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Type-III intermittency of a laser

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We observe transitions to chaos by type-III intermittency of a laser. A family of transitions is found in which the onset of intermittency is preceded by subharmonic period-N states. The laser used is an optically pumped far-infrared ring laser.

In dissipative systems making a transition to chaos, three "routes" have been predominantly found: the period-doubling route [1,2], the quasiperiodicity route [3], and the intermittency route [4–6]. Of the latter, three variations exist. Type-I intermittency is associated with a tangent bifurcation; type-II, with a Hopf bifurcation; and type-III, with a subharmonic bifurcation.

No type-III intermittency transition to chaos has yet been observed from optical systems, even though a theoretical prediction exists [7]. We show here that this type of transition to chaos occurs in lasers, from observations on a NH_3 far-infrared (FIR) undirectional ring laser, which was recently found to exhibit the dynamics of the Lorenz model in great detail [8–10]. We found not only one but a family of type-III intermittent transitions to chaos which differ in the order of the subharmonic state preceding the onset of intermittency.

The experimental setup used is a ring laser, which is described in [2], designed to fulfill the conditions of a single-mode traveling-wave operation. The active medium is NH_3; the $aR(7,7)$ rotational transition in the $v_2=1$ vibrational state of $^{14}NH_3$ is the laser transition. It is optically pumped with the $P(13)$ line of the N_2O laser via the vibrational $aQ(8,7)$ transition. The backward laser emission at 81-μm wavelength is detected by a Schottky-barrier diode. The pump intensity and the resonator tuning are utilized as control parameters.

Figure 1 gives the route to chaos that we observe at a $^{14}NH_3$ gas pressure of 40 μbar and a fixed resonator tuning while increasing the pump strength. At low pump intensity, the FIR emission pulses periodically. As the pump intensity is increased, a period doubling appears. Increasing the pump intensity further, a second period doubling does not take place as in the usual period-doubling route to chaos [1,2]; instead, new dynamics, as shown in Fig. 1(c), appear. This time evolution has the characteristics of type-III intermittency. It is clearly seen that the intensity of one component of the period-2 pulses grows while the intensity of the other component de-

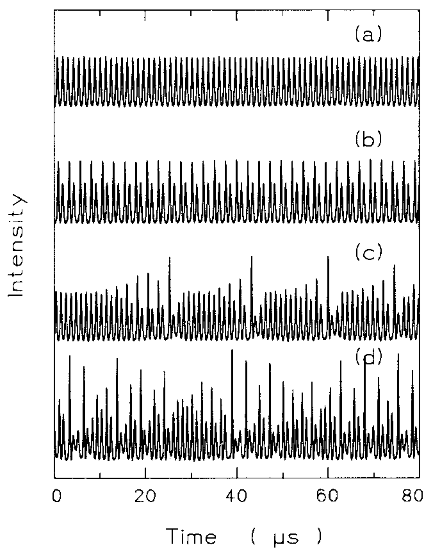

FIG. 1. Time dependence of the FIR laser output as the pump intensity is varied. Gas pressure is 40 μbar. (a) Stable oscillatory state. Pump intensity is 4 W/cm^2. (b) Period-doubled state. Pump intensity is 6 W/cm^2. (c) Type-III intermittency. Pump intensity is 7 W/cm^2. (d) Chaotic state. Pump intensity is 9 W/cm^2.

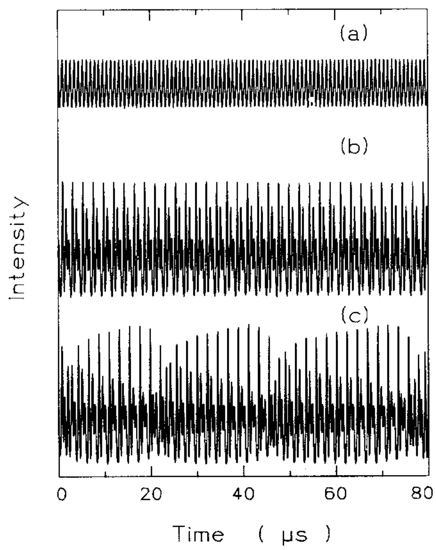

FIG. 2. Intermittency preceded by a period-3 state. Gas pressure is 50 μbar. Pump intensity is 7 W/cm^2. From (a) to (c) the resonator detuning is decreased.

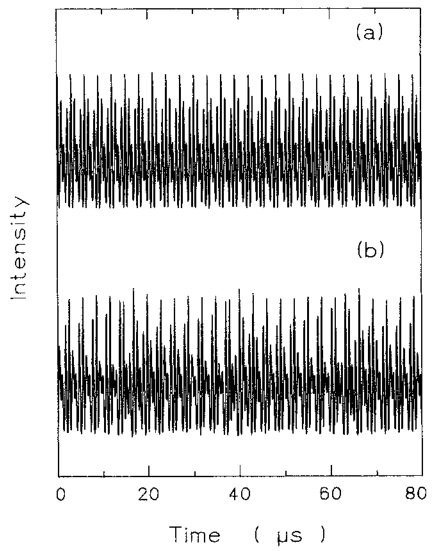

FIG. 3. Intermittency preceded by a period-4 state. Gas pressure is 52 μbar. Pump intensity is 7 W/cm^2. From (a) to (b) the resonator detuning is decreased. The period-1 state preceding the period-4 state is not shown for brevity.

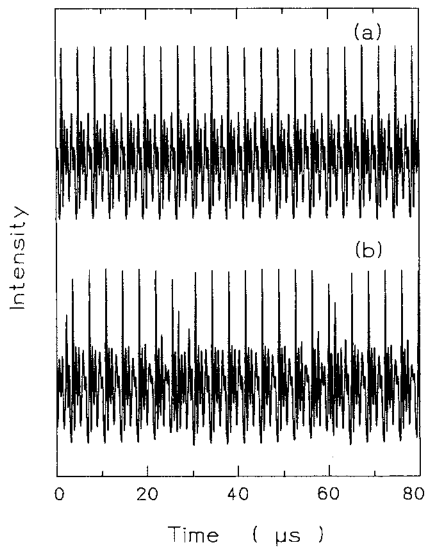

FIG. 4. Intermittency preceded by a period-5 state. Gas pressure is 54 μbar. Pump intensity is 7 W/cm^2. From (a) to (b) the resonator detuning is decreased. The period-1 state preceding the period-5 state is not shown for brevity.

creases. After regular pulsing of the intensity ("laminar phase"), the intensity variation loses its regularity and a turbulent burst appears; this repeats as in the intermittency scenario [11]. The duration of the laminar phases in this state is random. The average duration of the laminar phases depends on the control parameter. As the pump intensity is increased, the average duration of the laminar phases decreases and finally the dynamics is chaotic, as shown in Fig. 1(d). The same route to chaos is also observed with fixed pump intensity varying the resonator detuning.

Figure 2 shows another typical intensity variation of the laser emission. The gas pressure is 50 μbar and pump intensity is 7 W/cm^2. The resonator detuning is changed. The time variation of the intensity shows again the characteristics of type-III intermittency. In contrast to the route shown in Fig. 1, the intermittency is preceded by a period-3 state, and because of this difference the intensity variation of the three components is now characterized by one component growing and the other two decreasing.

Figures 3 and 4 show further intermittency transitions to chaos observed in the experiment. Figure 3 shows that intermittency is preceded by a period-4 state; and Fig. 4, a period-5 state. The sequences shown occur reproducibly when the control parameter is changed. No intervening states between them could be found.

The intermittent behavior of the laser is reversible, i.e., when the resonator detuning is reversed or the pump intensity is decreased, the inverse sequences of those shown above occur. The occurrence of such a type of intermittency depends on the operating gas pressure. Only in the range between 40 to 60 μbar can we observe these intermittencies; at lower gas pressure we have found type-I intermittency [12].

It is worth noting that in this gas-pressure range, Lorenz-model dynamics occurs when the pump intensity is reduced to values of about 1.5 W/cm^2. We therefore attribute the appearance of intermittency transitions to chaos to three-level coherence effects. At the pump-intensity level suitable for Lorenz chaos, the ac Stark line broadening induced by the pump field is still smaller than the pressure-broadened linewidth. At the pump intensity necessary for intermittency to occur, the ac Stark line broadening exceeds the pressure-broadened linewidth. Although theoretically the gain line profiles in laser-pumped gas lasers are different for forward or backward emission, we find the same family of intermittencies for forward and backward emission. The similar behavior in the two directions is probably explained by the averaging of the ac Stark-split line profiles along the resonator length. At the pump entrance the pump intensity is highest, while it decreases along the resonator length due to the absorption of the laser gas. Thus the integral gain

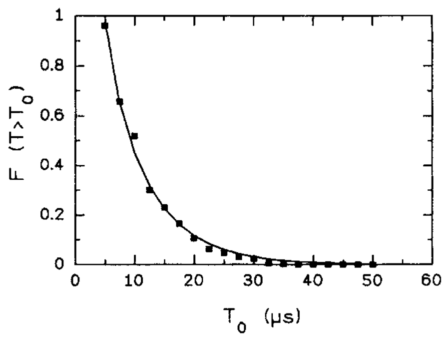

FIG. 5. Distribution of the fraction of laminar phases lasting longer than T_0. The experimental points are calculated from data shown in Fig. 1(c).

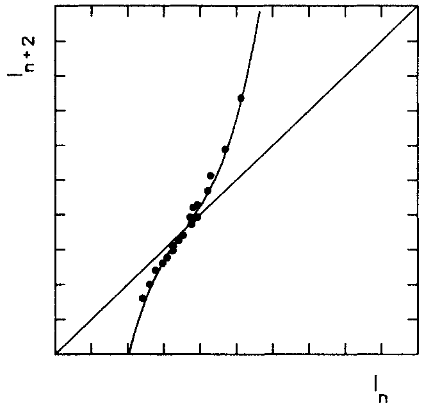

FIG. 6. Poincaré return map $I_{n+2}=f(I_n)$ constructed from the experimental data of Fig. 1(c). The circles represent the experimental values; the continuous curve is obtained by fitting the two parameters of relation (2) to the experimental points.

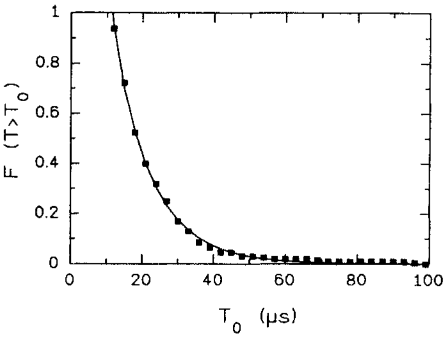

FIG. 7. Distribution of the fraction of laminar phases lasting longer than T_0. The experimental points are calculated from data shown in Fig. 2(c). The continuous line is a fit to the experimental points according to Eq. (1) for $\epsilon = 0.1 \pm 2\%$.

line in the forward direction is an average over ac Stark-split profiles of variable splitting and height. This averaging probably results in an integral-gain profile similar to the backward-gain line with a simple central maximum.

In order to confirm that the time behavior observed in the experiment represents type-III intermittency, we have calculated the statistical distribution of the duration of the laminar phases from the experimental data, of which Fig. 1(c) is a portion. According to [13], the distribution of laminar phases for type-III intermittency is

$$N(T > T_0) \propto \{\epsilon/[\exp(4\epsilon T_0) - 1]\}^{1/2}. \quad (1)$$

ϵ is the bifurcation parameter, which is 0 at the onset of intermittency. In the experiment, ϵ depends both on the pump intensity and resonator detuning. T_0 is the duration of laminar phases. N is the number of the laminar phases lasting longer than T_0. The distribution of the laminar-phase duration of type-III intermittency depends only on the bifurcation parameter ϵ.

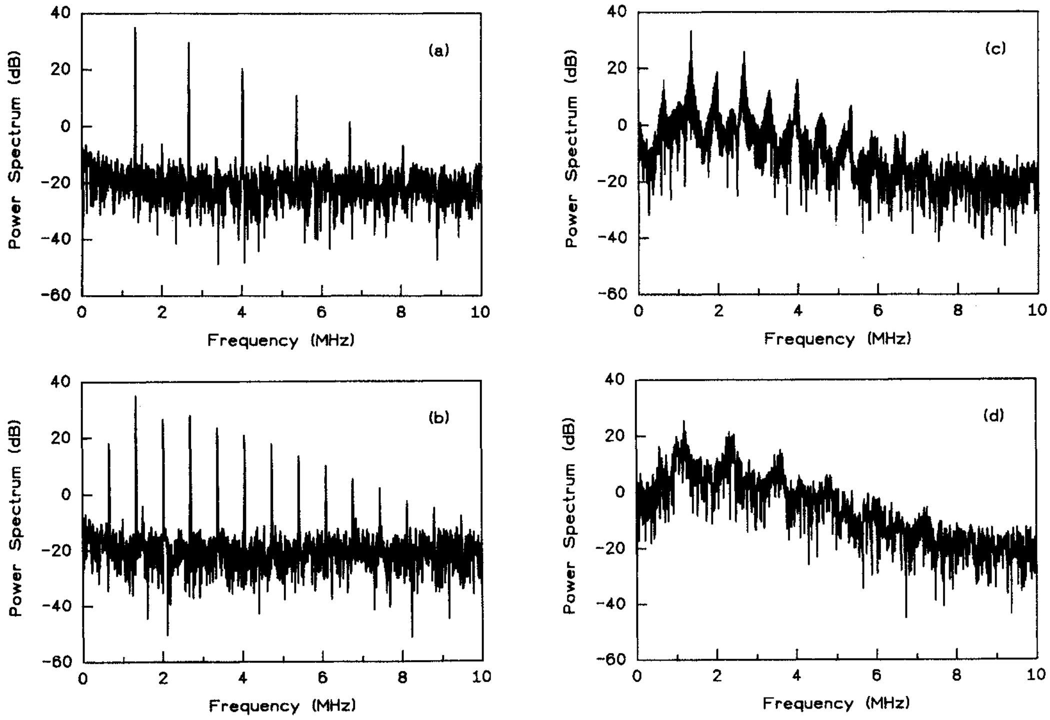

FIG. 8. Variation of the intensity spectrum of the laser as the cavity detuning is changed. Pump intensity is 9 W/cm^2. Gas pressure is 40 μbar. Shown is the intensity spectrum (a) corresponding to the stable oscillatory state, (b) corresponding to the period-doubled state, (c) corresponding to the type-III intermittent state, and (d) corresponding to the chaotic state.

The comparison of the experimental result with relation (1) is given in Fig. 5: the squares represent the fraction of laminar phases lasting longer than T_0 of the whole laminar phases. The solid curve represents the best fit by the relation (1) to the measured points obtained by a least-squares adjustment. From this calculation $\epsilon = 0.2 \pm 5\%$ is obtained.

Another characterization of type-III intermittency is by the Poincaré return map. According to [11], for type-III intermittency associated with a period-2 bifurcation this map can be expressed as

$$I_{n+2} = (1+2\epsilon)I_n + aI_n^3 , \qquad (2)$$

where a is a constant and ϵ is again the bifurcation parameter. The I_n values are the successive maxima of laser intensity. I_n values are used to construct the return map $I_{n+2} = f(I_n)$. Figure 6 is a typical result. In the figure the circles represent the experimental values; the continuous curve is obtained by fitting the two parameters of relation (2) to the experimental points. The value of ϵ thus calculated is $\epsilon = 0.25 \pm 10\%$.

As we cannot exactly measure the resonator detuning, it is difficult to give a relation between the pump intensity and the bifurcation parameter.

For the intermittency preceded by a period-3 state we have also calculated the distribution of the laminar-phase durations from the experimental data, which is shown in Fig. 7. The form of this distribution exhibits again the expected feature of the type-III intermittency.

As a typical example the variation of the intensity spectrum of the laser emission for variation from periodic to chaos through type-III intermittency is shown in Fig. 8. We clearly see that as the control parameter changed, the spectrum shows first a periodic bifurcation, then the bottom of the spectral lines gradually broadens, and finally the whole spectrum becomes a broadband noise spectrum. This variation of the spectrum is characteristically different from those of the other two routes to chaos [2,3].

Summarizing, we have observed routes of type-III intermittency to chaos in an optical system. Besides the usual type-III intermittency associated with a period-doubling bifurcation, a family of type-III intermittencies preceded by period-3, period-4, and period-5 states has also been observed.

We note that one of the routes of type-III intermittency transition to chaos observed here occurs also in the model [7] of single-mode laser equations that we have found by numerical investigation of this model. Although this model does not describe exactly our laser system, it shows that the occurrence of intermittency is not unique to the particular laser system used here.

Finally, since the occurrence of intermittency is apparently related to three-level coherence effects, we expect to reproduce our observations using the full three-level laser model [14,15].

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