
INDEX

- Admittance surfaces, 268–278
- All angle negative refraction, 8
- Alternate right-handed/left-handed (ARLH) sections, 199–207
- bandpass filters and, 203–207
 - complementary split ring resonators, 203–207
 - diplexers and, 203–207
 - S-band filter, 202
 - split ring resonators, 199–203
- Amplification of evanescent modes, 20–21, 288–292
- Antenna applications, 252–258
- angle of main radiation lobe, 254
 - electronically scanned antennas, 254–258
 - leaky-wave antenna, 254–258
 - left-handed media, 254–258
 - media pairs, 253
 - radiation limit of Chu for Q , 254
 - radiated power, 254
- Anti-symmetric resonances, 71
- ARLH. *See* alternate right-handed/left-handed.
- Babinet principle, 268–269, 272–273
- complementary split ring resonator planar arrays, 272–273
- Backward leaky modes, 19–20, 254–259
- Backward media, 2, 3
- Backward transmission line, 120–128
- backward wave, 120–121
 - characteristic impedance, 120
 - constitutive parameters, 123–124
 - design and fabrication, 128
 - dispersion of, 123
 - forward wave, 121
 - implementation of, 124–125, 128–131
 - composite right-/left-handed (CRLH), 124–128
 - left-handed structure, 120–121
 - right-handed structure, 121
 - transverse electromagnetic (TEM) mode propagation, 123–124
- Backward wave, 120–121
- Backward wave coupler, 246–248
- Backward-wave propagation, 2–4, 9–12
- Cerenkov radiation, 10–11
 - inverse Doppler effect, 10
 - negative Goos–Hanchen shift, 12
- Balanced composite right-/left-handed (CRLH) transmission lines, 127–128
- Bandpass filters, 198–227
- admittance inverters, 208
 - alternate right-handed/left-handed (ARLH) sections, 199–207
 - design methodology, 210

- Bandpass filters (*Continued*)
 hybrid approach, 210
 hybrid model, 210
 right-handed section implementation, 218–225
 ultra-wide, 219–227
- Bandwidth, enhancement of, 236–244
 phase shifters, 244
 rat race hybrid couplers, 239–243
- BC-SRR. *See* broadside-coupled split-ring resonator design.
- Bianisotropy, 65–69
- Bloch impedance, 120, 152, 155
- Bloch impedance. *See* Characteristic impedance
- Broadband device components, 236–244
- Broadside-coupled split-ring resonator design (BC-SRR), 60–62
- Bulk metamaterials
 alternative designs, 102–107
 chiral, 97–102
 ferrite, 92–97
 infrared frequencies, at, 79–80
 optical frequencies, at, 79–80, 106–107
 split ring resonators (SRRs) based, 65–70, 80–88
- Canalization devices, 302–303
- Cerenkov radiation, 10–11
- Characteristic (Bloch) impedance, 120
- Chiral media, 97–102
 backward-wave propagation, 98–99
 chiral nihility, 102
 racemic mixture, 97
- Chiral metamaterials, 97–102
- Chiral nihility, 102
- Circuit analysis approach, 44
- Circuit model comparisons, 175–180
 dual left-handed lines vs. resonant types, 175–180
- Coefficients, transmission and reflection, 13–15, 17
- Compact broadband device components, 236–244
- Complementary split ring resonators (CSRR), 119, 155–163
 admittance surfaces, 268–278
 alternate right-handed/left-handed (ARLH) sections, 203–207
 electromagnetic properties of, 156–160
 electro-inductive waves, 284–287
 equivalent circuit models, 156–160, 166–170
 filters, characteristics of, 207–224
 frequency-selective surface, 278
 left-handed transmission lines, 163–166
 metamaterial transmission line synthesis and, 163–175
 negative permittivity, 163–166
 numerical calculation, 160–163
 parameter extraction technique, 170–172
 planar arrays, 272–273
- Complex waves, 19–20
- Composite right-/left-handed (CRLH) transmission lines, 124–128
 balanced, 127–128
 coplanar waveguide (CPW)
 configuration, 129
 host propagating medium, 129
 distributed components, 129
 lumped elements, 129
 leaky-wave antennas, 254–255
 microstrip structure, 129
- Constitutive parameters
 backward transmission line and, 123–124
 bulk split-ring metamaterials, 65–70
- Coplanar waveguide (CPW), 129, 136
- Couplers in planar technology, 246–252
 backward wave, 246–248
 forward wave, 248–249
 improvements to, 249–252
- CPW. *See* Coplanar waveguide
- CRLH. *See* Composite right-/left-handed transmission lines
- Cross-polarization effects, 54–59, 99–100, 276–278
- CSRR. *See* Complementary split ring resonators
- Diplexers, 188–189
 alternate right-handed/left-handed (ARLH) sections, 206–207
- Dispersion relations
 of bulk metamaterials, 69, 83–87, 90–92

- of transmission-line metamaterials, 120–128
- of resonant type transmission-line metamaterials, 151, 167
- Distributed components, 129
- Double-negative media, 2
- Double-split split-ring resonator (2-SRR), 62
- Dual left-handed lines, resonant types vs., 175–180
- Dual transmission line. *See* backward transmission line.
- Dual transmission line. *See* purely left-handed transmission line.
- Dual-band components, 244–246
- Duality, 155, 272–273, 285
- Dynamic resonances, 71

- EBGs. *See* Electromagnetic band gaps
- EC-SRR. *See* Edge-coupled split ring resonator
- Edge-coupled split ring resonator (EC-SRR), 52–59
- EIWs. *See* Electro-inductive waves
- Electric resonances, 71
- Electro-inductive waves
 - applications of, 287
 - complementary split ring resonators, 284–287
- Electrodynamics of left-handed media, 1–35
- Electromagnetic band gap (EBG), 194, 227
 - transmission line, 191–192
- Energy density, 4–6
- Equivalent circuit models
 - of composite right/left handed (CRLH) transmission lines, 124–125
 - of complementary split ring resonators (CSRRs), 156–160
 - of complementary split ring resonators (CSRRs) loaded transmission lines, 166
 - of purely right/left handed (PRH and PLH) transmission lines, 121
 - of split ring resonators (SRRs), 52–65
 - of split ring resonators (SRRs) loaded transmission lines, 146
- Evanescent Fourier harmonics, 25–27, 289–290
- Evanescent mode amplification. *See* Amplification of evanescent modes

- Fermat principle, 9
- Ferrite lens, 296
- Ferrite metamaterials, 92–97
 - left-handed circularly polarized (LCP) wave, 93
 - magnetostatic surface waves (MSSWs), 95
 - right-handed circularly polarized (RCP) wave, 93
- Ferrites, low-loss cubic, 92
- Filters, 188–189
 - complementary split ring resonators (CSRR), 207–224
 - high-pass, 225–227
 - narrow bandpass, 198–207
 - planar, 193–198
 - S-band, 203
 - tunable, 227–233
 - ultra-wide bandpass, 225–227
- Forward leaky modes, 254–259
- Forward transmission line, phase velocity calculation, 122
- Forward wave coupler, 248–249
- Forward wave, 121
- Fourier harmonics, 26–27
- Frequency-selective surface, 278

- Goos–Hanchen shift, negative, 12
- Group velocity, 4–6
 - calculation of, 122
- Guided waves, 17–19

- Higher-order resonances, 70–73
- High-pass filters (HPFs), 225–227
- HPFs. *See* High-pass filters

- In vacuo* capacitance, 57, 100
- Indefinite media, 34–35
- Infrared frequencies, SRRs at, 75–80
- Inverse Doppler effect, 10
- Isotropic split-ring resonators, 73–75

- LCP. *See* Left-handed circularly polarized wave
- Leaky backward waves, 19–20
- Left-handed circularly polarized (LCP) wave, 93
- Left-handed media
- antenna applications and, 252–258
 - energy density, 4–6
 - Fermat principle, 9
 - group velocity, 4–6
 - impedance, 9, 14, 17, 20, 23, 29
 - impedance matrix, 30
 - left-handed
 - slabs, 16–20
 - triplet, 3
 - losses and dispersions, 32–34
 - negative refraction, 6–9
 - other effects, 9–12
 - Poynting vector, 3–6, 36, 41
 - slabs, $\epsilon/\epsilon_0 \rightarrow -1$ and $\mu/\mu_0 \rightarrow -1$, 20–32
 - wave fronts, 3–5, 10–11
 - wave numbers, 4, 19, 34
 - wave propagation, 2–4
 - wave vector, 6, 8, 12–15, 19, 35
- Left-handed metamaterials
- chiral bulk, 97–102
 - ferrite bulk, 92–97
 - split ring resonators (SRRs) bulk, 65–70, 80–88
 - planar transmission-line, 120–180
 - resonant type planar transmission line, 135–175
 - resonant/nonresonant planar transmission line (comparison), 175–180
- Left-handed slabs
- guided waves, 17–19
 - leaky waves, 19–20
 - reflection coefficients, 17
 - transmission coefficients, 17
 - with $\epsilon/\epsilon_0 \rightarrow -1$ and $\mu/\mu_0 \rightarrow -1$, 20–32
- Left-handed transmission lines, equivalent circuit models, 146–155
- Left-handed transmission line design, split ring resonators, 135–146
- coplanar waveguide, 136
 - CPW technology, 139–143
 - microstrip line, 136, 139–143
 - negative permeability transmission lines, 136–138
 - resonant-type approach, 135
 - size reduction, 144–146
- Left-handed triplet, 3
- Left-handed waves
- backward leaky modes, 19–20
 - complex waves, 19–20
 - guided waves, 17–19
 - surface waves, 15–16, 18
 - TEM waves, 3
- Longitudinal section electric (LSE), 13
- Longitudinal section magnetic (LSM) waves. *See* P-polarized waves
- Losses and dispersions, 32–34
- Pendry's perfect lens, 32
 - super-lens, 33–34
 - Veselago analysis, 32
- Low-loss cubic ferrites, 92
- yttrium iron garnets, 92
- Low-loss plasmas, 1
- LSE. *See* Longitudinal section electric
- LSM waves. *See* P-polarized waves
- Magnetic plasma, 105
- Magnetic resonances, 71
- Magneto-inductive lenses, 299–302
- Magneto-inductive waves (MIWs), 278–284
- applications of, 285–287
 - equation, 279–281
 - surfaces, 282–284
- Magnetostatic surface waves (MSSWs), 95, 295–299
- Matching device, perfect lens and, 29–32
- MB. *See* Mono-band
- Media pairs, 253
- Metallic plates, 44–46
- two-dimensional plasmas, 44–46
- Metallic waveguides, 44–46
- magnetic plasma, 105
 - one-dimensional plasmas, 44–46
- Metamaterials, left-handed, 80–91
- Metamaterial transmission lines, balanced composite right-/left-handed, 225–227
- Metamaterial transmission line synthesis

- compact broadband devices, 236–244
- complementary split ring resonators, 163–175
 - equivalent circuit models, 166–170
 - frequency response, 172–175
 - left-handed transmission lines, 163–166
 - negative permittivity, 163–166
 - parameter extraction, 170–172
- coupled-line couplers, 246–252
- dual-band components, 244–246
- microwave component miniaturization, 234–236
- Microstrip, 139–143
- Microwave applications, 187–258
- Microwave filters, 188–233
- MIWs. *See* Magneto inductive waves
- Mono-band (MB) circuits, 244
- MSSWs. *See* Magnetostatic surface waves
- Multi-tuning, stop-band filters and, 190–191

- Narrow bandpass filter, 198–207
- NB-SRR. *See* Nonbianisotropic split ring resonator
- Negative Goos–Hanchen shift, 12
- Negative magnetic permeability
 - bulk split-ring resonator metamaterials, 65–70
 - edge-coupled SSR, 52–59
 - split-ring resonator designs, 59–65
 - synthesis of, 51–80
- Negative permeability transmission lines, 136–138
- Negative permittivity transmission lines, 163–166
- Negative refraction, 6–9
 - all-angle, 8
- Negative ϵ and μ . *See* Left-handed
- Negative-permittivity, 44–50
 - spatial dispersion, 49–50
- Negative refractive media. *See* Left-handed media
- Nonbianisotropic split-ring resonator (NB-SRR), 62

- Non-resonant circuit analysis
 - approach, 44
- Notch tunable filters, 230–233

- One-dimensional plasmas
 - metallic waveguides and, 44–46
- One-dimensional split-ring resonator based
 - left-handed metamaterials, 81–85
- Optical frequencies, 75–80, 106–107
- Open EC-SRR, 111

- Parameter extraction technique, 170–172
- Pendry's perfect lens, 27–29, 32
- Perfect lens, 25–32
 - evanescent Fourier harmonics, 26–27
 - tunneling/matching device, 29–32
- Perfect tunneling, 21–25
- Phase compensation, 20–21
- Phase shifters, 244
- Phase velocity, calculation of, 122
- Planar arrays
 - complementary split ring resonator, 272–273
 - split ring resonator, 270–272
- Planar filters, 188–233
- Planar technology metamaterials, 119–180
 - backward transmission line, 120–128
 - circuit model comparison, 175–180
 - complementary split rings resonator (CSRR), 119
 - left-handed transmission lines, 135–146
 - three dimensional metamaterials, 132
 - two-dimensional (2D), 131–134
- Plates, metallic, two dimensional plasmas, 44–46
- PLH. *See* Purely left-handed transmission line
- P-polarized waves. *See* Longitudinal section magnetic (LSM) or transverse magnetic (TM) waves, 13
- PRH. *See* Purely right-handed transmission line
- Purely left-handed (PLH) transmission line, 125, 246
 - dual, 125
- Purely right-handed (PRH) transmission line, 125, 246

- Quasielectrostatic limit imaging, 292–295
 surface plasmons, 292–295
- Quasimagnetostatic limit imaging, 295–299
 magnetostatic surface waves, 295–299
- Quasistatic resonance, 70
- Racemic mixture, 97, 99
- Radiated power, 254
- Rat race hybrid couplers, 239–243
- RCP. *See* Right-handed circularly polarized wave
- Reflection coefficients, 17
 transmission coefficients and, 13–15
- Resonances, higher order, 70–73
- Resonant impedance surface imaging, 299–302
 magneto-inductive lenses, 299–302
- Resonant-type approach, 135
- Resonant-type balanced composite right/left-handed metamaterial transmission lines, 225–227
- Resonant-type transmission lines, dual left-handed vs., 175–180
- Right handed sections, bandpass filters and, 218–225
- Right-handed circularly polarized (RCP) wave, 93
- Scaling plasmas at microwave frequencies, 44–50
 metallic plates, 44–46
 metallic waveguides, 44–46
 wire media, 47–50
- Silver lens, 294
- Simultaneously negative ϵ and μ . *See* Left-handed
- Single split ring resonators, 268–269
 Babinet principle, 268–269
- Size reduction, split ring resonators and, 144–146
- Slabs, $\epsilon/\epsilon_0 \rightarrow -1$ and $\mu/\mu_0 \rightarrow -1$, 19–32
 perfect lens, 25–32
 perfect tunneling, 21–25
- Spatial dispersion, wire media and, 49–50
- Spirals, 62–65
 two-turns spiral resonator (2-SR), 62
- Split-ring resonator based left-handed metamaterials, 80–91
 continuous-medium approach, 87–88
 modeling and numerical accuracy of, 90–91
 one-dimensional, 81–84
 superposition hypothesis, 88–90
 three-dimensional, 85–87
 two-dimensional, 85–87
- Split-ring resonator metamaterials, bulk, 65–70
- Split-ring resonator designs, 59–65
 broadside-coupled, 60–62
 chiral, 99–100
 double-split, 62
 nonbianisotropic, 62
 spirals, 62–65
- Split-ring resonator planar arrays, 270–272
- Split-ring resonators (SRRs), 43
 admittance surfaces, 268–278
 alternate right-handed/left-handed (ARLH) sections and, 199–203
 Babinet principle for, 268–269
 complementary, 155–163
 duality, 155–163
 edge-coupled, 52–59
 equivalent circuit models, 52–65, 146–155
 higher-order resonances, 70–73
 isotropic, 73–75
 left-handed transmission line design and, 135–146
 negative permeability transmission lines, 136–138
 resonant-type approach, 135
 scaling down of, 75–80
 infrared frequencies, 75–80
 optical frequencies, 75–80
 size reduction, 144–146
- S-polarized waves, 13. *See* Longitudinal section electric (LSE); Transverse electric (TE)
- Spurious frequency bands, 193–197
- SRRs. *See* Split ring resonators
- Stop-band filters, 189–193
 electromagnetic band gap (EBG) transmission line, 191–192
 multi-tuning, 190–191

- Subdiffraction imaging devices, 287–303
 - canalization devices, 302–303
 - features of, 288–292
 - ferrite lens, 296
 - magnetostatic waves, 295–297
 - resonant impedance surfaces, 299–302
 - silver lens, 294
 - surface plasmons, 292–295
- Super-lens, 33–34
 - Veselago, 34
- Superposition hypothesis, 88–90
- Surface plasmons, 16, 292–295
- Surface waves, 15–16, 18
 - magnetostatic, 295–299
 - s-polarized, 16
- Symmetric resonances, 71
- Synthesis of negative magnetic permeability, 51–80
- Synthesis, bulk metamaterials, 43–109

- TEM. *See* Transverse electromagnetic mode propagation
- Three-dimensional SRR-based left-handed metamaterials, 85–87
- TM waves. *See* P-polarized waves
- Transmission coefficients, 17
- Transmission, reflection coefficients and, 13–15
- Transmission lines, negative permeability, 136–138
- Transverse electric (TE) waves, 13
- Transverse electromagnetic (TEM) mode propagation, 123–124
- Transverse magnetic (TM) waves. *See* P-polarized waves
- Tunable filters, 227–233
 - notch type, 230–233
 - varactor-loaded split rings resonators (VLSRRs), 227–233
- Tunneling
 - perfect, 21–25
 - perfect lens and, 29–32
- 2-SR. *See* Two-turns spiral resonator
- 2-SRR. *See* Double-split split ring resonator
- Two dimensional left handed structure, lumped elements and, 131–132

- Two dimensional metamaterials
 - bulk SRR based, 85–87
 - planar technology, 131–135
- Two dimensional plasma
 - metallic plates and, 44–46
- Two-turns spiral resonator (2-SR), 62

- Ultra-wide bandpass filter (UWBPF), 219–222, 225–227
 - resonant-type balanced composite right/left-handed metamaterial transmission lines, 225–227
- UWBPF. *See* Ultra-wide bandpass filters

- Varactor-loaded split rings resonators (VLSRRs), 227–233
 - equivalent circuit model, 228–230
 - model validation, 230
 - topology of, 228–230
- Veselago
 - analysis, 32
 - lens, 34
 - media, 2
- VLSRRs. *See* Varactor-loaded split rings resonators

- Wave impedance, 14
- Wave propagation, 2–4
- Wave transmission and guidance, left-handed slabs and, 16–20
- Waveguides, metallic
 - as one dimensional magnetic plasmas, 105
 - as one dimensional plasmas, 44–46
- Waves at interfaces, 13–16
 - surface, 15–16
 - transmission and reflection coefficients, 13–15
- Wire media, 47–50
 - spatial dispersion in, 49–50

- YIG. *See* Yttrium iron garnets
- Yttrium iron garnets (YIG), 92

