

## Contents

<i>List of contributors</i>	<i>page</i> xiii
<i>Preface</i>	xvi
<b>Part I Principles and techniques</b>	<b>1</b>
1 General principles and characteristics of optical magnetometers	3
<i>D. F. Jackson Kimball, E. B. Alexandrov, and D. Budker</i>	
1.1 Introduction	3
1.1.1 Fundamental sensitivity limits	4
1.1.2 Zeeman shifts and atomic spin precession	5
1.1.3 Quantum beats and dynamic range	8
1.2 Model of an optical magnetometer	8
1.3 Density matrix and atomic polarization moments	13
1.4 Sensitivity and accuracy	16
1.4.1 Variational sensitivity (short-term resolution) and long-term stability	16
1.4.2 Parameter optimization	18
1.4.3 Absolute accuracy and systematic errors	19
1.5 Vector and scalar magnetometers	20
1.6 Applications	21
2 Quantum noise in atomic magnetometers	25
<i>M. V. Romalis</i>	
2.1 Introduction	25
2.2 Spin-projection noise	26
2.3 Faraday rotation measurements	26
2.4 Quantum back-action	27
2.5 Time correlation of spin-projection noise	28
2.6 Conditions for spin-noise dominance	30
2.7 Spin projection limits on magnetic field sensitivity	32
2.8 Spin squeezing and atomic magnetometry	36
2.9 Conclusion	37

vi	<i>Contents</i>	
3	Quantum noise, squeezing, and entanglement in radiofrequency optical magnetometers	40
	<i>K. Jensen and E. S. Polzik</i>	
3.1	Sources of noise	40
3.1.1	Atomic projection noise	40
3.1.2	Photon shot noise	41
3.1.3	Back-action noise and QND measurements	42
3.1.4	Technical (classical) noise	42
3.1.5	Entanglement and spin squeezing	42
3.2	A pulsed radiofrequency magnetometer and the projection noise limit	43
3.2.1	Pulsed RF magnetometry	44
3.2.2	Sensitivity and bandwidth	45
3.3	Light–atom interaction	46
3.3.1	A spin-polarized atomic ensemble interacting with polarized light	47
3.3.2	Conditional spin squeezing	48
3.3.3	Larmor precession, back-action noise, and two atomic ensembles	48
3.3.4	Swap and squeezing interaction	49
3.4	Demonstration of high-sensitivity, projection-noise-limited magnetometry	50
3.4.1	Setup, pulse sequence, and procedure	50
3.4.2	The projection-noise-limited magnetometer	52
3.5	Demonstration of entanglement-assisted magnetometry	54
3.6	Conclusions	57
4	$M_x$ and $M_z$ magnetometers	60
	<i>E. B. Alexandrov and A. K. Vershovskiy</i>	
4.1	Dynamics of magnetic resonance in an alternating field	60
4.1.1	Bloch equations and Bloch sphere	60
4.1.2	Types of magnetic resonance signals: $M_z$ and $M_x$ signals	62
4.2	$M_z$ and $M_x$ magnetometers: general principles	63
4.2.1	Advantages and disadvantages of $M_z$ magnetometers	66
4.2.2	Advantages and disadvantages of $M_x$ magnetometers	67
4.2.3	Attempts to combine advantages of $M_x$ and $M_z$ magnetometers: $M_x$ – $M_z$ tandems	72
4.3	Applications: radio-optical $M_x$ and $M_z$ magnetometers	73
4.3.1	Alkali $M_z$ magnetometers	73
4.3.2	$M_x$ magnetometers	75
4.3.3	$M_x$ – $M_z$ tandems	79
4.4	Summary: $M_x$ and $M_z$ scheme limitations, prospects, and application areas	82

<i>Contents</i>		vii
5	Spin-exchange-relaxation-free (SERF) magnetometers <i>I. Savukov and S. J. Seltzer</i>	85
5.1	Introduction	85
5.2	Spin-exchange collisions	86
5.2.1	The density-matrix equation	86
5.2.2	Simple model of spin exchange	90
5.3	Bloch equation description	92
5.4	Experimental realization	95
5.4.1	Classic SERF atomic magnetometer arrangement	95
5.4.2	Zeroing the magnetic field	98
5.4.3	Use of antirelaxation coatings	98
5.4.4	Comparison with SQUIDs	99
5.5	Fundamental sensitivity	101
6	Optical magnetometry with modulated light <i>D. F. Jackson Kimball, S. Pustelny, V. V. Yashchuk, and D. Budker</i>	104
6.1	Introduction	104
6.2	Typical experimental arrangements	106
6.3	Resonances in the magnetic field dependence	108
6.3.1	Frequency modulation	108
6.3.2	Amplitude modulation	111
6.3.3	Polarization modulation	113
6.4	Effects at high light powers	113
6.5	Nonlinear Zeeman effect	116
6.6	Magnetometric measurements with modulated light	118
6.7	Conclusion	122
7	Microfabricated atomic magnetometers <i>S. Knappe and J. Kitching</i>	125
7.1	Introduction	125
7.2	Sensitivity scaling with size	126
7.3	Sensor fabrication	131
7.4	Vapor cells	133
7.5	Heating and thermal management	134
7.6	Performance	135
7.7	Applications of microfabricated magnetometers	137
7.8	Outlook	139
8	Optical magnetometry with nitrogen-vacancy centers in diamond <i>V. M. Acosta, D. Budker, P. R. Hemmer, J. R. Maze, and R. L. Walsworth</i>	142
8.1	Introduction	142
8.1.1	Comparison with existing technologies	143
8.2	Historical background	144
8.2.1	Single-spin optically detected magnetic resonance	145
8.3	NV center physics	146

viii	<i>Contents</i>	
	8.3.1 Intersystem crossing and optical pumping	146
	8.3.2 Ground-state level structure and ODMR-based magnetometry	148
	8.3.3 Interaction with environment	150
	8.4 Experimental realizations	152
	8.4.1 Near-field scanning probes and single-NV magnetometry	152
	8.4.2 Wide-field array magnetic imaging	157
	8.4.3 NV-ensemble magnetometers	158
	8.5 Outlook	161
9	Magnetometry with cold atoms	167
	<i>W. Gawlik and J. M. Higbie</i>	
	9.1 Introduction	167
	9.2 Experimental conditions	168
	9.2.1 Constraints and advantages of using cold atoms for magnetometry	168
	9.2.2 Cold samples of atoms above quantum degeneracy	168
	9.3 Linear Faraday rotation with trapped atoms	170
	9.4 Nonlinear Faraday rotation	173
	9.4.1 Low-field, DC magnetometry	173
	9.4.2 Coherence evolution	174
	9.4.3 High-field, amplitude-modulated magneto-optical rotation	175
	9.4.4 Paramagnetic nonlinear rotation	175
	9.5 Magnetometry with ultra-cold atoms	176
	9.5.1 Overview of ultra-cold atomic magnetometry methods	176
	9.5.2 Figures of merit	180
	9.5.3 Details of spinor magnetometry	182
	9.5.4 Comparison with thermal-atom magnetometry	185
	9.5.5 Applications	187
10	Helium magnetometers	190
	<i>R. E. Slocum, D. D. McGregor, and A. W. Brown</i>	
	10.1 Introduction	190
	10.2 Helium magnetometer principles of operation	191
	10.2.1 Helium resonance element	192
	10.2.2 Helium optical pumping radiation sources	192
	10.2.3 Optical pumping of metastable helium	194
	10.2.4 Observation of optically pumped helium	196
	10.2.5 Observation of magnetic resonance signals in optically pumped helium	197
	10.3 Conclusions	202
11	Surface coatings for atomic magnetometry	205
	<i>S. J. Seltzer, M.-A. Bouchiat, and M. V. Balabas</i>	
	11.1 Introduction and history	205

	<i>Contents</i>	ix
11.2	Wall relaxation mechanisms	208
11.2.1	Origin and time dependence of the disorienting interaction	208
11.2.2	Methods of investigation	209
11.2.3	Quantitative interpretation	212
11.3	Coating preparation	213
11.4	Light-induced atomic desorption (LIAD)	217
11.5	Recent characterization methods	219
12	Magnetic shielding	225
	<i>V. V. Yashchuk, S.-K. Lee, and E. Paperno</i>	
12.1	Introduction	225
12.2	Ferromagnetic shielding	225
12.2.1	Simplified estimation of ferromagnetic shielding efficiency for a static magnetic field	226
12.2.2	Multilayer ferromagnetic shielding	227
12.2.3	Optimization of permeability: annealing, degaussing, shaking, tapping	232
12.2.4	Magnetic-field noise in ferromagnetic shielding	235
12.2.5	Examples of ferromagnetic shielding systems	236
12.3	Ferrite shields	238
12.3.1	Permeability	238
12.3.2	Fabrication and the effect of an air gap	239
12.3.3	Thermal noise	240
12.4	Superconducting shields	241
12.4.1	Principles	242
12.4.2	Materials and fabrication	243
12.4.3	Image field	244
<b>Part II</b>	<b>Applications</b>	249
13	Remote detection magnetometry	251
	<i>S. M. Rochester, J. M. Higbie, B. Patton, D. Budker, R. Holzlöhner, and D. Bonaccini Calia</i>	
13.1	Introduction	251
13.2	A remotely interrogated all-optical <sup>87</sup> Rb magnetometer	252
13.3	Magnetometry with mesospheric sodium	256
14	Detection of nuclear magnetic resonance with atomic magnetometers	265
	<i>M. P. Ledbetter, I. Savukov, S. J. Seltzer, and D. Budker</i>	
14.1	Introduction	265
14.2	The NMR Hamiltonian	267
14.3	Challenges associated with detection of NMR using atomic magnetometers	268
14.4	Remote detection	269

x	<i>Contents</i>	
14.5	Solenoid matching of Zeeman resonance frequencies	272
14.6	Flux transformer	273
14.7	Nuclear quadrupole resonance	274
14.8	Zero-field nuclear magnetic resonance	275
14.8.1	Thermally polarized zero-field NMR <i>J</i> spectroscopy	275
14.8.2	Parahydrogen-enhanced zero-field NMR	278
14.8.3	Zeeman effects on <i>J</i> -coupled multiplets	281
14.9	Conclusions	282
15	Space magnetometry	285
	<i>B. Patton, A. W. Brown, R. E. Slocum, and E. J. Smith</i>	
15.1	Introduction	285
15.1.1	Achievements of space magnetometry	285
15.1.2	Challenges unique to space magnetometers	286
15.1.3	Magnetic sensors used in space missions	287
15.2	Alkali-vapor magnetometers in space applications	287
15.2.1	Initial development of Earth's-field alkali magnetometers	287
15.2.2	Sensor design	288
15.2.3	NASA missions employing alkali-vapor magnetometers	289
15.3	Helium magnetometers in space applications	293
15.3.1	Introduction	293
15.3.2	Future helium space magnetometers	298
16	Detection of biomagnetic fields	303
	<i>A. Ben-Amar Baranga, T. G. Walker, and R. T. Wakai</i>	
16.1	Sources of biomagnetism	303
16.2	Development of biomagnetic field detection	304
16.3	Medical applications	308
16.4	Magnetocardiography with atomic magnetometers	310
16.5	Magnetoencephalography with an atomic magnetometer	313
16.6	Summary	316
17	Geophysical applications	319
	<i>M. D. Prouty, R. Johnson, I. Hrvoic, and A. K. Vershovskiy</i>	
17.1	Airborne magnetometers and gradiometers	319
17.2	Ground magnetometers/gradiometers	321
17.3	Marine magnetometers/gradiometers	323
17.4	Vector magnetometry with optically pumped magnetometers	324
17.5	Earthquake studies	329
17.6	Applications of magnetometers to detecting unexploded ordnance (UXO)	331
17.6.1	Introduction to the problem	331
17.6.2	Using magnetometers for UXO detection	332
17.6.3	Mathematics of UXO detection	333

<b>Part III Broader impact</b>	337
18 Tests of fundamental physics with optical magnetometers	339
<i>D. F. Jackson Kimball, S. K. Lamoreaux, and T. E. Chupp</i>	
18.1 Overview and introduction	339
18.2 Searches for permanent electric dipole moments	341
18.2.1 Basic experimental setup for an EDM experiment	344
18.2.2 Sensitivity to EDMs	345
18.2.3 Electric fields and coherence times for various systems	346
18.2.4 Magnetometry and comagnetometry in EDM experiments	349
18.3 Anomalous spin-dependent forces	352
18.3.1 Background	352
18.3.2 Experiments	355
18.4 <i>CPT</i> and local Lorentz invariance tests	361
18.5 Conclusion	364
19 Nuclear magnetic resonance gyroscopes	369
<i>E. A. Donley and J. Kitching</i>	
19.1 Introduction	369
19.2 NMR frequency shifts and relaxation	373
19.2.1 Spin exchange	374
19.2.2 Quadrupole surface frequency shifts	375
19.2.3 General wall relaxation	377
19.2.4 Magnetic-field gradients	377
19.2.5 Noble-gas self-relaxation	378
19.3 Alkali shifts and relaxation mechanisms	379
19.4 Two-spin NMR gyroscope	379
19.5 Comagnetometer	381
19.6 Miniaturization	383
19.7 Conclusion	383
20 Commercial magnetometers and their application	387
<i>D. C. Hovde, M. D. Prouty, I. Hrvoic, and R. E. Slocum</i>	
20.1 Introduction	387
20.2 Specifications	388
20.2.1 Noise	388
20.2.2 Resolution	391
20.2.3 Sensitivity	391
20.2.4 Sample rate and cycle time	392
20.2.5 Bandwidth	392
20.2.6 Absolute error and drift	393
20.2.7 Gradient tolerance	394
20.2.8 Dead zones	395
20.2.9 Heading error	395
20.2.10 Range of measurement	397

xii	<i>Contents</i>	
20.3	History of commercial magnetometry	398
20.3.1	Fluxgate magnetometers	398
20.3.2	SQUID magnetometers	399
20.3.3	Proton-precession and Overhauser magnetometers	399
20.3.4	Alkali metal magnetometers: rubidium, cesium, and potassium	401
20.3.5	Helium-3 and helium-4 magnetometers	402
20.4	Military applications	403
20.5	Anticipated improvements	404
	<i>Index</i>	406