Index

a
acousto-optic modulators (AOMs) 120, 260, 520
adaptive mode selection 527–528
adiabatic elimination 48
Alice/Bob’s decision variable 443
Alice–Bob samples 435
alpha parameter 203
ammonia (NH₃) ring laser 125
amplified spontaneous emission (ASE) 379, 485
– Er/Yb-doped fiber 486
amplitude death 229
amplitude modulation (AM) 356, 366
– transmission function for 356
amplitude-shift keying (ASK) 366
analog communication 353
analog-to-digital converter (ADC) 12, 452
analytical approach 161–172
angular velocity 118
anticipative synchronization 227, 239
antiphase dynamics 96, 110, 120–122, 244–245
antiphase synchronization 213, 244–245
AOMs. See acousto-optic modulators (AOMs)
APDs. See avalanche photodiodes (APDs)
aplications 5, 12
Ar⁺ pump laser power 117
atomic polarization 41
atom-photon interaction 45, 46
attractor 32, 176, 177
– butterfly 32
– chaotic 32
– for Lorenz model 32
– strange 32
authentication 348–349
autocorrelation function 153–154
auxiliary system approach 313, 314
auxiliary-system approach for generalized synchronization
– experimental analysis on 313
– experimental setup 314–316
– model for 324–327
– numerical analysis on 327–328
avalanche photodiodes (APDs) 393, 395, 474

b
bandwidth enhancement 91, 92
– for random number generation 465
basic sciences 3
basin boundary 555
beam splitter (BS) 544
BER. See bit error rate (BER)
bias 491
biasing laser current 470
bidirectional message transmission 439
bifurcation 36–38, 67, 68
bifurcation diagram 520
– for Logistic map 30
– for Lorenz model 34
– for semiconductor laser 178
biological communication 423, 424
binary voltage signal 420
birefringent plate (BP) 139, 246, 374, 375
bit error rate (BER) 3, 353, 362–365, 397–399, 438
– error-free operation of 394
– test 386
– tester 486
– vs Q factor 364
bivalve shells 349, 350
blind source separation 533, 542–547
bluray disk (BD) 21
binary random bit sequences 447
bounded observability 430–435
box-counting dimension 555, 556
BP. See birefringent plate (BP)
Bragg grating 485
brain 424, 425
bubbling 230
carbon dioxide (CO$_2$) laser 128–132, 220
carrier density 156
carrier-photon interaction 45–46
C codes 581
CCOTDR 539–542
central limit theorem 542
challenge–response protocols 445
chaos 6–8
– and noise from real experimental data 66–67
– control, CO$_2$ laser, electro-optic modulator 519
– in electro-optic systems 98–107
– history of research activities of 4
– Ikeda-type nonlinear delay dynamics 98–101
– in electro-optic systems 98
– in fiber lasers 107–115
– in gas lasers 124–135
– in semiconductor lasers 69–98
– in solid-state lasers 115–124
– synchronization of (See synchronization of chaos)
chaos communication 346–348, 351, 353, 369–425
– advantages for 352
– analog communication 353
– basic idea of 346–348
– chaos-synchronization-based communication 351–352
– coherent 353
– compatibility 352
– hardware keys 348–349
– hardware-based communication 351
– multiplexing and noise tolerance 353–354
– numerical analysis of 373
– performance of
– bit-error rate 362–365
– eye diagram 365–368
– modulation format 365–368
– $Q$ factor 362–365
– signal-to-noise ratio 362–365
– privacy 352
– subcarrier 353
– synchronization for 349–351
– systems 365, 383, 405, 408, 417
chaos in laser
– characteristics of 64–65
– generation techniques 59–60
– class C lasers, satisfying the condition for 63
– external modulation 62
– high-dimensional laser systems 63
– Ikeda-type passive optical systems 63–64
– insertion of nonlinear element 62–63
– multimode lasers 63
– optical coupling and injection 62
– optical feedback 60–62
– intensity dynamics 8
chaos masking (CMS) 354–357, 371, 373, 403–405
– block diagram of 355
chaos mirror 548
chaos modulation 357–360, 402–405
chaos on-off keying 360–362
chaos pass filtering effect 355–356
chaos shift keying (CSK) 354, 360–362, 392, 403–405
chaos synchronization 8–9, 285
– experimental results of 287–290
– experimental setup 285–290
– generalized synchronization 285–289
– identical synchronization 301
– in two semiconductor lasers with optical feedback 293–300
– parameter dependence of 290–293
chaos theory, basic 26
– logistic map 26
– bifurcation diagram 28–30
– chaotic sequence 27–28
– Lyapunov exponent 30–31
– recurrence formula 26–27
– Lorenz model 31
– bifurcation diagram 33
– Lorenz equations 31
– Lyapunov exponent 33–34
– sensitive dependence on initial conditions 32–33
– temporal waveform and attractor 32
– reconstruction of attractor 35–36
– in time-delayed phase space 35–36
– route to chaos 36
– intermittency 37–38
– period-doubling 36–37
– quasiperiodicity 37
chaos-based all-optical communication system 379
chaos-masking cryptographic scheme 382
chaotic carriers 348, 352, 390, 399, 439
chaotic correlation optical time-domain reflectometer (CCOTDR) 539–542
chaotic cryptosystems 408
chaotic dynamics in a solid-state laser
– multimode laser model with spatial hole burning 141–142
– single-mode laser model 140–141
chaotic dynamics in gas laser 142–143
chaotic fluctuations 375
chaotic instabilities 525
chaotic lasers 533
– for engineering applications 3
– for random number generation 452
– for remote sensing 539
– intensity fluctuations of 465
– system 475
– waveform of 516
chaotic lidar (CLIDAR) system 533–537
chaotic light scattering 551–554
chaotic optical waveforms 392
chaotic oscillations 131, 422, 526
chaotic oscillator 529
chaotic pulsing system 384
chaotic radar (CRADAR) system 536–539
chaotic scattering 548
chaotic search 527, 528
chaotic signal, AC component of 462
chaotic source signals, non-Gaussianity of 547
chaotic temporal waveform. See temporal waveforms
chaotic transmission system 379
chaotic waveforms 360, 371, 421, 513
– bandwidths of 536
– time-delayed signal 513
chaotic wavelength division multiplexing 421–423
chaotic wavelength fluctuations 373
chaotic wavelength-division multiplexing (CWDM) 421–422
chaotic-laser-based random number generators 452
chaotic-PIC-based communication system 397
characteristic equation 164, 172, 207
Christmas balls 552
Chua’s circuit 487
cipher 344
ciphertext-only-attack 406–407
class A laser 49–50
class B laser 48–50
class C laser 48, 50
classification of laser models 48–51
CLIDAR 533–537
closed-loop configuration 227–228, 292–293, 312
CMOS semiconductor device 481
code 344
CO2 gas laser, with saturable absorber 142
coherence 6
coherence collapse 71
coherent communication 353
coherent coupling 223
coherently coupled lasers 215–216
CO2 laser 220–223
– controlling chaos 518–520
CO2 ring laser 132
code-division multiple-access (CDMA) 353, 542
coherence, characteristic of laser 6
coherent optical feedback 274
colliding-pulse mode-locked lasers (CPMLL) 415–417
combined Tausworthe method 496
commercial optical-fiber networks 3
commercial physical random number generators 488
– Intel chip (Intel) 488–489
– quantis (ID quantique) 490
– random master (Toshiba) 489–490
– random streamer (FDK) 490
commercial random number generator 488
communicating spatiotemporal information 418
communication applications 446
communication by controlling chaos 529–532
communication security 436
communication system 388, 404 See also
chaos communication
communication technique 420
communication theory of secrecy systems 405
compact disk (CD) 21
compatibility 352
complete synchronization 225
concealment 405
consistency 263–265. See also generalized synchronization
– application of 269–270
– in laser systems 265–268
continuous feedback control 513, 514, 518–521
continuous time delay error signal 520
continuous time-delayed feedback method 513
continuous-wave (CW) 521, 533
controlling chaos 7, 12, 13, 511–532
controlling chaos in lasers
– applications of 525–530
Index

- dynamical memory 528–529
- relative intensity noise (RIN) 525–527
- continuous feedback control method 513–514, 518–521
- occasional proportional feedback (OPF) method 512–513, 515–518
- nonfeedback control method 514–515
- loss modulation 521–523
- semiconductor lasers, high-frequency injection method for 523–525
- stabilization to high-periodic oscillations 525
- OGY method 511–512, 530–532
- conventional cryptologists 406
- correlation optical time-domain reflectometer (COTDR) 539
- coupled electro-optic systems 247
- coupled Lang–Kobayashi equations 293, 296
  - in auxiliary system approach 325
  - for generalized synchronization 325–326
  (See also auxiliary-system approach)
  - for identical synchronization 295–296
- coupling schemes 223
- coupling strength mutual vs. unidirectional coupling 437
- C programming language 581
- CRADAR 536–539
- cross-correlation 230–231, 290–293, 301
- cryptography 10, 343–344, 406, 429, 500

\( e \)
- electrical signals, AC components 471
- electric field 41, 156, 158
  - amplitude 156, 158, 296
  - phase 156, 158, 296
- electron-hole pairs 40–41
- electronic circuit 217, 369–370, 487
- electro-optic Mach–Zehnder interferometer 384, 402
- electro-optic modulator (EOM) 521
- electro-optic phase chaos 401
- electro-optic system 14, 64, 69, 98–107, 139, 384–386
  - chaos in 98
  - intensity chaos in 103–105
  - numerical model for chaotic dynamics in 140
  - phase chaos in 105–107
  - synchronization of chaos in 245
  - wavelength chaos in 101–103
- electroencephalogram (EEG) data 542
  - embedding 35
  - encoded waveforms 406
- encoding/decoding method 354–362, 403–405
  - encoding/decoding techniques
    - chaos masking 354–357
    - chaos modulation 357–360
    - chaos shift keying 360–362

\( d \)
- data acquisition 432
- data encryption 398
- data recovery 398
- decoding performance, security allocation 400
- delayed optical bistable system 518
- deterministic chaos 6–7, 19, 24–26
- deterministic random number generators 446
- DFB lasers 394, 414, 471
- Dichtl method 504
  - postprocessing method 504, 505
- Diehard 457, 503
- Diehard statistical tests 457
- Diehard suite 467
- Diehard tests 456, 462, 503
- differential phase shift keying (DPSK) modulation 400–403
- differential phase shift QKD (DPS–QKD) experiments 472
- diffusive coupling 218
- digital communication systems 367, 368
- digital versatile disk (DVD) 21
- digital-to-analog converter (DAC) 469
- dimensionless equations 184–188
- dimensionless Lang-Kobayashi equations 184–187
- dispersion compensation fibers (DCFs) 11, 396
- dispersion-shifted fibers (DSF) 352, 474
- distillation process 449
- distributed Bragg reflector (DBR) 373
- distributed feedback (DFB) lasers 377, 452, 471
- dominant-mode ratio (DMR) 527
- Doppler effect 118, 525
- double-heterostructure 40–41
- double-schroll attractor 488
- doublescroll chaotic system 531
- DPS–QKD scheme 472
- DPSK light 402
- DPSK modulation 402
- drug delivery 270
- dual synchronization 421
- dynamical control of chaotic green laser 21
- dynamical information hiding technique 424
- dynamical memory 528–530
Index

– recipe for 503–504
highly reflective coated (HRC) 411, 412, 469
Hilbert transform 282–283
history of laser and chaos 3–4
homoclinic cycle 129
Hopf bifurcation 91
Hurst exponent 409
hyperchaos 191
hysteresis 95, 111,116–117, 130–131

i
ICA 542–547
identical synchronization 214, 224–225, 233, 239, 295
– rate equations in closed-loop configuration 337–339
– linear stability analysis of 308
– conditional Lyapunov exponent 309–310
– linearized equations 308–309
– open- vs. closed-loop configurations 312–313
Ikeda chaos 63–64
Ikeda model 99
imaginary electric field 160
incoherent communication 353
incoherent coupling 223
independence 448
independent component analysis (ICA) 542–547
– algorithms for 544
– blind source separation 542
– optical chaotic signals 544
– separation ability of 545
information-theoretic security 16, 427–431
– bidirectional message transmission 439–440
– bounded observability 430–431
– chaotic lasers, implementation of 431–435
– computational security 428
– concept of 429
– history of 429–430
– ultralong fiber laser system 441–444
– Maurer’s satellite scenario 429–430
– public channel cryptography 435–439
– scheme for 430
– secure key distribution 427–428
– theoretical framework of 429
– Venn diagram for 431
information theory 428–431
InGaAs photodetector 537
InGaAsP/InP single-mode DFB semiconductor lasers 383
injection locking 88, 89, 130, 215, 216, 223, 227, 232, 288–293
in situ chaotic optical communication system 393
integrated tandem device (ITD) 413–415
intelligent transport systems (ITS) 543
intensity chaos 103–105
intensity fluctuation 23
intermittency route to chaos 37–38
intrinsic entropy 478
irregular pulsations of laser output 8

j
Jacobian matrix 51, 56, 162–164, 170–172, 180, 181, 229, 272, 273

k
Kaplan–Yorke (KY) dimension 190, 192–194
key agreement 429
key distribution scheme 435, 436
keyless cryptography 429
kink 71, 81–82, 148
Kolmogorov–Sinai (KS) entropy 190, 192–194, 413
Kolmogorov–Smirnov (KS) test 457, 503
KY dimension 190, 192–194

l
Lang–Kobayashi equations 14, 15, 135, 156–161, 166, 185, 194, 293, 338, 475, 524
– bifurcation diagrams 197
– dimensionless 185–188
– with gain saturation 194–199
– histogram 195, 196
– linearized 163, 170
– numerical results 195
– temporal waveforms 196
– synchronization of chaos
–– open loop 293
–– closed loop 338
Langvin equation 24
laser amplification 130
laser biasing current 412
laser cavity 38
laser current 22
laser demonstrates Lorenz chaos 522
laser diode (LD) 116, 529
laser dynamics 6
laser emission, polarization of 381
laser instabilities 19–23
– in ruby laser 19
laser intensity 525
– stroboscopic recording of 522, 523
– tools for measurement of instability 66
traces of 517
laser medium 38
laser models 48–51
– class A lasers 49–51
– class B lasers 48–49
– class C lasers 48
– comparison with 68–69
laser output
– instabilities of 20
– temporal waveforms of 455
laser propagates 415
laser pump power 519
lasers 6–8
– fiber 109–115
– gas 124–135
– semiconductor 69–98
– solid-state 115–124
laser system, block diagram of 515
laser theory, basic
– light–matter interaction for laser radiation 38
– chaotic instability in lasers, mechanism of 45–46
– elements of laser 38–39
– mechanism of laser oscillation 39–40
– radiative recombination of electron–hole pairs 40–41
– rate equations for laser dynamics 41–44
– relaxation oscillation frequency 44–45
– two-atomic-level description 39–40
laser, history of research activities of 4
laser-chaos-based physical random number generators 453, 502
laser-diode-pumped Nd:YAG laser 124
lasers powers 440
laundering 425
leader-laggard relationship 240, 245
least significant bits (LSBs) 461, 463
legitimate user 407
LFFs. See low-frequency fluctuations
L-I characteristics 70–71, 80, 95, 147
L-I curve 147–149
light detection and ranging (LIDAR) 533
light-emitting diodes (LEDs) 552
light-matter interaction 38–39
linear congruential method 493
linear derivation 163
linear stability analysis 14, 15, 51
– conditional Lyapunov exponent 229–230
– for oscillatory trajectory 179–181, 188–190, 196–199
– for steady state solutions with optical feedback 169–172
– for steady-state solutions without optical feedback 162–166
– eigenvalues of Jacobian matrix 162–165
– relaxation oscillation frequency 165–166
– for generalized synchronization 331–335
– for identical synchronization 308–312
– oscillatory trajectory 179–184, 196–199, 308, 331
– steady state solutions 162–173
linearized equations
– for calculation of maximum Lyapunov exponent 53
– for coupled differential equations 271–273
– derivation, in Lorenz model 51–53
– general formula 51, 52
– generalized synchronization 331
– identical synchronization 308
– Jacobian matrix 51
– Lang-Kobayashi equations 163, 170, 197
– Lorenz model 52–53
– Rössler model 55
linearized variables 163, 170, 180
linewidth enhancement factor 157, 203
lithium neodymium tetraphosphate 120
LNP laser array 252
Logistic map 26–30
Lorenz chaos 31
Lorenz equations 31
Lorenz–Haken chaos 34, 124–128
Lorenz-Haken equations 25
Lorenz model 31–36
loss modulation 521, 525–526
low-frequency fluctuations (LFFs) 75–77, 149–151, 155, 241, 413, 437
– mechanism of 137–139
Lyapunov exponent
– general formula 53–54
– Lang-Kobayashi equations 183–185, 190, 191, 193, 195
– Logistic map 30–31
– Lorenz model 33–34
– without time delay, general formula for 53–54
Lyapunov spectrum 185, 190–192

m
Mach–Zehnder interferometer 472, 474
Mach–Zehnder lithium niobate (LiNbO3) modulator 379
Mach–Zehnder modulators 245, 246
Mach–Zehnder transmission curve 384
map 26
Maurer’s satellite scenario 429
maximum Lyapunov exponent 7, 181–185, 189, 197–198
Maxwell-Bloch equations 46
memory time 478, 479
Mersenne Twister 505
Mersenne twister 496, 505
message decoding 372
message decoding, schematic diagrams of 404
message, encoding of 372
time series of 404
message signal, encoding of 372
message, recovery of 389
metastability 481
methyl iodide 128
Michelson interferometer 533, 536
microscopic intrinsic noise 477
microscopic noise 475
model
generalized synchronization 324
semiconductor laser with optical feedback 156
synchronization of chaos 293
modular neural network 408
monobit generation method 452, 460
monolithic photonic integrated circuits 410
M sequence 494
multibit generation 461
Multidisciplinary University Research Initiative (MURI) 375
multi-Gbits/s intensity chaos encoder 385
multimode laser model, with spatial hole
burning 141–142, 280
multimode solid-state lasers 120
antiphase dynamics 120–122
multiple-input multiple-output (MIMO) 542
multiplexing 353–354
communication 421–423
mutual chaos pass filtering (MCPF) 436
mutual coupling 223, 228, 229, 435–439

n
N-mode laser 142
Nd-doped fiber laser 110
Nd:YAG laser 20–21, 220, 221, 370, 371, 515–517
NdP2O5 solid-state laser 118
neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal 123
neodymium-doped yttrium orthovanadate (Nd:YVO4) microchip solid-state lasers 116, 543–544
neutral density filter (NDF) 241, 463
NH3 laser 520, 521
NIST Federal Information Processing Standards Publication (FIPS) tests 483
NIST special publication 800–22 456, 497, 506
NIST SP 800–22 statistical test 456–459, 497–500
approximate entropy test 508
binary matrix rank test 507
cumulative sums (Cusums) test 506–507
Discrete Fourier Transform (Spectral) test 507
frequency (monobit) test 506
frequency test within block 506
linear complexity test 508–509
longest-run-of-ones in block 507
maurer universal statistical test 508
nonoverlapping template matching test 507
overlapping template matching test 507–508
random excursions test 508
random excursions variant test 508
runs test 507
serial test 508
noise 8, 23, 24, 66, 67
noise communication 346
nondeterministic bit 475
nondeterministic random number generators (NRNG) 446
nonfeedback control 514–515, 521–525
non-Gaussianity 547
nonlinear equations 8
nonperiodic-templates test 502
nonreturn-to-zero (NRZ) 365, 366, 455
– formats 365
– eye patterns for 367
– pseudorandom message 379
– waveform 390
novel chaos-generation process 402
numerical analysis
– dimensionless equations 184–187
– numerical results of chaotic dynamics of semiconductor laser with optical feedback 172
– linear stability analysis for oscillatory trajectory 179–181
– maximum Lyapunov exponent 181–184
– numerical results of chaotic dynamics 172–179
– on generalized synchronization of chaos in auxiliary system approach 327, 373
numerical model, for a chaotic semiconductor laser
– coherent optical feedback 135
– low-frequency fluctuations 137
– optoelectronic feedback 136–137
Index

performance evaluation of chaos communication 390–405
period-doubling route to chaos 36–37, 71, 72, 74, 75
phase chaos 105–107, 400–403
– oscillations 255
phase modulation (PM) 366
phase noise 486
phase shift keying 366
phase synchronization 255
phase-shift keying (PSK) 366
photodetector (PD) 374, 469
photon detectors 472
photonic crystals 547
photonic emission, quantum mechanics of 485
photonic integrated circuit (PIC) 377, 394, 411, 469
– for chaos communication 394–400, 410–417
– different types of 377
– for random number generation 469
photonic integrated device 411
photon lifetime 44, 45
photoreceiver 392
physical random number generators 449, 480–488
– chaotic dynamics, in electronic circuits 487
– optical noise 485–486
– quantum noise 484–485
– radiation, from radioactive nuclide 486–487
– thermal noise
– direct amplification of 480–481
– metastability 481–482
– two oscillators with frequency jitter 482–483
– traditional physical devices 487–488
– with chaotic lasers 452–471
PICASSO project 377
PICs designed 470
p-n junction 40–41
Poincaré sections 36, 112
Poisson’s distribution law 487
polarization encoding 419–421
polarization-rotated optical feedback 275–276
polarization 22
polarization controller (PC) 419, 540
polarization-maintaining fibers 452
polarizing beam splitter 534
polyhedral mirror–ball structures 554
population inversion 39, 41
population lifetime 44–45
positive Lyapunov exponent 182, 192
postprocessing 463, 490
potassium titanyl phosphate (KTP) crystal 123
privacy 352, 405–410
– amplification 435
private key 427
PRNG. See pseudorandom number generator (PRNG)
probability density function (PDF) 476, 542, 546–547
probability theory 428
proportion of p-values 501
pseudorandom bit sequence (PRBS) 385
pseudorandom number generator (PRNG) 446, 450, 451, 493
– combined Tausworthe method 496
– linear congruential method 493–494
– M sequence and generalized feedback shift register (GFSR) 494–496
– Mersenne Twister (MT) 496–497
pseudorandom number (PN) 533
public channel cryptography 435–439
pump energy 38–39
pump modulation 117, 525
p-value 499
Pyragas method 218–219

q
Q factor 362–368
Q-switching pulses 8, 128, 253
Quantis 490
quantum bit error rate (QBER) 472, 474
quantum cryptography 445
quantum key distribution (QKD) 427, 428, 472
quantum noise 484
quantum physical random number 484
quantum random number generator 484
quantum RNGs (QRNGs) 484
quasiperiodicity 37
quasiperiodicity route to chaos 37, 74, 75, 81, 82, 84–87, 153, 156, 176

r
radiative recombination 40
radio-frequency (RF) 459, 520, 535
radioactive nuclide 486
random bit generation 463, 465
random bit pattern 448, 455
random bit sequences 448, 454, 460, 467–469
random bit signal, eye diagram of 455
random bit stream, generation of 463
Random Master 489
random molecular distribution 488
random number 447
random number generation 11–13, 445–509
random number generators (RNGs) 11–13, 445–509
– chaotic lasers, bandwidth enhancement of 465–469
– chaotic lasers 447, 451–452
– Chua’s circuit 487
– computing/communication applications 446
– conventional random number generators 451–452
– Dichtl method, for postprocessing 504–505
– NIST special publication 800–22 test suite 497–502
– p-values 501–502
– generation speed, postprocessing for 463–464
– Mersenne Twister 505–506
– monobit generation, with one lasers 460
– monobit generation, with two lasers 452–460
– NIST special publication 800–22 506–508
– entropy rate 478–480
– p-values 499–501
– photonic integrated circuit (PIC) 469–472
– postprocessing 450
– postprocessing techniques for randomness improvement 490
– exclusive-OR (XOR) method 492–493
– von Neumann method 491–492
– randomness, statistical tests of 503
– strategies for statistical analysis 497–499
– independence 448–449
– physical random number generators 449–450
– pseudorandom number generator 451
– unpredictability 449
– with chaotic lasers, examples 452
random signal radars (RSRs) 536
Random Streamer 490
random bit generation 471
rate equations 41–44, 139, 140, 142, 144, 145
rays 550
real and imaginary electric fields 160, 299
real electric field 160
reconstruction of attractor 35–36
recurrence formula 26
Reed–Solomon (RS) code 397
regular-polyhedral mirror–ball structures 550–556
regular pulse package 78–79
relative intensity noise (RIN) 523, 525–527
relaxation oscillation frequency 44, 45, 55–57, 62, 119, 122, 165, 166, 207, 215
remote sensing
– chaotic lidar 533–536
– chaotic radar 536–539
retarded synchronization 227, 239
return-to-zero (RZ) formats 365, 366
RF amplifiers 535
RF spectrum analyzer 540
RIN 525–527
RNGs. See random number generators (RNGs)
root-mean-square (RMS) values 443
Rössler model 54–55
route to chaos
– intermittency 37–38
– period-doubling 36–37
– quasiperiodicity 37, 112–114
rotational relaxation rate 143
ruby laser 19–20
Runge–Kutta method 173, 187, 208–210
RZ 365–366
s
saddle-node bifurcation (SN) 91
scientific fiction 424–425
secret communication scheme 435
secret communication, history of 343
– cryptography 343–344
– noise communication 346
– steganography 344–346
secret key agreement, satellite scenario for 429
secret key distribution 440, 441
secure communication 343
secure key distribution 427–444
secure key generation 5, 8, 433–434
security 9, 344, 399, 406–410, 427–431
self-mixing laser Doppler velocimetry scheme 120, 121
self-similar dimension 555–556
semiconductor laser with optical feedback, analytical approach of 161
– linear stability analysis for steady-state solutions
– with optical feedback 169–173
– without optical feedback 162–166
– steady-state solutions
– with optical feedback 166–169
– without optical feedback 161–162
semiconductor laser with optical feedback, model for 156
– Lang–Kobayashi equations 156–158
– derivation of the electric-field amplitude and phase 158–159
Index

— — derivation of the real and imaginary electric fields of 160–161
— — parameter values used for numerical simulation 157

semiconductor lasers 7, 21, 463
— analysis of chaotic laser dynamics 145–210
— analysis of synchronization of chaos 285–313
— bandwidth of 447
— chaos, use of 446
— controlling chaos 523–527
— derivation of rate equations 199–206
— dynamical behavior of 77, 78
— experimental analysis of 145–156
— for optical disks 21
— injection current of 524
— intensity fluctuation of laser output 22
— interferometer 516–519
— numerical model for chaotic dynamics in 135
— radiative recombination of electron–hole pairs in 40–41
— random number generation 452
— secure key distribution 474
— short-cavity regime 78–79
— with injection current modulation 93
— — under the limits of weak and short feedback 206–208
— with optical injection and coupling 88–92
— with optical self-feedback 7
— with optoelectronic feedback 83–87, 383–384
— with polarization-rotated optical feedback 79–83

semiconductor optical amplifier (SOA) 395, 471

short cavity regime 78
sifted key generation rate 474
signal-to-noise ratio (SNR) 22, 353, 364, 383, 404
signal/reference waveforms 535, 538

single-mode DFB InGaAsP–InP semiconductor lasers 537
single-mode distributed-feedback (DFB) 535
single-mode fiber (SMF) 395
single-mode laser model
based on Maxwell–Bloch equations 46–47
sensitive dependence on initial conditions 6, 27–28, 32–33
short cavity regime 78–79
single-mode ring laser equations 47
signal-to-noise ratio (SNR) 362–365

slowly varying envelope 201, 204, 206
slowly varying envelope approximation 47, 201
software-based cryptography 406
solid-state lasers 19
— for second-harmonic generation, green problem in 20–21
— with external modulation 116
— with short cavity length 116
spatiotemporal chaos 417–418
spatiotemporal chaos communications 417
spatiotemporal encoding 417–418
special trading authentication system 349
spontaneous emission 39
spontaneous emission noise 485
static keys 348
statistical evaluation of random numbers 497
steady state solutions 161–162
steganography 10, 344–346, 406
stimulated emission 39
subcarrier communication 353
subcarrier frequency 390
subcarrier modulation 390–394
substitution 343–344
symmetry breaking 240–243
synchronizability 350
synchronization 5, 8, 9, 211, 212
synchronization of chaos 5, 8–9, 211, 213–214, 347, 348, 351, 352
— identical synchronization 214
— cross-correlation values 213
— defined 212
— for communication applications 216–217
— electro-optic systems 245–248
— fiber lasers 248–250
— gas lasers 253–254
— solid-state lasers 250–253
— in electronic circuits 217
— Pecora–Carroll method 217–218, 270–271
— Pyragas method 218–219
— in feedback systems 225–230
— vertical-cavity surface-emitting lasers 243–245
— with coherent optical feedback 231–236, 285–313
— with mutual coupling 240–243
— with optical injection 239–240
— with optoelectronic feedback 237–239
— with polarization-rotated optical feedback 236–237
— numerical model for
Index

--- in unidirectionally coupled electro-optic system 277
--- in unidirectionally coupled fiber lasers 278–279
--- in unidirectionally coupled gas lasers 281–282
--- in unidirectionally coupled semiconductor lasers 274–277
--- in unidirectionally coupled solid-state lasers 279–281
--- of periodic oscillations 213
--- parameter dependence 305
--- generalized synchronization 258–263
--- phase synchronization 254–258
--- stability of the synchronous solutions 214–215
synchronous solution
--- for identical synchronization 295
--- for generalized synchronization 327

\( t \)
Tang–Statz–deMars equations 116, 141, 142, 280
temporal waveforms
--- and attractor 32
--- and correlation plots 303
--- and radio-frequency (RF) spectra of laser output intensity 149, 151, 315
--- chaotic 123, 228, 251, 254, 265
--- investigation of delay time of 232
--- irregular 21
--- length of 546
--- numerical results of 174, 303, 330
--- of binary codes 528
--- of laser intensity without gain saturation 195
--- of Nd:YVO₄ solid-state microchip laser output with pump modulation 117
--- of noise 8
--- of the two mixed chaotic signals 545
--- of VCSEL 245
--- relaxation oscillation of laser intensity 44
--- restabilization of 82
--- unstable 9
tetrahedron 547–556
thermal noise 480–483
time-delay embedding 35, 126
time-delayed feedback systems 357
time-dependent standard deviation 477
time-interval analyzer (TIA) 474
time series analysis 406, 408, 409
time-varying 349, 350
traditional physical device 487, 488
transistor 481
transmission function 356
transmitted signal 371
transmitter
--- chaotic signals of 359
--- laser output power 372
--- RF spectra of 355
--- unperturbed signal 373
transmitter–receiver synchronization 424
transverse Lyapunov exponent. 229, 230 See also conditional Lyapunov exponent
transverse-magnetic(TM) polarization
modes 419
TV camera 382
TV signal 381
TV synchronism 383
TV video signal 381–383
two-atomic-level description 39, 40
two dimensional map 292
two types of synchronization 305

\( u \)
ultralong fiber laser (UFL) system 441–444
ultrashable laser 13
unauthorized user 399, 400
unidirectional coupling 223
uniformity of p-values 501
unpredictability 192, 449, 475
unstable periodic orbits (UPOs) 511–513

\( v \)
variable optical attenuator (VOA) 392, 412
variational equations 163
vertical-cavity surface-emitting lasers (VCSELs) 93–98, 139, 243
--- numerical model for chaotic dynamics in 139
--- optical feedback 96, 97
--- optical injection 97, 98
--- polarization-resolved temporal dynamics of 97
video signals 381
von Neumann method 491
von Neumann postprocessing method 491, 492

\( w \)
Wada basin property 547
wave length division multiplexing (WDM) 400
waveforms 535. See also temporal waveforms
wavelength chaos 102, 103
wavelength division multiplexing (WDM) 421–423
Index

wavelength filters (WFs)  421
wavelength-tunable distributed-Bragg-reflector (DBR) semiconductor laser  246
wireless optical communication  548
wire-tap channel  429

X
XOR device  452, 459, 492

Z
zero-lag synchronization  242, 243