

# Contents

<b>1</b>	<b>Introduction . . . . .</b>	<b>1</b>
1.1	Barium Strontium Titanate (BST) Varactors . . . . .	2
1.2	Digitally Tunable Capacitors Comprising SOI/SOS Switches . . . .	4
1.3	MEMS Tunable Capacitors . . . . .	6
1.4	Discussions on Some Tunable Capacitor Specifications . . . . .	9
1.4.1	Linearity Specification . . . . .	9
1.4.2	RF Power Handling Specification . . . . .	10
	References . . . . .	11
<b>2</b>	<b>Characterizations of RF Tunable Devices . . . . .</b>	<b>13</b>
2.1	Single Device Connected in Series . . . . .	13
2.2	Single Device Connected in Shunt . . . . .	20
2.3	A Network Consisting of RF Tunable Capacitors . . . . .	25
2.3.1	A Network Without Integrated Inductors . . . . .	25
2.3.2	A Network with Integrated Inductors . . . . .	27
	Appendix: $C_{F,Min}$ and $C_{F,Max}$ Derivations . . . . .	35
	References . . . . .	36
<b>3</b>	<b>Circuit Modeling of RF Tunable Devices and Their Networks . . . .</b>	<b>39</b>
3.1	Theory Background of Circuit Modeling . . . . .	39
3.2	Modeling Approach . . . . .	43
3.2.1	Fitting the S-Parameter Magnitude Responses for All Tunable Capacitors in $C_{min}$ State First . . . . .	44
3.2.2	Fitting S-Parameter Magnitude Frequency Response Curves for $C_1 = C_{1,max}$ or $C_2 = C_{2,max}$ and Rest $C_i = C_{i,min}$ . . . . .	45
3.2.3	Fitting S-Parameter Magnitude Frequency Response Curves for $C_3 = C_{3,max}$ or $C_4 = C_{4,max}$ and Rest $C_i = C_{i,min}$ . . . . .	45

3.2.4	Fitting the S-Parameter Magnitude Responses for all Tunable Capacitors in $C_{\max}$ State . . . . .	47
3.2.5	Brief of Modeling in Higher Frequency Bands . . . . .	48
3.3	Model Accuracy Validation . . . . .	49
3.4	Modeling Series and Shunt Tunable Capacitors . . . . .	52
3.4.1	Modeling Tunable Series Capacitor . . . . .	52
3.4.2	Modeling Tunable Shunt Capacitor . . . . .	54
3.5	Modeling an MEMS Capacitor Tuner in Low Frequency Band . . . . .	56
3.6	Modeling an Integrated MEMS Tuner in Broad Frequency Band . . . . .	60
	References . . . . .	65
<b>4</b>	<b>Nonlinearity Analysis . . . . .</b>	<b>67</b>
4.1	Roots of RF Tunable Device Nonlinearity . . . . .	67
4.2	$S_{21}$ of RF Tunable Capacitor Connected in Shunt . . . . .	71
4.3	$IP_2$ and $IP_3$ Definition and Test Setup for RF Tunable Capacitors . . . . .	72
4.4	$IP_2$ and $IP_3$ Formula Derivation of RF Tunable Capacitors . . . . .	74
4.5	$IIP_2$ and $IIP_3$ Estimation of an MEMS Tunable Capacitor . . . . .	77
4.6	Estimation of the Second and the Third Order Harmonic Products . . . . .	79
4.7	Nonlinearity of Multi-Stage RF Tunable Devices . . . . .	80
	References . . . . .	81
<b>5</b>	<b>Tunable Matching Networks . . . . .</b>	<b>83</b>
5.1	Fundamentals of Impedance Matching . . . . .	83
5.2	Method of Specifying Tunable Matching Networks . . . . .	88
5.2.1	Specifying Impedance Matching Performance . . . . .	89
5.2.2	Specifying RF Power Handling Capability . . . . .	95
5.2.3	Specifying Linearity Requirements . . . . .	99
5.3	Design of Tunable Matching Networks . . . . .	100
5.3.1	Design Considerations . . . . .	100
5.3.2	Design of New Tunable Matching Network with Broad Tuning Range . . . . .	115
5.4	Some Analyses of Tunable Matching Network . . . . .	124
5.4.1	Digitized Capacitance Value Impacts on Matching Performance . . . . .	124
5.4.2	Analysis of Tunable Capacitance Error Impacts on Matching Performance . . . . .	130
	Appendix 1: Relative Transducer Gain $\Delta G_T$ Formula Derivation . . . . .	137
	Appendix 2: A Matlab Code for RTG Calculation of TMN . . . . .	138
	References . . . . .	140

<b>6 Matching Network Tuning and Control Methods</b>	143
6.1 Optimizer Tuning of Tunable Matching Network	144
6.1.1 Single Frequency Sweeping Optimal Tuning	144
6.1.2 Duplex Frequency Pair Tuning	148
6.1.3 Frequency Band Tuning	151
6.2 Analytic Tuning Algorithm for Tunable Pi-Network	154
6.2.1 Main Parameters for Impedance Match of Tunable Networks	155
6.2.2 Composite Components Frequently Used in Algorithm	156
6.2.3 Formulas Used for Perfect Match and Main Tuning Algorithm	158
6.2.4 Formulas and Tuning Algorithm Used for Best Match	161
6.2.5 Comparison of Algorithm and Simulation Results	165
6.3 Tuning Algorithm for Tunable Capacitor-Bridged Double Pi-Network Topology	169
6.3.1 Converting to a Equivalent Pi-Network	169
6.3.2 Tuning Algorithm Discussion and Modifications	171
6.4 New Method of Tunable Matching Network Adaptive Control	175
6.4.1 System Description of Algorithm Based Adaptive Control	176
6.4.2 Key Blocks of Adaptive Control Loop	179
6.4.3 Implementation of Prototype Adaptive Control Loop	184
Appendix 1: MWO Script of Single Frequency Tuning Algorithm	191
Appendix 2: Script of Duplex Pair Frequency Tuning Approach	197
Appendix 3: Script of Frequency Band Tuning Approach	205
Appendix 4: Formula Derivations of Sect. 6.2	210
Derivation of Formulas (6.14)–(6.17)	210
Derivation of Input Reflection Coefficient	212
Appendix 5: Matlab Code for Tuning Algorithm	214
References	233
<b>7 Tunable Filters and Filter Frequency Automatic Control Loop</b>	235
7.1 Tunable SPSZ Notch Filters	236
7.2 A Simple Tunable Band-Pass Filter	240
7.3 Tunable SVD Filter	243
7.3.1 Circuit Topology and RF Performance of A Prototype MEMS Tunable SVD Filter	244

7.3.2	Linearity Requirement Analysis of SVD Filters . . . . .	248
7.4	Tunable Filter Frequency Automatic Control Loop . . . . .	252
7.4.1	Mathematical Models and Formulation . . . . .	254
7.4.2	Simulation Models and Closed-Form Solution Validation . . . . .	260
7.4.3	Frequency Automatic Control Loop Performance . . . . .	263
7.4.4	An Implementation Example of Notch Filter Control Loop . . . . .	272
	Appendix 1: Transfer Function Derivation of Notch Filter . . . . .	275
	Appendix 2: Derivation of Frequency Control Loop First Order Differential Equation . . . . .	276
	Appendix 3: Derivation of Frequency Control Loop Second Order Differential Equation . . . . .	278
	Appendix 4: Matlab Code for Frequency Control Loops . . . . .	280
	First-Order Control Loop . . . . .	280
	Second-Order Control Loop . . . . .	281
	References . . . . .	282
<b>8</b>	<b>Tunable Antennas . . . . .</b>	<b>283</b>
8.1	Fundamentals of Small Tunable Antennas . . . . .	283
8.1.1	Basic Parameters of Characterizing Antennas . . . . .	284
8.1.2	Fundamental Limitations of Small Tunable Antennas . . . . .	286
8.2	A Tunable Antenna for Mobile Phone Use . . . . .	292
8.3	Tunable Duplexing Antennas . . . . .	296
	References . . . . .	301
<b>9</b>	<b>Miscellaneous . . . . .</b>	<b>303</b>
9.1	S-Parameter Matrix of Test Fixture for De-embedding Measurement Data . . . . .	303
9.1.1	Introduction . . . . .	303
9.1.2	Derivation of S-Parameters from Measurements . . . . .	304
9.1.3	De-embedding Network Matrix . . . . .	307
9.1.4	Mathematical Description of De-embedding . . . . .	309
9.1.5	Discussions . . . . .	310
9.2	Some Conversion Formulas and Network Component or Parameter Extraction Calculations . . . . .	311
9.2.1	Conversion Formulas from Generic CBDPN to PI Network . . . . .	311
9.2.2	Element Calculations of T Network from S-Parameter Measurements . . . . .	313
9.2.3	Formulas for Shunt Capacitor and Its Q Factor Calculations from S Parameters . . . . .	314
9.2.4	Formulas for Series Inductor and Its Q Factor Calculations from S-Parameters . . . . .	315

- 9.3 Impedance Transformation Formulas for Maury Tuner
  - Creating an Antenna Impedance at a Network Output Port . . . . . 316
  - 9.3.1 Introduction . . . . . 316
  - 9.3.2 S Matrix Determination of a Transition Section . . . . . 318
  - 9.3.3 Impedance Transformation Formula for Defining Maury Tuner Impedance to Obtain Given Antenna Impedance . . . . . 321
  - 9.3.4 Discussions . . . . . 324
  - 9.3.5 Validation of Setting Defined Load Reflection Coefficient at the Reference Plan of the TMN Output Port . . . . . 325
- 9.4 LTE/LTEA Frequency Band Allocations . . . . . 330
  - 9.4.1 FDD LTE/LTEA Frequency Band Allocations . . . . . 330
  - 9.4.2 TDD LTE/LTEA Frequency Band Allocations . . . . . 331
- Appendix 1: Generic CBDPN to Pi Network Conversion . . . . . 332
- Appendix 2: Calculations of T-Network Elements from S-Parameter Measurements . . . . . 334
- Appendix 3: Shunt Capacitor and Its Q Factor Calculations from Measured S-Parameters . . . . . 338
- Appendix 4: Series Inductor and Its Q Factor Calculations from Measured S-Parameters . . . . . 341
- References . . . . . 343
- Index . . . . . 345**

RF Tunable Devices and Subsystems: Methods of  
Modeling, Analysis, and Applications

Gu, Q.

2015, XVI, 353 p. 241 illus., 153 illus. in color.,

Hardcover

ISBN: 978-3-319-09923-1