

## Index

### **a**

add-drop filter 1, 3, 10  
 angular momentum distributions 73, 74  
 angular momentum index 111–113  
 antisymmetric modes 48, 93, 94, 96–98,  
 115, 116, 131–134, 151, 159, 160,  
 172, 205, 209, 245

### **b**

Baker's algorithm 10, 50–52, 227  
 for intensity spectrum calculation 52  
 Padé approximation with 50–52, 94  
 for processing FDTD simulation data  
 38  
 band-pass filter (BPF) 104, 105, 169, 263,  
 302  
 beam propagation method (BPM) 36, 37  
 biosensing 3  
 bisbenzo-cyclobutene (BCB) 206, 284  
 bistability loops 300  
 bootstrapping technique 55, 58  
 boundary element method (BEM) 37

### **c**

Cartesian coordinate system 14, 38–45  
 chaotic microcavity lasers  
 Limaçon microcavity lasers 79–82  
 quadrupolar-shaped microcavity lasers  
 76–78  
 waveguide coupled 86–87  
 wavelength-scale microcavity lasers  
 82–86  
 circular microdisks 92

semiconductor lasers 70  
 whispering-gallery modes in 65–69,  
 92–93  
 circular-side hexagonal microcavity lasers  
 209–211  
 circular-side polygonal microcavities  
 (CSPMs) 193–197  
 circular-side square microcavity  
 174–180  
 circular-side square microlaser 177–179  
 continuous-wave (CW) 4, 58, 74, 75, 109,  
 142, 145, 163, 172, 173, 207, 208,  
 212, 236, 261, 263, 293, 294, 298  
 coupled-cavity laser 284, 295, 310, 313  
 courant stability condition 45, 46

### **d**

deformed circular microcavities  
 microdisk lasers, local boundary defect  
 70–72  
 spiral-shaped microcavity lasers  
 72–75  
 waveguide-connected spiral  
 microcavity lasers 75  
 deformed hexagonal microlaser 212  
 deformed microring 10, 91, 111–114, 119  
 dense wavelength division multiplexing  
 (DWDM) systems 171  
 dielectric slab waveguide 14, 29  
 directional-emission square  
 semiconductor laser 163–165  
 discrete Fourier transform (DFT) 50  
 distributed Bragg reflectors (DBRs) 27

- distributed feedback (DFB) laser 26–28, 251
  - divinylsiloxane bisbenzocyclobutene (DVS-BCB) 157
  - droplet microlasers 5
  - droplet-based microlasers 5
  - dual-mode lasing square microcavity lasers 168
  - dual-mode square microlaser 168–171, 180
  - dual-transverse-mode lasing 147, 165
- e**
- edge-emitting semiconductor lasers 13, 28, 31–32
  - Eigenvalue equations 127–128
    - for TE modes 19–21
    - for TM modes 21
    - for vertical-cavity surface-emitting lasers (VCSEL) 22–24
  - electric field patterns 191
  - electromagnetic waves 1, 2, 46, 59, 62
  - energy distribution ratio 292
  - equilateral triangle resonator (ETR)
    - device fabrication 140–142
    - Eigenvalue equation 127–128
    - evanescent fields in external regions 125–127
    - lasing characteristics 142–145
    - microlaser 144
    - transverse modes 124–125
    - wave equations for TE and TM mode 123–124
  - erbium-doped fiber amplifier (EDFA) 104, 167, 169, 263, 264
  - etching technique processes 5
  - external cavity semiconductor lasers 26
- f**
- fabrication process 4, 5, 171, 197, 205, 230, 231, 283, 290, 313
  - Fabry–Pérot (FP) cavity 11, 13, 21, 24–26, 28, 135, 251, 283
  - far-field emission
    - by FDTD simulation 134
    - intensity 83
    - mode Q-factors 131–133
    - patterns 2, 151
  - far-field pattern (FFP) 2, 72, 117–119, 290, 296, 310, 311
  - fast Fourier transform (FFT) 37, 50, 62
  - finite-difference time-domain (FDTD)
    - method
      - absorption boundary condition 46–48
      - Cartesian coordinate system
        - 2D 38–41
        - 3D 41–43
      - cylindrical coordinate system 43–45
      - Maxwell’s equations 38
      - microcavities simulation 48–50
      - numerical stability condition 45–46
      - Padé approximation 37–52
      - simulation 95, 107
      - technique 129, 154
    - finite-element method (FEM) 37, 152, 201, 286
    - first-order perturbation theory 5
    - four transverse modes 164
    - Fourier transform patterns 289–291
    - full-width at half maximum (FWHM) 7, 169, 213
- g**
- GaAs modified limaçon microcavity 84
- h**
- Hakki–Paoli method 26
  - Hankel function 66, 67, 92, 187, 222, 224
  - Helmholtz equation 15, 66, 72, 186
  - hexagonal microcavities
    - circular-side hexagonal microcavity lasers 209–211
    - mode coupling 200–201
    - numerical simulation of 201–203
    - periodic orbits 197–200
    - symmetry analyses 200–201
    - wavelength-scale hexagonal microcavity 203–209
    - WGMs in 203–205

highly nonlinear fiber (HNLF)  
169

hybrid cavity lasers  
fabrication processes 290–292  
lasing characteristics 292–295  
mode field distributions 288–290  
Q factor enhancement 292–295  
robust single-mode operation  
295–297

hybrid deformed microring lasers  
111–114

hybrid mode behaviors 283

hybrid square-rectangular laser (HSRL)  
283, 309

Hybrid Square/Rhombus-Rectangular  
Lasers (HSRRLS) 309–312

**i**

inductive-coupled plasma (ICP)  
techniques 101

inductively coupled plasma (ICP)  
dry etching process 207  
etching techniques 163, 290, 292

InGaAs/InGaAsP microcavity laser  
71

input optical power 6, 308

integrated lab-on-a-chip systems 5

integrated microlasers 11, 275

internal field intensity distribution 112,  
113

**k**

*k*-space patterns 157, 159–162

**l**

lasing threshold 1, 4, 69, 75, 211, 295,  
296, 299

limaçon microcavity lasers 79–82

limaçon-shaped microcavity 82

liquid droplet microcavities 5

lithography 5

logic gates 306–309, 313

longitudinal-mode intervals 25, 26, 103,  
109, 144, 155–159, 161, 163, 164,  
172, 177, 210, 283, 299

**m**

magnified spectrum 161

Maxwell's equations 13, 14, 37–39, 43,  
45, 62, 67, 137, 139, 140, 150, 152,  
201, 225

metal–organic chemical vapor deposition  
163, 290

microcavity lasers  
dynamical states for 255  
experiment and simulated results  
268–269  
modulation bandwidth enhancement  
269–271  
nonlinear dynamics 263–268  
optically injected microdisk laser 263,  
265  
rate equation model 253–254

microcylinder lasers 70, 219, 230–236,  
244

microdisk lasers 2, 4, 8–10, 65–72, 75,  
91–119, 147, 219, 236, 252, 253,  
255, 256, 261–271, 275, 276, 266

microlasers 4, 258  
integrated microlasers 275  
microwave generation 271–275

microring lasers 91, 107–114, 119

microsquare laser 165–168, 173, 272,  
273

microwave power amplifier (PA) 272

microwave spectra 255, 257, 273–275

mode analysis  
high Q modes 154–157  
mode confinement 139–140  
mode light ray approximation  
135–138  
mode Q factors 138–139

mode coupling 107  
symmetry analysis 150–154, 200–201  
and vertical radiation loss 225–230  
in waveguide-connected microdisks  
94–100

mode-field distributions 288–290  
analytical solutions 129  
mode degeneracy and classify  
128–129

- mode frequencies 52, 54, 59, 60, 67, 73, 85, 99, 129, 134, 152, 153, 156, 157, 191, 192, 194, 201, 222, 227, 268, 270, 271
  - mode gain
    - for TE modes 29–30
    - for TM modes 30–31
  - mode hopping 296, 299, 301
  - mode-intensity spectrum 157, 160, 161, 287
  - mode Q-factor 138–139
    - enhancement for hybrid modes 286–288
    - far-field emission 131–133
    - measurement 7–10
    - output efficiency and 6–7
  - mode wavelengths 7, 16, 17, 31, 33, 34, 58, 69, 93, 94, 96, 98, 100, 102, 107, 115, 116, 123, 124, 128, 132, 134, 137–139, 143–145, 149, 150, 155–157, 163, 164, 166, 167, 175, 176, 180, 203, 206, 207, 210, 211, 213, 214, 222, 225, 226, 228, 229, 232–234, 236, 237, 239, 242–244, 248, 268, 270, 271, 276, 283, 285–289, 293, 295–298, 300, 312, 313
  - multilayer dielectric slab waveguide
    - distributed feedback lasers 26–28
    - edge-emitting semiconductor lasers 31–32
    - effective index approximation method 35
    - Eigenvalue equation 19–21
    - Fabry–Perot cavity 24–26
    - guided and radiation modes 17–18
    - mode gain 28–31
    - optical confinement factor 28–31
    - phase shift of total internal reflection 21–22
    - Si-on-SiO<sub>2</sub> slab waveguide 32–33
    - TE and TM modes in 14–15
    - three-layer slab waveguides 15–17
    - for vertical-cavity surface-emitting lasers 22–24, 33–35
  - multiple-quantum-well (MQW)
    - active layer 71
    - epitaxial laser wafer 207
  - multiport output microdisk lasers 117–119
- n**
- nondeformed circular microcavities
    - circular microdisk semiconductor lasers 70
    - whispering-gallery modes 65–70
  - nondeformed circular microdisk 65–70, 92, 94–96
  - non-return-zero (NRZ) signals 105
  - nonzero electric fields 14, 15, 124, 149
  - normalized intensity 111–113
- o**
- octagonal resonator microlasers 211–214
  - optical bandpass filter 169, 302
  - optical bistability 11, 283, 297–303, 305, 313
  - optical bistable semiconductor lasers 297
  - optical confinement factor 6, 10, 13, 28–34, 36, 253
  - optical delay line (ODL) 302
  - optical intensity time series 255–257
  - optically injected microdisk laser 263, 265
  - optical signal-to-noise ratios (OSNRs) 170
  - optical spectra analyzer (OSA) 231
  - optical spectrum analyser (OSA) 231
  - output coupling 2, 6, 7, 65, 71, 96, 97, 99, 100, 119, 131–135, 142, 144, 253, 254
  - output efficiency 6–7, 134, 135, 211
  - output optical signals 303–305
  - output waveguide 6, 9, 10, 75, 88, 91, 94–103, 106–108, 111, 117–119, 133–135, 140, 143, 145, 147, 157–159, 161–164, 166, 168,

171–174, 176, 178–180, 206–208,  
210, 211–213, 215, 236, 253, 254,  
259, 263, 264, 273

## **p**

### Padé approximation

Baker's algorithm 50–52  
FDTD method *see* finite-difference  
time-domain (FDTD) method  
light delay simulation for coupled  
microring resonators 57–59  
simulation for coupled microdisks  
53–54

p-electrode metal 101, 102

perfect matched layer (PML) absorbing  
boundary condition 94, 227

photonic crystal waveguide 59–62

photonic integrated circuits 5, 147, 174,  
206, 252, 276, 313

photonic integration 2, 4, 65, 70, 88, 185,  
180

plasma-enhanced chemical vapor  
deposition (PECVD) 101, 141,  
163

### polygonal microcavities

circular-side polygonal microcavities  
193–197

symmetry analyses 186–190

3D equilateral-triangular microcavity  
245–246

3D square microcavity 246–247

WGMs, numerical simulations of 190

Poynting vector 28, 134

propagation constants 14, 16–19, 23, 26,  
29, 33, 56, 124, 128, 203, 226, 237,  
238, 311

## **q**

Q factor enhancement 292–295

quadrupolar-shaped microcavity 76–79,  
86, 87

quantum sources 4

quantum-dot microcylinder laser  
219

quarter-wave-shifted DFB lasers 28

## **r**

rate equation model 253–254

reactive ion etching (RIE) 163, 290

RF microwave spectra 255

## **s**

saturable absorption effect 298, 302

scanning electron microscope (SEM) 71,  
112, 141, 142, 163, 230, 290

scattering matrix (S-matrix) techniques  
220, 222–225, 229

semiconductor microdisk lasers 8, 91

semiconductor microlasers

mode Q factor 6–10

output efficiency 6–7

semiconductor microsquares 156

side-mode suppression ratios (SMSRs)  
103, 163, 207, 211, 236, 263, 273,  
294, 295, 301

silica microdisks 5, 7

single mode fiber (SMF) 11, 104, 167,  
169, 174, 263, 264, 272, 275, 283,  
294, 298, 299, 312

single-mode lasing 81, 113, 148, 211,  
295, 306, 312

spiral-ring microcavity 74, 75

spiral-shaped microcavity 72–75

square microcavities 10, 11, 147–180,  
185, 190, 192, 197, 199, 209, 211,  
245–248, 283–287, 290, 296,  
298–301, 303–306, 310–313

square microlaser 147, 163–165,  
168–174, 177–180, 252, 276

square microresonators 161, 164,  
177, 179

square optical microcavities 147

square resonator patterns 163

square/rhombus microcavity (SRM)  
310

square semiconductor microlasers 163

standard contact photolithography 101,  
207, 311

symmetric modes 49, 94, 96, 98, 115,  
131, 133, 134, 209

**t**

- thermoelectric cooler (TEC) 9, 74, 103, 207, 230, 263, 272, 293, 298
- 3D circular microcavity 223, 225, 244
- 3D FDTD simulation 225, 228–230, 245–247
- 3D FDTD method
  - Cartesian coordinate system 41–43
  - cylindrical coordinate system 43–45
- three-dimensional (3D) microdisk 65
- 3D equilateral-triangular microcavity 245–246
- 3D microcavities 220
  - effective index method 220–222
  - mode coupling and vertical radiation loss 225–230
  - scattering matrix (S-matrix) techniques 222–225
  - semiconductor microcylinder lasers 230–236
  - vertical radiation loss 236–244
- three-layer symmetry waveguide 22
- total internal reflection (TIR) 1, 13, 16, 18, 21–22, 66, 76, 86, 87, 124, 128, 135–137, 148, 149, 155, 185, 241, 242
- transverse electric (TE) mode 14, 66, 92, 123, 148, 186, 232, 284
- transverse magnetic (TM) modes 15, 66, 92, 148, 186, 221
- twin-microdisk resonator 275
- 2D circular microcavity 222
- 2D circular microdisk 66, 92
- 2D FDTD method 38–41, 211
- 2D hexagonal microcavity 198
- 2D microdisk 66, 68, 93, 222
- 2D regular polygonal microcavity 187

**u**

- unfolded plane wave 135, 136
- uni-travelling-carrier photodiode (UTC-PD) 168
- unidirectional emission microdisk lasers
  - deformed-microring 111–113
  - direct modulation characteristics of 103–106
  - lasing characteristics 100–103

**v**

- vertical cavity surface emitting laser (VCSEL) 1, 13, 19, 22–24, 33, 36, 251, 252

**w**

- waveguide-connected spiral microcavity lasers 75
- waveguide coupling 86
  - circular-side square microcavity laser 174–180
  - efficiency 75
  - square microcavities 157–163
- whispering-gallery mode (WG)
  - applications 2–5
  - hexagonal microcavities 197
  - reflectivity of 284–286
  - microdisk lasers 219
  - microlasers 252
  - optical microcavities 185
  - radiofrequency and optical domain 2
  - ultra-high-Q microcavities 5
- wide-angle emission deformed microdisk lasers 113–117

**z**

- zigzag propagation 33



