

Table of Contents

The Quantum Leap from Lab to Application	13
1 Quantum solutions – beyond “classical” limitations	13
2 From the first to the second quantum revolution	14
3 Technological and economic prospects	16
Gauging the State of Developments	19
1 On the route to a key emergent technology	19
1.1 Motivation and inspiration	19
1.2 Pathways to innovation and quantum ecosystems	20
1.3 Evaluating and directing progress in the field	22
2 Current technological challenges	24
2.1 Integration and upscaling	24
2.2 Quantum infrastructures	27
3 Current strategical challenges	31
3 Tributes and future prospects	34
 1 Quantum Sensing	 40
Sensitive Opportunities in a New World	41
Nitrogen-Vacancy Centers: A Quantum Sensor for Magnetic Fields	 43
1 Introduction	43
2 Quantum magnetometry with NV centers	44
2.1 Advantages	48
2.2 Limitations	49
2.3 Overcoming limitations with the wide-field magnetometer	 50
2.4 The instrument	51
3 Specific diamond development for wide-field	54
3.1 Diamond substrates, homoepitaxial growth, and nitrogen-doped δ -layers	 54
4 Applications	57
4.1 Magnetic nanoparticle measurement	58

4.2 Material science – steel alloys	61
5 Conclusions and outlook	64
6 Acknowledgements	65
7 References	66
Quantum Magnetometry Based Flow Metering	69
1 Quantum magnetometry with optically pumped magnetometers	70
2 The concept of quantum magnetometry-based flow metering	72
3 The added value for flow metering	76
4 References	79
Laser Threshold Magnetometry	81
1 The idea: Improving sensitivity via laser readout	81
2 Measuring stimulated emission from NV centers	86
3 Magnetic-field-dependent light amplification with strong signals and record contrast	89
4 References	92
Material Testing with Optically Pumped Magnetometers	95
1 General introduction	96
2 Magnetic measuring of defects in materials	96
3 Quantum sensing with optically pumped magnetometers	98
4 Magnetic response to the fatigue processes	100
5 Measuring the magnetic fatigue response	102
6 Conclusions and outlook	107
7 References	108
Fraunhofer CAP	111
1 Fraunhofer CAP and the UK perspective	111
2 Cold-atom sensor technologies	112
2.1 Introduction to atom interferometers	113
2.2 Introduction to laser requirements for quantum sensors	114
2.3 Tapered amplifier development	117
3 SPADs for time-resolved remote spectroscopy	118
3.1 Remote sensing of hydrogen	118
3.2 Results on remote sensing of hydrogen	120
4 Photonic integration for quantum sensing	122
4.1 Integrated sources of quantum light	122
4.2 Micro-optic integration for scanning magnetometers	125

5 Conclusions and outlook	128
6 References	129
2 Quantum Imaging	134
Correlated Photon Pairs Perform “Division of Labor” across Wavelength Region	135
References	140
Quantum Holography with Undetected Light	141
1 From classical to quantum holography	141
2 Nonlinear interferometer for imaging	143
3 Phase-shifting holography	145
4 Quantum holography with undetected light	147
5 Noise resilience	148
6 References	151
Quantum Ghost Imaging with Asynchronous Detection . .	153
1 Introduction	153
2 Quantum ghost imaging (QGI)	155
3 Results	160
4 Image reconstruction	161
5 Relevant quantum benefits	162
5.1 Uniform energy distribution: Relaxed safety thresholds . .	162
5.2 Incoherent source: Improved image quality	163
5.3 Inherent randomness: Non-detectability and superior protection.	163
6 Conclusions and outlook	164
7 References	165
Quantum Fourier Transform Infrared Spectroscopy	167
1 Introduction	167
2 The quantum Fourier transform spectrometer	169
2.1 Correlated photon source	169
2.2 Nonlinear interferometer	171
2.3 Spectral analysis	173
3 Conclusions and outlook	178
4 References	178
Quantum Imaging with Undetected Photons in the Mid-Infrared	181
1 Quantum imaging in nonlinear interferometers	181

1.1 Spontaneous parametric downconversion.	
Sources for correlated photon pairs	182
1.2 Imaging with undetected photons in nonlinear interferometers	183
1.3 State-of-the-art quantum imaging in the mid-infrared . .	184
2 MIR quantum imaging with large aperture crystals in long-pass interferometer configuration	185
2.1 Design considerations	185
2.2 Setup and results	187
2.3 Conclusions and outlook	190
3 References	190
Terahertz Spectroscopy with Visible Photons	193
1 Introduction	194
2 Generation of correlated terahertz-visible photon pairs . . .	195
3 Terahertz spectroscopy with visible light	199
4 Quantum-inspired terahertz spectroscopy with pulsed sources	202
5 Conclusions and outlook	204
6 References	205
 3 Quantum Communication	 210
Quantum Communication: Secure Communication by Quantum Key Distribution	211
Quantum Communication Systems and Protocols	213
1 Motivation	213
2 Quantum communication systems for optical networks . . .	215
2.1 Massively multiplexed quantum channels	215
2.2 Simultaneous transmission of quantum and classical channels	217
2.3 A real-time experimentation QKD platform for quantum-secure telecom infrastructures	218
3 Conclusions and outlook	223
4 References	223
Satellite-Based Entanglement Communication at Fraunhofer IOF	225
1 Entanglement-based quantum communication in space . . .	225
2 Basic link considerations	227

3 High performant entangled photon sources	230
4 Conclusions and outlook	233
5 References	234
Photonic Components for Quantum Technologies	235
1 Introduction	235
2 Active components for integration	236
2.1 Single-photon avalanche detectors	237
2.2 InP-based photonic integrated circuits	239
3 Hybrid integration	241
3.1 PolyBoard platform	242
3.2 Micro-optical bench	246
4 Conclusions and outlook	249
5 References	249
Modular Nanoelectronics for Quantum Communication . .	251
1 Motivation	251
2 Modular electronics platform	253
2.1 Chiplet technology	254
2.2 Digital signal processors	256
2.3 Analog digital converter	257
2.4 Digital analog converter	259
2.5 Time-to-digital converters	259
2.6 Further development of the chiplet toolbox	260
3 QKD test environment for circuit development	261
4 Conclusions and outlook	263
5 References	264
Low-Noise Quantum Frequency Converters for the	
Quantum Internet	267
1 Quantum internet	268
1.1 Quantum networks	269
1.2 The quantum interface	270
1.3 The Quantum Internet Demonstrator Project at QuTech	271
2 Quantum frequency conversion	272
2.1 Performance requirements of a QFC, every photon counts	272
2.2 Working principle, design challenges, and state of the art	273

2.3 NORA – a noise-reduced approach for a QFC	274
2.4 Prototyping and testing of NORA QFC	276
3 Next steps	279
4 References	280
4 Quantum Computing	284
Introduction	285
Quantum Computing from Materials to Application	291
1 Silicon carbide – a promising material for quantum computing	292
2 SiC semiconductor technology and simulation	295
3 Integration and material aspects for quantum computing	298
4 Quantum computing for simulation und optimization	301
5 Conclusions and outlook	305
6 References	306
Leveraging Microelectronics for Large-Scale Quantum Computing Hardware	309
1 Introduction hardware for quantum computing	310
1.1 Qubit platforms – a technologic overview	311
2 Challenges toward meaningful systems	312
3 Concrete potential for segments of the quantum computing stack	313
3.1 Superconducting qubits	314
3.2 Spin-based quantum dot qubits	317
3.3 Photonic qubits	318
3.4 Neutral atoms	319
3.5 2D and 3D integration	320
3.6 Co-integration with CMOS logic	321
4 Conclusions and outlook	322
5 References	323
Error Characterization, Mitigation, and Correction	325
1 Quantum gate error characterization	325
1.1 From process to gate set tomography	326
1.2 Long-sequence quantum process tomography	330
1.3 Crosstalk characterization	331
2 Error mitigation	332

3 Quantum error correction	336
3.1 Classical error correction	337
3.2 Three-qubit bitflip code	338
3.3 Threshold theorem of fault-tolerant quantum computing	339
4 References	340
Quantum HPC Algorithms and Workflows	343
1 Motivation: Quantum computers as accelerators of HPC systems	343
2 Technologies and approaches	344
3 Hybrid simulation at the algorithmic level	345
4 NISQ quantum applications	347
5 Toward hybrid HPC / quantum workflows	349
6 Characterization of hybrid workflows and algorithms	350
7 Important parameters for integrating QC into HPC systems	351
8 Conclusions and outlook	353
9 References	354
Quantum Machine Learning	355
1 Introduction	355
2 What is Machine Learning?	356
3 What is Quantum Computing?	357
4 What is Quantum Machine Learning?	359
5 Current limitations for QML	363
6 Suggestions for QML in the NISQ era	367
7 Conclusions and outlook	369
8 References	370
Qompiler: Interoperable and Standardizable	
Quantum Software Stack	373
1 Introduction	374
2 Progress beyond state of the art	375
3 The need for a standardized software stack	377
4 Qrisp: Quantum high-level programming language	379
5 Standardizable interface	381
6 Exploitation paths	383
7 Conclusions and outlook	384
8 References	385

Approaches to the Structured Development, Test, and Operation of Quantum-Based ICT systems	387
1 Introduction	388
2 Related work	388
3 Quantum DevOps	389
4 Overview of tools for Quantum DevOps	392
4.1 Tools for the DEV subcycle	393
4.2 Tools for the OPS subcycle	394
4.3 Overall DevOps automation	395
5 Benchmarking for Quantum DevOps	396
5.1 Transpilation and quantum circuit optimization	397
5.2 Simulations under suitable noise models	398
5.3 QPU backend decision	398
5.4 Execution on the QPU	399
6 Use cases	400
6.1 Traveling salesman problem in Quantum DevOps	400
6.2 Variational quantum convolutional neural networks with enhanced image encoding for image classification	403
7 Conclusions and outlook	405
8 References	406
Fraunhofer Competence Network Quantum Computing	409
1 Fraunhofer Competence Network Quantum Computing: Aim and structure	409
2 Fraunhofer as an enabler for research and industry	411
3 Current projects using the IBM Quantum System One	412
4 Conclusions and outlook	414
5 References	415
List of Authors	417