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Optoelectronic circuits with delayed feedback provide a convenient bench-top platform to study a wide range of nonlinear dynamic systems, from ultrastable clocks to complex chaotic device.

Every time we turn on a computer, we are reminded that nothing happens instantaneously. All physical systems exhibit a finite time delay between the moment we provide a stimulus and the moment the system returns a response. In many situations, the response also depends nonlinearly on the input, such that the evolution of the system in the present depends very sensitively on its state in the past. Such nonlinear time-delay systems can display complex dynamic behaviour, but in fact they are ubiquitous in nature and include such examples as predator–prey relationships, cell regulation and neural synchronization.

But somewhat surprisingly, even though nonlinear delay dynamics have wide relevance in both fundamental science and technology, there are few laboratory systems with which their complexity can be readily studied. Consequently, much of the fundamental science of how nonlinearity and delay interact remains unexplored. Recent years, however, have seen the development of a range of optical systems that have opened up the richness and complexity of nonlinear delay dynamics to systematic experimental study[1-3]. Reporting in *Physical Review Letters*, Callan *et al.*[4] highlight a significant advance in this field by using a type of optoelectronic circuit called an optoelectronic oscillator to study the way in which an external perturbation can switch a nonlinear delay system between stable and chaotic operation. An optoelectronic oscillator is a system in which the intensity of a continuous-wave laser (one that, in contrast to a pulsed laser, produces a continuous light beam) is modulated by an electronically driven nonlinear optical device before being fed into a long length of optical fibre, which introduces delay (Fig. 1a).

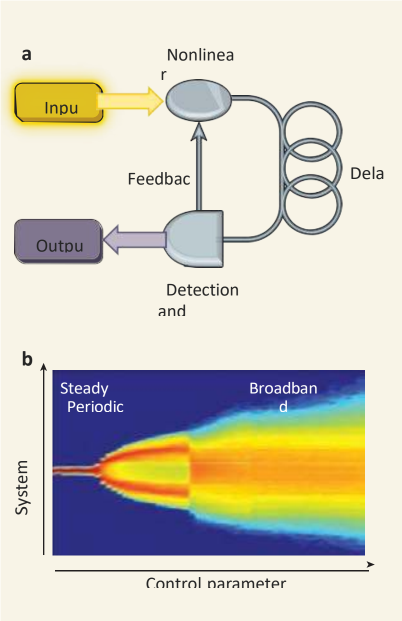

Figure 1 | Working principle and dynamic behaviour of an optoelectronic oscillator. a, Generic architecture of the system: the input, the optical signal from a laser, is modulated nonlinearly before propagating in an optical fibre, which provides time delay. Detection and filtering at the fibre output convert the optical signal into an electronic signal, part of which is taken as the output of the system and part of which is fed back to re-drive the nonlinear modulation of the optical input. b, The system output is illustrated generically via a bifurcation diagram, which plots the amplitude of the output as a function of a control parameter that can be taken as proportional to the intensity of the input after modulation. Optoelectronic oscillators typically exhibit three dynamic regimes: steady state, which is independent of the control parameter; periodic oscillation, in which two discrete output values (the 'zeros' and 'ones' of a pulse train, for example) are seen; and a broadband chaotic regime. The colour scale represents the amplitude distribution of the output (blue is zero, red is maximum). The originality of Callan and colleagues' study[4] is that the steady-state and chaotic regimes of the system coexist and can be readily switched from one to the other using a small perturbation.

After propagation in the fibre, the delayed light is detected electronically, and this output is then used as an input to drive the modulation of the laser once again. The properties of the delayed output thus feed back into the system to modify the input, which in turn generates a new output and so on, in a periodic (oscillatory) manner. This is clearly not a simple system and, indeed, such oscillators exhibit a wide range of rich dynamics[2] (Fig. 1b).

One common application of optoelectronic oscillators is to use the feedback between input and output to force the system to generate a precise repetitive signal that can be used as an ultrastable clock at microwave frequencies for applications such as radar[5]. But optoelectronic oscillators can also be configured to generate chaotic noise-like waveforms over a wide range of frequencies, and it is the novel dynamics of this regime that Callan and colleagues[4] have investigated in their study. The particular originality here lies in the authors' ability to switch the dynamics of the system in a controlled way between two fundamentally different states. By increasing the amplitude of an applied perturbation (noise from an optical amplifier), they can study the transition from the system's steady state to a mode of broadband chaos. The transition regime is associated with the generation of a series of ultrashort pulses that slowly grow in amplitude and progressively merge until the fully developed chaotic regime is reached. Although the noise characteristics of the generated chaos are subtle, a specific characteristic of the system output is that it is 'featureless'. In other words, there is essentially no residual signature of any periodicity in the output even though the noise is actually generated by a cyclic oscillator. The authors[4] mention one particular application of their system in distributed sensor networks (used, for example, in automated information gathering in areas such as home energy management and real-time object tracking). In addition, their system could also have real advantages in applications to improve communications security[6], in which alternative chaos-generating nonlinear delay-based systems[7] have shown real promise at data transmission rates above 10 Gbit s−1. The results will also have a wide impact on the fundamental science of nonlinear dynamics because they highlight how optoelectronic systems provide versatile bench-top tools to study the dynamics of nonlinear delay systems. The advanced technological development of optoelectronic components allows convenient manipulation of almost all the important system parameters, such as delay, nonlinearity, and the form and frequency bandwidth of the dynamic response. In addition, although Callan and colleagues' work considers only one oscillator, a natural extension would involve coupling between several oscillators. This would open up new perspectives for studying synchronization dynamics[8] and neural-network-like approaches for informatics such as the emerging field of reservoir computing[9]. Optoelectronic systems allow researchers to create a 'bench-top nonlinear simulator' of essentially any complex system of interest, and their increasingly widespread use is sure to provide further insights into the science and applications of chaos.

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