is intended in the first instance for use by oppressed graduate students in physics and electrical engineering, who have to get their apparatus working long enough to take some data before they can graduate. When they do, they'll find that real-world design work has much the same harassed and overextended flavour, so in the second instance, it's intended for working electro-optical designers. It can be used as a text in a combined lecture-laboratory course aimed at graduate students or fourth-year undergraduates, and as a self-teaching guide and professional reference by working designers.

The warm reception which the first edition received suggests that despite its faults it has filled a real need. In this edition, everything has been revised, some previously over-terse sections have been expanded, and more than 100 pages' worth of new material has been added. Component lists and electronic designs have been updated where needed. Only a very few things have been dropped, owing to space constraints or component obsolescence.

Organization

Textbooks usually aim at a linear presentation of concepts, in which the stuff on page n does not depend on your knowing pages $n + 1 \dots N$. This is very valuable pedagogically, since the reader is initially unfamiliar with the material and usually will go through the book thoroughly, once, under the guidance of a teacher who is presenting information rapidly. Reference books are written for people who already have a grasp of the topic but need to find more detail or remind themselves of things dimly remembered. Thus they tend to treat topics in clumps, emphasizing completeness, and to be weak on overall explanations and on connections between topics.

Those two styles work pretty well in some subject areas, but design lore is not one of them. Its concepts aren't branched like a tree, or packed like eggs in a crate, but rather are interlinked like a fishnet or a sponge; thus a purely linear or clumped presentation of lore is all but impossible without doing violence to it. Nonetheless, to be any use, a lore book must be highly accessible, both easy to work through sequentially and attractive to leaf through many times.

Computer scientists use the concept of locality of reference—it's a good thing if an algorithm works mainly with data near each other in storage, since it saves cache misses and page faults, but all the data have to be there, regardless. That's the way I have tried to organize this book: most of the lore on a particular topic is kept close together in the book for conceptual unity and easy reference, but the topics are presented in a sufficiently linear order that later chapters build mainly on earlier ones, and important connections are noted in both forward and backward directions¹. A certain amount of messiness results, which (it is to be hoped) has been kept close to a minimum. This approach gives rise to one minor oddity, which is that the same instruments are considered from different angles in different chapters, so some flipping of pages is required to get the whole picture.

The book is organized into three sections: Optics; Electronics and Signal Processing; and Special Topics In Depth (Front Ends and Bringing Up The System). There is also Supplementary Material, available from the web sites ftp://ftp.wiley.com/public/sci_tech_med/electro-optical and <http://electrooptical.net>, which comprises Chapter 20 on Thermal Control and chapter problems for the whole book.

The material is presented in varying levels of detail. The differences in the detail levels reflect the amount of published lore and the measured density of deep potholes that people

¹Because electro-optical lore is so interconnected, useful connections which are tangential to the discussion are relegated to footnotes. An occasional polemic is found there too.

fall into. For example, there are lots of potholes in optomechanical design, but weighty books of relevant advice fill shelf after shelf. Anyway, mechanical problems aren't usually what cause instrument projects to fail—unexamined assumptions, inexperience, and plain discouragement are. To get the job done, we talk instead about how to avoid common mistakes while coming up with something simple that works reliably.

The one big exception to this general scheme is Chapter 1. It pulls in strands from everywhere, to present the process and the rhythm of conceptual design, and so contains things that many readers (especially beginners) may find unfamiliar. Don't worry too much about the technical aspects, because there's more on all those things later in the book, as well as pointers to other sources.

A complete instrument design course based on this book would probably have to wait for a first- or second-year graduate class. Undergraduate students with a good grasp of electromagnetism, physical optics, and Fourier transforms might benefit from a fourth-year course on optical instruments based selectively on the first ten chapters. To get the most out of such a course, the audience should be people with instruments of their own to build, either in a lab course, as a senior project, or as part of their graduate work. Because of the complicated, interdisciplinary nature of instrument building, the laboratory part of the course might best be done by teams working on an instrument project rather than individually, provided that each designer knows enough about everybody else's part to be able to explain it.

Chapter Problems

Chapter problems for the book are available on the websites listed above. Making complicated tasks intuitive is the true realm of lore—knowing the mathematical expression for the fringe pattern of a defocused beam is less useful than knowing which way to turn which knob to fix it. The most powerful method for gaining intuition is to use a combination of practical work and simple theoretical models that can be applied easily and stay close to the real physics. Accordingly, the emphasis in the problems is on extracting useful principles from theory and discussion.

Most of the problems have been taken from real design and scientific work, and so tend to be open-ended. Most students will have had a lot of theoretical training, but nowadays most will not have the skills of a Lightning Empiricist, a gimlet-eyed designer who's fast at mental rule-of-thumb calculations and who sanity checks everything by reflex. Perhaps this book can help fix that.

Errata

A certain number of errors and misconceptions—hopefully minor—are bound to creep into a book of this type, size and scope, unfortunately. I welcome your comments and corrections, large and small: errata and omissions will be made available at ftp://ftp.wiley.com/public/sci_tech_med/electro-optical/errata2.txt <http://electrooptical.net/www/beos2e/errata2.txt>, and will be incorporated in future printings. Send email to hobbs@stanfordalumni.org.

P. C. D. HOBBS

Briarcliff Manor, New York
Michaelmas (September 29), 2008

ACKNOWLEDGMENTS

To acquire lore, one needs a big sandbox and long uninterrupted stretches of time to spend there, absorbed in the play. I am forever grateful to my parents for providing that sort of environment in my growing up, and for believing in me even when only the mess was visible.

I learned most of this material through participating in the stimulating and supportive technical cultures of the places where I've been fortunate enough to study and to work: the Edward L. Ginzton Laboratory at Stanford University, Stanford, California; the Department of Physics and the Department of Geophysics & Astronomy at the University of British Columbia and Microtel Pacific Research (both in Vancouver BC) and, for twenty-one years, the IBM Thomas J. Watson Research Center at Yorktown Heights, New York. I owe a special debt to IBM and to my managers there, Arthur Ciccolo, Frank Libsch, and John Mackay, for supporting this project and for generously allowing me time and resources to work on it.

I also wish to thank some of the many other gifted people who I have been privileged to have as close colleagues, teachers, and friends, particularly J. Samuel Batchelder (who first suggested I write this book), Donald M. DeCain, Kurt L. Haller, Gordon S. Kino, the late Roger H. Koch, Brian A. Murray, Martin P. O'Boyle, Marc A. Taubenblatt, Theodore G. van Kessel, and Robert H. Wolfe. Without them I'd still be stuck in one of those potholes way back along the road.

Most of all, I wish to thank my wife, Maureen, and our offspring Bronwen, Magdalen, and Simon, for their patience and encouragement while I wrote and wrote.

P. C. D. H.