TABLE OF CONTENTS

1 EXECUTIVE SUMMARY 18

1.1 Historical metamaterials market 18
1.2 Recent growth 20
1.3 Global market revenues, current and forecast 20
1.4 Regional analysis 24
1.5 Market opportunity assessment 26
1.6 Investment funding in metamaterials 29
1.7 Market and technology challenges 30
1.8 Industry developments 2020-2024 31

2 METAMATERIALS OVERVIEW 33

2.1 What are metamaterials? 33
2.1.1 Electromagnetic metamaterials 33
2.1.2 Metasurfaces 34
2.1.2.1 Meta-Lens 35
2.1.2.2 Metasurface holograms 36
2.1.2.3 Flexible metasurfaces 37
2.1.2.4 Reconfigurable intelligent surfaces (RIS) 37
2.1.2.4.1 Passive RIS 39
2.1.2.4.2 Semi-passive RIS 39
2.1.2.4.3 Active RIS 40
2.2 Manufacturing methods 41
2.2.1 Wet etching 42
2.2.2 Dry phase patterning 43
2.2.3 Roll-to-roll (R2R) printing 43
2.2.4 Atomic layer deposition 45
2.2.5 Laser ablation 46
2.2.6 Extreme UV lithography (EUVL) 47

Copyright © Future Markets, Inc 2024. All rights reserved.

2.2.7 RF metamaterials manufacturing 48
2.2.8 Optical metamaterials manufacturing 49
2.3 Types of metamaterials 50
2.3.1 Passive vs active metamaterials 51
2.3.2 Optical Metamaterials 52
2.3.2.1 Photonic metamaterials 52
2.3.2.2 Optical filters 53
2.3.2.3 Tunable metamaterials 55
2.3.2.4 Frequency selective surface (FSS) based metamaterials 55
2.3.2.5 Plasmonic metamaterials 56
2.3.2.6 Invisibility cloaks 56
2.3.2.7 Perfect absorbers 57
2.3.2.8 Optical nanocircuits 57
2.3.2.9 Metamaterial lenses (Metalenses) 57
2.3.2.10 Holograms 58
2.3.2.11 Materials selection 59
2.3.2.12 Applications 60
2.3.3 Electromagnetic metamaterials 60
2.3.3.1 Double negative (DNG) metamaterials 61
2.3.3.2 Single negative metamaterials 61
2.3.3.3 Electromagnetic bandgap metamaterials (EBG) 61
2.3.3.4 Bi-isotropic and bianisotropic metamaterials 62
2.3.3.5 Chiral metamaterials 62
2.3.3.6 Electromagnetic Invisibility cloak 63
2.3.4 Radio frequency (RF) metamaterials 63
2.3.4.1 RF metasurfaces 63
2.3.4.2 Frequency selective surfaces 64
2.3.4.3 Tunable RF metamaterials 64
2.3.4.4 RF metamaterials antennas 64

Copyright © Future Markets, Inc 2024. All rights reserved.

2.3.4.5 Absorbers 65
2.3.4.6 Luneburg lens 65
2.3.4.7 RF filters 66
2.3.4.8 Applications 66
2.3.5 Terahertz metamaterials 67
2.3.5.1 THz metasurfaces 68
2.3.5.2 Quantum metamaterials 68
2.3.5.3 Graphene metamaterials 69
2.3.5.4 Flexible/wearable THz metamaterials 69
2.3.5.5 THz modulators 70
2.3.5.6 THz switches 70
2.3.5.7 THz absorbers 70
2.3.5.8 THz antennas 71
2.3.5.9 THz imaging components 71
2.3.6 Acoustic metamaterials 71
2.3.6.1 Sonic crystals 71
2.3.6.2 Acoustic metasurfaces 71
2.3.6.3 Locally resonant materials 72
2.3.6.4 Acoustic cloaks 72
2.3.6.5 Hyperlenses 73
2.3.6.6 Sonic one-way sheets 73
2.3.6.7 Acoustic diodes 73
2.3.6.8 Acoustic absorbers 73
2.3.6.9 Applications 74
2.3.7 Tunable Metamaterials 74
2.3.7.1 Tunable electromagnetic metamaterials 75
2.3.7.2 Tunable THz metamaterials 75
2.3.7.3 Tunable acoustic metamaterials 76
2.3.7.4 Tunable optical metamaterials 76

Copyright © Future Markets, Inc 2024. All rights reserved.

2.3.7.5 Applications....77
2.3.8 Nonlinear metamaterials....78
2.3.9 Self-Transforming Metamaterials....79
2.3.10 Topological Metamaterials....79
2.3.11 Materials used with metamaterials....80
2.4 Technology Readiness Level (TRL)....82
3 MARKETS AND APPLICATIONS FOR METAMATERIALS....85
3.1 Competitive landscape....85
3.2 SWOT analysis....86
3.3 Future market outlook....87
3.4 Global revenues for metamaterials, by market, 2017-2035 (Millions USD)....90
3.4.1 By end-use market....90
3.4.2 By region....92
3.5 ACOUSTICS....94
3.5.1 Market drivers and trends....94
3.5.2 Applications....95
3.5.2.1 Sound insulation....95
3.5.2.2 Vibration dampers....96
3.5.3 Market assessment....97
3.5.4 Global revenues 2017-2035....98
3.6 COMMUNICATIONS....101
3.6.1 Market drivers and trends....101
3.6.2 Applications....101
3.6.2.1 Wireless Networks....101
3.6.2.1.1 Reconfigurable antennas....102
3.6.2.1.2 Wireless sensing....102
3.6.2.1.3 Wi-Fi/Bluetooth....103
3.6.2.1.4 Transparent conductive films....106
3.6.2.1.5 5G and 6G Metasurfaces for Wireless Communications....107

Copyright © Future Markets, Inc 2024. All rights reserved.

3.6.2.2 Radomes 108
3.6.2.3 Fiber Optic Communications 109
3.6.2.4 Satellite Communications 110
3.6.2.5 Thermal management 111
3.6.3 Global revenues 2017-2035 112
3.7 AUTOMOTIVE 114
3.7.1 Market drivers and trends 115
3.7.2 Applications 115
3.7.2.1 Radar and sensors 115
3.7.2.1.1 Radar beamforming 116
3.7.2.1.2 Lidar beamformers 118
3.7.2.2 Autonomous vehicles 120
3.7.2.3 Anti-reflective plastics 120
3.7.3 Market assessment 121
3.7.4 Global revenues 2017-2035 123
3.8 AEROSPACE, DEFENCE & SECURITY 125
3.8.1 Market drivers and trends 125
3.8.2 Applications 126
3.8.2.1 Stealth technology 126
3.8.2.2 Radar 126
3.8.2.3 Optical sensors 128
3.8.2.4 Security screening 129
3.8.2.5 Composites 130
3.8.2.6 Windscreen films 131
3.8.2.7 Protective eyewear for pilots 132
3.8.2.8 EMI and RFI shielding 132
3.8.2.9 Thermal management 133
3.8.3 Market assessment 133
3.8.4 Global revenues 2017-2035 135
3.9 COATINGS AND FILMS 137

Copyright © Future Markets, Inc 2024. All rights reserved.

3.9.1 Market drivers and trends....137
3.9.2 Applications....138
3.9.2.1 Cooling films....138
3.9.2.2 Anti-reflection surfaces....139
3.9.2.3 Optical solar reflection coatings....139
3.9.3 Market assessment....140
3.9.4 Global revenues 2017-2035....141
3.10 PHOTOVOLTAICS....143
3.10.1 Market drivers and trends....143
3.10.2 Applications....143
3.10.2.1 Solar-thermal absorber....143
3.10.2.2 Coatings....144
3.10.3 Global revenues 2017-2035....145
3.11 MEDICAL IMAGING....147
3.11.1 Market drivers and trends....147
3.11.2 Applications....147
3.11.2.1 MRI imaging....147
3.11.2.2 Non-invasive glucose monitoring....149
3.11.3 Global revenues 2017-2035....149
3.12 CONSUMER ELECTRONICS & DISPLAYS....151
3.12.1 Market drivers and trends....151
3.12.2 Applications....151
3.12.2.1 Holographic displays....151
3.12.2.2 Metalenses in smartphones....152
3.12.2.3 AR/VR....152
3.12.2.4 Multiview displays....153
3.12.2.5 Stretchable displays....154
3.12.2.6 Soft materials....155
3.12.2.7 Anti-reflection (AR) coatings....157

Copyright © Future Markets, Inc 2024. All rights reserved.

3.13 COMPOSITES....158
3.13.1 Market drivers and trends....158
3.13.2 Applications....159
4 COMPANY PROFILES....160
4.1 Acoustic Metamaterials Group Ltd....160
4.2 Alcan Systems....162
4.3 Alphacore, Inc....163
4.4 Armory Technologies....164
4.5 Anywaves....165
4.6 BlueHalo LLC....166
4.7 Breylon....167
4.8 DoCoMo....169
4.9 Droneshield Limited....170
4.10 Echodyne, Inc....172
4.11 Edgehog Advanced Technologies....174
4.12 Emrod....175
4.13 Evolv Technologies, Inc....177
4.14 EM Infinity....179
4.15 Face® Companies....179
4.16 Filled Void Materials (FVMat) Ltd....180
4.17 Fractal Antenna Systems, Inc....181
4.18 Greenerwave....183
4.19 H-Chip Technology Group....183
4.20 HyMet Thermal Interfaces SIA....184
4.21 Imagia....185
4.22 Imuzak Co., Ltd....185
4.23 Inkspace Imaging....187
4.24 Kuang-Chi Technologies Co. Ltd....188
4.25 Kymeta Corporation....188

Copyright © Future Markets, Inc 2024. All rights reserved.

4.26 LATYS 191
4.27 Leadoptik, Inc. 192
4.28 Lumotive 192
4.29 Magic Shields, Inc. 195
4.30 Magment AG 196
4.31 Metaboards Limited 197
4.32 Metafold 3D 198
4.33 Metahelios 199
4.34 Metalenz, Inc. 200
4.35 Metamagnetics, Inc. 202
4.36 META® 203
4.37 MetaSeismic 205
4.38 MetaShield LLC 206
4.39 Metasonixx 207
4.40 Metavoxel Technologies 208
4.41 Metawave Corporation 208
4.42 Morphotonics 211
4.43 Multiwave Imaging 211
4.44 Nanohmics Inc. 212
4.45 Nature Architects 212
4.46 Neurophos LLC 213
4.47 NIL Technology 214
4.48 Nissan Motor Co., Ltd. 215
4.49 NKT Photonics A/S 216
4.50 Notch, Inc. 217
4.51 OPT Industries 217
4.52 PARC 218
4.53 Phoebus Optoelectronics LLC 219
4.54 Phononic Vibes srl 219

Copyright © Future Markets, Inc 2024. All rights reserved.

4.55 Pixie Dust Technologies, Inc. 220
4.56 PlanOpSim 221
4.57 Pinpoint Medical 222
4.58 Pivotal Commware, Inc. 222
4.59 Plasmonics, Inc. 223
4.60 Protemics GmbH 224
4.61 Radi-Cool, Inc. 225
4.62 SMENA Catalysis AB 226
4.63 Merford UK (Sonobex Ltd.) 226
4.64 SoundBounce by Lios 227
4.65 Spectralics 228
4.66 Specom Oy 229
4.67 STMicroelectronics 231
4.68 Teraview Limited 231
4.69 Tianjin Shanhe Optoelectronics Technology Co. Ltd. 232
4.70 Tunoptix, Inc. 232
4.71 Ultimetas 233
4.72 Vadient Optics 234

5 RESEARCH METHODOLOGY 235

5.1 Report scope 235
5.2 Research methodology 235

6 REFERENCES 237

List of Tables

Table 1. Types of metamaterials and their properties. 19
Table 2. Market summary for metamaterials. 20
Table 3. Global revenues for metamaterials and metasurfaces, total, 2017-2035 (Millions USD), Conservative estimate. 22

Copyright © Future Markets, Inc 2024. All rights reserved.

Table 4. Global revenues for metamaterials and metasurfaces, by region, 2017-2035 (Millions USD).....25
Table 5. Market opportunity assessment matrix for metamaterials and metasurfaces applications.....27
Table 6. Investment funding in metamaterials and metasurfaces companies.....29
Table 7. Market and technology challenges in metamaterials and metasurfaces.....30
Table 8. Metamaterials and metasurfaces industry developments 2020-2023.....31
Table 9. Comparison of metamaterials manufacturing methods.....41
Table 10. Comparison of types of metamaterials-frequency ranges, key characteristics, and applications. 51
Table 11. Optical Metamaterial Applications.....60
Table 12. Applications of radio frequency metamaterials.....66
Table 13. Applications of acoustic metamaterials.....74
Table 14. Types of tunable terahertz (THz) metamaterials and their tuning mechanisms.....75
Table 15. Tunable acoustic metamaterials and their tuning mechanisms.....76
Table 16. Types of tunable optical metamaterials and their tuning mechanisms.....76
Table 17. Markets and applications for tunable metamaterials.....77
Table 18. Types of self-transforming metamaterials and their transformation mechanisms.....79
Table 19. Key materials used with different types of metamaterials.....81
Table 20. Technology Readiness Level (TRL) Examples.....82
Table 21. Global revenues for metamaterials, by end-use market, 2017-2035 (Millions USD).....90
Table 22. Global revenues for metamaterials and metasurfaces, by region, 2017-2035 (Millions USD).....92
Table 23. Metamaterials and metasurfaces in sound insulation-market drivers and trends.....94
Table 24. Market assessment for metamaterials and metasurfaces in acoustics.....97
Table 25. Market opportunity assessment for metamaterials in acoustics.....98
Table 26. Global revenues for metamaterials and metasurfaces in acoustics, 2017-2035 (Millions USD)...99
Table 27: Metamaterials and metasurfaces in electronics and communications-market drivers and trends.....101
Table 28. Unmet need, metamaterial solution and markets.....104
Table 29. Market opportunity assessment for metamaterials and metasurfaces in communications.....111
Table 30. Global revenues for metamaterials and metasurfaces in communications, 2017-2035 (Millions USD).....113
Table 31. Metamaterials and metasurfaces in the automotive sector-market drivers and trends.....115

Copyright © Future Markets, Inc 2024. All rights reserved.

Table 32. LiDAR beam steering technologies. 118
Table 33. Automotive lidar requirements....119
Table 34. Market assessment for metamaterials and metasurfaces in automotive....121
Table 35. Market opportunity assessment for metamaterials and metasurfaces in automotive. 122
Table 36. Global revenues for metamaterials and metasurfaces in automotive, 2017-2035 (Millions USD). 123
Table 37. Metamaterials and metasurfaces in aerospace, defence and security-market drivers and trends. 125
Table 38. Market assessment for metamaterials and metasurfaces in aerospace, defence & security. 133
Table 39. Market opportunity assessment for metamaterials and metasurfaces in aerospace, defence & security. 134
Table 40. Global revenues for metamaterials in aerospace, defence & security, 2017-2035 (Millions USD). 135
Table 41. Metamaterials in coatings and films-market drivers and trends. 137
Table 42. Applications of metamaterials in coatings and thin films....138
Table 43. Market assessment for metamaterials and metasurfaces in coatings and films....140
Table 44. Market opportunity assessment for metamaterials and metasurfaces in coatings and films. 140
Table 45. Global revenues for metamaterials and metasurfaces in coatings and films, 2017-2035 (Millions USD). 141
Table 46: Metamaterials and metasurfaces in photovoltaics-market drivers and trends....143
Table 47. Global revenues for metamaterials and metasurfaces in photovoltaics, 2017-2035 (Millions USD). 145
Table 48: Metamaterials and metasurfaces in medical imaging-drivers and trends....147
Table 49. Global revenues for metamaterials and metasurfaces in medical imaging, 2017-2035 (Millions USD). 149
Table 50: Metamaterials and metasurfaces in consumer electronics and displays-drivers and trends. 151
Table 51: Metamaterials and metasurfaces in composites-drivers and trends. 158

List of Figures

Figure 1. Classification of metamaterials based on functionalities. 18
Figure 2. Global revenues for metamaterials and metasurfaces, total, 2017-2035 (Millions USD). 21

Copyright © Future Markets, Inc 2024. All rights reserved.

Figure 3. Global revenues for metamaterials and metasurfaces, by market, 2017-2035 (Millions USD). 23
Figure 4. Global revenues for metamaterials and metasurfaces, by region, 2017-2035 (Millions USD). 24
Figure 5. Metamaterials example structures. 33
Figure 6. Metamaterial schematic versus conventional materials. 34
Figure 7. Scanning electron microscope (SEM) images of several metalens antenna forms. 36
Figure 8. Transparent and flexible metamaterial film developed by Sekishi Chemical. 37
Figure 9. The most common designs for photonic MMs: (a) SRRs, (b) wood pile structures, (c) colloidal crystals, and (d) inverse opals 53
Figure 10. Invisibility cloak. 57
Figure 11. Electromagnetic metamaterial. 61
Figure 12. Schematic of Electromagnetic Band Gap (EBG) structure. 62
Figure 13. Schematic of chiral metamaterials. 63
Figure 14. Metamaterial antenna. 65
Figure 15. Terahertz metamaterials. 67
Figure 16. Schematic of the quantum plasmonic metamaterial. 68
Figure 17. Properties and applications of graphene metamaterials. 69
Figure 18. Nonlinear metamaterials- 400-nm thick nonlinear mirror that reflects frequency-doubled output using input light intensity as small as that of a laser pointer. 78
Figure 19. Technology Readiness Level (TRL) for metamaterials and metasurfaces. 84
Figure 20. SWOT analysis: metamaterials market. 86
Figure 21. Global revenues for metamaterials, by end-use market, 2017-2035 (Millions USD). 91
Figure 22. Global revenues for metamaterials and metasurfaces, by region, 2017-2035 (Millions USD). ...92
Figure 23. Prototype metamaterial device used in acoustic sound insulation. 95
Figure 24. Metamaterials installed in HVAC sound insulation the Hotel Madera Hong Kong. 96
Figure 25. Robotic metamaterial device for seismic-induced vibration mitigation. 97
Figure 26. Global revenues for metamaterials and metasurfaces in acoustics, 2017-2035 (Millions USD)..99
Figure 27. Wireless charging technology prototype. 104
Figure 28. Flat-panel satellite antenna (top) and antenna mounted on a vehicle (bottom). 106
Figure 29. META Transparent Window Film. 108
Figure 30. Radi-cool metamaterial film. 111

Copyright © Future Markets, Inc 2024. All rights reserved.

Figure 31. Global revenues for metamaterials and metasurfaces in communications, 2017-2035 (Millions USD). 113
Figure 32. Metamaterials in automotive applications. 116
Figure 33. Lumotive advanced beam steering concept. 117
Figure 34. Illustration of EchoDrive operation. 120
Figure 35. Anti-reflective metamaterials plastic. 121
Figure 36. Global revenues for metamaterials and metasurfaces in automotive, 2017-2035 (Millions USD). 123
Figure 37. Metamaterials invisibility cloak for microwave frequencies. 126
Figure 38. Metamaterials radar antenna. 128
Figure 39. Metamaterials radar array. 128
Figure 40. Evolv Edge visitor screening solution. 130
Figure 41. Lightweight metamaterial microlattice. 131
Figure 42. metaAIR eyewear. 132
Figure 43. Global revenues for metamaterials in aerospace, defence & security, 2017-2035 (Millions USD). 135
Figure 44. Schematic of dry-cooling technology. 139
Figure 45. Global revenues for metamaterials and metasurfaces in coatings and films, 2017-2035 (Millions USD). 141
Figure 46. Metamaterial solar coating. 144
Figure 47. Global revenues for metamaterials and metasurfaces in photovoltaics, 2017-2035 (Millions USD). 145
Figure 48. A patient in MRI scan modified by metasurface. 148
Figure 49. Global revenues for metamaterials and metasurfaces in medical imaging, 2017-2035 (Millions USD). 149
Figure 50. Stretchable hologram. 154
Figure 51. Design concepts of soft mechanical metamaterials with large negative swelling ratios and tunable stress-strain curves. 156
Figure 52. Anywaves antenna products. CubeSat S-band antenna, CubeSat X-band antenna and UAV cellular antenna. 165
Figure 53. Brelyon monitor. 168
Figure 54. RadarZero. 170

Copyright © Future Markets, Inc 2024. All rights reserved.

Figure 55. Schematic of MESA System. 172
Figure 56. EchoGuard Radar System. 173
Figure 57. Edgehog Advanced Technologies Omnidirectional anti-reflective coating. 174
Figure 58. Emrod architecture. 1. A transmitting antenna. 2. A relay that is essentially lossless, doesn't require any power, and acts as a lens refocusing the beam extending the travel range. 3. A rectenna that receives and rectifies the beam back to electricity. Metamaterials allow converting wireless energy back into electricity efficiently. 176
Figure 59. Commercial application of Emrod technology. 176
Figure 60. Evolv Edge screening system. 177
Figure 61. FM/R technology 181
Figure 62. Metablade antenna. 182
Figure 63. MTenna flat panel antenna. 189
Figure 64. Kymeta u8 antenna installed on a vehicle. 190
Figure 65. LIDAR system for autonomous vehicles. 193
Figure 66. Light-control metasurface beam-steering chips. 194
Figure 67. Metamaterials film 197
Figure 68. Metaboard wireless charger 198
Figure 69. Orion dot pattern projector. 201
Figure 70. A 12-inch wafer made using standard semiconductor processes contains thousands of metasurface optics. 201
Figure 71. metaAIR. 204
Figure 72. Nissan acoustic metamaterial. 216
Figure 73. Metamaterial structure used to control thermal emission. 224

Copyright © Future Markets, Inc 2024. All rights reserved.