TEMPORAL KERR CAVITY SOLITONS IN OPTICAL RESONATORS

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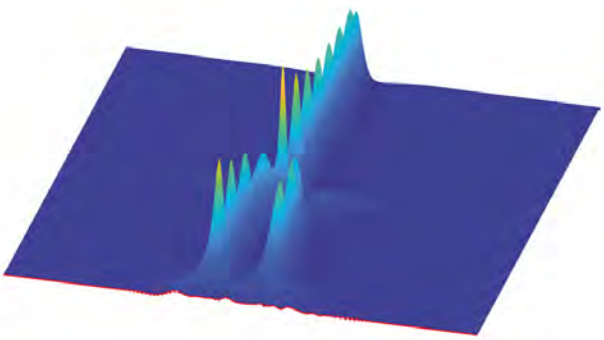


Cavity Solitons are short optical pulses that propagate indefinitely in driven optical resonators. They are sustained by a double balance which prevents them from spreading or declining. This complex mechanism makes them "dissipative structures", a general term coined by Ilya Prigogine to describe patterns emerging from noise in nonlinear systems. In the past decade, cavity solitons have attracted a lot of attention both for their fundamental interest and many potential applications. This article aims at introducing the reader to these fascinating objects.

https://doi.org/10.1051/photon/202312252

Pattern formation is a subfield of nonlinear physics which studies the spontaneous formation of ordered structures in homogenous dissipative systems. It was pioneered by Alan Turing with his seminal paper 'the chemical basis of morphogenesis" and Nobel Prize laureate Ilya Prigogine, who coined the term "dissipative structure" to describe the patterns. They showed that the combination of autocatalytic (nonlinear) chemical reactions and transport (diffusion), may lead to the spontaneous formation of ordered patterns. A well-known example is the so-called 'Brusselator' model, describing a system of four simple reactions where the homogenous state becomes unstable for certain parameters. The dissipative structures that emerge from noise are sustained by a double balance between dissipation and injection on the one hand and diffusion and nonlinearity on the other. Dissipative structures are unique, robust attractors with large basins of attraction. When the system is driven out of equilibrium, into the basin, it always converges to the same dissipative structure. Because nonlinearities and transport are ubiquitous in nature, many different physical systems are prone to the spontaneous emergence of patterns. Well-known examples include roll clouds or windblown ripples in the sand (see Figure 1). Not all are fully understood, or describable using simple models but, in some cases, the agreement between experiments and simple reaction-diffusion type equations can be striking.

OPTICAL DISSIPATIVE STRUCTURES

The agreement between theoretical prediction and experimental observation is nowhere more striking than in optics where Fabry-Perot resonator incorporating a Kerr nonlinear medium have been shown [1,2] to be remarkably well modeled by an equation very similar to the reaction diffusion models used by Prigogine. Two different configurations, shown in Figure 2, are possible. Spatial resonators, where the pattern is transverse to the propagation direction and temporal (dispersive) resonators where the pattern emerges in the longitudinal direction. In these resonators, the loss is compensated by coherent driving and the diffraction (or dispersion) is compensated by the Kerr nonlinearity of the intracavity medium. Both are •••

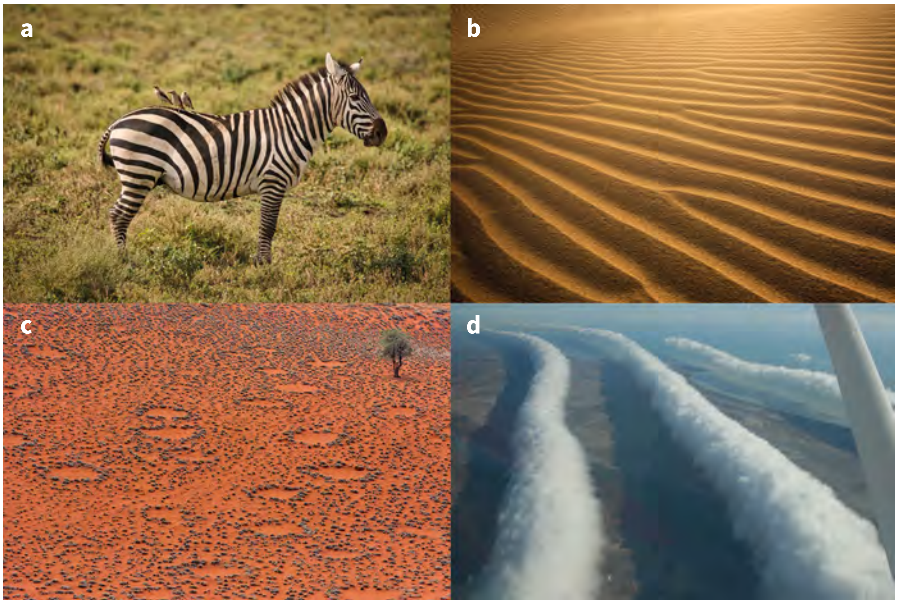


Figure 1. Examples of the spontaneous formation of patterns in Nature. The field of nonlinear pattern formation aims at modelling and understanding this ubiquitous behavior. In optics, time domain patterns consist in very short optical pulses that form spontaneously from noise (see the table of contents image). (a,b,c) © istock ; (d) © Mick Petroff Wikipedia.

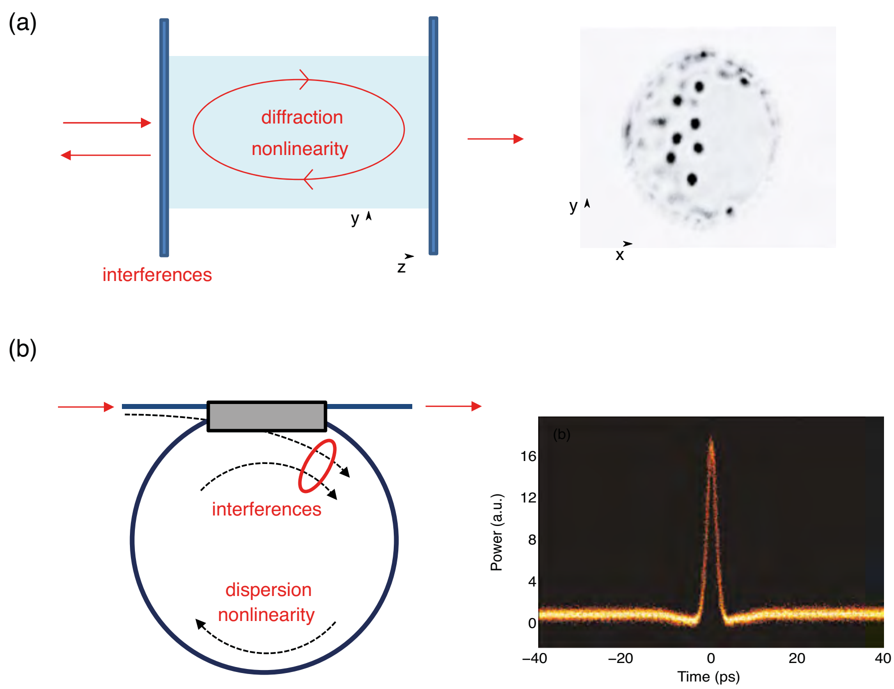


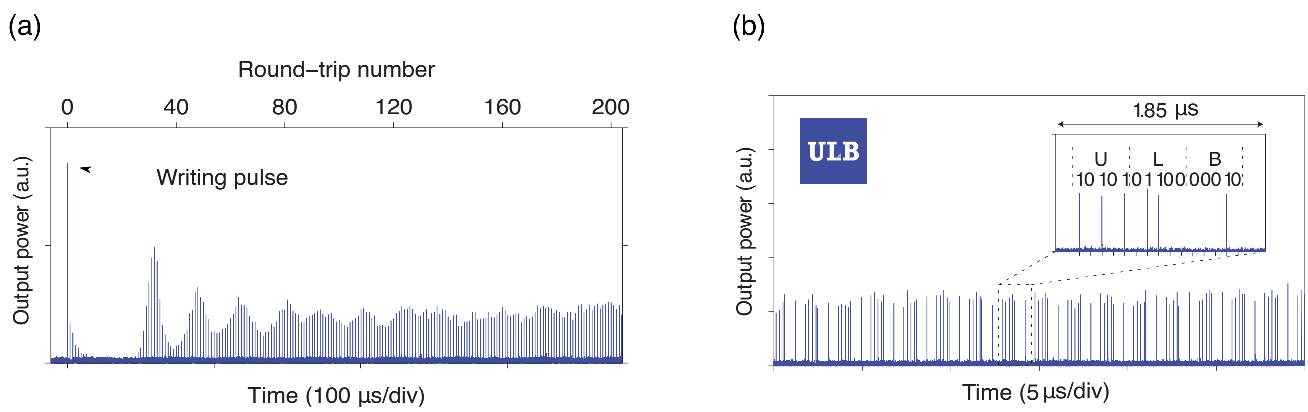
Figure 2. Cavity solitons have been demonstrated in both spatial (a) and temporal (b) configurations. In a spatial Fabry-Perot resonator, the driving beam is homogeneous and the solitons consist of bright localized spots. In a temporal Fabry-Perot resonator, the light is confined in a guided mode (an optical fiber for example) and the localization occurs in the time domain (short pulse). Interestingly, both are described by the same equation: the driven dissipative nonlinear Schrodinger equation, often called the Lugiato-Lefever equation [1]. (Figure 2a) taken with permission from X. Hachair *et al.*, Phys. Rev. A **69**, 043817 (2004); (Figure 2b) taken with permission from Opt. Lett. **41**, 4526 (2016).

well described by a simple equation, the driven dissipative nonlinear Schrodinger equation, which is also used in many other fields, such as condensed matter science and hydrodynamics. In plasma physics, localized sech-shaped solutions of the equation called "cavitons" have been theoretically and experimentally investigated since the 1980s. In the context of optics, the same solutions correspond to stable localized optical structures that travel indefinitely in the resonator and are called 'cavity solitons' (CSs). In dispersive resonators, they are temporal pulses while in the spatial case they correspond to localized spots (see Figure 2). The first experimental observation of cavity solitons was the spatial version, obtained in a semiconductor microcavity [3] and the temporal version was later observed in a fiber cavity [4]. The one-dimensional temporal version is the focus of the present article.

DRIVEN OPTICAL SOLITONS

As short robust pulses, temporal CSs are strongly connected to mode-locked lasers, which are the most common systems for the excitation of short pulses. Pulse train generation is a very important subfield of optics, one that finds many applications, from optical clocks to micromachining. Mode-locked lasers may host solitons which are also sustained by a double balance between the Kerr nonlinearity and second

Figure 3. Experimental excitation of cavity solitons. (a) A writing pulse is sent in the cavity when no solitons are present. After a short period of time, a soliton emerges and oscillates until it settles to a stationary state. Residual oscillations are due to noise (mostly driving laser noise). (b) Bit storage using cavity solitons by sending several writing pulses. The chosen pattern corresponds to ASCII code for ULB (Université libre de Bruxelles). The bit stream is stored and repeats at the output as long as the driving beam (continuous wave) is sent to maintain the 6 solitons in the resonator. In a fiber cavity, storage of up to 4500 bits has been demonstrated. Taken from F. Leo *et al.*, Nat Photon **4**, 471 (2010) with the authorization of Springer Nature.



order dispersion on the one hand and gain and loss on the other hand. The difference is that CSs are "driven" solitons. The energy is provided through coherent interaction, while the gain in mode-locked laser is incoherent. This seemingly minor difference leads to fundamentally important differences between pulse trains generated from a driven Fabry-Perot and from a laser. Driven solitons coexist with a stable homogeneous state. The system is bistable, and the background is the same whether a soliton is present in the cavity or not. This is because the driving saturation is "local", which is very different than lasers where the stored energy in the medium is most often distributed across the cavity roundtrip time. CSs are hence independent from one another and can be individually excited and erased, which opens exciting possibilities for storing and processing information using light [4]. An example of cavity soliton excitation and short bit string storage in a fiber cavity are shown in Figure 3. A simulation of the writing process corresponding to these experimental parameters is shown as the table of content image. A short pulse (at a different wavelength) is sent in the cavity and triggers a local instability which gradually transforms into a soliton. This transient dynamic highlights the connection to dissipative structures forming out of equilibrium as introduced by Prigogine.

Coherent driving also allows for other interesting possibilities for applications. By modulating the driving, solitons can be manipulated which allows to reconfigure the pulse trains [5]. Solitons can be added or removed, temporally shifted or frequency shifted, providing unprecedented dynamical flexibility for pulse train generation.

Moreover, as dissipative structures and solitons, CSs are unique attractors such that the power, duration and phase are fixed by the experimental parameters. Any local perturbation would lead to a restoring force for these parameters, such that CSs tend to shed noise in both quadratures. This makes them well suited for the generation of low phase noise signals. So-called quiet points can be found or engineered where the soliton's parameters have little dependence on the driving frequency, hence cleaning the driving signal. Very low phase noise RF signals have been demonstrated using CSs.

PLATFORMS AND APPLICATIONS

CSs can be excited in any Kerr nonlinear temporal resonators (see some examples in Figure 4). Beyond fiber cavities, they have been generated in photonic integrated circuits (PICs) [6] and in bulk free space cavities [7] where sub-40 fs solitons have been excited. Microresonators are probably the most striking and promising platform for future applications. Beyond the obvious portability and low-power operation of PICs, the excitation of stable CSs in microscale resonators lead to the generation pulse trains at very high repetition rates (up to the THz range), which is not easily achievable with other technologies. Integrated lasers exist but the emission of ultra-short pulses remains a challenge. CSs can be very short and have the advantages of emerging naturally in purely passive systems, greatly facilitating the design of the PIC as compared to lasers where gain and saturable absorbers need to be integrated. High repetition-rate microresonator CSs have been harnessed for telecommunications and calibration of astronomical spectrographs amongst other applications.

LIMITATIONS

All these interesting features come with a caveat. The local gain saturation, which allows for multistabilty, also means that the conversion efficiency is low. In a passive resonator, energy conservation imposes that the maximum output peak power is the input power. It is not a strict limit because of weak temporal coupling (dispersion) but it is a good rule of thumb. In a soliton configuration, the resonator hence acts as a fast shutter, generating stable short pulses, but with very weak output power. This is in striking contrast with lasers where ultra-high peak power can be achieved.

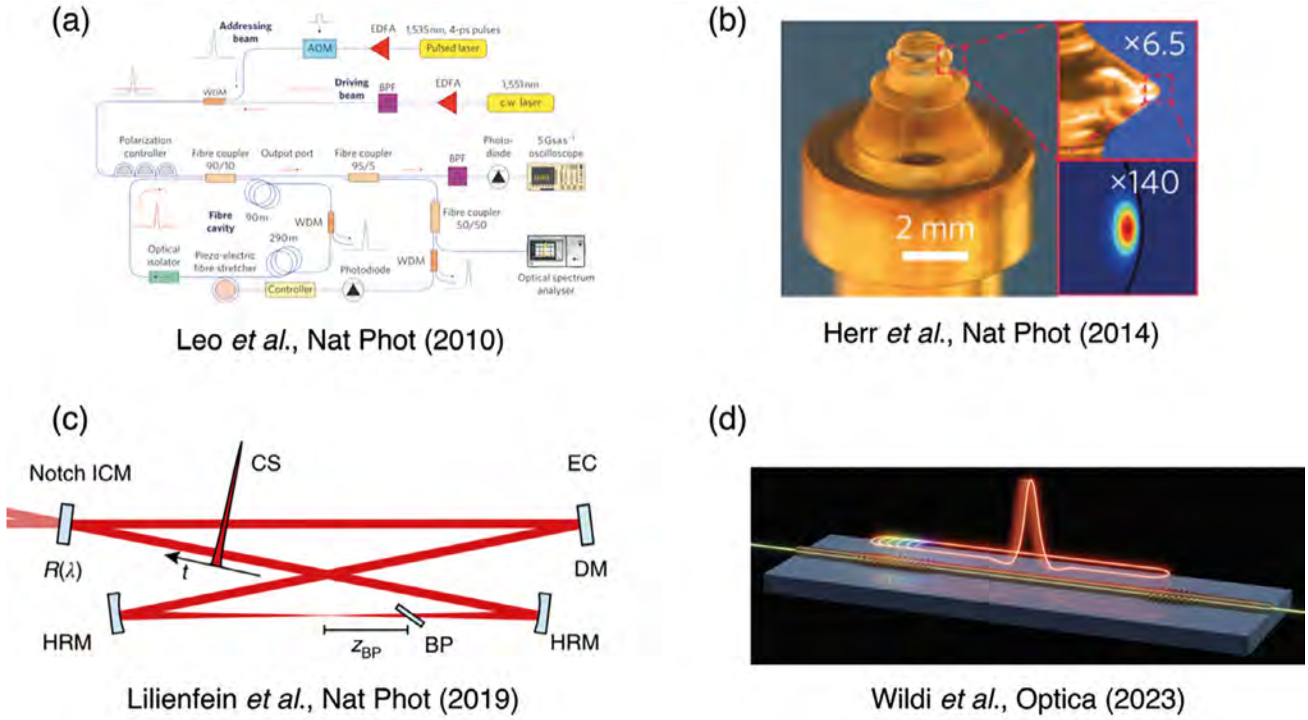


Figure 4. Cavity solitons are very general and can be excited in any type of Kerr nonlinear resonator. Solitons have been excited in fibers, microresonators and bulk cavities among others. Integrated photonics is interesting for applications requiring high repetition rate pulse trains such as telecommunication and parallel ranging (LidAR). Many different platforms have emerged in the past decade, using materials such as Silicon nitride, Aluminum Gallium Arsenide or Lithium Niobate. Figures taken with authorization from (a) F. Leo *et al.*, Nat Photon **4**, 471 (2010); (b) T. Herr *et al.*, Nature Photonics **8**, 145 (2014); (c) N. Lilienfein *et al.*, Nature Photonics **13**, 214 (2019); (d) T. Wildi *et al.*, Optica **10**, 650 (2023)

NOVEL DIRECTIONS

These limitations triggered a wealth of recent studies aiming at increasing the output power. Recent proposals include coupled resonators, where a second resonators is introduced to store and redistribute the pump power; Parametric driving, where nonlinear phase sensitive amplification is used to drive the resonator; and active cavities, where both incoherent gain and coherent driving are harnessed to generate high power phase locked solitons. Moreover, many novel platforms for integrated soliton generation are emerging. For example, materials which also possess a second order nonlinearity, such as III-V semiconductors or lithium niobate can be used to convert the soliton to novel spectral regions such as the visible or the midinfrared, which is important for spectroscopic applications.

CONCLUSION

Starting as a mere curiosity, predicted first in charge density waves and driven plasmas, CSs have now evolved into a burgeoning area of research with both fundamental and applied interest. The field of CS generation in nonlinear resonators is evolving in many promising directions, from new ways of driving resonators to novel integrated platforms.

The author thanks Miro Erkintalo and Pedro Parra-Rivas for their help.

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