

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)
- applications 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

C

carbon dioxide (CO₂) 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, CO₂ 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
- conditional Lyapunov exponent 229–230, 273, 309–311, 333–336
- 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

- 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
- 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 phaseshift 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
- 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

- encryption 405
 - engineering applications 3
 - with chaotic lasers 13
 - entropy generation, macroscopic effect 477
 - entropy rate 475
 - entropy source 475
 - erbium-doped fiber amplifiers (EDFAs) 11, 248, 352, 379, 414, 420, 441
 - erbium-doped fiber laser 109–110, 373–375, 386–390
 - ion-pair concentration of fiber 112
 - laser intensity 110
 - nonlinear dynamic behavior 110
 - erbium-doped fiber-ring laser (EDFRL) 216, 373, 388, 419
 - erbium-doped optical fiber amplifier (EDFA) 540
 - Euler's method 208–210
 - exclusive OR (XOR) postprocessing
 - method 452, 492
 - experimental analysis
 - generalized synchronization 314
 - semiconductor laser with optical feedback 145–156
 - synchronization of chaos 285–293
 - external cavity frequency 60, 153
 - external cavity modes 168–169
 - eye diagram 367
- f**
- Fabry-Perot cavity 38, 199
 - Fabry-Perot laser diode 527
 - Fabry-Perot semiconductor lasers 241
 - fast Fourier transform (FFT) 175, 176
 - fast temporal dynamics 114
 - FastICA algorithm 545
 - feedback
 - control 511–521
 - optical 69–79
 - optoelectronic 83–87
 - polarization-rotated optical 79–83
 - system 225–227
 - feedback-induced instability 22
 - in a semiconductor laser 21–23
 - fiber lasers 109, 112, 386–390
 - numerical model for chaotic dynamics 140
 - fiber-optic communication channel 388
 - field experiment on chaos
 - communication 377–381, 401–403
 - field programmable gate array (FPGA) 474
 - fluctuating signal 362
 - forward error-collection (FEC) methods 397
 - fourth-order Runge-Kutta method 209
 - fractal optical devices 547, 550
 - fractal optics 547
 - regular-polyhedral mirror-ball structures, fractal patterns in 550–556
 - wireless optical communications, chaos mirror for 548–550
 - fractal pattern 550
 - frequency jitter 482
 - frequency modulation (FM) 366
 - frequency shift keying (FSK) 366
 - frequency-shifted feedback-light
 - injection 117
 - fringe contrast function 536
 - full-width half-maximum (FWHM) 536, 538
- g**
- gain-absorption section (GAS) 411, 469
 - gain saturation 194–199
 - effect 475
 - gas laser 142
 - with saturable absorber 128
 - Gaussian distribution 480, 542
 - Gaussian noise 363
 - Gaussian statistics 363
 - generalized feedback shift register (GFSR)
 - method 494, 495
 - generalized synchronization 225, 227, 258
 - auxiliary system approach 259, 313–314
 - dependence of synchronization quality on 336–337
 - dependence on optical phase of feedback light 322–324
 - with high correlation 225
 - numerical analysis 327–328
 - linear stability analysis 331–334
 - with low correlation 258
 - parameter dependence 329–331
 - numerical simulation for 302
 - two-dimensional (2D) maps 334–335
 - in auxiliary-system approach 313–324
 - generation of chaos 7
 - GFSR 494
 - GHz-clocked DPS-QKD experiment 472
 - Ginzburg-Landau equation 408
 - Gram-Schmidt orthogonalization 210
 - green problem 20, 21, 122, 123
- h**
- hardware 9, 351
 - hardware key 348–350, 407
 - He-Xe laser 127
 - HFI method 523–527
 - high-frequency injection (HFI) technique 22, 523–527
 - high-quality random number generators

- 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
- Langevin 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’s chaotic output waveform 540
 - 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
 - schematic diagrams of 404
 - 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
- NdP₅O₁₄ 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

- polarization-rotated optical feedback 135–136
- semiconductor laser with optical feedback 172–184
- synchronization of chaos 300, 303

O

- occasional proportional feedback (OPF)
 - method 512–513, 515–518
- OCCULT project 375–377
- OGY algorithm 530
- OGY method 511, 512, 530–532, 551
- on-off phase shift keying 361
- open-loop configuration 399
- one-pair device 351
- open-loop configuration 225–227, 292–293, 312
- optical-carrier frequency 62, 215
- optical chaos communication 4, 9–11, 369–425 *See also* chaos communication
 - electro-optic systems 384–386
 - encoding and decoding schemes 403–405, 417
 - multiplexing communications 421–423
 - polarization encoding 419–421
 - spatiotemporal encoding 417–418
 - European project for 375–377
 - experimental system for 387
 - fiber lasers 386–390
 - history of 369
 - in electronic circuits 369–370
 - in optical systems 370–375
 - integrated photonic circuit 410–417
 - analogy to biological communication systems 423–424
 - world of scientific fiction 424–425
 - optical phase chaos 400–403
 - bit-error-rate (BER) performance 397–399
 - chaos communication experiment 396–397
- forward error-collection (FEC)
 - methods 397
- photonic integrated circuits (PIC) 394–396
- subcarrier modulation 390–394
- unauthorized users, analysis for 399–400
- practical implementation of 369
- privacy issues 405–410
- private communications 370
- research activities of 376
- schematic setup for 380
- semiconductor lasers, with optical feedback 377–383
- semiconductor lasers, with optoelectronic feedback 383–384

- state-of-the-art performance of 391
- Optical Chaotic Communications Using Laser Transmitters (OCCULT) project 375
- optical chaotic systems 372
- optical circulator (OC1) 539
- optical communication 3, 9–11, 23, 369–425
 - with chaotic semiconductor lasers 21, 375
 - with synchronized chaotic lasers 9–11
- optical data storage systems 21
- optical disk 21–23
- optical feedback into semiconductor laser 21
- optical feedback phase 407
- optical fiber laser, antiphase response of 111
- optical frequency detuning 302–303
- optical injection 91
 - bandwidth enhancement of chaos 91–92
- optical intensity in laser cavity 7
- optical isolators 465, 540
- optical network 379
- optical noise
 - for random number generation 485
 - for secure key distribution 441
- optical phase of feedback light 322, 336
- optical ray 547
- optical signals 396
- optical spectra 288
- optical systems 417
- optical timedomain reflectometer (OTDR) 539
- optical wavelength detuning 288–293, 465
- optical-confinement devices
 - Q-value of 555
- optical-feedback-induced chaos
 - in semiconductor lasers 355
- optical-fiber communications 465
- optical-fiber components 454
- optoelectronic feedback loop 383
- orthogonal polarizations 111
- oscillation frequency 8

P

- parameter dependence
 - generalized synchronization 320, 329
 - synchronization of chaos 305
- parameter estimation 406, 408
- parameter mismatch 225, 228, 388
- passive Q-switching 128
 - of CO₂ lasers 253
 - pulse 129
- pattern generator 525
- PDF 542, 546–547
- Pecora-Carroll method 217, 218, 270, 271
 - for synchronization 270

- 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

- 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 431–440
 - short-cavity regime 78–79
 - with injection current modulation 93
 - with optical feedback 69–77, 206–208, 372, 377–383
- 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 envelop 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
 - in semiconductor lasers 230–245, 285–313, 435–440
 - 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

- 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
- transposition 343
- transverse Lyapunov exponent. 229, 230 *See also* conditional Lyapunov exponent
- transverse-magnetic(TM) polarization modes 419
- TV camera 382
- TV signal 381
- TV synchronization 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
- ultrastable 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

- 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