

Contents

Abbreviations and Symbols	III
1 Nondestructive Inspection of Composite Materials	1
1.1 Applications of Composite Materials	2
1.2 Fiber Plastic Manufacturing	5
1.2.1 Typical Process-Related Defects	5
1.3 Investigation of Composite Materials	6
1.3.1 Overview of mmW Imaging Systems	11
1.4 Scope of the Thesis	12
1.5 Thesis Outline	13
2 Electromagnetic Propagation in Composite Materials	15
2.1 Composite Structure and Constituents	16
2.1.1 Dielectric Properties of Bulk Materials	17
2.2 Electromagnetic Properties of Fiber Bundles	18
2.2.1 Scattering by Thin Fibers	18
2.2.2 Scattering by Accumulated Fibers	22
2.2.3 Effective Medium Approximation	24
2.3 Electromagnetic Properties of Composite Materials	27
2.3.1 Stratified Media	28
2.3.2 Dielectric Gratings	30
2.3.3 Rigorous Coupled-Wave Analysis (RCWA)	34
2.3.4 Diffraction Efficiency of Composite Materials	40
2.4 Millimeter-Wave Pulse Propagation	44
2.4.1 Pulse Modeling	44
2.4.2 Propagation of Pulses in Arbitrary Media	49
2.4.3 Propagation Model Verification	51
2.5 Discussion	54
3 Radar Imaging Fundamentals and System Architecture	57
3.1 Frequency-Modulated Radar Operating Principle	58
3.1.1 Single-Target Scenario	59
3.1.2 Multi-Target Scenario	60
3.2 Accuracy Constraints	61
3.2.1 Frequency Chirp Nonlinearity	62
3.2.2 The Lower Cramér-Rao Bound	65
3.2.3 Multi-Target Accuracy Estimation	66
3.2.4 Spectral Shape in a Multi-Target Scenario	68

3.3	Clutter, its Effects and Mitigation Methods	71
3.3.1	Magnitude Normalization	72
3.3.2	Time Gating	73
3.3.3	Spatial Filtering	75
3.3.4	Background Removal	75
3.3.5	Subspace Projection	75
3.3.6	Matching Layer	76
3.3.7	Discussion of Clutter Mitigation Methods	77
3.4	Limitations on the Signal's Penetration Depth	79
3.4.1	Physical Limitations	79
3.4.2	Signal Processing	83
3.5	MMIC-Based Radar Front End	85
3.5.1	Transistor Technologies	86
3.5.2	WR10 Front End	87
3.5.3	WR3 Front End	89
3.6	Demonstrator Setup	91
3.7	Discussion	92
4	Radar-Based Tomographic Imaging of Composite Materials	95
4.1	System Performance Estimation	96
4.1.1	Penetration Depth Estimation	97
4.1.2	Depth Resolution Estimation	98
4.1.3	Lateral Resolution Estimation	102
4.1.4	Sensitivity Estimation	104
4.1.5	Accuracy Estimation	107
4.2	Intensity-Based Evaluation	109
4.2.1	Laboratory Sample with Inserted Resin Wedge	110
4.2.2	Laboratory Sample with Two Adjacent Resin Wedges	112
4.2.3	Laboratory Sample with Dry Fiber	114
4.2.4	Clutter Mitigation Techniques	116
4.3	Phase Deviation-Based Evaluation	123
4.3.1	Laboratory Sample with Inserted Resin Wedge	126
4.3.2	Laboratory Sample with Two Adjacent Resin Wedges	128
4.3.3	Laboratory Sample with Dry Fibers	129
4.4	Discussion	130
5	Conclusion and Prospects	133
A	Dielectric Loss Tangent and Absorption Coefficient	137
B	Analytic Closed-Form Radial Distribution Function	139
C	Compact Imaging System Approach	141
	Bibliography	145
	Publications	171