Chaos in lasers

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Chaos in lasers is related to deterministic chaos in single mode lasers. The onset of deterministic chaos in a dynamical system requires at least a 3-dimensional phase space. We recall that a 3D dynamical system is characterized by 3 coupled first order differential equations as

$$\dot{\vec{x}} = \vec{f}(\vec{x}), \text{ with } \vec{x} = (x_1, x_2, x_3).$$

If the system is dissipative, it has attractors, and the sum of the Lyapunov exponents λ_i of an attractor is negative. This can be satisfied by the following sets of λ_i signs: (-,-,-); (-,-,0); (-,0,0); (-,0,+). The first set has contraction in all 3 directions, thus yielding a stable equilibrium point attractor. The second set yields a stable limit cycle. The third one corresponds to a torus (quasiperiodic motion with 2 incommensurate basic frequencies). Eventually the fourth one (with the obvious constraint that the positive exponent be smaller than the absolute value of the negative one, in order to satisfy the dissipativity condition) is a "strange" attractor. A positive Liapunov exponent means that an arbitrarily small initial difference between two points on the attractor grows exponentially to a sizable value. This sensitive dependence on the initial conditions has been called "deterministic chaos". We show how the above minimal conditions for chaos can be satisfied by a single mode laser.

Contents

Deterministic chaos in a single mode laser

The semiclassical laser dynamics emerges from coupling the Maxwell equations for a classical optical field in a cavity with N atoms. We consider each atom as a two-level quantum system, described by a density matrix, and coupled near resonance to the optical field via an electric dipole moment $d = \mu(\rho_{12} + \rho_{21})$; here μ is the matrix element of the dipole operator between upper and lower atomic states (for an allowed transition μ is of the order of the electronic charge times the Bohr radius,that is, $\mu \approx 10^{-29}$ Cm) and ρ_{12}, ρ_{21} are the off diagonal components of the atomic density matrix ρ .

For the time being, we introduce some simplifying assumptions, namely:

- the field is in a single mode with uniform amplitude, that is, its amplitude is given by

$$e(r,t) = E(t)e^{i\omega t}f(r)$$

where $f(r)$ is the stationary configuration of the cavity mode. In the case of one dimensional cavities, limited along the z axis by two mirrors separated by L and unbounded in the transverse directions x ,y , $f(r) = \frac{k}{2} \sin kz; k = n\pi/L$, where n is an integer which specifies the cavity mode. The frequency ω is related to the nearest cavity resonance $\omega_n = n\pi c/L$, c being the light speed in the cavity, by the mistuning relation

$$\vartheta = \omega - \omega_n$$

- the cavity mode has a loss rate κ due the mirror reflectivity R and to diffraction on the open transverse boundary; if diffraction is negligible, then κ is just due to the mirror losses and is given by

$$\kappa = \frac{c}{L} \frac{1}{1-R}$$

- the wave equation yields a trivial dispersion relation between the optical frequency and the wave-number; in the so called SVEA (slowly varying envelope approximation), the envelope E of the field is coupled to the resonant Fourier component P of the atomic polarization via the first order equation

$$\dot{E} = -(\kappa + i\vartheta)E + gP \quad (1)$$

where the coupling constant g is related to the matrix elements μ and the cavity volume V (taken filled with atoms) by the relation

$$g^2 = \frac{\omega\mu^2}{h\epsilon_0 V}$$

(just to give the order of magnitude, at optical frequencies and for $V = 1cm^3$, with the above given value of μ,it is $g^2 \approx 10^8 s^2$);

- the atoms are uniformly distributed in the cavity and its collective dynamics is represented by the polarization, which is the sum of the dipole moments per unit volume $P = \frac{N}{V} d$.

If we call $\Delta = N(\rho_{12} + \rho_{21})$ the population inversion that some ‘’pumping’’ mechanism induces on the atomic medium; then the atomic Bloch equations for P and Δ are respectively

$$\dot{P} = -(\gamma_\perp + i\delta)P + gE\Delta \quad (2)$$

and

$$\dot{\Delta} = -\gamma_{II}(\Delta - \Delta_0) - 2g(E^*P + EP^*) \quad (3)$$

In these equations, $\gamma_\perp$ is the dissipation rate for the polarization, $\delta = \omega - \omega_{at}$ is the detuning between the field frequency ω and the center ω_{at} of the atomic line(for simplicity ,we consider a homogeneous atomic line where ω_{at} is the same for all the N atoms), γ_{II} is the dissipation rate for Δ, and Δ_0 is the equilibrium inversion imposed by the pump in the absence of field. The above equations, together with the complex conjugate ones, make a closed set of 5 coupled equations called ‘’the Maxwell-Bloch equations’’ (MB). We restrict for simplicity to the resonant case in the absence of mistuning and detuning; in such a case, field and polarization are real and the equations reduce to 3 real ones, namely

$$\begin{aligned}\dot{E} &= -\kappa E + gP \\ \dot{P} &= -\gamma_\perp P + gE\Delta \\ \dot{\Delta} &= -\gamma_{II}(\Delta - \Delta_0) - 4gEP\end{aligned} \tag{4}$$

These real MB equations for a resonant single-mode laser have been around since 1963. They are isomorphic to the dynamical equations of the 1963 Lorenz chaotic model. This fact was recognized by H.Haken in 1975 (Haken, 1975). Already in 1963 two young laser physicists, A.Z. Grasyuk and A N.Oraevski, had given numerical solutions of MB showing that irregular behavior was well above the errors due to limited digits of the numerical simulation (Grasyuk&Oraevsky, 1963). However the optical community was not yet able to draw a bridge with Lorenz-like phenomena ,as evidenced by a positive Liapunov exponent. One may ask why chaos is not ubiquitous in single mode lasers. In fact, time-scale considerations rule out the full MB dynamics for most available lasers. Lorenz 3D system is made of 3 dynamical variables with damping rates close to each other. On the contrary in MB the 3 damping rates $\kappa, \gamma_\perp, \gamma_{II}$ can be wildly different from each other. If one rate constant is much higher than the others, after a transient the corresponding dynamical equation can be solved at quasi-equilibrium (adiabatic elimination procedure). and then we are left with $n < 3$ equations, thus ruling out chaos. The following classification has been introduced A.110 (http://www.inoa.it/home/arecchi/Papers.php)

Class A (e.g. He-Ne, Ar, Kr, dye lasers): $\gamma_\perp \approx \gamma_{II} >> \kappa$. The atomic variables are much faster than the cavity field. The last two MB are solved at equilibrium and a single nonlinear field equation describes the laser.1D means fixed point attractor, hence coherent emission.

Class B (e.g. ruby, Nd,CO2, most diode lasers): $\gamma_\perp >> \kappa \geq \gamma_{II}$.

Polarization is fast, the middle MB is eliminated and two rate equations for field and population are left. 2D means stable fixed point, but also periodic oscillation for suitable parameter setting.

Class C (far IR lasers with slow molecular damping) : $\gamma_\perp \approx \gamma_{II} \approx \kappa$.

The full MB set has to be used, hence Lorenz chaos is generic.

The first evidence of deterministic chaos in a single mode laser was given for Class B, CO2 lasers. Experimental verification was given by the chaotic fluctuations of the laser power output, proportional to $E(t)^* E(t)$. The topological explanation for the creation and destruction of chaotic attractors in class B lasers with modulation was given in [Schwartz,(1988)]. In order to increase dimension D from 2 to 3 and make it possible a positive Liapunov exponent, the following configurations have been proposed and tested: i) Introduction of a time dependent parameter to make the 2D system non autonomousA.90 (http://www.inoa.it/home/arecchi/Papers.php). Precisely, an intra-cavity electro-optical modulator is driven at a frequency close to the oscillation frequency $\Omega \approx \sqrt{2\kappa\gamma_{II}}$, and linear stability analysis predicts a perturbed 2D system. For a CO2 laser, the relevant frequency range is 50-100kHz. ii) Injection of a field from an external laser is detuned approximately by the above, and with respect to the external reference, the cavity field has two quadrature components which represent independent dynamical variables. Hence the system is 3D A.110 (http://www.inoa.it/home/arecchi/Papers.php). iii) Cavity as a bidirectional ring rather than a Fabry-Perot A.120 (http://www.inoa.it/home/arecchi/Papers.php). At variance with the standing wave case, in the bidirectional case the two fields have no mutual phase constrains, thus they represent separate variables. Furthermore, a detuning provides a population grating yielding scattering processes whereby the dynamic dimensions are even more than 3. iv) Add an overall feedback besides that due to the cavity mirrors, by modulating the losses with a signal proportional to the detected output intensity. If the feedback loop has a time constant comparable with $1/\kappa$ and $1/\gamma_{II}$, it contributes a third equation, promoting the system to 3D

A.134,142 (http://www.inoa.it/home/arecchi/Papers.php).

Since feedback, modulation or external injection are currently used in laser applications, the presence of chaotic regions puts a caution on the generalized trust in the laser regularity.

As for Class A single mode lasers, chaos would require 2 independent perturbations, thus it would be a highly artificial dynamical system. However, a multimode laser can easily get chaotic as soon as i) there are at least 3 modes; ii) they are coupled by convenient nonlinearities (see Sec.3). As for Class C lasers, a clean evidence of Lorenz chaos was demonstrated in far IR lasers [Weiss et al.(1988)]; these systems however do not have wide applications, since their wavelength is in a spectral region where most materials are highly absorbing.

A case study: HC= homoclinic chaos in a class B laser and synchronization to an external reference

Among the chaotic scenarios, the so called HC (Homoclinic Chaos), consisting of trains of equal spikes with erratic interspike separation, was explored in CO2 and in diode lasers with feedback (see Fig.1).

Fig.1 shows the experimental set up and displays the 3 coupled equations. The first two are the standard rate equations for the intensity x coupled to the population inversion y via the Einstein constant G. k_0 and γ are the damping rates for x and y, respectively, p_0 is the pump rate. Two equations do not give chaos, and in fact a generic laboratory laser is not chaotic. We add a third equation as follows. The detected output intensity provides a voltage z which drives an intracavity loss modulator (see added z term in the first equations. In the feedback loop, R and b_0 act as control parameters. The third damping rate β is of the same order as the other two.

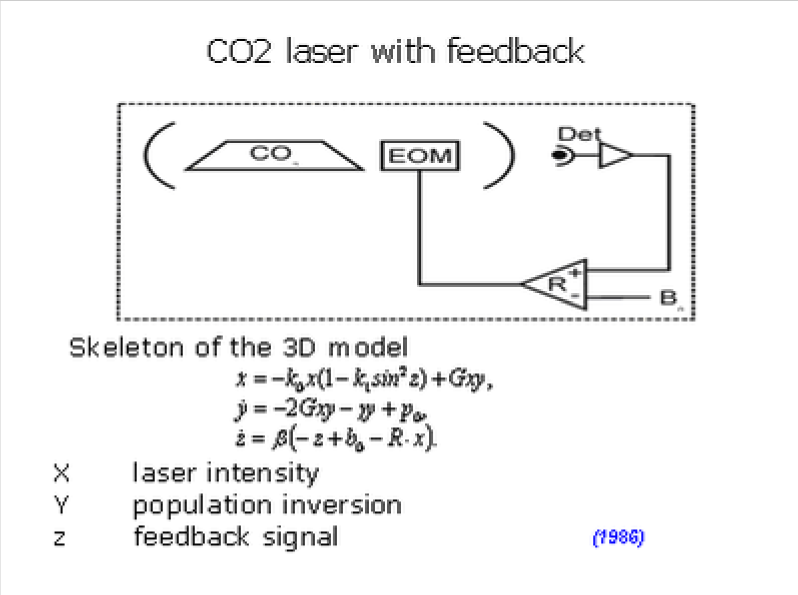

Figure 1: CO2 laser with feedback: experimental set up and the 3 coupled equations. CO2 is the gas where an electric discharge provides molecular population inversion at the laser frequency; EOM is an electro-optic loss modulator driven by the voltage z of the feedback loop; R is the gain of the feedback amplifier and Bo a d.c. bias voltage A.134 (http://www.inoa.it/home/arecchi/Papers.php)

The dynamics (Fig.2) consists of trains of almost equal intensity spikes, separated by erratic inter-spike intervals (ISI). In b) we zoom on two successive spikes, to show their repeatability. By a threshold we may cut the small chaotic fluctuations and observe a spiking of regular shape; however, chaos results in the variable ISI. In c) we build a 3-D phase space by an embedding technique. Each point reports the intensity sampled at time t and after two short delays τ and 2τ. The figure is built over many spikes. The part of the orbit with a single line is the superposition of the large spikes, the small chaotic tangle corresponds to the small non-repetitive pulses. The experimental phase space (Fig.2c) suggests that it is due to a homoclinic structure existing near a saddle focus equilibrium point *S*. When the system undergoes the so-called Shilnikov bifurcation, *S* has a homoclinic trajectory which escapes from *S* through a 2-dimensional unstable manifold associated with a complex conjugate pair of eigenvalues $\gamma \pm i\omega$ $(\gamma > 0)$ and returns back through a 1-dimensional stable manifold associated with a negative eigenvalue $-\alpha$ $(\alpha > 0)$. We call α the contraction rate and $\gamma \pm i\omega$ the complex expansion rate. If $\alpha < \gamma$ [Shilnikov], this local relation at *S* provides a complicated global phase space flow structure referred to as homoclinic chaos (HC). Since the return time to *S* is affected by the uncertainty in the expanding region, around *S* the system displays a high susceptibility $\chi = response/stimulus$. Away from *S*, the system is less sensitive to external perturbations and displays a repeatable loop. Time-wise, large spikes of equal shape repeat at chaotic inter-spike intervals. In fact the feedback laser model exhibits in addition a saddle node bifurcation; in such a case HC stays rather for heteroclinic chaos [Kuznetsov, (1998)]. Due to the high susceptibility, a small perturbation applied around *S* strongly affects the *ISI*; we exploit this fact to synchronize the HC laser to an external signal. If the driving frequency is close to the natural one

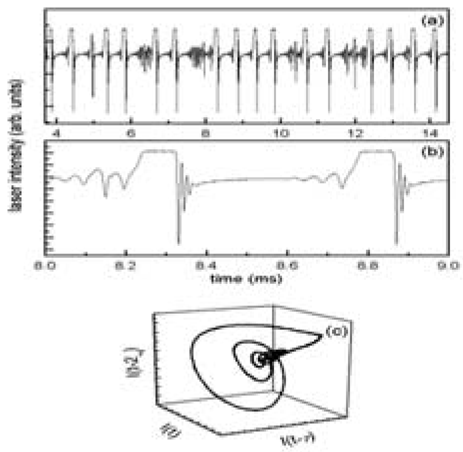

Figure 2: a) trains of almost equal intensity spikes, separated by erratic inter-spike intervals (ISI). b) zoom on two successive spikes, to show their repeatability. c) 3-D phase space built by an embedding technique. Each point reports the intensity sampled at time t and after two short delays τ and 2τ. The figure is built over many spikes. The part of the orbit with a single line is the superposition of the large spikes, the small chaotic tangle corresponds to the small non-repetitive pulses. A.286 (http://www.inoa.it/home/arecchi/Papers.php)

(associated with the average <*ISI*>) we have a 1:1 locking.

Fig.3 shows the laser synchronization to a small forcing signal. In the feedback amplifier we introduce a periodic input which is a small percentage of the feedback signal. A forcing frequency close to $2\pi/ < ISI >$ induces a 1:1 locking; at lower frequencies we have 1:2 and 1:3 locking, at higher frequencies we have 2:1 etc locking regimes.

It looks as a promising implementation of a time code: indeed, networks of coupled *HC* systems may reach a state of collective synchronization lasting for a finite time, in presence of a suitable external input. This opens powerful analogies with the *feature binding* phenomenon characterizing neuron organization in a perceptual task.

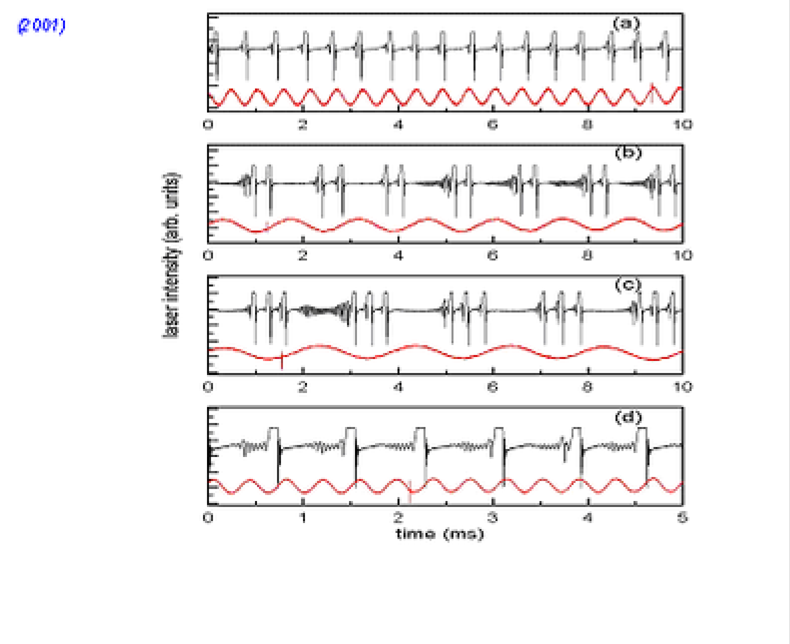

Figure 3: Laser synchronization to a small forcing signal of frequency close to (a) or smaller (b and c)or larger (d) than, the natural HC frequency $2\pi/ < ISI >$. A.286 (http://www.inoa.it/home/arecchi/Papers.php)

Control of laser chaos

Controlling chaos consists in perturbing a chaotic system in order to stabilize a given unstable periodic orbit (*UPO*) embedded in the chaotic attractor[E. Ott & et al.,(1990); T.Shinbrot et al.,(1993)]. However, other unstable orbits outside the attractor may also be controlled using an experimental continuation method [Carr, (1996)]. Different methods for controlling chaos have been proposed based on i) determination of the stable and unstable manifolds on the Poincare Section (*PS*)[E. Ott & et al., (1990)], ii) delayed feedback procedure [Pyragas, (1992)] and iii) open loop perturbations[Lima & Pettini, (1990)]. The OGY's (Ott, Grebogi and Yorke) method for controlling chaos consists of slight readjustments of a control parameter each time the trajectory crosses the PS. Since a generic UPO is mapped on the PS by an ordered sequence of crossing points, OGY is able to stabilize such a sequence whenever the chaotic trajectory visits closely a neighborhood of one of the saddle PS points. It does this by performing a projection onto the stable manifold of the UPO. The time lapse for a natural passage of the flow within a fixed neighbourhood (hence for switching on the control process) can be very large. To minimize such a waiting time, a technique of targeting has been also introduced [T.Shinbrot et al.,(1990)]. OGY inspired an easily realizable experimental technique called OPF (Occasional Proportional Feedback), and demonstrated in a chaotic diode oscillator [Hunt, (1991)]. The OPF technique is based not only on feedback, but also on pulse duration, delay and amplitude [Carr,(1996)]. Roy et al. applied OPF to control of high dimensional chaos in a multimode laser system [R. Roy et al., (1992)]. Such a laser is a diode laser – pumped solid state Nd –doped yttrium aluminium garnet (Nd: YAG) laser containing a KTP(potassium titanyl phosphate) doubling crystal inside the optical cavity . The multimode laser with an intracavity crystal is an example of a system of globally coupled nonlinear oscillators. Such coupled oscillators have been found to be of relevance and interest in several physical, chemical and biological systems. The applicability of OPF as well as many other methods of controlling UPOs [Schwartz, (1997)], is not limited to stabilizing a chosen periodic orbit embedded in chaotic attractors or unstable steady states. Gills et al. demonstrated that OPF is able to track an unstable steady state in a chaotic multimode Nd: YAG laser with a nonlinear KTP crystal. Their results demonstrated the extension of the stability range over one order of magnitude, from a pump power about 20% above the threshold to more than 300% above the threshold [Gills et al., (1992)]. The successful application of this technique has been also reported by Liu and Ohtsubo in a delayed optical bistable system that consists of a laser- diode interferometer with delayed optoelectronic feedback [Liu & Ohtsubo, (1994)]. A delayed continuous feedback method (DCF) [Pyragas, (1992)] considers a dynamical system ruled by a set of unknown ordinary differential equations, and having some scalar variable accessible for measurements. Furthermore, the system possesses at least one input accessible for external forcing. The above assumptions are met by the equations

$$\dot{y} = P(x, y) + F(t)$$

$$\dot{x} = Q(y, x)$$

where *y* represents the output scalar variable, *x* the remaining variables of the dynamical system, *F(t)* is an input signal which perturbs the dynamical evolution of the variable *y*, and *P* and *Q* are two nonlinear functions. Suppose that the system exhibits chaotic dynamics when *F=0* and *T* represents the period of an unstable periodic orbit embedded in the chaotic attractor. To achieve stabilization of the selected UPO, an external feedback line which reinjects into the system the difference between the signals *y(t)* and $y(t-\tau)$ is used. The applied control signal will be given by: $F(t)=K[y(t-\tau)-y(t)]$, where the weight *K* has to provide a negative feedback (*K<0*) and represents a time delay. Stabilization of the selected *UPO* is achieved when τ equals the period *T*. DCF requires, a priori, the knowledge of the unstable orbit periodicity and it can be easily applied to non-autonomous systems in which the period is fixed by the forcing term. Bielawski et al. checked this method to control and track unstable orbits of a CO2 laser with modulated losses [Bielawski et al., (1994)]. The original DCF scheme can be replaced by a suitable filter (called “washout filter”) inserted in a feedback loop. Robustness, speed and general validity of this scheme in laser systems was reported by [Meucci et al., (1996)]. Closed loop control techniques have been demonstrated in fast electronic oscillators and in principle applicable to in optical systems with latency time below 1ns. However, for controlling and sustaining chaos in systems with fast time scales, open loop methods are preferable for two reasons: 1) they have no feedback time scale with which to compete. 2) Many nonlinear optical systems now are sufficiently modeled so it is easier to add a forcing term to control the dynamics in an open loop setting, rather than using a control filtering scheme which uses a multi-dimensional closed loop feedback. In general, a closed loop control requires a scheme to get the local variation around an unstable periodic orbit as a function of parameters , and this is not an easy task in higher dimensional systems. Nonfeedback methods traditionally make use of the effect of harmonic perturbations in the global dynamics. The effects of resonant perturbations (induced optical bistability and chaos control) and on loss modulated lasers was reported by [Chizhevsky et al., (1997)] Another nonfeedback method whose effectiveness has been proved in periodically driven chaotic systems is Phase Control of Chaos (PCC). In this control scheme, the control parameter is the phase difference between the main driving and a small harmonic perturbation that is applied to the system , either parametric or as an additional external forcing. The effectiveness of PCC in controlling or enhancing the intermittent behavior emerging after an interior crisis in a modulated laser was given by A.335 (http://www.inoa.it/home/arecchi/Papers.php). See [Scholl & Schuster, (2007)] for an overview on the subject not limited to laser control.

References

The references of INOA group are listed as [A.#] where the number # refers to the List of publications in the homepage: [1] (http://www.inoa.it/home/arecchi/Papers.php)

- S. Bielawski, D. Derozier and , P. Glorieux, Controlling unstable periodic orbits by a delayed continuous feedback, Phys. Rev. E 49, R971 (1994)
- T. W. Carr and I. B. Schwartz, Controlling high-dimensional unstable steady states using delay, duration and feedback, Physica D 96, 17 (1996).
- C. V. Chizhevsky, R. Corbalan and A. N. Pisarchik, Attractor splitting induced by resonant perturbations, Phys. Rev.E 56 1580 (1997)

- Z. Gills, C. Iwata, R. Roy, I. B. Schwartz and I. Triandaf, Tracking Ustable Steady States: Extending the Stability Range of a Multimode Laser System , Phys. Rev. Lett. 69, 3169 (1992)
- A. Z. Grasyuk and A. N. Oraevsky , Vol. Varenna 1963 Radio Eng. & Electron. Phys. 9, 424 (1963)
- H. Haken, Analogy between Higher Instabilities in Fluids and Lasers, Phys. Lett. A 53, 77 (1975)
- E. R. Hunt, Stabilizing high-period orbits in a chaotic system: The diode resonator, Phys. Rev. Lett. 67, 1953 (1991)
- Y. A. Kuznetsov, Elements of Applied Bifurcation Theory, Springer,(1998)
- R. Lima and M. Pettini, Suppression of chaos by resonant parametric perturbations, Phys. Rev. A 41, 726 (1990)
- Y. Liu and J. Ohtsubo, Experimental control of chaos in a laser-diode interferometer with delayed feedback, Opt. Lett. 19, 448(1994)
- R. Meucci, M. Ciofini and R. Abbate , Suppressing chaos in lasers by negative feedback, Phys. Rev. E 53, R2528 (1996)
- E. Ott , C.Grebogi, and J.A. Yorke, Controlling Chaos, Phys. Rev. Lett. 64, 1196 (1990)
- K. Pyragas, Continuous control of chaos by self-controlling feedback, Phys. Lett. A 170, 421 (1992)
- R. Roy, T. W. Murphy, T. D. Maier, Z. Gills and E. R. Hunt, Dynamical control of a chaotic laser: experimental stabilization of a globally coupled system, Phys, Rev. Lett. 68, 1259 (1992)
- E. Scholl and H. G. Schuster (Eds.), Handbook of Chaos Control, Wiley-VCH, (2007)
- I. B. Schwartz, Sequential Horseshoe Formation in the Birth and Death of Chaotic Attractors, Phys. Rev. Lett. 60, 1359 (1988).
- I. B. Schwartz, T. W. Carr and I. Triandaf, Tracking controlled chaos: Theoretical foundations and applications, CHAOS 7,664 (1997)
- L. P. Shilnikov and A. Shilnikov, Shilnikov bifurcation, Scholarpedia, 2(8),1891 (2007)
- T.Shinbrot, E. Ott, C. Grebogi and J. A. Yorke, Using chaos to direct trajectories to targets, Phys. Rev. Lett. 65, 3215 (1990)
- C. O. Weiss, N. B. Abraham and U. Hubner, Homoclinic and Heteroclinic Chaos in a Single-Mode Laser, Phys. Rev. Lett. 61, 1578 (1988)

Internal references

- John W. Milnor (2006) Attractor. Scholarpedia, 1(11):1815.

- Edward Ott (2008) Attractor dimensions. Scholarpedia, 3(3):2110.

- John Guckenheimer (2007) Bifurcation. Scholarpedia, 2(6):1517.

- Edward Ott (2006) Controlling chaos. Scholarpedia, 1(8):1699.

- James Meiss (2007) Dynamical systems. Scholarpedia, 2(2):1629.

- Eugene M. Izhikevich (2007) Equilibrium. Scholarpedia, 2(10):2014.

- Giovanni Gallavotti (2008) Fluctuations. Scholarpedia, 3(6):5893.

- Rodolfo Llinas (2008) Neuron. Scholarpedia, 3(8):1490.

- Jeff Moehlis, Kresimir Josic, Eric T. Shea-Brown (2006) Periodic orbit. Scholarpedia, 1(7):1358.

- Anatoly M. Samoilenko (2007) Quasiperiodic oscillations. Scholarpedia, 2(5):1783.

- Leonid Pavlovich Shilnikov and Andrey Shilnikov (2007) Shilnikov bifurcation. Scholarpedia, 2 (8):1891.

- Philip Holmes and Eric T. Shea-Brown (2006) Stability. Scholarpedia, 1(10):1838.

- David H. Terman and Eugene M. Izhikevich (2008) State space. Scholarpedia, 3(3):1924.

- Arkady Pikovsky and Michael Rosenblum (2007) Synchronization. Scholarpedia, 2(12):1459.
- Paul So (2007) Unstable periodic orbits. Scholarpedia, 2(2):1353.

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