

SERIES IN OPTICS AND OPTOELECTRONICS

# Laser-Based Measurements for Time and Frequency Domain Applications

*A Handbook*



**Pasquale Maddaloni • Marco Bellini**  
**Paolo De Natale**



**CRC Press**  
Taylor & Francis Group

A TAYLOR & FRANCIS BOOK

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

© 2013 by Taylor & Francis Group, LLC  
Taylor & Francis is an Informa business

No claim to original U.S. Government works

Printed on Acid-free paper  
Version Date: 20130108

International Standard Book Number-13: 978-1-4398-4151-8 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, 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) (<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>

---

# Contents

---

<b>Foreword</b>	<b>xv</b>
<b>Preface</b>	<b>xvii</b>
<b>Authors</b>	<b>xix</b>
<b>1 Shedding light on the art of timekeeping</b>	<b>1</b>
1.1 The great show of Time and Light, the curtain rises! . . . . .	1
1.2 Brief history of timekeeping: time-frequency equivalence . . . . .	2
1.3 The parallel story of the speed of light . . . . .	6
1.3.1 The laser arrives: length-frequency equivalence and the birth of optical frequency metrology . . . . .	14
1.3.2 Role of $c$ in fundamental physics . . . . .	17
1.4 In the end, time and light met up again: optical atomic clocks and outline of the book . . . . .	20
<b>2 Characterization and control of harmonic oscillators</b>	<b>25</b>
2.1 The ideal harmonic oscillator . . . . .	25
2.1.1 Synchronization in coupled oscillators . . . . .	32
2.1.2 Beating two oscillators . . . . .	35
2.2 Self-sustained oscillators . . . . .	36
2.3 The noisy oscillator . . . . .	41
2.4 Phase noise . . . . .	41
2.4.1 Review of mathematical tools . . . . .	42
2.4.2 Fundamental noise mechanisms . . . . .	44
2.4.2.1 Fluctuation-dissipation theorem (FDT) . . . . .	48
2.5 Phase noise modelling . . . . .	51
2.5.1 The Leeson effect . . . . .	54
2.5.2 The Allan variance . . . . .	57
2.5.3 Oscillator power spectrum in the carrier frequency domain . . . . .	62
2.5.3.1 Effect of frequency multiplication on the power spectrum . . . . .	65
2.6 Noise reduction in oscillators . . . . .	66
2.6.1 Phase-locked loops . . . . .	66
2.6.1.1 Optical phase-locked loops . . . . .	74
2.6.2 Injection locking . . . . .	76
2.7 Phase noise measurements . . . . .	80
2.7.1 Frequency counting . . . . .	80
2.7.2 Homodyne techniques . . . . .	81
2.7.3 Heterodyne techniques . . . . .	82
2.7.4 Self-heterodyning . . . . .	83

2.8	Amplitude noise measurements . . . . .	84
2.8.1	AM noise in optical systems . . . . .	85
<b>3</b>	<b>Passive resonators</b>	<b>87</b>
3.1	Microwave cavities . . . . .	88
3.2	Basic properties of bulk optical cavities . . . . .	94
3.2.1	Fabry-Perot etalon . . . . .	95
3.2.2	Paraxial ray analysis . . . . .	101
3.2.3	Wave analysis . . . . .	102
3.3	Cavity-design considerations . . . . .	106
3.3.1	Quarter wave stack reflectors . . . . .	107
3.3.2	Prism-based cavities . . . . .	111
3.4	Ultrastable cavities . . . . .	117
3.4.1	Thermal stability . . . . .	117
3.4.2	Vibration insensitive optical cavities . . . . .	123
3.5	Fiber cavities . . . . .	128
3.5.1	Directional coupler-based fiber cavities . . . . .	129
3.5.2	Resonators based on closely faced fiber tips . . . . .	131
3.5.3	FBG-based fiber resonators . . . . .	132
3.6	Whispering gallery mode resonators . . . . .	137
3.6.1	Wave theory of whispering gallery modes . . . . .	137
3.6.2	WGMs in a ray-optical picture . . . . .	150
3.6.3	Mode $Q$ and volume . . . . .	152
3.6.4	WGM evanescent coupling . . . . .	154
3.6.5	Fabrication and applications of whispering gallery resonators . . . . .	159
<b>4</b>	<b>Continuous-wave coherent radiation sources</b>	<b>163</b>
4.1	Principles of masers . . . . .	164
4.1.1	The hydrogen maser . . . . .	171
4.2	Compendium of laser theory . . . . .	176
4.2.1	The active medium . . . . .	177
4.2.1.1	Einstein A and B coefficients for absorption and emission . . . . .	177
4.2.1.2	Line-broadening mechanisms . . . . .	180
4.2.2	The pump . . . . .	183
4.2.3	The resonator . . . . .	186
4.2.4	Rate equations for a four-level system . . . . .	188
4.2.4.1	Transient behavior and relaxation oscillation . . . . .	191
4.3	Frequency pulling . . . . .	193
4.4	Achieving single-mode oscillation . . . . .	194
4.4.1	Line selection . . . . .	197
4.4.2	Single-transverse mode selection . . . . .	198
4.4.3	Single-longitudinal mode selection . . . . .	198
4.5	The laser output . . . . .	202
4.5.1	Spatial coherence . . . . .	202
4.5.2	Spectral and temporal coherence . . . . .	203
4.5.3	The effect of spontaneous emission . . . . .	205
4.5.3.1	Intrinsic laser linewidth . . . . .	206
4.5.3.2	Amplified spontaneous emission . . . . .	211
4.6	Laser frequency fluctuations and stabilization techniques . . . . .	213

4.6.1	Side-lock to an atomic/molecular resonance . . . . .	219
4.6.2	Pound-Drever-Hall method . . . . .	220
4.6.2.1	$10^{-16}$ -level laser frequency stabilization . . . . .	225
4.6.2.2	WGM resonators for laser frequency stabilization . . . . .	228
4.6.3	Hänsch-Couillaud technique . . . . .	231
4.6.4	Laser frequency stabilization by locking to an optical fiber-delay line	233
4.6.5	Injection locking . . . . .	237
4.7	Intensity fluctuations . . . . .	240
4.7.1	High-sensitivity photodiode array . . . . .	243
4.7.2	Optical ac coupling . . . . .	244
4.7.3	The laser as quasi-ideal oscillator . . . . .	246
4.8	Some specific laser systems . . . . .	249
4.8.1	He-Ne laser . . . . .	250
4.8.2	Carbon dioxide laser . . . . .	251
4.8.3	Dye lasers . . . . .	253
4.8.4	Ion-doped lasers and optical amplifiers . . . . .	257
4.8.4.1	Nd:YAG laser . . . . .	257
4.8.4.2	Ti:Sa laser . . . . .	258
4.8.4.3	Erbium-doped fiber amplifiers (EDFAs) . . . . .	259
4.8.4.4	Ytterbium-doped fiber amplifiers (YDFAs) . . . . .	260
4.8.4.5	Narrow-linewidth fiber lasers . . . . .	263
4.8.5	Semiconductor lasers . . . . .	268
4.8.5.1	Heterostructure diode lasers . . . . .	269
4.8.5.2	Distributed feedback (DFB) lasers . . . . .	285
4.8.5.3	Tapered semiconductor amplifiers . . . . .	288
4.8.5.4	Multiple-quantum-well lasers . . . . .	289
4.8.5.5	Vertical-cavity surface-emitting lasers . . . . .	292
4.8.5.6	Quantum cascade lasers . . . . .	292
4.8.5.7	Interband cascade lasers . . . . .	300
4.8.6	Nonlinear laser cw sources . . . . .	302
4.8.6.1	Sum frequency generation . . . . .	305
4.8.6.2	Optical parametric oscillators . . . . .	306
4.8.6.3	Difference frequency generators . . . . .	312
4.8.6.4	Tunable far-infrared radiation . . . . .	317
<b>5</b>	<b>High-resolution spectroscopic frequency measurements</b>	<b>323</b>
5.1	Interferometric wavelength measurements . . . . .	323
5.2	Spectroscopic frequency measurements . . . . .	328
5.2.1	Principles of absorption laser spectroscopy . . . . .	329
5.3	Frequency modulation spectroscopy . . . . .	329
5.3.1	Harmonic detection . . . . .	330
5.3.2	Wavelength modulation spectroscopy . . . . .	331
5.3.3	Single- and two-tone frequency modulation spectroscopy . . . . .	331
5.4	Magnetic rotation spectroscopy . . . . .	337
5.5	Cavity-enhanced spectroscopy . . . . .	341
5.5.1	Cavity-enhanced absorption spectroscopy . . . . .	342
5.5.2	Off-axis integrated cavity output spectroscopy . . . . .	343
5.5.3	Noise immune cavity-enhanced optical heterodyne molecular spectroscopy . . . . .	346
5.5.4	Cavity ring-down spectroscopy . . . . .	348

5.5.4.1	Phase-shift (PS) CRDS . . . . .	350
5.5.4.2	Saturated-absorption cavity ring-down spectroscopy . . . . .	351
5.6	Doppler-free saturation spectroscopy . . . . .	354
5.6.1	Frequency locking to a Lamb dip . . . . .	358
5.6.2	Cavity-enhanced Doppler-free saturation spectroscopy . . . . .	361
5.6.2.1	Doppler-free NICE-OHMS . . . . .	363
5.7	Doppler-free polarization spectroscopy . . . . .	364
5.8	Doppler-free two-photon spectroscopy . . . . .	368
5.9	Second-order Doppler-free spectroscopy . . . . .	372
5.10	Sub-Doppler spectroscopy in atomic/molecular beams . . . . .	374
5.10.1	Effusive beams . . . . .	374
5.10.2	Supersonic beams . . . . .	377
5.10.3	Buffer-gas-cooling . . . . .	379
5.11	Ramsey fringes . . . . .	381
5.12	Laser frequency standards using thermal quantum absorbers . . . . .	387
5.12.1	Iodine-stabilized lasers . . . . .	388
5.12.2	Acetylene-stabilized lasers . . . . .	388
5.12.3	Methane-stabilized lasers . . . . .	389
5.12.4	OsO <sub>4</sub> -stabilized lasers . . . . .	389
5.12.5	Atomic hydrogen standard . . . . .	390
5.12.6	Calcium standard . . . . .	393
5.13	Fourier transform spectroscopy . . . . .	394
5.14	Raman spectroscopy . . . . .	398
5.14.1	Coherent anti-Stokes spectroscopy . . . . .	405
5.14.2	Stimulated Raman scattering . . . . .	410
<b>6</b>	<b>Time and frequency measurements with pulsed laser systems</b>	<b>413</b>
6.1	Introduction . . . . .	413
6.2	Theory of mode locking . . . . .	415
6.3	Mode-locking mechanisms and dispersion compensation schemes . . . . .	417
6.3.1	Ti:sapphire lasers and Kerr-lens mode locking . . . . .	417
6.3.2	Fiber-based lasers and nonlinear-polarization-rotation mode-locking . . . . .	419
6.4	Optical frequency comb synthesis from mode-locked lasers . . . . .	421
6.4.1	Comb stabilization . . . . .	421
6.4.2	Measurements with a frequency comb . . . . .	425
6.4.2.1	Measuring frequency differences . . . . .	425
6.4.2.2	Measuring absolute frequencies with an octave-spanning comb . . . . .	426
6.4.2.3	Absolute optical frequency synthesizer . . . . .	427
6.4.2.4	Direct frequency-comb spectroscopy . . . . .	429
6.4.2.5	Other measurement schemes and applications . . . . .	435
6.4.3	Relevant properties of a mode-locked laser for frequency-comb applications . . . . .	440
6.4.4	Microresonator-based frequency combs . . . . .	441
6.5	Extension of OFCSs into novel spectral regions . . . . .	444
6.5.1	High-order laser harmonics and extensions to the XUV . . . . .	444
6.5.1.1	Generation and properties of high-order laser harmonics . . . . .	446
6.5.1.2	Ramsey-type spectroscopy in the XUV with high-order harmonics . . . . .	448
6.5.1.3	Cavity-enhanced XUV frequency combs . . . . .	456

6.5.1.4	Attosecond pulses . . . . .	459
6.5.2	Mid- and far-infrared OFCSs . . . . .	460
<b>7</b>	<b>Frequency standards</b>	<b>465</b>
7.1	General features of frequency standards and clocks . . . . .	465
7.2	Quartz oscillators . . . . .	466
7.2.1	Factors affecting crystal oscillator frequency accuracy . . . . .	471
7.2.2	Factors affecting frequency stability . . . . .	473
7.2.3	State-of-the-art ultrastable quartz oscillators . . . . .	473
7.3	Cryogenic sapphire oscillators . . . . .	473
7.4	Photonic microwave oscillators based on WGM resonators . . . . .	479
7.5	Generation of ultrastable microwaves via optical frequency division . . . . .	480
7.6	Trapping and cooling of neutral atoms . . . . .	482
7.6.1	Optical molasses . . . . .	483
7.6.2	Magneto-optical traps . . . . .	489
7.6.3	Bose-Einstein condensation . . . . .	492
7.6.3.1	Magnetic trapping . . . . .	492
7.6.3.2	Evaporative cooling . . . . .	493
7.6.3.3	Probing a BEC . . . . .	495
7.7	Cold stable molecules . . . . .	498
7.7.1	Stark decelerator . . . . .	498
7.8	Trapping and cooling of ions . . . . .	500
7.8.1	Paul traps . . . . .	500
7.8.1.1	Linear Paul traps . . . . .	504
7.8.2	Penning traps . . . . .	505
7.8.3	Trap loading . . . . .	507
7.8.4	Ion cooling techniques . . . . .	507
7.8.4.1	Laser cooling . . . . .	508
7.8.4.2	Sympathetic cooling . . . . .	511
7.8.5	Spectroscopy of trapped particles in the Lamb-Dicke regime . . . . .	511
7.9	Microwave atomic standards . . . . .	513
7.9.1	Metrological properties of the active hydrogen maser . . . . .	513
7.9.1.1	Maser design . . . . .	513
7.9.1.2	Frequency shifts . . . . .	513
7.9.1.3	Automatic tuning of the resonant cavity . . . . .	515
7.9.1.4	Frequency stability . . . . .	516
7.9.1.5	Cryogenic hydrogen masers . . . . .	517
7.9.2	Cesium clocks . . . . .	518
7.9.2.1	Cesium-beam frequency standards . . . . .	518
7.9.2.2	Cesium fountain clocks . . . . .	521
7.9.2.3	Uncertainty budget in a Cs fountain clock . . . . .	527
7.9.3	Rubidium clocks . . . . .	532
7.9.3.1	Rb fountain clocks . . . . .	533
7.9.3.2	Lamp-based Rb cell standards . . . . .	534
7.9.3.3	Laser-based Rb cell frequency standards . . . . .	535
7.9.4	Microwave ion clocks . . . . .	539
7.10	Time transfer and frequency dissemination . . . . .	541
7.10.1	Realization of time scales . . . . .	542
7.10.1.1	Realization of TAI . . . . .	542

7.10.1.2	Coordinated universal time . . . . .	543
7.10.2	Transmitting time information . . . . .	543
7.10.2.1	Portable clocks . . . . .	546
7.10.2.2	Global positioning system . . . . .	547
7.10.3	Frequency transfer . . . . .	550
7.10.3.1	A democratic absolute frequency chain . . . . .	550
7.10.3.2	Dissemination of microwave frequency standards . . . . .	551
7.10.3.3	Optical frequency transfer . . . . .	552
<b>8</b>	<b>Future trends in fundamental physics and applications</b>	<b>557</b>
8.1	Optical atomic clocks . . . . .	557
8.1.1	Trapped ion optical clocks . . . . .	559
8.1.1.1	Systematic frequency shifts . . . . .	562
8.1.2	Neutral atoms optical lattice clocks . . . . .	564
8.2	The hydrogen atom as an inexhaustible wellspring of advances in precision spectroscopy . . . . .	570
8.2.1	Determination of the Rydberg constant and of the proton radius . . . . .	572
8.3	Spectroscopy of cold, trapped metastable helium . . . . .	575
8.4	Measurements of fundamental constants . . . . .	578
8.4.1	Boltzmann constant $k_B$ . . . . .	578
8.4.2	Newton gravitational constant $G$ . . . . .	580
8.5	Constancy of fundamental constants . . . . .	582
8.5.1	Fine structure constant $\alpha$ . . . . .	584
8.5.1.1	Proton-to-electron mass ratio $\beta$ . . . . .	586
8.5.2	Speed of light $c$ . . . . .	588
8.5.2.1	Frequency dependence of $c$ and the mass of the photon . . . . .	588
8.5.3	Newton's gravitational constant . . . . .	590
8.6	Tests of fundamental physics laws . . . . .	590
8.6.1	Spectroscopic tests of spin-statistic connection and symmetrization postulate . . . . .	590
8.6.2	Search for the electron dipole moment . . . . .	594
8.6.3	Parity violation in chiral molecules . . . . .	595
8.7	Perspectives for precision spectroscopy of cold molecules . . . . .	600
8.8	Tests of general relativity: from ground-based experiments to space missions	603
8.8.1	Testing the Einstein Equivalence Principle . . . . .	604
8.8.1.1	Tests of UFF . . . . .	604
8.8.1.2	Tests of LLI . . . . .	605
8.8.1.3	Tests of LPI . . . . .	608
8.8.2	Test of post-Newtonian gravity . . . . .	610
8.8.3	Tests of the gravitational inverse square law . . . . .	611
8.8.3.1	Detection of gravitational waves . . . . .	611
8.9	Quantum-enhanced time and frequency measurements . . . . .	613
8.9.1	Standard quantum limit in physical measurements . . . . .	613
8.9.2	Using nonclassical light states for quantum-enhanced measurements . . . . .	615
8.9.3	Applications to time and frequency measurements . . . . .	620
8.9.3.1	Quantum logic spectroscopy . . . . .	620
8.9.3.2	Time and frequency quantum metrology . . . . .	621
8.9.3.3	Quantum positioning and clock synchronization . . . . .	623
8.10	Environmental metrology . . . . .	625



<i>Contents</i>	xiii
8.10.1 Geophysical survey of volcanic areas . . . . .	625
8.10.2 Detection of very rare isotopes . . . . .	628
8.10.3 Stratospheric survey with tunable diode laser spectrometers . . . . .	628
8.10.4 Fiber sensing of physical and chemical parameters . . . . .	630
8.10.4.1 Strain sensing . . . . .	632
8.10.4.2 Acceleration measurements . . . . .	633
8.10.4.3 Chemical sensing by optical-fiber ring resonators . . . . .	634
<b>Bibliography</b>	<b>637</b>
<b>Index</b>	<b>701</b>