

# Contents

<b>1. Bulk Acoustic and Surface Acoustic Waves</b> .....	1
1.1 Bulk Acoustic Waves.....	1
1.1.1 Elastic Waves in Solids .....	1
1.1.2 Wavevector and Group Velocity .....	4
1.1.3 Behavior of BAWs at a Boundary .....	6
1.1.4 Diffraction.....	8
1.1.5 Piezoelectricity.....	8
1.1.6 Evanescent Fields .....	11
1.1.7 Waveguides.....	12
1.1.8 Behavior at the Boundary Between Waveguides .....	13
1.1.9 Open Waveguides .....	15
1.2 Waves in a Semi-infinite Substrate.....	17
1.2.1 Excitation of L- and SV-type Waves .....	17
1.2.2 Excitation of SH-type Waves.....	18
1.2.3 Leaky SAWs.....	20
1.2.4 Leaky and Nonleaky SAWs .....	21
1.2.5 SSBW .....	22
References .....	22
<b>2. Grating</b> .....	25
2.1 Basic Structure .....	25
2.1.1 Fundamentals.....	25
2.1.2 Reflection Center .....	26
2.2 Behavior in Periodic Structures .....	27
2.2.1 Bragg Reflection .....	27
2.2.2 Energy Storing Effect .....	30
2.2.3 Fabry–Perot Resonator.....	31
2.3 Equivalent Circuit Analysis .....	32
2.3.1 Analysis.....	32
2.3.2 Dependence of Reflection Characteristics on Parameters	35
2.4 Metallic Grating .....	39
2.4.1 Fundamental Characteristics .....	39
2.4.2 SAW Dispersion Characteristics .....	40
2.4.3 Approximated Dispersion Characteristics .....	42
References .....	46

<b>3. Interdigital Transducers</b> .....	47
3.1 Fundamentals .....	47
3.1.1 Bidirectional IDTs .....	47
3.1.2 Unidirectional IDTs .....	48
3.2 Static Characteristics .....	52
3.2.1 Charge Distribution .....	52
3.2.2 Electromechanical Coupling Factor .....	53
3.2.3 Element Factor .....	55
3.2.4 Complex Electrode Geometries .....	56
3.2.5 Effect of IDT Ends .....	59
3.3 IDT Modeling .....	61
3.3.1 Delta-Function Model .....	61
3.3.2 Equivalent Circuit Model .....	65
3.3.3 Other Models .....	66
3.4 Influence of Peripheral Circuit .....	68
3.4.1 Summary .....	68
3.4.2 Smith Chart and Impedance Matching .....	70
3.4.3 Achievable Bandwidth .....	73
3.5 $p$ Matrix .....	74
3.5.1 Summary .....	74
3.5.2 IDT Characterization by Using $p$ Matrix .....	76
3.5.3 Discussion on Unidirectional IDTs .....	77
3.6 BAW Radiation .....	79
3.6.1 Phase Matching Condition .....	79
3.6.2 Radiation Characteristics .....	81
References .....	84
<b>4. Transversal Filters</b> .....	87
4.1 Basics .....	87
4.1.1 Weighting .....	87
4.1.2 Basic Properties of Weighted IDTs .....	91
4.1.3 Effects of Peripheral Circuits .....	92
4.2 Design of Transversal Filters .....	97
4.2.1 Fourier Transforms .....	97
4.2.2 Remez Exchange Method .....	100
4.2.3 Linear Programming .....	101
4.3 Spurious Responses .....	103
4.3.1 Diffraction .....	103
4.3.2 Bulk Waves .....	107
4.3.3 Other Parasitic Effects .....	110
4.4 Low-Loss Transversal Filters .....	112
4.4.1 Multi-IDT Structures .....	112
4.4.2 Transversal Filters Employing SPUDTs .....	114
4.4.3 Combination of SPUDTs and Reflectors .....	117
References .....	120

<b>5. Resonators</b>	123
5.1 One-Port SAW Resonators	123
5.1.1 Introduction	123
5.1.2 Fabry–Perot Model	127
5.2 Spurious Responses	130
5.2.1 Beam Diffraction and Transverse Modes	130
5.2.2 Transverse-Mode Analysis	131
5.2.3 Effect of BAW Radiation	138
5.3 Two-Port SAW Resonators	141
5.3.1 Summary	141
5.3.2 Fabry–Perot model	143
5.3.3 Multi-Mode Resonator Filter	145
5.3.4 Cascade Connection of Resonators	148
5.4 Impedance Element Filters	149
5.4.1 $\pi$ -Type Filters	149
5.4.2 Lattice-Type Filters	152
5.4.3 Ladder-Type Filters	153
References	160
<b>6. Selection of Substrate Material</b>	163
6.1 Substrate Material and Device Characteristics	163
6.1.1 Orientation	163
6.1.2 Influence of Substrate and Electrode Materials	164
6.2 Evaluation of Acoustic Properties by Effective Permittivity	167
6.2.1 Effective Permittivity	167
6.2.2 Approximate Expressions	173
6.3 Single Crystals	174
6.3.1 Quartz	174
6.3.2 LiNbO <sub>3</sub>	176
6.3.3 LiTaO <sub>3</sub>	179
6.3.4 Li <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	182
6.3.5 Langasite	183
6.4 Thin Films	184
References	188
<b>7. Coupling-of-Modes Theory</b>	191
7.1 Fundamentals	191
7.1.1 Collinear Coupling	191
7.1.2 Periodic Structures	196
7.1.3 Excitation	200
7.2 COM Theory for SAW Devices	200
7.2.1 Derivation	200
7.2.2 COM Equations in Other Forms	203
7.2.3 Inclusion of Electrode Resistivity	204
7.2.4 Examples	206

7.3	Determination of COM Parameters .....	214
7.3.1	Perturbation Theory .....	214
7.3.2	Wave Theory Based Analysis .....	216
7.3.3	Analysis for Multi-Electrode IDTs .....	221
7.4	COM-Based Simulators .....	227
7.4.1	SAW Device Simulation .....	227
7.4.2	Inclusion of Peripheral Circuit .....	230
7.4.3	Results of Simulation .....	231
	References .....	235
<b>8.</b>	<b>Simulation of SH-type SAW Devices .....</b>	<b>237</b>
8.1	Physics of SH-Type SAWs .....	237
8.1.1	Summary .....	237
8.1.2	Propagation and Excitation on a Uniform Surface .....	237
8.1.3	Behavior on a Grating .....	243
8.1.4	Electrical Characteristics of IDTs .....	246
8.1.5	Effects of Back-Scattered BAWs .....	248
8.1.6	Influence of Grating Edge .....	249
8.2	COM Theory for SH-Type SAWs .....	250
8.2.1	COM Parameter Derivation .....	250
8.2.2	Simulation .....	254
8.2.3	COM Parameters for Rayleigh-Type SAWs .....	263
8.3	Derivation of Approximate Dispersion Relations .....	266
8.3.1	Derivation of Plessky's Dispersion Relation .....	266
8.3.2	Derivation of Abbott's Dispersion Relation .....	267
	References .....	268
<b>A.</b>	<b>Physics of Acoustic Waves .....</b>	<b>271</b>
A.1	Elasticity of Solids .....	271
A.2	Piezoelectricity .....	275
A.3	Surface Acoustic Waves .....	278
A.4	Effective Acoustic Admittance Matrix and Permittivity .....	282
A.5	Acoustic Wave Properties in 6mm Materials .....	284
A.5.1	Rayleigh-Type SAWs .....	284
A.5.2	Effective Permittivity for BGS Waves .....	285
A.5.3	Effective Acoustic Admittance Matrix .....	287
A.6	Wave Excitation .....	287
A.6.1	Integration Path .....	287
A.6.2	Electrostatic Coupling .....	288
A.6.3	BGS Wave Excitation .....	289
A.6.4	SSBW Excitation .....	290
	References .....	291

<b>B. Analysis of Wave Propagation on Grating Structures</b> . . . . .	293
B.1 Summary . . . . .	293
B.2 Metallic Gratings . . . . .	294
B.2.1 Bløtekjær's Theory for Single-Electrode Gratings . . . . .	294
B.2.2 Wagner's Theory for Oblique Propagation . . . . .	296
B.2.3 Aoki's Theory for Double-Electrode Gratings . . . . .	297
B.2.4 Extension to Triple-Electrode Gratings . . . . .	301
B.3 Analysis of Metallic Gratings with Finite Thickness . . . . .	304
B.3.1 Combination with Finite Element Method . . . . .	304
B.3.2 Application to Extended Bløtekjær Theories . . . . .	306
B.4 Wave Excitation and Propagation in Grating Structures . . . . .	310
B.4.1 Effective Permittivity for Grating Structures . . . . .	310
B.4.2 Evaluation of Discrete Green Function . . . . .	312
B.4.3 Delta-Function Model . . . . .	315
B.4.4 Infinite IDTs . . . . .	316
References . . . . .	318
<b>Index</b> . . . . .	321