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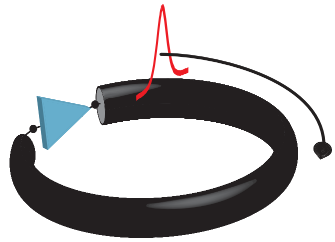
## FEATURES





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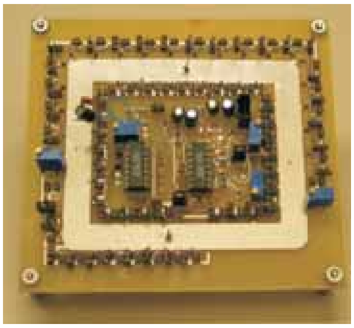

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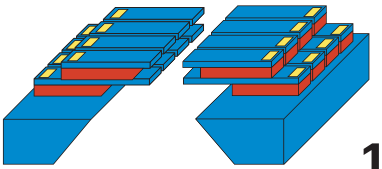

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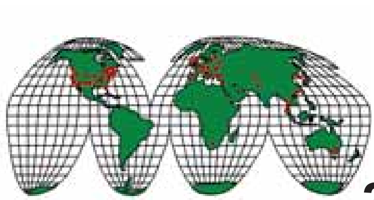

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## DEPARTMENTS



## COLUMNS

# Editor's Column

M.Y. LANZEROTTI

This issue features two University Research Highlights articles. The first article is "Electrical Soliton Modelocking," by David S. Ricketts, Xiaofeng Li, and Donhee Ham at the Harvard University Electronics and IC Research Laboratory, where Prof. Ham is Assistant Professor of Electrical Engineering in the Division of Engineering and Applied Sciences. The website for Prof. Ham's Research Group is: http://people.deas.harvard.edu/~donhee/donheeham.htm

The second article is "Semiconductor Traps for Laser-Cooled Atomic Ions and Scalable Quantum Computing," by D. Stick, W. K. Hensinger, S. Olmschenk, and C. Monroe at the University of Michigan, where Prof. Monroe is Professor of Physics and Director of the NSF Focus Physics Frontier Center (Frontiers of Optical Coherent and Ultrafast Science). The webpage for Prof. Monroe's Research Group is: http://iontrap.physics.lsa.umich.edu.

Thank you again for taking the time to read the LEOS newsletter. We appreciate all of your comments and feedback! Please send comments to myl@us.ibm.com.



## IEEE Lasers and Electro-Optics Society




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# Electrical Soliton Modelocking

*David S. Ricketts, Xiaofeng Li and Donhee Ham*


## Abstract

We recently developed for the first time an electrical modelocked circuit that self-generates a periodic, stable train of electrical solitons. This electrical soliton oscillator was enabled by combining a nonlinear transmission line where solitons can propagate with an amplifier that "tames" the "unruly" dynamics of the electrical soliton. The taming function of the amplifier resembles the saturable absorption in optics. Moreover, the overall oscillator is a direct analog of the soliton modelocked laser in optics. This paper highlights these recent developments with the exciting possibilities they offer.


## Introduction

We recently introduced the first electrical modelocked circuit that self-generates a periodic, stable train of electrical solitons [1-3]. This electrical soliton oscillator, which is a direct analogue of the soliton modelocked laser in optics [4], was made possible by connecting a nonlinear transmission line (NLTL), which supports electrical soliton propagation, around a unique transistor-based amplifier in a circular topology [Fig. 1].

Electrical soliton generation per se is not new: over the past 40 years, the NLTL has been extensively used to create electrical solitons for sharp pulse generation applications [5]. This traditional approach, however, almost exclusively uses the NLTL as a "2-port (input + output)" device that requires an external high-frequency input to produce the soliton output. What distinguishes our circuit is that it is an oscillator ["1-port (output-only)" system] that self-generates electrical solitons without requiring an external high-frequency input, just as is done in the optical soliton laser. This 1-port oscillator is a self-contained, self-regulated system that provides much improved pulse control and quality over the 2-port NLTL.

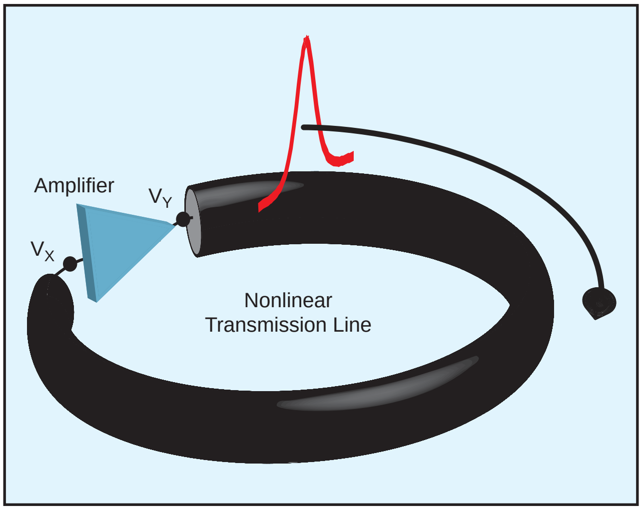


*Figure 1: Electrical soliton modelocked oscillator.*

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By nature, electrical solitons are "unruly," which had rendered previous attempts to build the electrical soliton oscillator unsuccessful, usually resulting in chaotic oscillations [2,6]. The key to our success was finding a way to "tame" the electrical solitons: the transistor amplifier in Fig. 1 was uniquely designed to stabilize soliton oscillation, in addition to providing gain. The stabilizing functionality of this amplifier much resembles the saturable absorber widely used in optical modelocking [4]. Our three prototypes attested to the validity of the electrical soliton oscillator concept, with our latest chip-scale prototype producing a 293-ps soliton pulse width. Now with the concept firmly demonstrated, the soliton oscillator, especially its NLTL, can be quickly scaled and optimized to provide a much narrower pulse width close to 1 ps [7].

As the ultrashort light pulses generated by modelocked lasers have found numerous applications, so too will the picosecond-duration electrical pulses generated by the electrical soliton oscillator. Applications include all-electrical picosecond-resolved metrology [5, 8], time-domain reflectometry (TDR) [9], ranging radars, microwave imaging, and pulse-based wireless or chip-to-chip communications. With this work, the electrical soliton is no longer a specialized laboratory exercise, but can now be engineered and utilized in a medium that touches our everyday lives, modern electronics, for the wide array of applications. This paper highlights these exciting new developments.

## NLTL & Electrical Solitons - A Review

This section briefly reviews electrical solitons on the NLTL to provide the necessary background for our electrical soliton oscillator work presented later. Solitons are a unique class of pulse-shaped waves that propagate in nonlinear dispersive media [10]. They maintain spatial confinement of wave energy in a pulse shape over the course of propagation and exhibit singular nonlinear dynamics. Balance between nonlinearity and dispersion creates the soliton phenomena. Common in Nature, solitons are found in various nonlinear dispersive media, e.g., hydrodynamic solitons in shallow water and optical solitons in fibers [10].

In the electrical domain, the nonlinear transmission line (NLTL), a 1D ladder network of inductors and varactors [Fig. 2(a), top] or alternatively a linear transmission line periodically loaded with varactors [Fig. 2(a), bottom], serves as a nonlinear dispersive medium. In the NLTL, the nonlinearity originates from the varactors while the dispersion arises from the structural periodicity. For certain pulse-shaped voltage waves on the NLTL, the nonlinearity balances out the dispersion, and these pulses propagate on the NLTL maintaining their exact

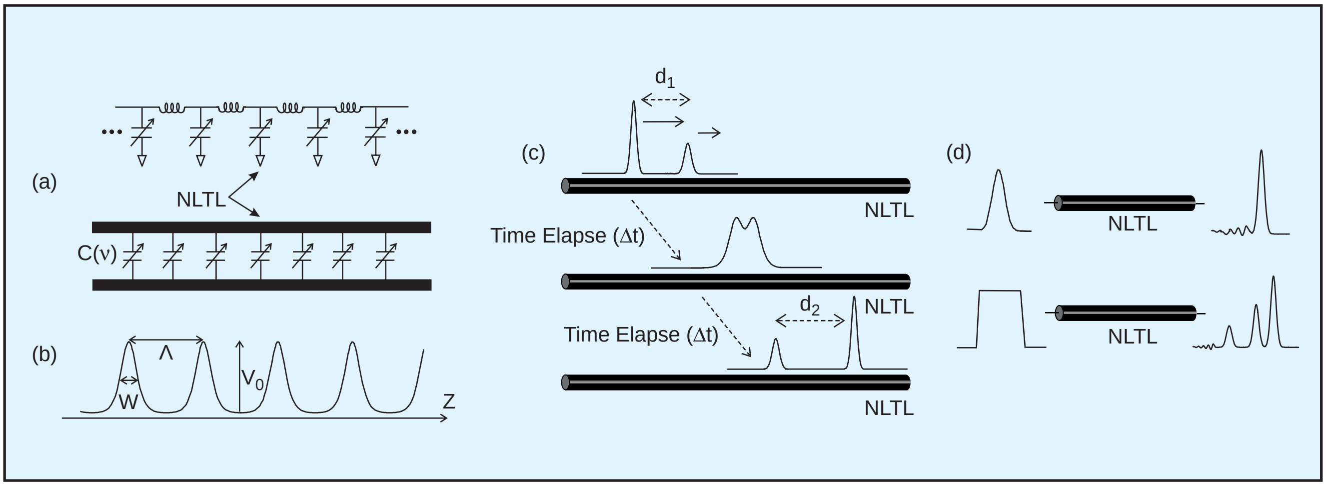
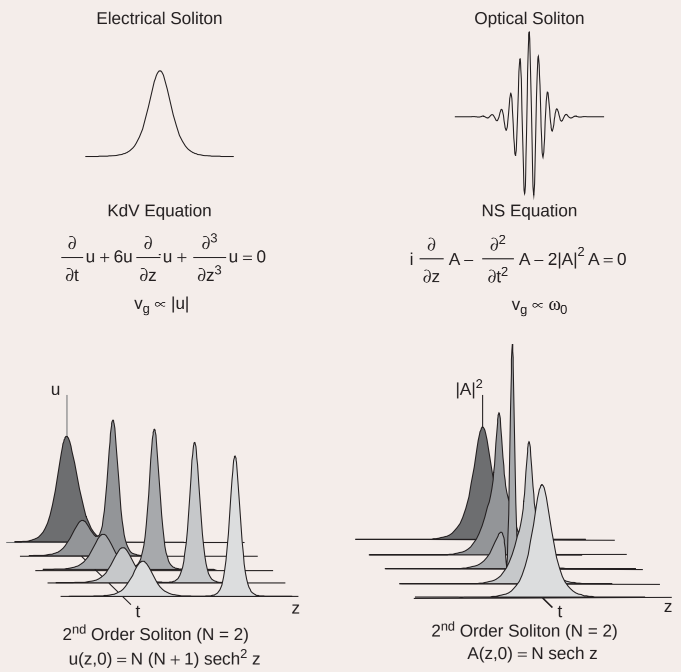



*Figure 2: (a) Nonlinear transmission line (NLTL). (b) A general soliton waveform on the NLTL. (c) Solitons' amplitude-dependent speed and nonlinear collision on an NLTL. (d) Hypothetical transient, soliton-forming processes on the NLTL.*

shape (in the absence of loss). These are electrical solitons described by the Korteweg-DeVries (KdV) equation [10]. The general soliton propagation solution on the NLTL is a periodic train of soliton pulses [Fig. 2(b)]. In the presence of loss, the solitons cannot maintain their exact shape in the course of propagation since they have to lose energy, but they still maintain spatial confinement of wave energy in a pulse shape through a unique soliton damping process [11]. See the inset for comparison between electrical and optical solitons.

In addition to their ability to maintain spatial confinement of wave energy, the electrical solitons on the NLTL possess other unique properties [10]. To begin with, a taller soliton travels faster than a shorter one on the NLTL. Due to this amplitude-dependent speed, if a taller soliton is placed behind a shorter one as shown at the top of Fig. 2(c), the taller one will catch up with the shorter one and move ahead of it after a collision [Fig. 2(c)]. When two solitons collide [middle of Fig. 2(c)], they do not linearly superpose, but rather experience significant amplitude modulations (nonlinear collision). After the collision [bottom of Fig. 2(c)], the two solitons that have returned to their original shapes have however acquired a permanent time (phase) shift, shown by the difference in $d_1$ and $d_2$ in Fig. 2(c). The three soliton properties above, i.e., 1) amplitude-dependent speed, 2) amplitude modulation during




Comparison of the electrical soliton and the optical soliton: Top: The electrical soliton is a baseband pulse with no underlying carrier signal. Middle: The electrical soliton is based on KdV dynamics, while the optical soliton is derived form the nonlinear Schrödinger equation (NSE). Electrical soliton velocity is amplitude dependent. Optical soliton velocity is carrier frequency dependent. Bottom: Shown here is the time evolution of a second order electrical and optical soliton. The second order electrical soliton separates into two solitons, while the second order optical soliton changes shape, or "breathes," as it propagates [10]."

the collision, and 3) phase modulation after the collision, are the key obstacles to constructing a stable soliton oscillator, as will be seen shortly.

Non-soliton waves can also travel on the NLTL, but only by changing their shape to form into a soliton or solitons. A non-soliton pulse close to soliton shape will be sharpened into a soliton [Fig. 2(d), top]. A non-soliton pulse that is significantly different from soliton shape will break up into multiple solitons of different amplitudes [Fig. 2(d), bottom].

It should be finally noted that one can vary the values of the two components (inductors and varactors) comprising the NLTL across a wide range to obtain a specific soliton pulse width over many decades. This is in contrast with the optical fiber whose properties, predetermined by materials and geometry, are not adjustable by the designer.

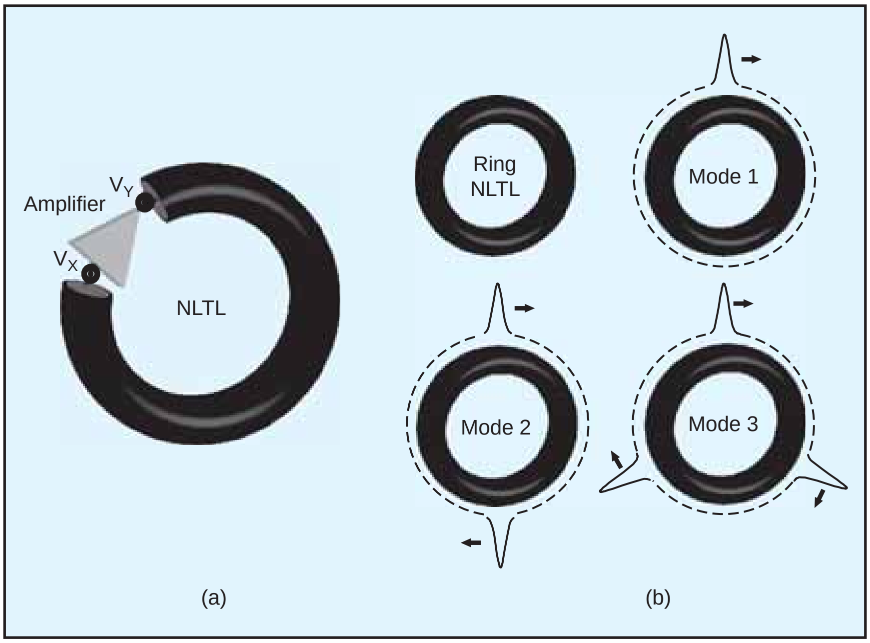



*Figure 3: (a) Soliton oscillator topology. (b) Ring NLTL. Mode 1 ($l = \Lambda$), Mode 2 ($l = 2\Lambda$), Mode 3 ($l = 3\Lambda$).*

## Electrical Soliton Oscillator - Topology and Operating Principles

As pointed out earlier, the essence of our work is the construction of an oscillator that self-generates a periodic train of electrical solitons without requiring an external high-frequency input. The starting idea to build our soliton oscillator was to combine a ring NLTL with a non-inverting amplifier inserted in the ring [Fig.3 (a)] [1,2]. The ring NLTL supports certain soliton circulation modes determined by the periodic boundary condition, $l = n\Lambda (n=1,2,3,\ldots)$ ($l$: circumference of the ring NLTL, $\Lambda$: spacing between two adjacent solitons) [Fig.3(b)]. The intention of the amplifier is to provide gain to initiate startup and to compensate loss in steady state. The ultimate goal of this topology is to self-generate and self-sustain one of the soliton circulation modes of Fig. 3(b).

The topology does indeed lead to oscillations, self-starting from noise. However, when standard amplifiers are used in the topology, the oscillations tend to be plagued with instability problems, exhibiting significant variations in pulse amplitude and repetition rate [2,6]. See Fig. 4

The oscillation instabilities arise because the circular loop topology of Fig. 3(a) not only generates the desired soliton circulation mode, but can also excite other parasitic solitons [1,2]. The desired and parasitic solitons continually collide while circulating in the loop due to their generally different amplitudes and resultant speed difference (due to previously mentioned solitons' amplitude-dependent speed). It is these soliton collision events that cause the significant modulations in the pulse amplitude and repetition rate (these undesirable effects of the soliton collision were described earlier), leading to the oscillation instabilities.

We overcame the instability problems and obtained a stable soliton oscillator in [1-3] by developing a special amplifier, which not only provides gain but also incorporates three stability mechanisms to prevent the soliton collision events in steady state. The three stability mechanisms are:

Reduced signal saturation: If the amplifier saturates its output significantly in Fig. 3(a), the amplifier output will be close to a square pulse. As explained with Fig. 2(d), bottom, this square pulse will break apart into multiple solitons of differing amplitudes, traveling down the NLTL. These multiple solitons will circulate around the loop at different speeds (due to the amplitude-dependent speed), and be again distorted by the amplifier, creating even more solitons of different amplitudes and speeds. This process repeats itself, and the solitons continue to circulate in the loop at different speeds, continually colliding with one another, causing oscillation instabilities. It is therefore necessary to minimize signal saturation.

Perturbation rejection: In steady-state oscillation the amplifier should attenuate any small ambient perturbation (e.g., noise) that could otherwise grow into parasitic solitons. Unless this is achieved, the desired soliton circulation mode and parasitic solitons will propagate at different speeds due to their generally different amplitudes, colliding and building up oscillation instabilities.

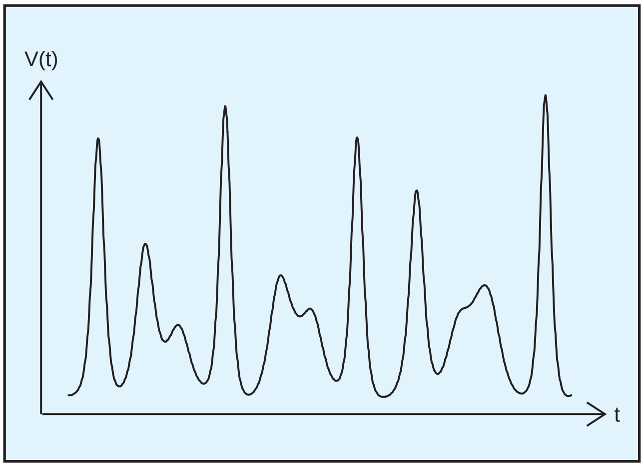


*Figure 4: Unstable oscillations that can result from Fig.3(a).*

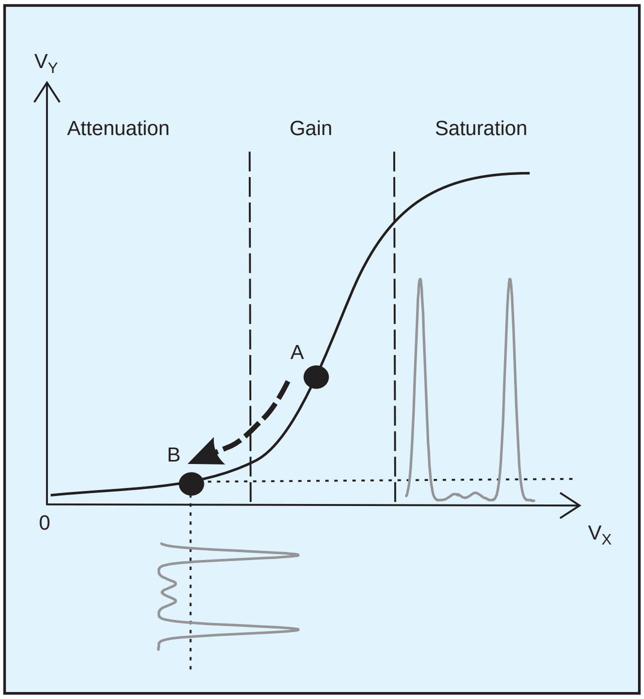


*Figure 5: Transfer curve of a saturating amplifier. Startup bias A is in the gain region. As the dc component of the amplifier output increases in initial transient, the bias is adaptively lowered (dashed arrow) towards steady-state bias B.*

Single mode selection: The amplifier should select a single soliton circulation mode in steady-state oscillation among the many possible modes [Fig. 3(b)]. If this is not achieved, various modes with generally different amplitudes will circulate in the loop at different speeds, leading to soliton collision events and hence unstable oscillations.

In [1-3], we achieved these three stability mechanisms by incorporating an adaptive bias control in a standard saturating amplifier. Figure 5, showing the input-output transfer curve of the saturating amplifier, explains how this is achieved. The transfer curve is divided into the attenuation, gain, and saturation regions based on the curve's tangential slopes. At start-up the amplifier is biased at point A in the gain region so that ambient noise can be amplified to initiate the oscillation start-up. As the oscillation grows and forms into a pulse train, the *dc* component of the amplifier output increases. This increase in the *dc* component is used to adaptively lower the amplifier bias (dashed arrow in Fig. 5). The reduced bias corresponds to an overall gain reduction, since a portion of the pulse enters the attenuation region. The bias point continues to move down on the curve until the overall gain becomes equal to the system loss, settling at the steady-state bias B.

In steady state with the bias at B, the three stability mechanisms are simultaneously satisfied. First, the reduced bias ensures that the peak portions of the input pulses do not enter the saturation region, reducing distortion (*reduced signal saturation*). Second, with the reduced bias, the steady-state input soliton train is placed *across* the attenuation and gain regions, causing small perturbations around the bias to be attenuated (*perturbation rejection*). Note that perturbation rejection is accomplished while maintaining gain for the main portions of the input soliton train to compensate loss. This threshold-dependent gain-attenuation mechanism is a technique widely employed in modelocked lasers in optics, where it is known as *saturable absorption* [4], but was originally introduced in electronics domain by Cutler for his linear pulse oscillator [12]. Third, the dependence of the steady-state bias on the *dc* component of the output leads to a mode-dependant gain since each mode has a different *dc* component. This can be used to select one particular mode *(single mode selection)*.

## Electrical Soliton Oscillator - Experimental Results

Three soliton oscillator prototypes have confirmed the concepts and operating principles of our soliton oscillator. The first two prototypes [1, 2] were built using discrete components (measured pulse widths: 43 ns and 827 ps) in order to explicitly examine the detailed dynamics of the soliton oscillator. The third prototype [3] was implemented on a CMOS integrated circuit (measured pulse width: 293 ps). Figure 6 shows the measured steady-state soliton oscillations from each prototype. Note that the pulse widths of 43 ns to 293 ps were engineered by our choice of circuit components.

The most fascinating dynamics of the soliton oscillator can be observed by following the pulse around the oscillator loop in steady state. Figure 7 shows such spatial dynamics measured from our first prototype [1,2]. At the output of the amplifier the pulse (width: 100 ns) is not exactly a soliton and, hence, sharpens into a soliton while propagating down the NLTL. Once the soliton is formed (width: 43 ns), it does not further sharpen since it is now a soliton. Instead, the loss on

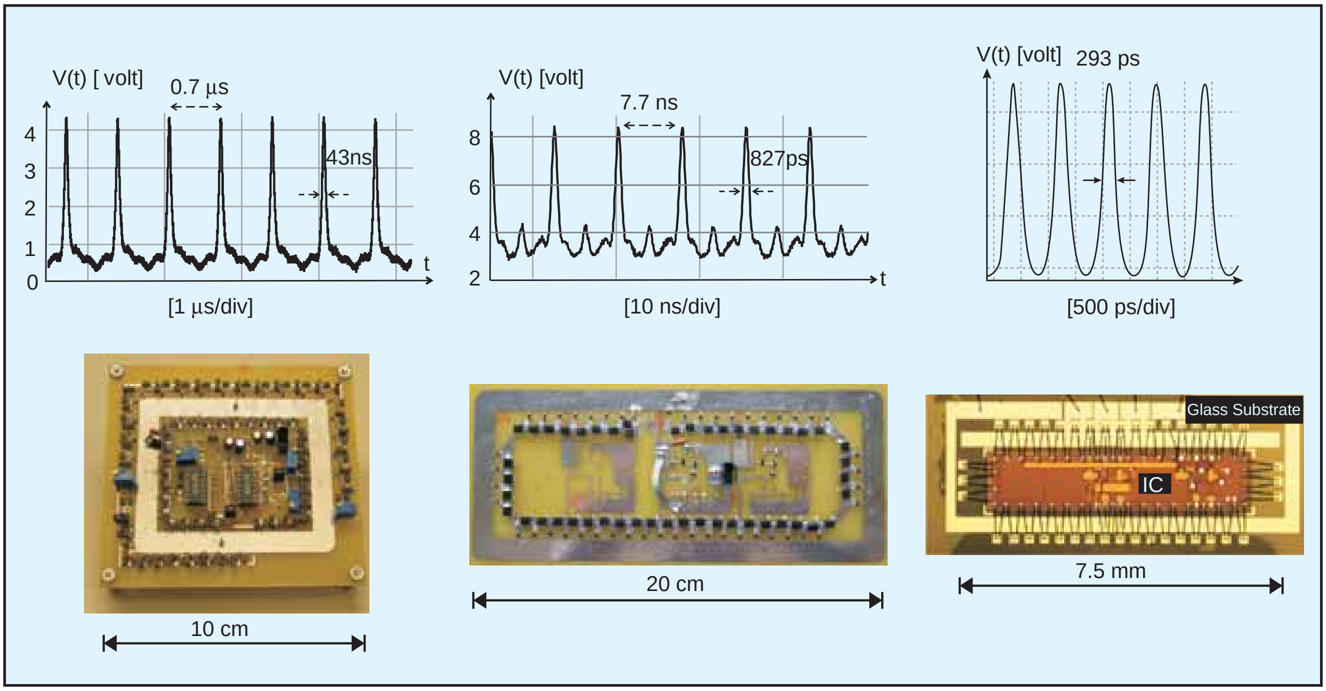



*Figure 6: (Left) First soliton oscillator (pulse width: 43 ns, pulse repetition rate: 1.4 MHz). (Center) Second soliton oscillator (pulse width: 827 ps, pulse repetition rate: 130 MHz). (Right) Third, chip-scale soliton oscillator (pulse width: 293 ps, pulse repetition rate: 1.14 GHz)*

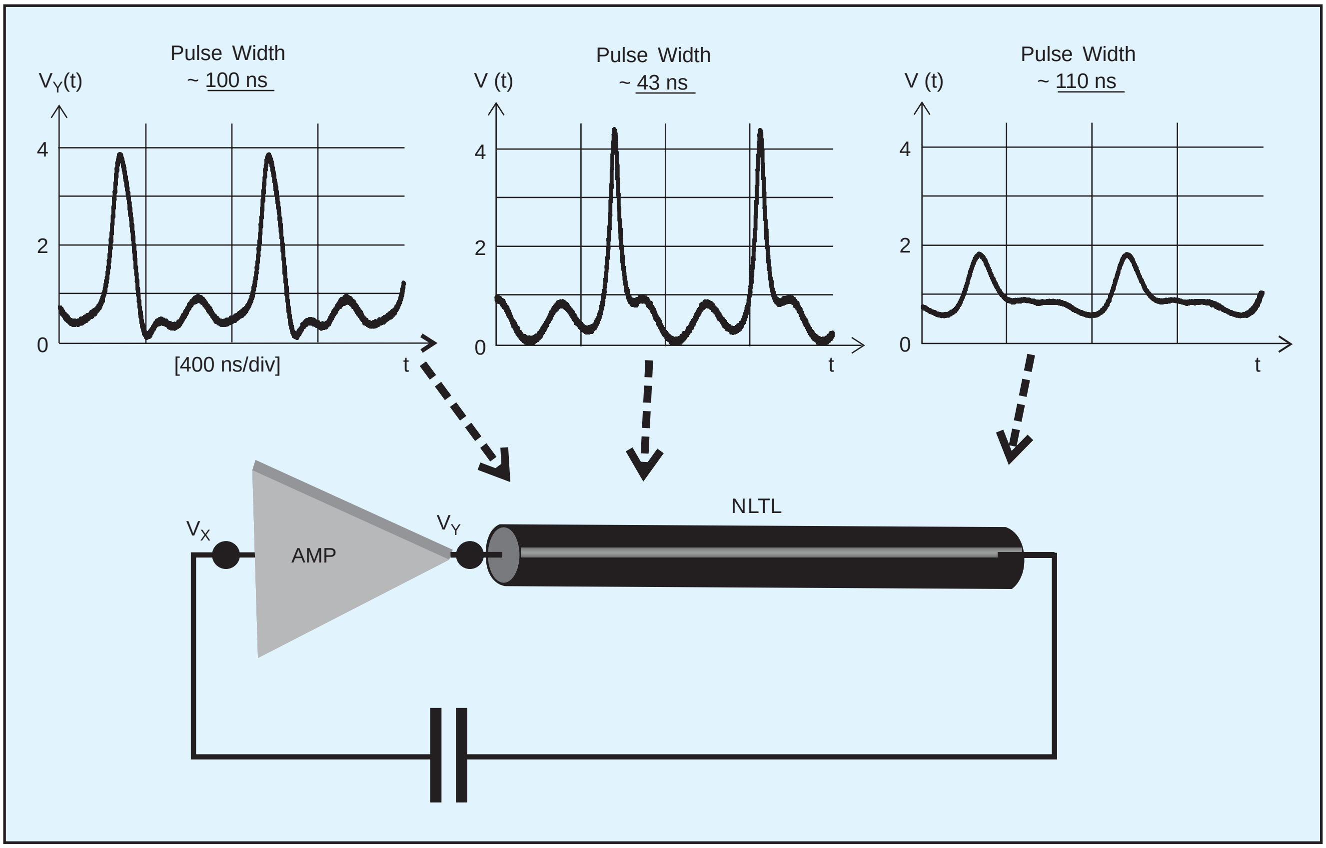



*Figure 7: Measured spatial dynamics of the soliton oscillator in steady state.*

the NLTL becomes the dominant process, and the soliton exhibits a unique soliton damping [11] as it further travels down the NLTL, reducing its amplitude and velocity while increasing its width (note that in the NLTL the loss is significantly higher than in optical fiber). At the end of the NLTL, the pulse width has increased to 110 ns. It is this clear existence of the transition point between two distinctively different processes, the pulse sharpening and widening, that unequivocally confirms the formation of the soliton at that transition point.

## Future Extensions

The minimum pulse width of 293 ps achieved in our latest prototype is not a record number as compared to the state-of-the-art 2-port GaAs NLTL (480-fs rise time) [7]. The value of our work so far, rather, lies in the clear demonstration of the soliton oscillator concept. Now with the concept firmly demonstrated, the soliton oscillator can be quickly extended to a significantly higher speed (shorter pulse width). For instance, the ultrafast GaAs NLTL in [7] can be incorporated in our soliton oscillator to substantially reduce the soliton pulse width down close to 1 ps.

Placing such an ultrafast NLTL in the electrical soliton oscillator raises an important question on the impact of the amplifier bandwidth on the minimum soliton pulse width. While the propagation of a 1-ps wide pulse on the stand-alone NLTL is feasible [7], amplifiers, even in the state-of-the-art solid-state technologies, cannot provide bandwidth for such a sharp pulse. The experimental results in Fig. 7 clearly suggest, however, that the soliton compression on the NLTL may be able to overcome the bandwidth limitation of the amplifier, and hence, it may be feasible to achieve a 1-ps pulse width using the NLTL of [7] despite the relatively slower amplifier. The explicit demonstration of this interesting possibility remains an open question, and would be a natural future extension of this work.

Such picosecond electrical soliton oscillators will offer a new platform for all-electrical ultrafast time-domain metrology. This is because the short pulse duration directly translates to high temporal resolution in time-domain measurements: the narrow electrical pulses can be used to sample, or take "snapshots" of, rapidly varying electrical signals with picosecond temporal resolution [5,8]. Similarly, the picosecond electrical pulses can be used as probe signals for high-precision time-domain reflectometry (TDR) [9]. While the electrical soliton oscillator with the picosecond pulses will never compete with the optical modelocked laser with its femtosecond pulses, it will allow wide applications in an all-electrical medium.

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