# Contents

**Preface**  XIII

1  Fusion Research  1
   1.1  Reaction Scheme  1
   1.2  Magnetic Plasma Confinement  4
      1.2.1  Tokamak  5
      1.2.2  Stellarator  6
      1.2.3  Physics Issues of Magnetic Confinement  7
      1.2.4  Plasma Heating  10
   1.3  Plasma Diagnostic  11
      1.3.1  Generic Arrangements  12
      1.3.2  Microwave Diagnostics  15
   References  17

2  Millimeter-Waves in Plasmas  19
   2.1  Basic Equations  20
   2.2  Plasma Dielectric Tensor, General Properties  23
   2.3  Dielectric Tensor from Kinetic Theory  25
   2.4  Cold-Plasma Limit  29
   2.5  Derivation within Fluid Description  32
   2.6  Discussion of Cold-Plasma Dispersion Relations  34
      2.6.1  Nonmagnetized Plasma, \( \vec{B}_0 = 0 \)  34
      2.6.2  Magnetized Plasma, Parallel Propagation, \( \vec{k} \parallel \vec{B}_0 \)  37
      2.6.3  Magnetized Plasma, Perpendicular Propagation, \( \vec{k} \perp \vec{B}_0 \)  39
      2.6.4  Slightly Oblique Propagation  41
   2.7  Finite-Temperature Correction to Cold-Plasma Dielectric Tensor  42
      2.7.1  Finite Larmor Radius Expansion  42
      2.7.2  Warm-Plasma Approximation  44
      2.7.3  Relativistic Corrections  46
   2.8  Inhomogeneous Plasma  48
      2.8.1  WKB Approximation  49
      2.8.2  Refraction  51
Contents

2.8.3 Ray Tracing 53
2.9 Finite-Size Probing Beam 54
2.9.1 Gaussian Beam Description 54
2.10 Radiation Transfer 58
2.10.1 Transparent Plasma 58
2.10.2 Plasma Emitting and Absorbing 60
2.10.3 Multiple Chords, Imaging 61

References 62

3 Active Diagnostics 65
3.1 Interferometry 65
3.1.1 Single-Chord Interferometry 68
3.1.2 Multiple Chords 69
3.2 Polarimetry 70
3.2.1 Faraday Effect 71
3.2.2 Cotton–Mouton Effect 75
3.2.3 Common Generalized Description 77
3.3 Reflectometry 83
3.3.1 Time Delay Measurement 86
3.3.2 Phase Change at Cutoff 89
3.3.3 Profile Reconstruction 92
3.3.4 Localization of Reflecting Layer 93
3.3.5 Relativistic Corrections 95
3.3.6 Influence of Density Fluctuations 95
3.4 Scattering 100
3.4.1 Single-Particle Thomson Scattering 101
3.4.2 Doppler Shift 102
3.4.3 Incoherent Scattering 104
3.4.4 Relativistic Incoherent Scattering Spectrum 106
3.4.5 Role of Density Fluctuations 108
3.4.6 Coherent Scattering 108
3.4.7 Electron and Ion Feature 110
3.4.8 Summarizing Comments 113

References 115

4 Passive Diagnostics 117
4.1 Bremsstrahlung 118
4.2 Electron Cyclotron Emission 122
4.2.1 Electron Motion in a Static \( \vec{B} \)-Field 122
4.2.2 Electric Field and Spectrum, Single Electron 123
4.2.3 Perpendicular Observation, Characteristic Modes 126
4.2.4 Spectrum, Electron Ensemble 128
4.2.5 Absorption Coefficient 130
4.2.6 Emission Profile 132
4.2.7 \( \vec{B}_0 \)-Field Varying along Sightline 135
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.8</td>
<td>Optical Depth of Most Relevant Modes</td>
<td>137</td>
</tr>
<tr>
<td>4.2.9</td>
<td>Visibility Depth and Localization</td>
<td>139</td>
</tr>
<tr>
<td>4.2.10</td>
<td>Electron Cyclotron Absorption Measurement</td>
<td>142</td>
</tr>
<tr>
<td>4.3</td>
<td>Electron Bernstein Wave Emission</td>
<td>143</td>
</tr>
<tr>
<td>5.1</td>
<td>Guided Waves</td>
<td>151</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Transmission Line Properties</td>
<td>151</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Waves on a Lossy Transmission Line</td>
<td>151</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Terminated Transmission Line</td>
<td>153</td>
</tr>
<tr>
<td>5.1.4</td>
<td>Classification of Transmission Lines</td>
<td>157</td>
</tr>
<tr>
<td>5.2</td>
<td>Coaxial Transmission Line</td>
<td>161</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Characteristic Properties</td>
<td>162</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Losses and Limits of Coaxial Lines</td>
<td>162</td>
</tr>
<tr>
<td>5.3</td>
<td>Rectangular Waveguides</td>
<td>163</td>
</tr>
<tr>
<td>5.3.1</td>
<td>TE Waves</td>
<td>164</td>
</tr>
<tr>
<td>5.3.2</td>
<td>TM Waves</td>
<td>166</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Attenuation in Rectangular Waveguides</td>
<td>166</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Fundamental TE₁₀ Wave</td>
<td>167</td>
</tr>
<tr>
<td>5.4</td>
<td>Circular Waveguides</td>
<td>170</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Fields in Circular Waveguides</td>
<td>171</td>
</tr>
<tr>
<td>5.4.2</td>
<td>TM Waves</td>
<td>172</td>
</tr>
<tr>
<td>5.4.3</td>
<td>TE Waves</td>
<td>173</td>
</tr>
<tr>
<td>5.4.4</td>
<td>Loss in Circular Waveguides</td>
<td>175</td>
</tr>
<tr>
<td>5.5</td>
<td>Multimode Waveguides</td>
<td>176</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Number of Modes Propagating</td>
<td>176</td>
</tr>
<tr>
<td>5.5.2</td>
<td>Multimode Propagation</td>
<td>178</td>
</tr>
<tr>
<td>5.5.3</td>
<td>TE₁₁ Mode in Overmoded Circular Waveguides</td>
<td>179</td>
</tr>
<tr>
<td>5.6</td>
<td>Corrugated Circular Waveguides</td>
<td>182</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Fields of Corrugated Circular Waveguides</td>
<td>183</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Characteristics of HE₁₁ Hybrid Mode</td>
<td>185</td>
</tr>
<tr>
<td>5.7</td>
<td>Gaussian Beams</td>
<td>185</td>
</tr>
<tr>
<td>5.7.1</td>
<td>Solution of Approximate Wave Equation</td>
<td>185</td>
</tr>
<tr>
<td>5.7.2</td>
<td>Transformation of Gaussian Beams</td>
<td>186</td>
</tr>
<tr>
<td>5.7.3</td>
<td>Lenses and Curved Mirrors</td>
<td>191</td>
</tr>
<tr>
<td>5.7.4</td>
<td>Truncation of Gaussian Beams</td>
<td>193</td>
</tr>
<tr>
<td>5.7.5</td>
<td>Coupling Coefficient for Fundamental Gaelian Beams</td>
<td>194</td>
</tr>
<tr>
<td>5.8</td>
<td>Vacuum Windows</td>
<td>196</td>
</tr>
<tr>
<td>5.8.1</td>
<td>Single-Disk Window</td>
<td>196</td>
</tr>
<tr>
<td>5.8.2</td>
<td>Half-Wave Window</td>
<td>197</td>
</tr>
<tr>
<td>5.8.3</td>
<td>Thin Window</td>
<td>198</td>
</tr>
</tbody>
</table>
Contents

5.8.4 Antireflection Coating 198
References 199

6 Radiation Generation and Detection 201
6.1 Signal Sources 201
6.1.1 Backward-Wave Oscillator 201
6.1.2 Solid-State Oscillators 203
6.1.2.1 Gunn Oscillator 203
6.1.2.2 IMPATT Oscillator 205
6.1.3 Multiplier Chain 206
6.2 Antennas 208
6.2.1 Basic Definitions 208
6.2.2 Antenna Temperature 211
6.2.3 Pyramidal Horn 212
6.2.4 Conical Horn 214
6.2.5 Excitation of Gaussian Beams 215
6.2.6 Antenna Arrays 217
6.3 Detection 221
6.3.1 Overview and Classification 221
6.3.2 Bolometer 223
6.3.3 Hot Electron Bolometer 225
6.3.4 Noise Equivalent Power, NEP 226
6.3.5 Schottky Diode 227
6.3.6 Schottky Diode Frequency Multiplier 229
6.3.7 Diode Direct Detector 231
6.3.8 Schottky Detector Noise 233
6.4 Heterodyne Detection 236
6.4.1 Square-Law Mixer 237
6.4.2 Diode Mixer 239
6.4.3 Two-Port Mixer 241
6.4.4 Mixer Construction 245
6.5 Thermal Noise 246
6.5.1 Noise Temperature 247
6.5.2 Noise Figure 249
6.5.3 Noise Temperature of Cascaded Systems 250
6.5.4 Mixer Noise Temperature 251
6.5.5 Noise Temperature of Heterodyne Receiver 253
6.5.6 Measurement of Noise Temperature 255
6.6 Sensitivity Limits 256
6.6.1 Shot Noise Term 256
6.6.2 Thermal Radiation Term 258
6.6.3 Influence of Bandwidth 259
6.6.4 Noise-Equivalent Power, Incoherent Detection 260
6.6.5 Noise-Equivalent Power, Coherent Detection 261
6.6.6 Minimum Detectable Temperature 263
6.7 Correlation Radiometry 264
6.7.1 Intensity Fluctuations 264
6.7.2 Cross-Correlation Function 265
6.7.3 Intensity Fluctuations and Coherence 266
6.7.4 van Cittert-Zernike Theorem 268
6.7.5 Intensity Interferometer 269
6.7.6 Accuracy of Cross-Correlation Measurements 270
6.7.7 Alternative Decorrelation 271
References 273

7 Components and Subsystems 275
7.1 Two-Port Characterization 275
7.1.1 Scattering Parameters 275
7.1.2 Transmission and Reflection 278
7.1.3 Directional Coupler 281
7.1.4 Nonreciprocal Devices 283
7.2 Network-Analysis Measuring Techniques 286
7.2.1 Transmission Measurement 286
7.2.2 Reflection Measurement 287
7.2.3 Substitution Measurement 288
7.2.4 Measurements Using Noise Sources 289
7.3 Frequency- and Polarization-Selective Filters 290
7.3.1 General Definitions 291
7.3.2 Waveguide Band-Stop Filter 292
7.3.3 Band-Pass Filter in Overmoded Waveguide 293
7.3.4 Metallic Meshes 296
7.3.5 Polarization Filters 298
7.4 Phase Measurement 299
7.4.1 Phase Measurements with Analog Output 299
7.4.2 All-Digital Phase Measurement 301
7.4.3 Phase Determination by Software 303
7.5 Signal Linearity 304
7.5.1 Gain Compression 304
7.5.2 Intermodulation 305
7.6 Frequency Stability 308
7.6.1 Control Loop Components 308
7.6.2 PLL Circuits in the Millimeter-Wave Range 309
7.6.3 Comments on the Theoretical Concept 310
References 313

8 Architecture of Realized Millimeter-Wave Diagnostic Systems 315
8.1 Interferometer 315
8.1.1 Comments on Wavelength 316
8.1.2 Mach–Zehnder Interferometer 318
8.1.3 Mach–Zehnder Heterodyne Interferometer 319
### Appendix C: Tables and Material Constants

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.1 Waveguides, Technical Data</td>
<td>395</td>
</tr>
<tr>
<td>C.2 Waveguides, Theoretical Relations</td>
<td>396</td>
</tr>
<tr>
<td>C.3 Dielectric Materials, Electrical Data</td>
<td>396</td>
</tr>
<tr>
<td>C.4 Dielectric Materials, Mechanical Data</td>
<td>397</td>
</tr>
<tr>
<td>C.5 Dielectric Materials, Names</td>
<td>397</td>
</tr>
<tr>
<td>C.6 Gunn Oscillators</td>
<td>398</td>
</tr>
</tbody>
</table>

References 398

Index 401