## Contents

*List of contributors*  
Page xiii

*Preface*  
Page xvi

### Part I  Principles and techniques

1  General principles and characteristics of optical magnetometers  
*D. F. Jackson Kimball, E. B. Alexandrov, and D. Budker*  
1.1 Introduction  
1.1.1 Fundamental sensitivity limits  
1.1.2 Zeeman shifts and atomic spin precession  
1.1.3 Quantum beats and dynamic range  
1.2 Model of an optical magnetometer  
1.3 Density matrix and atomic polarization moments  
1.4 Sensitivity and accuracy  
1.4.1 Variational sensitivity (short-term resolution) and long-term stability  
1.4.2 Parameter optimization  
1.4.3 Absolute accuracy and systematic errors  
1.5 Vector and scalar magnetometers  
1.6 Applications  
2  Quantum noise in atomic magnetometers  
*M. V. Romalis*  
2.1 Introduction  
2.2 Spin-projection noise  
2.3 Faraday rotation measurements  
2.4 Quantum back-action  
2.5 Time correlation of spin-projection noise  
2.6 Conditions for spin-noise dominance  
2.7 Spin projection limits on magnetic field sensitivity  
2.8 Spin squeezing and atomic magnetometry  
2.9 Conclusion  

3 Quantum noise, squeezing, and entanglement in radiofrequency optical magnetometers 40

K. Jensen and E. S. Polzik

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 Mx and Mz magnetometers 60

E. B. Alexandrov and A. K. Vershovskiy

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: Mx and My signals 62

4.2 Mx and My magnetometers: general principles 63
  4.2.1 Advantages and disadvantages of Mx magnetometers 66
  4.2.2 Advantages and disadvantages of My magnetometers 67
  4.2.3 Attempts to combine advantages of Mx and My magnetometers: Mx–My tandems 72

4.3 Applications: radio-optical Mx and My magnetometers 73
  4.3.1 Alkali My magnetometers 73
  4.3.2 Mx magnetometers 75
  4.3.3 Mx–My tandems 79

4.4 Summary: Mx and My scheme limitations, prospects, and application areas 82
## Contents

### 5 Spin-exchange-relaxation-free (SERF) magnetometers

*I. Savukov and S. J. Seltzer*

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

*D. F. Jackson Kimball, S. Pustelny, V. V. Yashchuk, and D. Budker*

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

*S. Knappe and J. Kitching*

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

*V. M. Acosta, D. Budker, P. R. Hemmer, J. R. Maze, and R. L. Walsworth*

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
## Contents

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  
\textit{W. Gawlik and J. M. Higbie}  
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  
\textit{R. E. Slocum, D. D. McGregor, and A. W. Brown}  
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  
\textit{S. J. Seltzer, M.-A. Bouchiat, and M. V. Balabas}  
11.1 Introduction and history 205
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
V. V. Yashchuk, S.-K. Lee, and E. Paperno
  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

Part II Applications 249
13 Remote detection magnetometry 251
  S. M. Rochester, J. M. Higbie, B. Patton, D. Budker, R. Holzlöhner, and D. Bonaccini Calia
  13.1 Introduction 251
  13.2 A remotely interrogated all-optical $^{87}\text{Rb}$ magnetometer 252
  13.3 Magnetometry with mesospheric sodium 256
14 Detection of nuclear magnetic resonance with atomic magnetometers 265
  M. P. Ledbetter, I. Savukov, S. J. Seltzer, and D. Budker
  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
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.5 Solenoid matching of Zeeman resonance frequencies</td>
<td>272</td>
</tr>
<tr>
<td>14.6 Flux transformer</td>
<td>273</td>
</tr>
<tr>
<td>14.7 Nuclear quadrupole resonance</td>
<td>274</td>
</tr>
<tr>
<td>14.8 Zero-field nuclear magnetic resonance</td>
<td>275</td>
</tr>
<tr>
<td>14.8.1 Thermally polarized zero-field NMR J spectroscopy</td>
<td>275</td>
</tr>
<tr>
<td>14.8.2 Parahydrogen-enhanced zero-field NMR</td>
<td>278</td>
</tr>
<tr>
<td>14.8.3 Zeeman effects on J-coupled multiplets</td>
<td>281</td>
</tr>
<tr>
<td>14.9 Conclusions</td>
<td>282</td>
</tr>
<tr>
<td>15 Space magnetometry</td>
<td>285</td>
</tr>
<tr>
<td>B. Patton, A. W. Brown, R. E. Slocum, and E. J. Smith</td>
<td></td>
</tr>
<tr>
<td>15.1 Introduction</td>
<td>285</td>
</tr>
<tr>
<td>15.1.1 Achievements of space magnetometry</td>
<td>285</td>
</tr>
<tr>
<td>15.1.2 Challenges unique to space magnetometers</td>
<td>286</td>
</tr>
<tr>
<td>15.1.3 Magnetic sensors used in space missions</td>
<td>287</td>
</tr>
<tr>
<td>15.2 Alkali-vapor magnetometers in space applications</td>
<td>287</td>
</tr>
<tr>
<td>15.2.1 Initial development of Earth’s-field alkali magnetometers</td>
<td>287</td>
</tr>
<tr>
<td>15.2.2 Sensor design</td>
<td>288</td>
</tr>
<tr>
<td>15.2.3 NASA missions employing alkali-vapor magnetometers</td>
<td>289</td>
</tr>
<tr>
<td>15.3 Helium magnetometers in space applications</td>
<td>293</td>
</tr>
<tr>
<td>15.3.1 Introduction</td>
<td>293</td>
</tr>
<tr>
<td>15.3.2 Future helium space magnetometers</td>
<td>298</td>
</tr>
<tr>
<td>16 Detection of biomagnetic fields</td>
<td>303</td>
</tr>
<tr>
<td>A. Ben-Amar Baranga, T. G. Walker, and R. T. Wakai</td>
<td></td>
</tr>
<tr>
<td>16.1 Sources of biomagnetism</td>
<td>303</td>
</tr>
<tr>
<td>16.2 Development of biomagnetic field detection</td>
<td>304</td>
</tr>
<tr>
<td>16.3 Medical applications</td>
<td>308</td>
</tr>
<tr>
<td>16.4 Magnetocardiography with atomic magnetometers</td>
<td>310</td>
</tr>
<tr>
<td>16.5 Magnetoencephalography with an atomic magnetometer</td>
<td>313</td>
</tr>
<tr>
<td>16.6 Summary</td>
<td>316</td>
</tr>
<tr>
<td>17 Geophysical applications</td>
<td>319</td>
</tr>
<tr>
<td>M. D. Prouty, R. Johnson, I. Hrvoic, and A. K. Vershovskiy</td>
<td></td>
</tr>
<tr>
<td>17.1 Airborne magnetometers and gradiometers</td>
<td>319</td>
</tr>
<tr>
<td>17.2 Ground magnetometers/gradiometers</td>
<td>321</td>
</tr>
<tr>
<td>17.3 Marine magnetometers/gradiometers</td>
<td>323</td>
</tr>
<tr>
<td>17.4 Vector magnetometry with optically pumped magnetometers</td>
<td>324</td>
</tr>
<tr>
<td>17.5 Earthquake studies</td>
<td>329</td>
</tr>
<tr>
<td>17.6 Applications of magnetometers to detecting unexploded ordnance (UXO)</td>
<td></td>
</tr>
<tr>
<td>17.6.1 Introduction to the problem</td>
<td>331</td>
</tr>
<tr>
<td>17.6.2 Using magnetometers for UXO detection</td>
<td>332</td>
</tr>
<tr>
<td>17.6.3 Mathematics of UXO detection</td>
<td>333</td>
</tr>
</tbody>
</table>
Part III  Broader impact

18  Tests of fundamental physics with optical magnetometers  339
    D. F. Jackson Kimball, S. K. Lamoreaux, and T. E. Chupp
    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  CPT and local Lorentz invariance tests  361
    18.5  Conclusion  364

19  Nuclear magnetic resonance gyroscopes  369
    E. A. Donley and J. Kitching
    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
    D. C. Hovde, M. D. Prouty, I. Hrvoic, and R. E. Slocum
    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
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

Index 406