

# Contents

|          |                                                     |           |
|----------|-----------------------------------------------------|-----------|
|          | <i>Foreword by Lute Maleki</i>                      | page ix   |
|          | <i>Foreword by David Leeson</i>                     | xii       |
|          | <i>Preface</i>                                      | xv        |
|          | How to use this book                                | xvi       |
|          | Supplementary material                              | xviii     |
|          | <i>Notation</i>                                     | xix       |
| <b>1</b> | <b>Phase noise and frequency stability</b>          | <b>1</b>  |
|          | 1.1 Narrow-band signals                             | 1         |
|          | 1.2 Physical quantities of interest                 | 5         |
|          | 1.3 Elements of statistics                          | 9         |
|          | 1.4 The measurement of power spectra                | 13        |
|          | 1.5 Linear and time-invariant (LTI) systems         | 19        |
|          | 1.6 Close-in noise spectrum                         | 22        |
|          | 1.7 Time-domain variances                           | 25        |
|          | 1.8 Relationship between spectra and variances      | 29        |
|          | 1.9 Experimental techniques                         | 30        |
|          | Exercises                                           | 33        |
| <b>2</b> | <b>Phase noise in semiconductors and amplifiers</b> | <b>35</b> |
|          | 2.1 Fundamental noise phenomena                     | 35        |
|          | 2.2 Noise temperature and noise figure              | 37        |
|          | 2.3 Phase noise and amplitude noise                 | 42        |
|          | 2.4 Phase noise in cascaded amplifiers              | 49        |
|          | 2.5 ★ Low-flicker amplifiers                        | 52        |
|          | 2.6 ★ Detection of microwave-modulated light        | 62        |
|          | Exercises                                           | 65        |
| <b>3</b> | <b>Heuristic approach to the Leeson effect</b>      | <b>67</b> |
|          | 3.1 Oscillator fundamentals                         | 67        |
|          | 3.2 The Leeson formula                              | 72        |

|          |                                                                             |            |
|----------|-----------------------------------------------------------------------------|------------|
| 3.3      | The phase-noise spectrum of real oscillators                                | 75         |
| 3.4      | Other types of oscillator                                                   | 82         |
| <b>4</b> | <b>Phase noise and feedback theory</b>                                      | <b>88</b>  |
| 4.1      | Resonator differential equation                                             | 88         |
| 4.2      | Resonator Laplace transform                                                 | 92         |
| 4.3      | The oscillator                                                              | 96         |
| 4.4      | Resonator in phase space                                                    | 101        |
| 4.5      | Proof of the Leeson formula                                                 | 111        |
| 4.6      | Frequency-fluctuation spectrum and Allan variance                           | 116        |
| 4.7      | ★★ A different, more general, derivation of the resonator<br>phase response | 117        |
| 4.8      | ★★ Frequency transformations                                                | 121        |
| <b>5</b> | <b>Noise in delay-line oscillators and lasers</b>                           | <b>125</b> |
| 5.1      | Basic delay-line oscillator                                                 | 125        |
| 5.2      | Optical resonators                                                          | 128        |
| 5.3      | Mode selection                                                              | 130        |
| 5.4      | The use of a resonator as a selection filter                                | 133        |
| 5.5      | Phase-noise response                                                        | 138        |
| 5.6      | Phase noise in lasers                                                       | 143        |
| 5.7      | Close-in noise spectra and Allan variance                                   | 145        |
| 5.8      | Examples                                                                    | 146        |
| <b>6</b> | <b>Oscillator hacking</b>                                                   | <b>150</b> |
| 6.1      | General guidelines                                                          | 150        |
| 6.2      | About the examples of phase-noise spectra                                   | 154        |
| 6.3      | Understanding the quartz oscillator                                         | 154        |
| 6.4      | Quartz oscillators                                                          | 156        |
|          | Oscilloquartz OCXO 8600 (5 MHz AT-cut BVA)                                  | 156        |
|          | Oscilloquartz OCXO 8607 (5 MHz SC-cut BVA)                                  | 159        |
|          | RAKON PHARAO 5 MHz quartz oscillator                                        | 162        |
|          | FEMTO-ST LD-cut quartz oscillator (10 MHz)                                  | 164        |
|          | Agilent 10811 quartz (10 MHz)                                               | 166        |
|          | Agilent noise-degeneration oscillator (10 MHz)                              | 167        |
|          | Wenzel 501-04623 (100 MHz SC-cut quartz)                                    | 171        |
| 6.5      | The origin of instability in quartz oscillators                             | 172        |
| 6.6      | Microwave oscillators                                                       | 175        |
|          | Miteq DRO mod. D-210B                                                       | 175        |
|          | Poseidon DRO-10.4-FR (10.4 GHz)                                             | 177        |
|          | Poseidon Shoebox (10 GHz sapphire resonator)                                | 179        |
|          | UWA liquid-N whispering-gallery 9 GHz oscillator                            | 182        |

|                                              |            |
|----------------------------------------------|------------|
| 6.7 Optoelectronic oscillators               | 185        |
| NIST 10 GHz opto-electronic oscillator (OEO) | 185        |
| OEwaves Tidalwave (10 GHz OEO)               | 188        |
| Exercises                                    | 190        |
| <b>Appendix A Laplace transforms</b>         | <b>192</b> |
| <i>References</i>                            | 196        |
| <i>Index</i>                                 | 202        |