

Contents

1	Introduction	1
1.1	The Terahertz Spectral Region	1
1.2	History of Terahertz Research	5
1.2.1	Early Twentieth Century Research	8
1.2.2	The Years 1920–1940	8
1.2.3	The Years 1940–1950	10
1.2.4	The Years 1950–1960	12
1.2.5	The Years 1960–1970	14
1.2.6	The Years 1970–1980	15
1.2.7	The Years 1980–1990	16
1.3	Reasons for Increased Interest	19
2	Optical Principles at Terahertz Frequencies	23
2.1	Fundamentals of Gaussian Beams	24
2.2	Gaussian Beam Propagation	29
2.3	Coupling of Gaussian Beams	34
2.4	Absorption of Radiation by Materials and Resonant Effects	38
2.5	Nonlinear Interactions with Matter and Terahertz Anisotropy	43
2.6	Polarized Light	44
2.7	Stokes Parameter	45
2.8	Chirp	46
3	Optical Components	51
3.1	Introduction	51
3.2	Reflection and Absorption	52
3.3	Materials for Windows, Filters, and Lenses	53
3.3.1	Polyethylene (PE)	53
3.3.2	Polypropylene (PP)	55
3.3.3	Polystyrene (PS)	55
3.3.4	Polytetrafluorethylene (PTFE, Teflon)	55
3.3.5	Poly-4-methylpentene-1 (PMT, TPX)	55

3.3.6	Tsurupica (Picarin).....	56
3.3.7	Polyethylene Terephthalate (PET, Mylar)	56
3.3.8	Parylene	56
3.3.9	Fluorogold	57
3.3.10	Zitex	57
3.3.11	Crystalline Quartz.....	57
3.3.12	Sapphire	58
3.3.13	Silicon and Germanium.....	59
3.3.14	Diamond.....	59
3.3.15	Alkali Halides	60
3.3.16	KRS-5	61
3.3.17	Material Considerations	62
3.4	Windows	62
3.5	Filters.....	63
3.5.1	Black Polyethylene (PE) Absorption Filters.....	64
3.5.2	Alkali Halide Filters (Yoshinaga Filters)	65
3.5.3	Scattering Filters	65
3.5.4	Reststrahlen Filters.....	67
3.5.5	Resonant Mesh Filters	67
3.5.6	Thick Metal Plate Filters	70
3.5.7	Cold Filters	71
3.6	Antireflection Coating	71
3.7	Lenses	72
3.8	Mirrors	74
3.9	Light Pipes	76
3.10	Light Concentrators and Winston Cone	78
3.11	Polarizers and Polarization Transformers	79
3.12	Beam Splitters	83
3.13	Attenuators	84
3.14	Absorbers and Absorbing Materials	85
3.15	Lens-Antenna Systems	86
3.16	Waveguides and Horn Antennas	91
3.17	Photonic Bandgap Materials and Metamaterials	92
4	Sources	103
4.1	Introduction	103
4.2	Thermal Emission	104
4.3	Practical Thermal Sources.....	106
4.3.1	The Globar	106
4.3.2	Plasma Sources.....	107
4.4	Gas Lasers.....	109
4.4.1	Electrically Excited Gas Lasers	109
4.4.2	Optically Excited Gas Lasers.....	112

4.5	Bulk Semiconductor Lasers	120
4.5.1	Germanium Lasers	121
4.5.2	Lasing from Optically Excited Donors in Silicon	126
4.6	Quantum Cascade Laser.....	128
4.6.1	Principle of Operation	128
4.6.2	Performance	131
4.7	Photomixing for the Generation of Terahertz Radiation	136
4.7.1	Low-temperature-grown Gallium Arsenide	137
4.7.2	Schottky Diode.....	138
4.7.3	Metal–Insulator–Metal Diodes	139
4.7.4	Photodiodes	140
4.8	Harmonic Generators.....	141
4.9	Backward Wave Oscillator	144
4.10	Smith–Purcell Sources	148
4.11	Gyrotrons.....	151
4.12	Terahertz Sources Based on Relativistic Electrons.....	154
4.12.1	Coherent Synchrotron Radiation from Electron Storage Rings	156
4.12.2	Coherent Synchrotron Radiation from Linear Accelerators	159
4.12.3	Free-Electron Lasers	160
4.13	Parametric Oscillators	164
5	Detectors	169
5.1	Introduction	169
5.1.1	Detector Cooling	171
5.2	Detector Theory.....	172
5.2.1	Detector Parameters.....	173
5.2.2	Relationship Between Detector Parameters	174
5.2.3	Sources of Excess Noise	178
5.3	Thermal Detectors	180
5.3.1	The Golay Detector	183
5.3.2	Pyroelectric Detectors	185
5.3.3	Thermopiles	190
5.3.4	Power Meters.....	191
5.3.5	Semiconducting Bolometers.....	195
5.3.6	Superconducting Bolometers.....	198
5.3.7	Room Temperature Microbolometers	202
5.4	Photoconductive Detectors	203
5.4.1	Extrinsic Germanium Detectors	209
5.4.2	Indium Antimonide Detectors	212
5.4.3	Gallium Arsenide Detectors	217
5.4.4	Blocked Impurity Band Detectors.....	218

5.5	Heterodyne Detection	221
5.5.1	Heterodyne Detection Theory	222
5.5.2	Schottky Diode Mixer	228
5.5.3	Superconductor–Insulator–Superconductor Mixer	234
5.5.4	Hot Electron Bolometer Mixer	239
6	Spectroscopic Methods	247
6.1	Introduction	247
6.2	Grating Spectrometer	251
6.3	Fourier-Transform Spectrometer	257
6.3.1	Dispersive Fourier-Transform Spectrometer	262
6.4	Polarizing (Martin–Puplett) Interferometer	263
6.5	Fabry–Pérot Interferometer	267
6.6	Time-Domain Spectrometer	269
6.6.1	Simplified Models of THz Pulse Generation and Detection	276
6.6.2	Applications	281
6.7	Coherent Source Spectrometers	282
6.7.1	Spectrometers with Multiplier-Based Sources	284
6.7.2	Spectrometers with Backward Wave Oscillators	286
6.7.3	Spectroscopy by Tunable Terahertz Sideband Generation	288
6.7.4	Spectroscopy by Difference Frequency Generation	291
6.8	Heterodyne Spectroscopy	293
6.8.1	System Aspects	294
6.8.2	Back-End Spectrometers	297
6.8.3	Examples of Heterodyne Spectrometers	298
7	Terahertz Imaging	301
7.1	Introduction	301
7.2	Some Fundamentals of Imaging	304
7.3	Camera-Like Imaging	307
7.3.1	Contrast Formation	308
7.3.2	Imaging with Direct Detectors	311
7.3.3	Heterodyne Imaging	314
7.3.4	Three-Dimensional Heterodyne Imaging	316
7.4	Short-Range Imaging	317
7.4.1	Imaging with cw and Long-Pulse Sources	318
7.4.2	Photomixer-Based Imaging	319
7.4.3	Imaging with Quantum Cascade Lasers	321
7.4.4	Real-Time Imaging with cw Sources	321
7.4.5	Spectroscopic Imaging	323
7.4.6	Three-Dimensional Imaging with a Quantum Cascade Laser	323
7.4.7	Imaging with Time-Domain Spectrometers	325

7.4.8	Spectroscopic Imaging with Time-Domain Spectrometers	327
7.4.9	Three-Dimensional Imaging with Time-Domain Spectrometers	328
7.4.10	Real-Time Imaging with Time-Domain Spectrometers	330
7.5	Near-Field Microscopy	331
7.5.1	Aperture-Based Scanning Near-Field Microscopy	331
7.5.2	Aperture-Less Scanning Near-Field Microscopy	335
References		341
Index		375
About the Authors		381