Contents

Editor's Preface *xiii*
Series Editor's Preface *xv*

1 **Magnets for Small-Scale and Portable NMR** *1*
Bernhard Blümich, Christian Rehorn, and Wasif Zia
1.1 Introduction *1*
1.2 Compact Permanent Magnets *3*
1.2.1 Types of Permanent Magnets *3*
1.2.2 Stray-Field Magnets *5*
1.2.2.1 Classification *5*
1.2.2.2 Magnets for 1D and 2D Imaging *6*
1.2.2.3 Magnets for Bulk-Volume Analysis *7*
1.2.3 Center-Field Magnets *9*
1.3 Magnet Development *10*
1.3.1 Permanent Magnet Materials *10*
1.3.2 Magnet Construction and Passive Shimming *11*
1.3.3 Overview of Center-field Magnets for Compact NMR *11*
1.3.4 Strategies for Passive Shimming *13*
1.3.5 Shim Coils for Compact NMR Magnets *14*
1.4 Concluding Remarks *16*
References *16*

2 **Compact Modeling Techniques for Magnetic Resonance Detectors** *21*
Suleman Shakil, Mikhail Kudryavtsev, Tamara Bechtold, Andreas Greiner, and Jan G. Korvink
2.1 Introduction *21*
2.2 Fast Simulation of EPR Resonators Based on Model Order Reduction *22*
2.2.1 The Discretized Maxwell's Equations *23*
2.2.2 Model Order Reduction *29*
2.2.3 Structure-Preserving Model Order Reduction *33*
2.2.4 Planar Coil EPR Resonator *34*
2.3 System Level Simulation of a Magnetic Resonance Microsensor by Means of Parametric Model Order Reduction *39*
2.3.1 Model Description *40*

Bibliografische Informationen
http://d-nb.info/1145065325

digitalisiert durch DEUTSCHE NATIONAL BIBLIOTHEK

2.3.2 Parametric Model Order Reduction *43*
2.3.3 Compact Model Simulation Results *46*
2.3.4 Device–Circuit Co-simulation *46*
2.4 Conclusions and Outlook *54*
References *55*

3 Microarrays and Microelectronics for Magnetic Resonance *59*
Oliver Gruschke, Mazin Jouda, and Jan G. Korvink
3.1 Introduction *59*
3.2 Microarrays for Magnetic Resonance *59*
3.2.1 Theoretical Background *59*
3.2.2 Microtechnologies for MR Array Fabrication *61*
3.3 Integrated Circuits *63*
3.4 CMOS Frequency Division Multiplexer *64*
3.4.1 The Low-Noise Amplifier *64*
3.4.2 The Frequency Mixer *65*
3.4.3 The Bandpass Filter *66*
3.4.4 Measurements *67*
3.4.4.1 MRI Experiment *68*
3.5 Summary *70*
References *70*

4 Wave Guides for Micromagnetic Resonance *75*
Ali Yilmaz and Marcel Utz
4.1 Introduction *75*
4.2 Wave Guides: Theoretical Basics *78*
4.2.1 Propagating Electromagnetic Modes *78*
4.2.2 Characteristic Impedance and Transport Characteristics *79*
4.2.3 Theory of TEM Wave Modes *79*
4.2.4 Modeling of TEM Modes *80*
4.2.4.1 Losses in Transmission Lines *82*
4.2.5 Magnetic Fields in Planar TEM Transmission Lines *82*
4.2.6 Transmission Line Detectors and Resonators *83*
4.3 Designs and Applications *84*
4.3.1 Microstrip NMR Probes in MRI *84*
4.3.2 Microfluidic NMR *87*
4.3.3 Planar Detectors *87*
4.3.4 Microstrip Detectors *88*
4.3.5 Nonresonant Detectors *90*
4.3.6 Stripline Detectors *92*
4.3.7 Parallel Plate Transmission Lines *96*
4.3.8 Applications in Solid-State Physics *97*
4.3.9 Wave Guides for Dynamic Nuclear Polarization *98*
References *100*

5 **Innovative Coil Fabrication Techniques for Miniaturized Magnetic Resonance Detectors** *109*
Jan Korvink, Vlad Badilita, Dario Mager, Oliver Gruschke, Nils Spengler, Shyam Sundar Adhikari Parenky, Ulrike Wallrabe, and Markus Meissner
5.1 Wire-Bonding – A New Means to Miniaturize MR Detectors *109*
5.2 Microcoil Inserts for Magic Angle Spinning *114*
5.2.1 Backbone of the Magic Angle Coil Spinning (MACS) Technique *115*
5.2.2 Cost of Inductive Coupling *116*
5.2.3 Demonstrating the Improved Sensitivity of the MACS Technique from NMR Experiments *118*
5.2.4 Microfabricated MACS Inserts *118*
5.2.5 Double-Resonant MACS Insert *120*
5.3 Micro-Helmholtz Coil Pairs *123*
5.3.1 Helmholtz Coils in Magnetic Resonance *123*
5.3.2 Magnetic Field Profile *124*
5.3.3 Micromachining of Miniaturized Helmholtz Pairs *125*
5.4 High Filling Factor Microcoils *128*
5.4.1 Introduction *128*
5.4.2 Fabrication *130*
5.4.3 Results *130*
5.5 Coil Fabrication Using Inks *130*
References *136*

6 **IC-Based and IC-Assisted μNMR Detectors** *143*
Jonas Handwerker and Jens Anders
6.1 Technological Considerations and Device Models *143*
6.1.1 Complementary Metal Oxide Semiconductor Technologies *143*
6.1.2 Bipolar Complementary Metal Oxide Semiconductor Technologies *148*
6.2 Monolithic Transceiver Electronics for NMR Applications *151*
6.2.1 Optimal Integrated RF Front-ends for μNMR Applications *151*
6.2.2 Designing NMR Receivers in CMOS and BiCMOS *155*
6.2.2.1 LNAs for Widebandand Applications *156*
6.2.2.2 LNAs for Narrowband Applications *163*
6.2.3 Co-design of the Detection Coil and the LNA for SNR Optimization *167*
6.3 Overview of the State-of-the-Art in IC-Based and IC-Assisted μNMR *167*
6.3.1 Portable NMR Systems *167*
6.3.2 NMR Spectroscopy Systems *170*
6.3.3 MR Imaging and Microscopy Systems *171*
6.3.4 Intravascular NMR Systems *173*
6.4 Summary and Conclusion *174*
References *174*

7 MR Imaging of Flow on the Microscale *179*
Dieter Suter and Daniel Edelhoff
7.1 Introduction *179*
7.2 Methods – Flow Imaging *179*
7.2.1 Time of Flight *180*
7.2.2 Phase Contrast *181*
7.2.3 Mean Flow *182*
7.2.4 Limitations *182*
7.2.4.1 Velocity Range *183*
7.2.4.2 Temporal Stability *184*
7.2.4.3 Spatial Resolution *184*
7.3 Applications of Microscopic Flow Imaging *185*
7.3.1 Experimental Setup *186*
7.3.2 Characterization of Liquid Exchange in Aneurysm Models *186*
7.3.2.1 Aneurysm Models *186*
7.3.2.2 Methods *186*
7.3.2.3 Results *187*
7.3.2.4 Conclusion *189*
7.3.3 Phase–Contrast Measurements with Constant Flow *189*
7.3.3.1 Laminar Flow in a Pipe *189*
7.3.3.2 Flow and Wall Shear Stress in an Aneurysm Model *190*
7.3.4 Pulsatile Flow *192*
7.4 Discussion *194*
Acknowledgments *195*
References *195*

8 Efficient Pulse Sequences for NMR Microscopy *199*
Jürgen Hennig, Katharina Göbel-Guéniot, Linnéa Hesse, and Jochen Leupold
8.1 Introduction *199*
8.2 Spatial Encoding *200*
8.2.1 *k*-Space and More *200*
8.2.2 Slice Selection *204*
8.3 Contrast Mechanisms *206*
8.3.1 T_1-relaxation *206*
8.3.2 T_2-relaxation *207*
8.3.3 T_2*-decay *207*
8.4 Basic Pulse Sequences *211*
8.4.1 General Considerations *211*
8.4.2 Spin Echo Sequences *212*
8.4.3 Gradient Echo-Based Imaging *214*
8.4.3.1 FLASH-Type Gradient Echoes *214*
8.4.3.2 EPI *219*
8.4.4 Ultrashort TE *220*
8.5 Special Contrasts *222*
8.5.1 Diffusion *222*
8.5.1.1 Diffusion Limit of NMR Microscopy *224*
8.5.2 Flow *229*

8.5.2.1 Velocity Phase Imaging *229*
8.5.2.2 Time-of-Flight Imaging *230*
8.5.3 Susceptibility Mapping and QSM *230*
References *232*

9 Thin-Film Catheter-Based Receivers for Internal MRI *237*
Richard R. A. Syms, Evdokia Kardoulaki, and Ian R. Young
9.1 Introduction *237*
9.2 Catheter Receivers *237*
9.2.1 Internal Imaging *238*
9.2.2 Catheter Receiver Designs *238*
9.2.3 Elongated Loop Receivers *239*
9.2.4 Tuning and Matching *240*
9.2.5 B_1-Field Decoupling *241*
9.2.6 E-Field Decoupling *242*
9.3 Thin-Film Catheter Receivers *244*
9.3.1 Thin-Film Coils *244*
9.3.2 Thin-Film Interconnects *245*
9.3.3 MR-Safe Thin Film Interconnects *246*
9.4 Thin-Film Device Fabrication *249*
9.4.1 Design and Modeling *249*
9.4.2 Materials and Fabrication *249*
9.4.3 Mechanical Performance *251*
9.4.4 Electrical Performance *252*
9.5 Magnetic Resonance Imaging *255*
9.5.1 Imaging with Resonant Detectors *255*
9.5.2 Imaging with EBG Detectors *256*
9.5.3 Imaging with MI Detectors *257*
9.6 Conclusions *258*
Acknowledgments *259*
References *259*

10 Microcoils for Broadband Multinuclei Detection *265*
Jens Anders and Aldrik H. Velders
10.1 Introduction *265*
10.1.1 NMR Microcoils *266*
10.1.2 Broadband NMR Microcoils *267*
10.2 Microcoil-Based Broadband Probe NMR Spectroscopy *268*
10.2.1 Broadband Coil, Chip, and Probe Setup *269*
10.2.2 Non-tuned Broadband Planar Transceiver Coil NMR Data *269*
10.2.2.1 Homonuclear 1D NMR Experiments *269*
10.2.2.2 Heteronuclear 1D NMR Experiments *273*
10.2.2.3 Homo- and Heteronuclear 2D NMR Experiments *273*
10.2.3 Questions Arising for Broadband NMR *273*
10.3 An Engineer's Answers to the Questions *274*
10.3.1 General Remarks *274*
10.3.2 Coils *274*

10.3.3 Impedance Matching and Front-end Electronics *278*
10.3.4 Answers to the Questions *287*
10.3.5 Remaining Spectrometer Electronics *289*
10.4 Conclusion and Outlook *289*
Acknowledgment *290*
References *291*

11 Microscale Hyperpolarization *297*
Sebastian Kiss, Lorenzo Bordonali, Jan G. Korvink, and Neil MacKinnon
11.1 Introduction *297*
11.2 Theory *301*
11.2.1 Dynamic Nuclear Polarization *301*
11.2.1.1 Polarization Transfer and DNP Mechanisms *301*
11.2.1.2 DNP Instrumentation *302*
11.2.1.3 Challenges in DNP Instrumentation *303*
11.2.2 *para*-Hydrogen-Induced Hyperpolarization *304*
11.2.3 Spin-Exchange by Optical Pumping *309*
11.3 Microtechnological Approaches *312*
11.3.1 DNP *312*
11.3.1.1 Microtechnology for High-Field DNP Resonators *314*
11.3.1.2 Microresonators for Low- and Intermediate-Field DNP *318*
11.3.1.3 Microfluidics and DNP Resonators *322*
11.3.2 PHIP *323*
11.3.2.1 Gas-Phase Characterization of Reactors and Fluidic Networks *324*
11.3.2.2 Micro-PHIP in the Liquid Phase *327*
11.3.2.3 SABRE: A Micro-NMR Compatible PHIP Technique? *330*
11.3.2.4 Catalyst Solubility in Water *331*
11.3.2.5 Quantification *331*
11.3.2.6 High-Field SABRE *332*
11.3.3 Micro-SEOP for Nuclear Hyperpolarization *333*
11.4 Conclusion *337*
References *338*

12 Small-Volume Hyphenated NMR Techniques *353*
Andrew Webb
12.1 Different Modes of Hyphenation *353*
12.2 Types of Radio-Frequency Coils Used for Small-Scale Hyphenation *355*
12.3 Hyphenation of NMR and Pressure-Driven Microseparations *357*
12.3.1 Capillary High-Pressure Liquid Chromatography *357*
12.3.2 Capillary Gas Chromatography *358*
12.4 Electrically Driven Microseparations *359*
12.4.1 Capillary Electrophoresis NMR *360*
12.4.2 Capillary Isotachophoresis NMR *362*
12.5 Off-Line Hyphenation of Microsamples with Microcoil Detection *363*
12.6 Continuous Monitoring of *In Situ* Biological Systems *368*

12.7 Studies of Microfluidic Mixing and Reaction Kinetics *368*
12.8 Measurement of Flow Profiles in Flow Cells and Microchannels *370*
12.9 Conclusion *372*
References *372*

13 Force-Detected Nuclear Magnetic Resonance *381*
Martino Poggio and Benedikt E. Herzog
13.1 Introduction *381*
13.2 Motivation *381*
13.3 Principle *382*
13.4 Force versus Inductive Detection *384*
13.5 Early Force-Detected Magnetic Resonance *386*
13.6 Single-Electron MRFM *389*
13.7 Toward Nano-MRI with Nuclear Spins *390*
13.7.1 Improvements to Micro-fabricated Components *391*
13.7.2 MRI with Resolution Better than 100 nm *391*
13.7.3 Nanoscale MRI of Virus Particles *392*
13.7.4 Imaging Organic Nanolayers *396*
13.8 Paths Toward Continued Improvement *398*
13.8.1 Magnetic Field Gradients *398*
13.8.2 Mechanical Transducers *400*
13.8.3 Measurement Protocols *405*
13.8.4 Nano-MRI with a Nanowire Force Sensor *408*
13.9 Comparison to Other Techniques *412*
13.10 Outlook *414*
13.11 Conclusion *416*
References *416*

Index *421*