Fifty years of the fiber soliton

John M. Dudley is at the University de Franche-Comté and the CNRS Research Institute FEMTO-ST in Besancon, France.
Christophe Finot is at the University de Bourgogne and the CNRS Research Institute ICB in Dijon, France.
Goëry Genty is at the Tampere University of Technology in Finland.
Roy Taylor is at Imperial College London in the United Kingdom.

The study of temporal solitons has revolutionized fiber optics, yielded new classes of ultrafast laser, and opened multiple new interdisciplinary applications.

The year 2023 represents fifty years since Akira Hasegawa and Fred Tappert predicted that temporally-localized solitons could be generated in optical fiber. Temporal soliton physics now underpins many areas of ultrafast photonics including laser design, frequency comb generation, and interdisciplinary studies related to complexity and rogue waves.

Early solitons

In August 1834, Scottish engineer John Scott Russell saw an extraordinary sight on the Union Canal near Edinburgh. While studying how hull design influenced the canal boat speed, he observed what he called a "great solitary wave" that travelled for miles without spreading. We now understand that such stable wave propagation requires a precise balance between linear and nonlinear effects, and the study of such solitary waves or **solitons** has become central to the field of nonlinear science.

Solitons in optics were first observed in the early 1960s in spatial trapping and filamentation seen when the newly invented laser was focused into dielectrics and other media. These results were interpreted in terms of the balance between linear diffraction and spatial self-focusing (the nonlinear Kerr effect), and described using a new model - the **nonlinear Schrodinger equation (NLSE)**. In 1973, Hasegawa and Tappert showed that the 1-dimensional NLSE described pulse propagation in optical fiber, and they predicted the existence of stable temporal solitons that could be used for optical communications. Unfortunately, neither the waveguides nor the sources to test this experimentally were available at the time, and it took until 1980 to see fiber solitons in the laboratory. The success of these experiments, however, launched a revolution. The timeline in Figure 1 shows a selection of highlights.

Soliton basics

When a light pulse is injected in an optical fiber at low power, it experiences linear dispersion due to variation of the effective refractive index across its bandwidth. This induces a phase shift between its spectral components, and the pulse spreads out temporally by an amount depending on the fiber **group velocity dispersion (GVD)**. At higher power, nonlinear effects develop because an intense pulse modifies the refractive index through the optical Kerr effect resulting in an intensity-dependent **self-phase modulation (SPM)**. At wavelengths above around 1.3 μm in conventional silica fiber (the "anomalous dispersion" regime), the induced phase shifts from GVD and SPM can balance, and it is this that leads to the stable **fundamental soliton.** It turns out, however that stable solitons are only one of many solutions to the NLSE. Indeed, the initial concept of a soliton as being associated with invariant propagation can be generalized to include a much wider range of physical behavior resulting from the interaction between dispersion and nonlinearity. Such solutions typically include strong localization (temporal or spatio-temporal focusing), and can also display **periodic or breather** behavior.

Observing a particular type of soliton involves carefully matching fiber parameters and initial conditions, and **Figure 2** shows some of the different fiber solitons that can be excited. It is important to distinguish solitons excited by short pulses, and a broader class of **breather solutions** excited by a modulated or noisy continuous wave (CW). Also note that the dispersive and nonlinear evolution of a CW field is also described by the terminology of **modulation instability**. All the solitons shown in the figure are excited with anomalous dispersion except for the dark soliton as indicated. This is observed with normal dispersion as an intensity dip on a continuous background.

Solitons for communications.

The idea to use fiber solitons as information carriers was because they do not experience dispersive broadening. However, dispersion is not the only bottleneck in a fiber communications network – another limit is the intrinsic loss of glass, that attenuates a signal over long distances. Overcoming loss in soliton systems was therefore an early priority. Interestingly, it was a nonlinear effect – **Raman amplification** – that was proposed as a solution in 1983, and there was much excitement in 1988 when AT&T Bell Labs reported soliton transmission over 4000 km using distributed Raman gain. A disadvantage was that Raman amplification required high pump power, but it was clear that soliton transmission was robust and compatible with amplification. This said, other approaches were also studied, and a 1987 alternative was to accept the presence of loss, but to modify dispersion with distance to maintain the soliton condition, even as power decreased. Although elegant, such **dispersion decreasing fibers** were problematic from a development perspective, as they required precise fabrication control.

By 1989, however, an ideal solution presented itself with the Erbium-doped fibre amplifier (EDFA) which enabled amplification at much lower pump powers. Using EDFAs in soliton systems quickly became the favored approach, and by 1991 experiments had shown 10 Gbit/s transmission over a million kilometres. These experiments revealed deleterious effects such as soliton-soliton interactions and **Gordon-Haus timing jitter**, but ingenious solutions were quickly found through temporal and spectral filtering. By 1995, the **dispersion-management** concept was developed, concatenating fiber segments of opposite signs of dispersion but with a path average value that was low and anomalous. This greatly improved design flexibility, and laboratory “hero experiments” routinely yielded multi-10s of GBit/s transmission, at multiple wavelengths, and over trans-oceanic distances. Although it is often believed that soliton systems were never deployed outside the laboratory, a commercial dispersion-managed soliton system was installed in 2002 between Perth and Adelaide in Australia, eventually using 80 wavelength channels at 10 Gbit/s. However, scaling soliton systems is problematic, and subsequent long haul networks did not use soliton transmission. Nonetheless, **the legacy of soliton systems** is embedded in virtually all aspects of today’s optical communications networks, with optimised dispersion maps and techniques of nonlinearity mitigation being integral to achieving maximum bandwidth.

Ultrafast solitons in lasers.

Solitons attracted interest from the laser community when higher-order solitons were used for external pulse compression. Specifically, by injecting a picosecond pulse with a large soliton number (from an ultrafast laser) into fiber, sub-50 fs pulse generation was straightforward. Moreover, by exploiting the Raman soliton self-frequency shift, tunable pulse generation over 100's of nanometres was possible, providing another degree of freedom in pulse control. Soliton dynamics could extend the **generation and shaping of ultrashort pulses from lasers** into new regimes. The next step was to look for soliton effects inside the lasers themselves. The pioneers were Mollenauer and Stolen in 1984, who generated 150 fs pulses by coupling a mode-locked color center laser to a second cavity containing fiber. The idea was to excite stable soliton propagation, but the pulse shortening mechanism was actually shown to arise from interference between the pulse in the main cavity and the returning chirped pulse from the fiber. This was still a crucial milestone, and soliton concepts were rapidly applied to design ultrafast lasers.

The availability of rare earth doped fibers drove rapid growth in the ultrafast fiber laser industry in the 1990s. Although initial work targeted designs with circulating fundamental solitons, it was soon realised that stable pulses were generated over a wide parameter space balancing gain, loss, nonlinearity, dispersion, and a saturable absorber effect to sustain modelocking. In fact, even though an ultrashort pulse evolved significantly in a cavity, the only requirement for stable laser operation was that the pulse reproduced itself over a roundtrip. This led ultrafast lasers to be described as **dissipative soliton** systems. **Figures 3a and 3b** shows key design elements, and the balance between pulse-shaping mechanisms. Commercial interest has tended to favour saturable absorbers such as SESAMS or carbon nanotubes, but there are also all-fiber formats using nonlinear polarization rotation or nonlinear loop mirrors.

Some work did not involve fiber at all. Rather, soliton concepts were used to optimise dye and solid-state lasers by compensating SPM in the gain medium with GVD control using prisms or gratings (and later chirped mirrors). Although the nonlinear and dispersive effects occur in lumped elements rather than continuously as in a fiber, the same physics of soliton shaping governs the intracavity dynamics. Few-cycle pulse generation is now routine from such lasers, and probably the most widespread is the **Kerr-lens modelocked** Ti:Sapphire laser. This system is especially interesting, because the saturable absorber effect (originally discovered fortuitously) arises from nonlinear spatial self-focussing in the gain medium combined with a suitably positioned aperture (see **Figures 3c and 3d**). In a sense, since it exploits both temporal and spatial nonlinear effects, it can be considered a soliton laser in more ways than one.

Solitons and supercontinuum

The excitation of bright solitons in fiber requires anomalous GVD, and in conventional silica fiber, this meant that early experiments could only be carried out at wavelengths above 1.3 μm. However, this constraint was lifted in the late 1990s with the development of the microstructured or **photonic crystal fiber** (PCF), where a silica core is surrounded by a silica cladding with a periodic arrangement of air holes. Guidance in such a fiber arises from an effective total internal reflection mechanism (as in conventional fiber), but the extra degrees of freedom of air hole diameter and spacing enabled a new approach to dispersion engineering. In particular, it became possible with PCF to fabricate silica-based fiber with zero dispersion at much shorter wavelengths around 700-800 nm. Significantly, these wavelengths coincided with the operating range of the modelocked Ti: Sapphire laser. And it was by injecting femtosecond pulses from such a laser at 790 nm into a fiber with zero dispersion around 770 nm that **broadband supercontinuum generation** in PCF was observed in 1999. The dramatic spectral broadening attracted immediate attention for applications in optical frequency metrology, a field later recognized with the 2005 Nobel Prize in Physics to Hall and Hänsch.

Understanding the physics of supercontinuum generation was a challenge, but it was soon clarified that it centered on soliton dynamics. Specifically, the input pulse could be considered as a higher-order soliton that underwent temporal compression before effects such as third-order dispersion interrupted its expected periodic evolution and induced **soliton fission** - the ejection of a series of fundamental solitons. The spectrum was then shifted to shorter wavelengths through dispersive wave generation, and to longer wavelengths from the Raman soliton self-frequency shift. Interestingly, this underlying physics had essentially been identified in earlier fiber experiments studying spectral broadening over narrower bandwidths, but it was the unique properties of PCF that made the soliton signatures of supercontinuum generation so apparent. With the dynamics understood, a significant industry for supercontinuum sources has now developed for applications such as imaging, materials inspection, and microscopy.

Solitons in gases

Another class of PCF has enabled studies of soliton dynamics in gases. In particular, propagation in **hollow core PCF** guides light differently from standard fiber, confining light to a low-index hollow core by a two-dimensional photonic bandgap. One important early application in 2003 was megawatt peak power pulse transmission. This result was a dramatic scaling of soliton dynamics since typical interactions in solid core fiber were associated with only kilowatt peak powers. This scaling exploited the balance of the low intrinsic nonlinearity of air with engineered fiber GVD, and it was later shown that by filling the hollow core PCF with suitable gases, the fiber GVD could be easily tuned by varying gas pressure. This was a simple yet profound development that has opened up new regimes of temporal soliton physics. Results here include soliton compression to few-cycle pulses, widely tunable ultraviolet light sources, and novel soliton-plasma interactions. Recent work has used hollow core “capillary” fibers with radii around 100 μm to scale soliton dynamics even further, to multi-millijoule energies and terawatt peak powers.

Unstable solitons and rogue waves

Although the initial defining feature of temporal solitons was their stability, an extensive body of work has since studied the characteristics of unstable solitons generated from noise. A key result from 2007 introduced the concept of **optical rogue waves,** or random solitons emerging from supercontinuum generation. Specifically, noisy input pulses from a laser yield variable initial conditions such that solitons ejected from soliton fission propagate with different trajectories in both time and wavelength domains. A small number of solitons shift to very long wavelengths, and their statistical rarity and associated long-tailed probability distribution are analogous to the properties of the giant rogue waves on the ocean. Optical rogue waves have also been studied in noise-driven modulation instability. The dynamics here do not involve soliton fission, but rather the spontaneous localization of random peaks emerging from the breakup of a continuous wave or long pulse. These peaks can be interpreted (at least locally) in terms of the breather or soliton on finite background solutions to the NLSE shown in **Figure 2**.

Other developments

Although most studies of fiber solitons have considered propagation in the fundamental fiber mode, recent work has developed a more general picture of **soliton evolution in multimode fibers**. The idea here is to create conditions for different spatial modes in a fiber to propagate with the same group velocity (and to see anomalous GVD) so as to excite a multimode, yet stable, spatio-temporal envelope. Multimode soliton theory is complex, involving advanced simulation of coupled NLSEs, and bringing in subtle concepts from thermodynamics to interpret the observed behavior. Impressive results have been obtained observing spatio-temporal confinement in both step- and graded-index fibers, with potential applications in high power supercontinuum and fiber lasers, as well as in increased communications system capacity.

Another area of significant current interest is the study of trains of **temporal cavity solitons** in micro-resonator frequency combs. Although supercontinuum frequency combs also involve soliton dynamics, the microcomb exploits the ultra-precise temporal-locking of a regular train of solitons circulating within a microresonator cavity. The underlying dynamics are governed by the Lugiato-Lefever equation, very similar to the NLSE. Microcombs have tremendous potential in many areas of science, and it may well be that they become the main area where temporal solitons find direct societal applications in the future.

Perspectives and Conclusions

Anniversaries in science provide the opportunity to both recognize the pioneers who created a research field, as well as to reflect on the body of work that has resulted. And in the rush to develop new and better optical devices, we sometimes forget just how useful it can be to think about ideas that have come before, as they can often be a source of new inspiration. In the case of the temporal soliton, it is clear that there is an enormous amount to celebrate in its history. As an overview, **Figure 4** summarizes the many different areas discussed above where temporal solitons have major application impact. The Internet infrastructure that we rely on today embeds soliton design concepts in its core, and ultrafast science as we know it would not exist without the control of soliton dynamics in lasers. The study of soliton dynamics is a central area of the broader field of nonlinear dynamics and complexity, essential to understand phenomena ranging from pandemic evolution to climate change. Studies of soliton effects in other fields of physics are also building directly on processes first studied in fiber. But even as this broader work develops, the simplicity of optical systems may well mean that fiber solitons remain the clearest way to explore even the most exotic effects in nonlinear science.

References and Resources

A.Hasegawa, F. Tappert. Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. Anomalous dispersion. Appl. Phys. Lett. **23**, 142 (1973)

A.Hasegawa, F. Tappert. Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. II. Normal dispersion. Appl. Phys. Lett. **23**, 171 (1973)

J. R. Taylor (Ed.) Optical Solitons: Theory and Experiment. Cambridge University Press (1992)

A. Ankiewicz, N. Akhmediev. Solitons: Nonlinear Pulses and Beams (1997)

Philip St. J. Russell. Photonic Crystal Fibers. Journal of Lightwave Technology **24** 4729 (2006)

J. M. Dudley, J. R. Taylor (Eds) Supercontinuum generation in optical fibers. Cambridge (2010)

J. M. Dudley, M. Erkintalo, G. Genty. Rogue Waves of Light - Optics & Photonics News **26** (11) 34-41 (2015)

G. P. Agrawal. Nonlinear Fiber Optics. Sixth Edition. Elsevier (2019)

U. Keller. Ultrafast Lasers. Springer (2021)

List of Tables and Figures

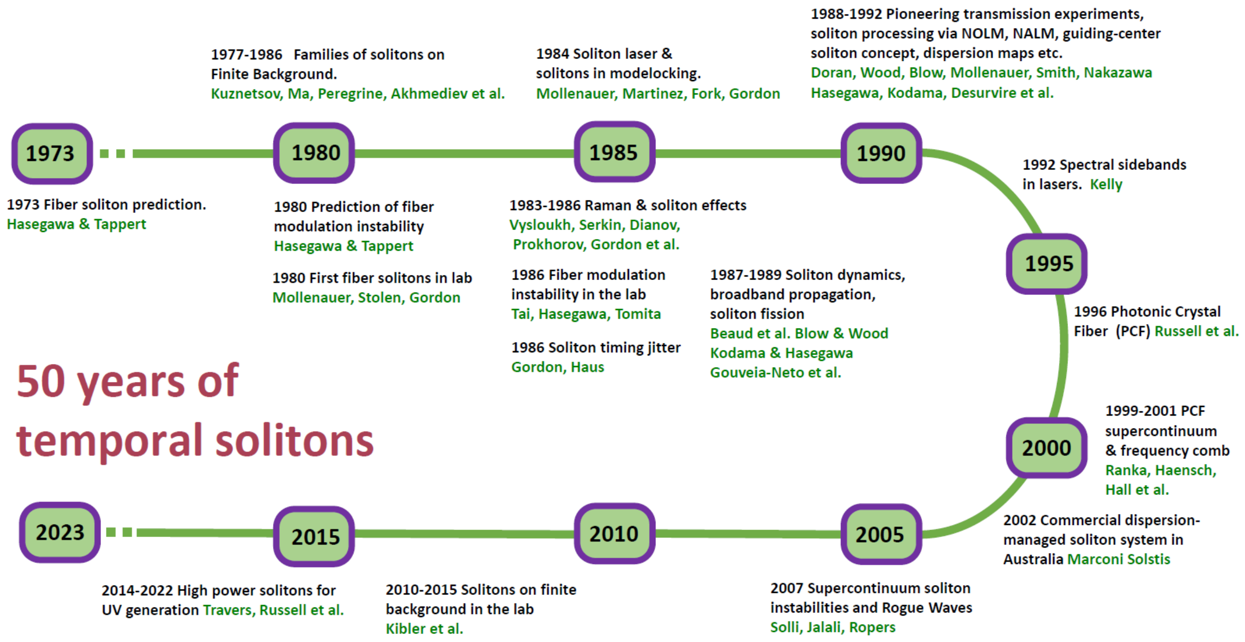


Figure 1 **Timeline.** Landmark results studying temporal solitons in optical fibers and lasers. NOLM: nonlinear loop mirror. NALM: nonlinear amplifying loop mirror.

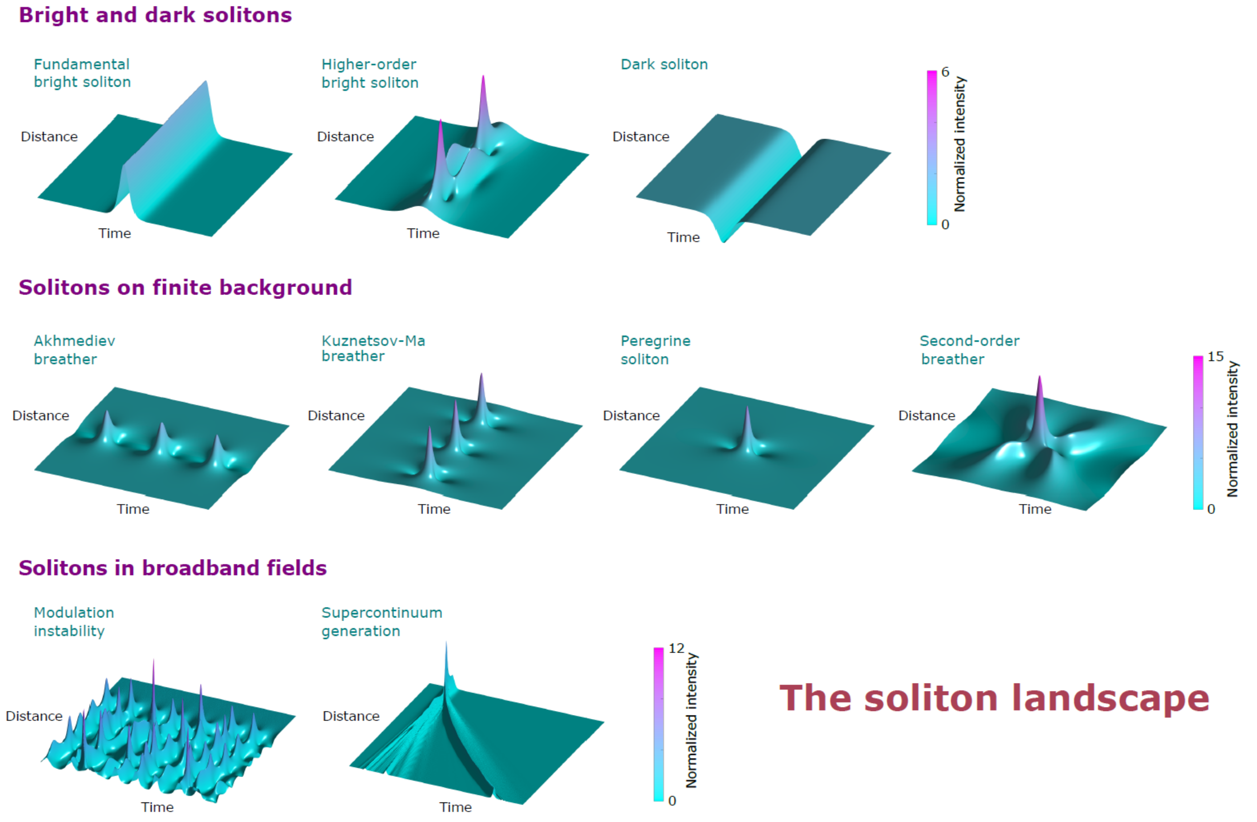
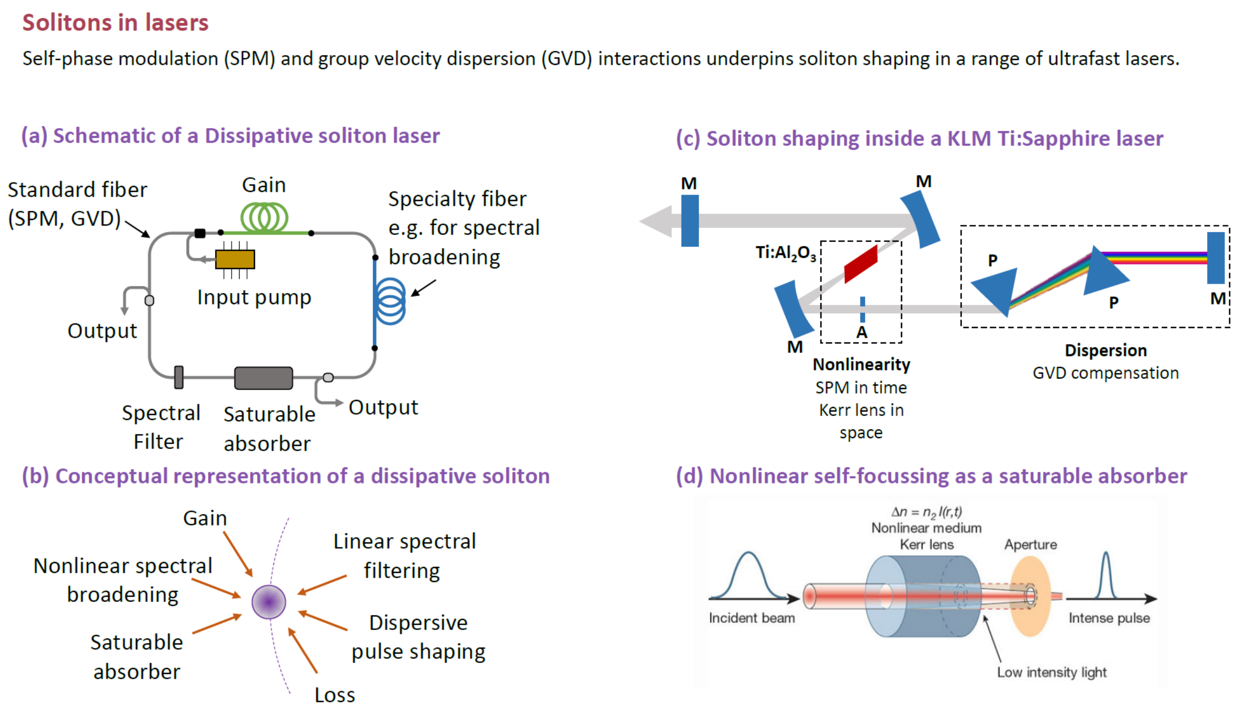


Figure 2 **The soliton landscape.** Known analytic results and numerical simulation of different classes of soliton and soliton dynamics that have been observed in optical fiber. Results shown include the fundamental bright and dark solitons as first proposed by Hasegawa and Tappert in 1973, a higher-order bright soliton, several classes of soliton on finite-background, as well as soliton dynamics associated with modulation instability and supercontinuum generation.



Solitons in lasers

Self-phase modulation (SPM) and group velocity dispersion (GVD) interactions underpins soliton shaping in a range of ultrafast lasers.

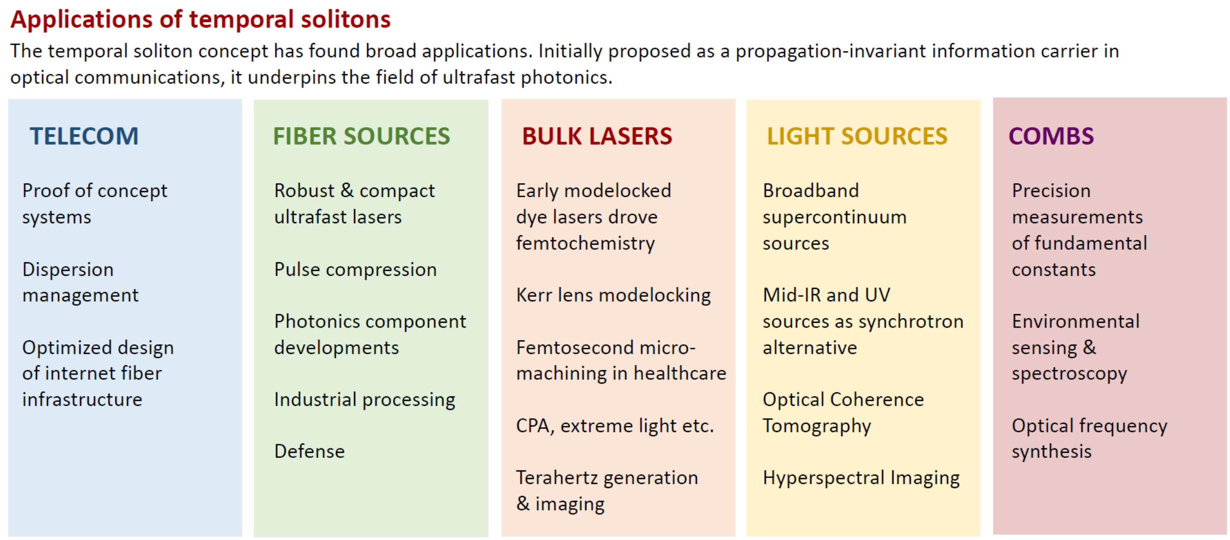
(a) Schematic of a Dissipative soliton laser

(b) Conceptual representation of a dissipative soliton

(c) Soliton shaping inside a KLM Ti:Sapphire laser

(d) Nonlinear self-focussing as a saturable absorber

Figure 3 **Solitons in modelocked lasers.** (a) Schematic of a fiber laser with multiple possible intracavity elements that can lead to "dissipative soliton" formation. (b) A conceptual representation of a dissipative soliton showing how different elements balance to yield a stable operating point. Operation can usually be observed over a range of parameters (dashed line). (c) Soliton shaping in a Kerr lens modelocked (KLM) Ti:Sapphire laser showing how SPM in the gain medium is compensated by GVD using a prism pair. GVD compensation can also be achieved in other ways e.g. chirped mirrors. Here M: mirror, P: prism, A: aperture. (d) Detail of how spatial nonlinear focusing (the Kerr lens) combines with an aperture to create a saturable absorber mechanism able to discriminate between ultrashort pulses which undergo self-focusing and a noise background which does not.



Applications of temporal solitons

The temporal soliton concept has found broad applications. Initially proposed as a propagation-invariant information carrier in optical communications, it underpins the field of ultrafast photonics.

TELECOM	FIBER SOURCES	BULK LASERS	LIGHT SOURCES	COMBS
Proof of concept systems Dispersion management Optimized design of internet fiber infrastructure	Robust & compact ultrafast lasers Pulse compression Photonics component developments Industrial processing Defense	Early modelocked dye lasers drove femtochemistry Kerr lens modelocking Femtosecond micro-machining in healthcare CPA, extreme light etc. Terahertz generation & imaging	Broadband supercontinuum sources Mid-IR and UV sources as synchrotron alternative Optical Coherence Tomography Hyperspectral Imaging	Precision measurements of fundamental constants Environmental sensing & spectroscopy Optical frequency synthesis

Figure 4 **Applications of temporal solitons.** Initially proposed as a propagation-invariant information carrier in optical communications, the temporal soliton now underpins the field of ultrafast photonics.