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GENERALIZED OPTICAL BISTABILITY AND CHAOS IN A LASER WITH A SATURABLE ABSORBER

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Resume: Des experiences menees sur un laser a absorbant saturable ont permis de mettre en evidence l'existence de bistabilite' optique generalisee et de chaos dans ce systeme. Des simulations numeriques ont confirme ces resultats.

Abstract .Generalized optical bistability and chaotic behaviour has been observed experimentally and reproduced numerically for a laser with a saturable absorber.

Since the study of the dynamical system theory gained interests among the physics community and the trend of finding prototypes of non-linear systems in the real physical systems started to develop, the laser with a saturable absorber (LSA), although being a system in which strong non-linearities come into play, failed to exhibit the expected behaviour of cascade bifurcations and chaotic dynamics at first experimental and numerical analyses. This indeed seemed rather strange because the " non-linear content " of the ruling equations for this system was quite similar to that of the well known Lorentz set of equations. These equations are given, in the most general form by : (1)

$$\begin{aligned}\dot{I} &= I * (A * \delta - \bar{A} * \bar{\delta} - 1) \\ \dot{\delta} &= -a * I * \delta - \int_0^\infty K(t') * (\delta(t-t') - 1) \\ \dot{\bar{\delta}} &= -\bar{a} * I * \bar{\delta} - \int_0^\infty \bar{K}(t') * (\bar{\delta}(t-t') - 1)\end{aligned}\tag{1}$$

where all the barred quantities refer to the absorber and K and $\bar{K}$ represent the memory functions containing the dynamics of the relaxation including levels different from the resonant ones. However only recently it has been shown that for a range of parameters corresponding to the experimental ones the LSA exhibits a wide variety of dynamical regimes and chaotic behaviours when the analyses with oversimplified models are abandoned and a detailed representation of the memory function is given. The experimental dynamical scenario becomes even more complex and regions of coexistence of two different

regimes are observed which so far have been only partially reproduced by numerical experiments. In the above set of equations as well in the experimental situation the control parameters have been taken to be A and $\bar{A}$. The first one is proportional to the pumping rate in the gain-medium and the second can be changed by varying the absorber's pressure. A third control parameter, very easy to handle from the experimental point of view, can be chosen to be the cavity detuning, this has the effect of reducing by the same factor A and a , as well $\bar{A}$ and $\bar{a}$ in Eqs.(1). If we consider the dependence of the steady state solution from the control parameter A it is found that above a given threshold value A_0 there are always two solutions ; a trivial one corresponding at $I=0$ which is always unstable and a solution different from zero which can be stable or unstable. The points representative of these solutions in the phase space $I, \delta, \bar{\delta}$ will be denoted by I_0 and I_+ respectively. The important fact is that the dynamical behaviour of this system can be understood in terms of the local dynamics of the points I_0 and I_+ (2). We will consider here the most interesting case in which both points are unstable, which correspond to a range of the parameter A between A_0 and A_H . In this case because of lacking of any stationary solution the system must wander in the phase space until it is attracted by a stable orbit. We have identified two types of stable orbits: the first type corresponds to an intensity pulsating solution getting very close to the plane $I=0$ which we will call type-I solution ,whereas the second one corresponds to a self-oscillating solution emerging from the Hopf bifurcation occuring at $A=A_H$ that we will call type-II solution. Very near to the threshold A_0 the typeI solution corresponds to an orbit visiting a large portion of the phase space not being influenced by the local dynamics of the point I_+ , we can think at this orbits as originating from an homoclinic orbit of the point I_0 , (Fig. 1.a). However as we move near A_H the previous orbit transforms into one approaching I_+ along the contracting manifold and spiralling outward on the unstable manifold (Fig.1.b). This orbit returns on the plane $I=0$ toward which it is strongly attracted. We could not observe an orbit of this kind not approaching the plane $I=0$, this would be somewhat connected with the existence of Shilnikov chaos in the LSA: since the motion near the plane $I=0$ is essentially bidimensional the homoclinic reinjection mechanism necessary for the occurrence of this type of chaos loses its efficiency.

Fig.1. Numerically simulated $P(o)$ type-I pulses (a) and $P(n)$ type-I pulses (b).

In Fig.(2) we can observe the domain of existence of different regimes of the LSA: Fig.2.a is an experimental phase diagram whereas Fig.2.b is a theoretical one. The type-I solutions are denoted by $P(n)$ with n being the number of spikes of the undulated tail whereas the type-II solutions are denoted by T or nT according to which step of the period doubling sequence they represent. We note that the passage from the pulse $P(n)$ to the pulse $P(n+1)$ occurs discontinuously and for some values of the control parameters they are separated by a whole period doubling sequence leading to chaotic behaviour. Two types of chaos, one associated with the type-I heteroclinic cycle joining I_0 and I_+ and the other originating from type-II instability are observed on LSA⁽³⁾.

Fig.2. Experimental phase diagram (a). The numbers inside white regions stand for $P(n)$ type-I pulses. The hatched area corresponds to laser-off or to multimode regime. The

thick line shows bistability between $P(n)$ and type-II pulses. Phase diagram as derived from numerical simulations (b), the thick line shows bistability between cw and several LSA regimes.

It is well known that LSA presents bistability between the I_0 and I_+ solutions, however the existence of the type-I and type-II LSA regimes described above leads to the presence of generalized bistability between the different solutions. Bistabilities between type-I instability and cw regime may appear, as observed on the operation with the 10P(20) line and low pressure SF_6 absorber. For the 10P(16) line at small frequency detuning a bistability between type-II instability and off regime has been observed. These observations point out that in the LSA phase space, an I_+ stable point and a stable type-I orbit coexists, as well an I_0 stable point and a stable type-II orbit. On the contrary a bistability between I_0 and type-I instability is unlikely to occur because type-I orbits evolve in the

phase space very close to the I_0 point, that, if stable would attract and destabilize the orbit. To complete the bistability list, a bistability is expected between an I_+ stable point and a type-II orbit, i.e. the coexistence of a limit cycle around the I_+ point independent of the stable I_+ point itself. We have not obtained a clear evidence of this bistable regime in our experimental observations. A last bistability case is between type-I and type-II instabilities, and this case has been illustrated in Fig.2.b. Such a generalized bistability has been observed for type-I $P^{(n)}$ instabilities at large numbers n . Instead a soft continuous transition is observed between type-II and low n type-I instabilities.

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