Ordered and Chaotic Electrical Solitons: Communication Perspectives

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ABSTRACT

While the use of sinusoidal electromagnetic waves as information carriers is taken as one of the principal axioms of today's wireless system design, certain nonsinusoidal waves may further enrich the scope and capacity of modern wireless engineering. Two notable nonsinusoid examples are *impulses* and *chaotic signals*. The short temporal width of impulses has enabled applications such as ranging radars and ultra wideband (UWB). The complex nature of chaotic signals offers a new means of encrypted communication. Here we review a new circuit paradigm, the *electrical soliton oscillator*, which can self-generate both impulse and chaotic signals of very large bandwidth by leveraging the singular dynamics of a nonlinear wave known as the electrical soliton. By combining a nonlinear transmission line with a unique amplifier that can "tame" the inherently unruly dynamics of solitons, the oscillator self-generates a stable, periodic train of short impulses. If the taming functions of the amplifier are turned off, the circuit self-generates chaotic signals by positively exploiting solitons' unruly nature. While still in its early stages, this soliton circuit may one day serve as the heartbeat of both impulse and chaotic wireless systems.

INTRODUCTION: IMPULSE AND CHAOTIC COMMUNICATIONS, AND ELECTRICAL SOLITONS

Information transmission using a radio-frequency sinusoidal signal is a well-established and enormously fruitful paradigm in modern wireless technology. In spite of this hegemony that will undoubtedly last into the foreseeable future, there also have long been efforts and some remarkable successes in utilizing wideband nonsinusoids as information-bearing signals. The rationale for these unorthodox efforts lies in that the physical properties of certain nonsinusoidal signals, most notably *impulses* (short baseband pulses) and *chaotic signals*, can provide certain advantages over the sinusoidal signal.

An example of a wireless system that uses impulses is the impulse ranging radar [1]. Its operating principle is diagrammed in Fig. 1a. A locally generated impulse is sent over a delay line and out into free space. The impulse transmitted into the free space hits an object and is reflected. The reflected pulse is received and propagated on the delay line where the portion of the locally generated impulse was already traveling. The position on the line where the received pulse meets the locally generated impulse can be detected and translated into ranging of the object. A shorter width of the impulse directly corresponds to a higher ranging resolution: one picosecond pulse width corresponds to a ranging resolution of 0.3 mm. In addition to this radar-specific high-accuracy ranging advantage, impulses offer benefits in the general communication context, including large bandwidth, immunity to multipath fading, good penetrating capability, and low probability of detection, all of which are more pronounced with shorter impulse duration. With such advantages over their sinusoid counterparts, impulse wireless systems have been steadily developed over the past 40 years. Their future pervasiveness may be debated, but impulse radars and radios are likely to share some of the mainstream communication market for certain applications in the booming ultra-wideband (UWB) revolution.[1]

The use of a chaotic signal for information transmission is an extreme example of nonsinusoidal signal use. The theory is to utilize *chaotic synchronization* [2] to "privately" synchronize a transmitter and a receiver. Just as two coupled sinusoidal oscillators can be frequency-synched via injection locking, two coupled chaotic oscillators can synchronize their chaotic outputs, converging from distant initial conditions [2].[2] Shown in Fig. 1b, a chaotic transmitter generates a chaotic carrier signal $c(t)$ and the transmitter sends out a modulated version $c(t) + m(t)$, where $m(t)$ is the information signal. An identical chaotic oscillator acts as a receiver, and coupled with the transmitter's oscillator by a common signal, produces a synchronized replica of $c(t)$. The information $m(t)$ is recovered as the difference between the receiver's input $c(t) + m(t)$ and the synchronized replica of $c(t)$. The commercial viability of this curious technology conceived in 1990s (e.g., [3, 4]) still remains to be

[1] While FCC restricts the commercial UWB applications to 3.1–10.6 GHz, in this article the UWB is meant rather liberally beyond the frequency range.

[2] This is a remarkable phenomenon, as a key property of isolated chaotic systems is their exponentially fast divergence in evolution, even with very close initial conditions.

seen. However, due to its potential for secure communication as an alternative to or an enhancement of conventional software-based and quantum-cryptographic systems, it is drawing significant attention from research communities, producing proof-of-concepts in circuits and laser systems [3, 4].

Furthering of the two highly interesting technologies, impulse and chaotic communications, or assessing how far they will reach in the future, would require studies from all spheres of communication engineering. This article is especially concerned with the circuit aspect, and reviews the *electrical soliton oscillator* recently developed by the authors [5, 6] (see also [7] for a review). This unique circuit self-generates a periodic train of short impulses or, alternatively, a chaotic signal, the essential commodities of impulse and chaotic communications,[3] and thus crosses the two poles of spectrum, order and chaos. Utilization of peculiar — and fascinating — nonlinear wave pulses known as solitons [8] in the electrical domain lies at the heart of the circuit. Soliton pulses are by nature unruly. By promoting the unruly behaviors, the chaotic soliton oscillator is attained. By "taming" the unruly behaviors, the stable soliton oscillator that self-generates the periodic train of electrical soliton impulses is obtained.

Circuits capable of impulse and chaotic signal generations [3] already abound, so why bother with the electrical soliton oscillator? The distinctive engineering advantage of electrical soliton pulses lies in their extremely short pulse duration, which can be made as small as one picosecond [9, 10]. The stable soliton oscillator can potentially generate a periodic train of these ultra-short soliton pulses, and the short pulse duration will maximize all of the aforementioned benefits of impulse communications (e.g., bandwidth, ranging resolution, etc.). Similarly, the chaotic signal produced by the chaotic soliton oscillator can potentially have a bandwidth as large as one terahertz due to the extremely short soliton pulse. This directly corresponds to an increased data rate in chaotic communication.

The two following sections review the history of solitons and their hallmark properties so as to provide a background. The rest of the article describes the electrical soliton oscillator in both stable and chaotic regimes. Now before diving into the business of electrical solitons, we would like to emphasize that applications mentioned in this article, especially chaotic communication, are in the embryonic stages, and are discussed here only to propose a possible opportunity.

SOLITONS: A BRIEF CHRONICLE

Solitons are highly localized pulse-shape traveling waves that are found in nonlinear dispersive media. They maintain spatial localization of wave energy in a pulse in the course of propagation (no dispersion) and exhibit singular nonlinear properties. In the absence of loss, solitons propagate perfectly preserving their shape. The soliton phenomenon is caused when nonlinearity counteracts dispersion. Soliton history is as intriguing as its phenomenon, warranting a brief description.

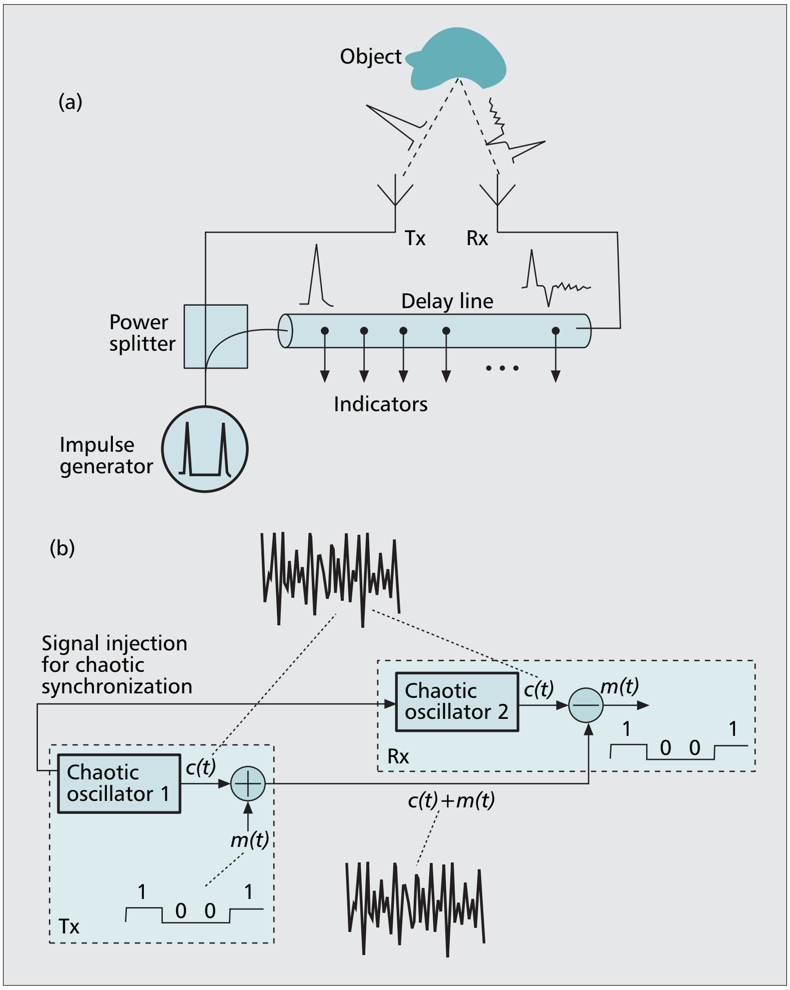


Figure 1. *a) Example architecture of an impulse ranging radar; b) basic concept of chaotic communication.*

Just like the legends told about Newton's apple and Archimedes' "Eureka!" moments, it was by serendipity that the Scottish naval engineer Scott Russell first discovered solitons in shallow water in Edinburgh's Union Canal in 1834. As he watched a barge being pulled along the canal by horses, the rope connecting the barge to the horses suddenly snapped. The monopulse "solitary" water wave created by the prow's rapid dip into the water traveled quickly down the canal with unnoticeable change in shape over several kilometers, which Russell observed by following the wave on horseback. The unusually low dispersion and long preservation of shape of the wave so provoked Russell that he built a water tank in his garden for follow-up studies. Not only did his experiments reproduce the solitary wave of low dispersion, but it also revealed other unique properties of the wave.

There ensued intellectual efforts to understand Russell's experiments. A majority of authorities, including Stokes, eventually disputed Russell's work, but Rayleigh argued in support of Russell. No firm conclusion was drawn and discussion was out in the open. Then, in 1895 came an unappreciated breakthrough when Korteweg and DeVries derived a nonlinear wave equation that modeled the shallow water wave, including both nonlinearity and dispersion. They

[3] *For both the impulse radio and impulse radar, a train of impulses rather than a single impulse is desired. For the impulse radio, the pulse position modulation in a stream of impulses is one of widely used modulation protocols. For the impulse radar, repetitive pulses allow for averaging the received signals to improve signal to noise ratio.*

In the electrical domain, the nonlinear transmission line (NLTL) serves as a nonlinear dispersive medium and, as such, can create electrical solitons. The NLTL has been extensively used during the past 40 years for sharp soliton pulse generations.

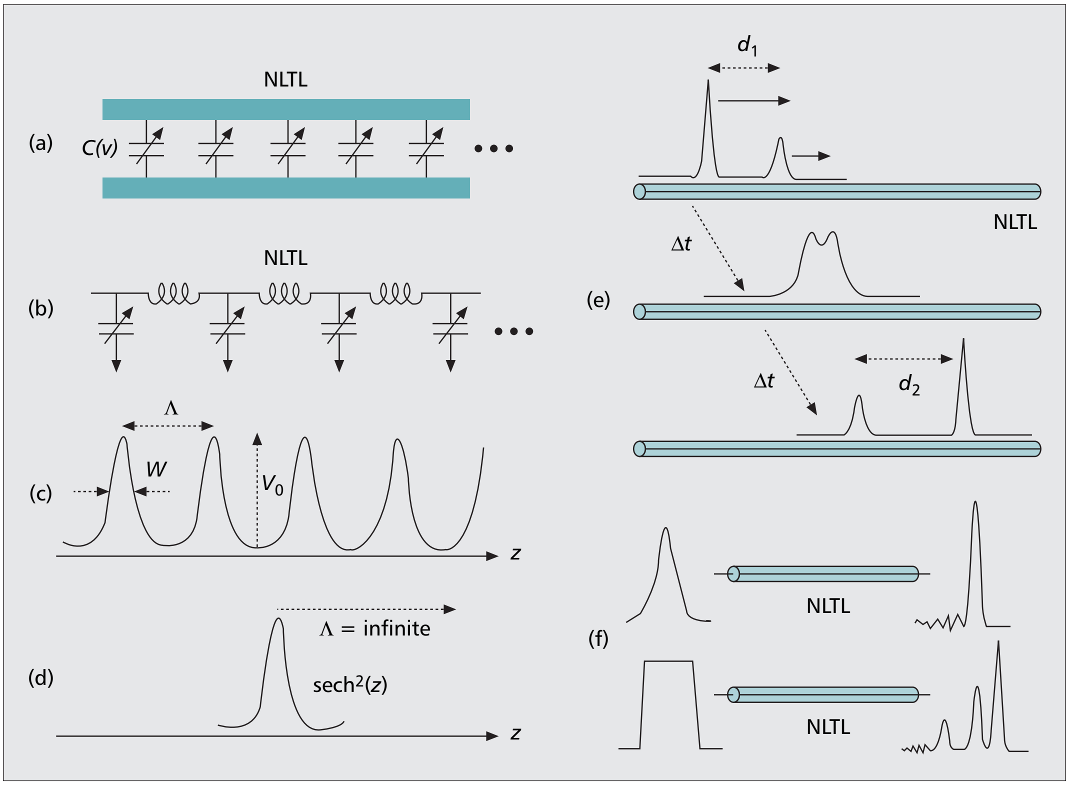


Figure 2. *a) Nonlinear transmission line (NLTL); b) alternative form of the NLTL; c) a general soliton waveform on an infinitely long NLTL; (d) mono-pulse case; e) illustration of solitons' amplitude-dependent speed and nonlinear collision; f) hypothetical transient soliton-forming processes on the NLTL.*

solved this now-celebrated "KdV" equation to attain a traveling-wave solution of permanent shape, matching Russell's experiments. Unfortunately, KdV's triumph went largely unnoticed for more than half a century. It was not realized that in addition to being the governing equation of the solitary wave in shallow water, the KdV equation can describe solitary waves in a variety of physical systems (e.g., plasma, crystal lattice). People also did not understand the underlying mechanisms of the KdV solitary wave beyond what Russell phenomenologically observed.

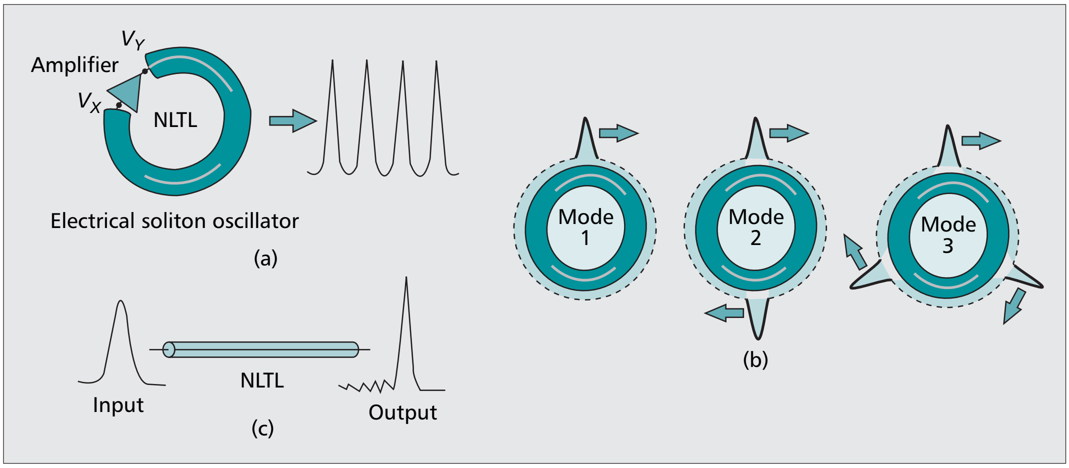
The general significance, fundamental physical mechanisms, and far-reaching implications of the KdV solitary wave were finally fully uncovered by Zabusky and Kruskal in 1965 [11]. By analyzing their computer experiments with the KdV equation to study plasma and nonlinear crystals, they rediscovered the KdV solitary wave, which they explained is made possible by balance between nonlinearity and dispersion. Zabusky and Kruskal further found that when two solitary wave pulses collide, they interact strongly but then emerge thereafter recovering their original shapes as if there had been no interaction at all (only a phase shift occurs as a consequence). To emphasize this particle-like nature of solitary waves, they coined the name *solitons* (like photon, electron, etc.).

Zabusky and Kruskal's work marks the beginning of an intense surge of research activities in solitary waves from various disciplines in science and engineering, and the importance of solitons has only increased. Solitons are now taken as an emblem of nonlinear phenomena. KdV solitons as well as solitons described by other types of equations are now known not only in shallow water, crystals, and plasma, but also in magnetically ordered media, Bose–Einstein condensates, and technologically important optical fibers in the form of light-wave solitons. Another technologically interesting soliton is the electrical soliton, as it can be utilized in electronics that touches our everyday life. Now let us turn our attention to electrical solitons.

Electrical Solitons: A Primer

In the electrical domain, the nonlinear transmission line (NLTL) serves as a nonlinear dispersive medium and, as such, can create electrical solitons. The NLTL has been extensively used during the past 40 years for sharp soliton pulse generations [9, 10]. The NLTL (Fig. 2a) is constructed from a normal transmission line (two conductors running in parallel) by periodically loading it with variable capacitors (varactors), such as reverse-biased *pn* junction diodes, whose capacitance changes with applied voltage. Alternatively, the NLTL can be obtained by forming an artificial ladder network of inductors and varactors (Fig. 2b). The nonlinearity of the NLTL originates from the varactors since their capacitance varies with applied voltage. The dispersion of the NLTL arises from the structural periodicity of the NLTL (periodic lumped varactor loading).

For certain pulse-shaped voltage waves on the NLTL, the nonlinearity balances out the dispersion, and they propagate maintaining their shape in the absence of loss. These are electrical



■ **Figure 3.** *a) Electrical soliton oscillator; b) ring NLTL and the first three soliton circulation modes; c) traditional approach to generate electrical solitons using an NLTL.*

In almost any wireless transceiver, one finds a dynamic circuit block that incessantly signals a sinusoid — an electrical oscillator. The oscillator is the heartbeat of wireless systems, providing frequency references amongst transmitters and receivers.

solitons, and are described by the KdV equation. The general wave solution on the NLTL obtained by solving the KdV equation is a periodic train of soliton pulses, also known as a cnoidal wave (Fig. 2c). For a given NLTL, an infinite number of cnoidal waves are possible via different combinations of the amplitude V_0, pulse spacing Λ, and pulse width *W*. Initial or boundary conditions will determine a specific cnoidal wave that can propagate. Figure 2d shows the special mono-pulse electrical soliton, whose cousin in shallow water was observed by Russell. When loss is present solitons cannot maintain their shape, but they still maintain spatial localization of energy in a pulse shape through a unique damping process [5].

Let us now look at some other relevant — and beautiful — properties of electrical solitons (or any KdV soliton) as a necessary background to understand the soliton oscillator. To begin with, a taller soliton travels faster than a shorter one. Due to this amplitude-dependent speed, if a taller soliton is placed behind a shorter one (Fig. 2e, top), the taller one will catch up with the shorter one and move ahead of it after a collision (Fig. 2e). During the collision (Fig. 2e, middle), the two solitons interact very strongly and experience a significant amplitude modulation (nonlinear collision). After the collision (Fig. 2e, bottom), the two solitons return to their original shapes, but they acquire a permanent time (phase) shift shown by the difference in d_1 and d_2 in Fig. 2e. Due to these properties, that is,

- *Amplitude-dependent speed*
- *Amplitude modulation during the collision*
- *Phase modulation after the collision,*

electrical solitons exhibit unruly behaviors in an oscillator, as shown below. Promotion of these behaviors leads to a chaotic soliton oscillator. Taming of the unruly solitons is necessary to attain a stable soliton oscillator that self-generates a periodic train of soliton pulses.

Nonsoliton waves can also propagate on the NLTL, but only by changing their shape to form into a soliton or solitons. A nonsoliton input close to soliton shape will be sharpened into a soliton (Fig. 2f, top). A nonsoliton input significantly different from soliton shape will break up into multiple solitons of different amplitudes (Fig. 2f, bottom). In either case, the input pulse becomes compressed traveling down the line. Once a soliton or solitons are formed, they propagate without further sharpening or breakup. The past 40 years have seen this transient electrical soliton-forming process occupying an especially significant place in modern electronics for sharp pulse generation [9, 10], with the record pulse width of down to one picosecond [10]. This unsurpassed electrical pulse width and correspondingly large bandwidth make the soliton use for impulse and chaotic communications significantly advantageous.

Self-Generation of Electrical Solitons

In almost any wireless transceiver, one finds a dynamic circuit block that incessantly signals a sinusoid — an electrical oscillator. The oscillator is the heartbeat of wireless systems, providing frequency references amongst transmitters and receivers. A popular form of the sinusoidal oscillator consists of an EM resonator (e.g., *LC* tank) and an amplifier [12]. The resonator shapes its output into a sinusoid. The amplifier injects energy into the resonator to match energy loss. The result is autonomy. While there is no sinusoidal signal driving the oscillator and the only energy source is a dc power supply, the oscillator self-generates a sinusoidal signal, initially self-starting by amplifying ambient noise.

The stable electrical soliton oscillator we recently developed [5,6] is the result of our original quest to build an analogue of the sinusoidal oscillator. By combining a *specially designed* non-inverting amplifier and a ring NLTL (Fig. 3a), the circuit self-generates a periodic train of electrical soliton pulses in steady state, initially self-starting from background noise. The periodic soliton train corresponds to one of the soliton circulation modes (Fig. 3b) that can form on the ring NLTL, thus satisfying the boundary condition that the ring's circumference should be an integer multiple of the spacing between two adjacent solitons. The amplifier is special, since

The multiple solitons will travel at different speeds due to their amplitude-dependent speed, eventually appearing again at the amplifier input at different times. This process repeats, creating many solitons with various amplitudes. These solitons circulate in the loop at different speeds, continually colliding with one another.

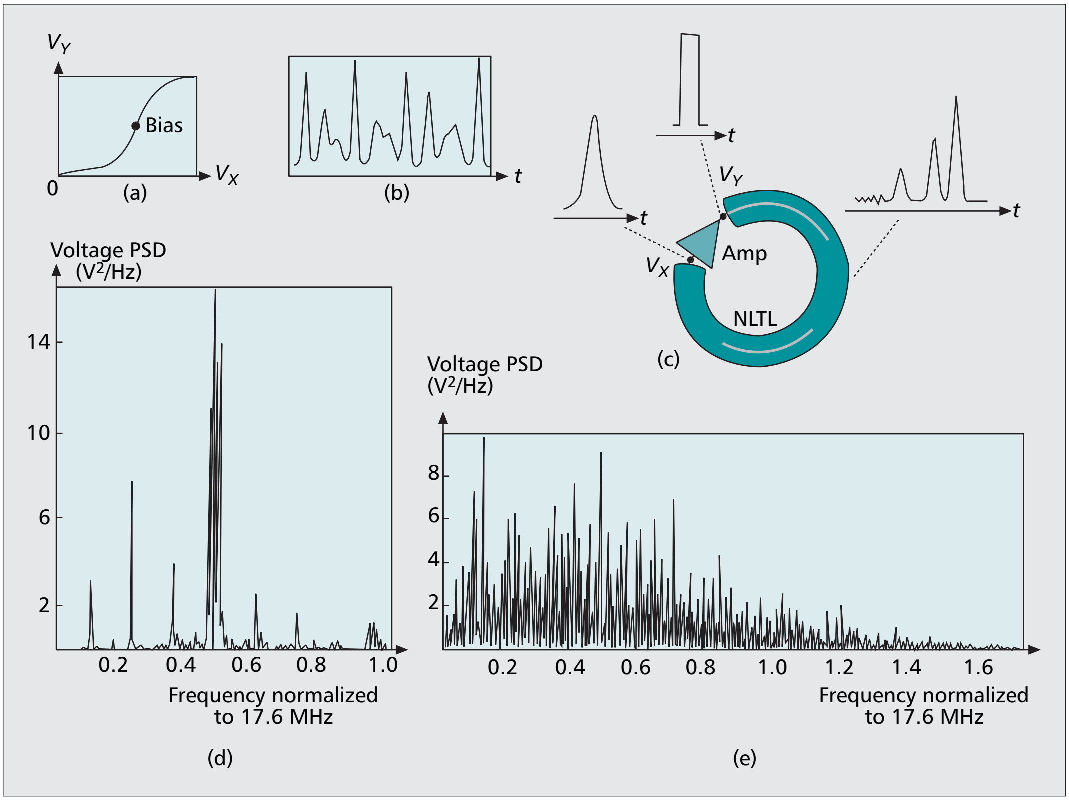


Figure 4. *a) Transfer function of a standard voltage-limiting amplifier; b) simulated unstable oscillation; c) impact of signal clipping and soliton dynamics; d) simulated power spectral density of the unstable oscillation signal with a weak nonlinearity of the NLTL; e) simulated power spectral density of the unstable oscillation signal with a strong nonlinearity of the NLTL.*

in addition to providing gain to initiate a startup and to compensate loss in steady state, it executes functions to "tame" the inherently unruly behaviors of solitons, which we discussed above. If these taming functions are removed from the amplifier, the solitons' unruly behaviors are promoted, and the resulting oscillations are plagued with instability problems, exhibiting chaotic behaviors with significant variations in pulse amplitude and repetition. This chaotic oscillator, however, can be positively exploited for chaotic communication.

The development of the electrical soliton oscillator marks a distinctive and meaningful departure from the past 40 years' work on the NLTL, which has been almost exclusively focused on generation of electrical solitons by driving the NLTL with an external high-frequency signal, as explained above via Fig. 2f (recreated in Fig. 3c). In constrast, the electrical soliton oscillator is self-contained, not requiring the external high-frequency input. In its stable operation regime, the electrical soliton oscillator also provides a better pulse-quality control than the traditional approach due to self-regulatory mechanism inherent in any stable oscillator. The electrical soliton oscillator is a newborn electrical cousin of soliton modelocked lasers that have already proliferated in the optical domain [13]. The rest of this article describes the detailed operation and prototype results of the electrical soliton oscillator, in both the chaotic and stable operation regimes.

Chaotic Electrical Soliton Oscillator

Let us consider a case where a standard voltage-limiting noninverting amplifier is used in the soliton oscillator of Fig. 3a. The transfer function of the amplifier is depicted in Fig. 4a. The amplifier is biased at a fixed operating point. Simulations show that the soliton oscillator exhibits an unstable oscillation with significant pulse amplitude and repetition rate variations (Fig. 4b).

The combination of the signal saturation in the amplifier and the inherent properties of solitons described above causes this oscillation instability. To see this, let us assume a soliton pulse appearing at the input of the amplifier at a certain time (V_X in Fig. 4c). This soliton will turn into a square pulse after passing through the amplifier, as the amplifier clips the top off of the input soliton (V_Y in Fig. 4c). This square pulse will break up into multiple solitons of different amplitudes traveling down the NLTL, as explained above (the rightmost waveform in Fig. 4c). The multiple solitons will travel at different speeds due to their amplitude-dependent speed, eventually appearing again at the amplifier input at different times. This process repeats, creating many solitons with various amplitudes. These solitons circulate in the loop at different speeds, continually colliding with one another. As discussed above, these soliton collision events lead to phase and amplitude modulations, rendering the oscillation unstable as in Fig. 4b.

Proving if the unstable oscillation is indeed chaotic is not straightforward; it demands mathematical rigors. We instead take a power spectral density of the oscillator output to observe the degree of the spread of the signal power in the frequency domain, as is done frequently [14]. A distribution of signal power over a broad range of frequencies is a key signature of a chaotic signal, even though it is not a sufficient condition for being chaotic. In our case, this method would do as it has been already mathematically proven that a simple NLTL with even three varactors can behave chaotically [8].

Figures 4d and 4e are the simulated power spectral densities of the unstable oscillation signals, for weaker and stronger nonlinearities of the NLTL, respectively. A larger nonlinearity is obtained by making the voltage dependence of the varactor capacitance more pronounced. With the weaker nonlinearity (Fig. 4d), the power spectral density is concentrated over a finite number of certain frequencies. As the nonlinearity increases (Fig. 4e), the power spectral density is significantly broadened, strongly indicating a chaotic signal generation.

There already exist various chaotic circuits, (e.g., Chua's circuit, or analog Lorenz chaos generator [3]). The distinctive advantage of the chaotic soliton oscillator over the existing chaotic circuits lies in its potential for an extremely large bandwidth. Due to the unique ability of the NLTL to compress soliton widths down to one picosecond or less, as demonstrated in [10] with an NLTL with Shottky diode varactors in a GaAs technology, the chaotic soliton oscillator could potentially generate a chaotic signal with a bandwidth approaching one terahertz, and hence can be an excellent candidate for broadband private chaotic communication.

Stable Electrical Soliton Oscillator

While the chaotic soliton oscillator is a useful by-product that can be positively exploited for broadband chaotic communication, in order to attain a self-generated periodic train of stable soliton pulses for impulse communication, oscillation instability needs to be suppressed. The discussion in relation to Fig. 4 indicates that signal distortion has a negative impact on the oscillation stability, suggesting that one might be able to obtain a stable soliton oscillation if signal distortion is mitigated. We tried a linear amplifier in the soliton oscillator of Fig. 3a, which was able to produce a periodic soliton pulse train [5]. In the same system, however, other oscillations uncontrollably appeared with slight changes in gain, termination, or pretty much with any external or internal perturbations, indicating a lack of robustness. These waveforms sometimes contained multiple solitons with varying amplitudes/spacings and pulses continuously moved relative to one another and collided, yielding what looks like Fig. 4b again. This experiment suggests that distortion reduction is a necessary, but not a sufficient condition to stabilize the oscillation.

In addition to the signal distortion in the amplifier, there are two other instability sources that need to be removed. First, in steady-state oscillation, any small ambient perturbations such as noise should be attenuated, which otherwise could grow into parasitic solitons. Unless the perturbations are attenuated, the desired soliton circulation mode and parasitic solitons will propagate at different speeds due to their generally different amplitudes, colliding to cause phase and amplitude modulations, hence building up oscillation instabilities. Second, only one soliton-circulation mode should be selected in steady state among many possible modes of Fig. 3b. 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 unstable oscillations.

The identification of these stability mechanisms, that is,

- *Distortion reduction*
- *Perturbation rejection*
- *Single mode selection,*

was an important initial step for our electrical soliton oscillator development [5, 6]. We subsequently implemented these stability mechanisms in a standard saturating amplifier by incorporating an adaptive bias control. Note that the transfer curve of the saturating amplifier is just like the one in Fig. 4a that caused chaotic oscillation, but the difference lies in the adaptive bias control. With Fig. 5, we will explain how the adaptive bias control works and how it achieves the three stability mechanisms.

Figure 5a shows the transfer curve of the amplifier, which is divided into the attenuation, gain, and saturation regions, based on the curve's tangential slopes. At startup, the amplifier is biased at **A** in the gain region so that ambient noise can be amplified to kick off oscillations. As the oscillations grow and form into a pulse train, the dc component of the amplifier output increases (Fig. 5b). This increase in the dc component is used to adaptively lower the amplifier bias (dashed arrow in Fig. 5a). The reduced bias corresponds to an overall gain reduction, since a portion of the pulse enters the attenuation region as the bias moves down the curve. The bias continues to move down until the decreasing overall gain eventually becomes equal to the system loss, settling at the steady-state bias **B** (Fig. 5a).

In steady state with the bias at **B**, the three stability requirements are simultaneously met. First, the reduced bias ensures that the peak portions of the input pulses do not enter the saturation region, reducing distortion. 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. Note that perturbation rejection is accomplished while maintaining gain for main portions of input soliton pulses to compensate loss. This threshold-dependent gain-attenuation mechanism is a technique widely employed in modelocked lasers (lasers that generate a train of periodic light pulses) in optics, where it is known as *saturable absorption*. Interestingly, this technique was originally introduced in electronics domain by Cutler for his liner pulse oscillator [15]. Third, the dependence of

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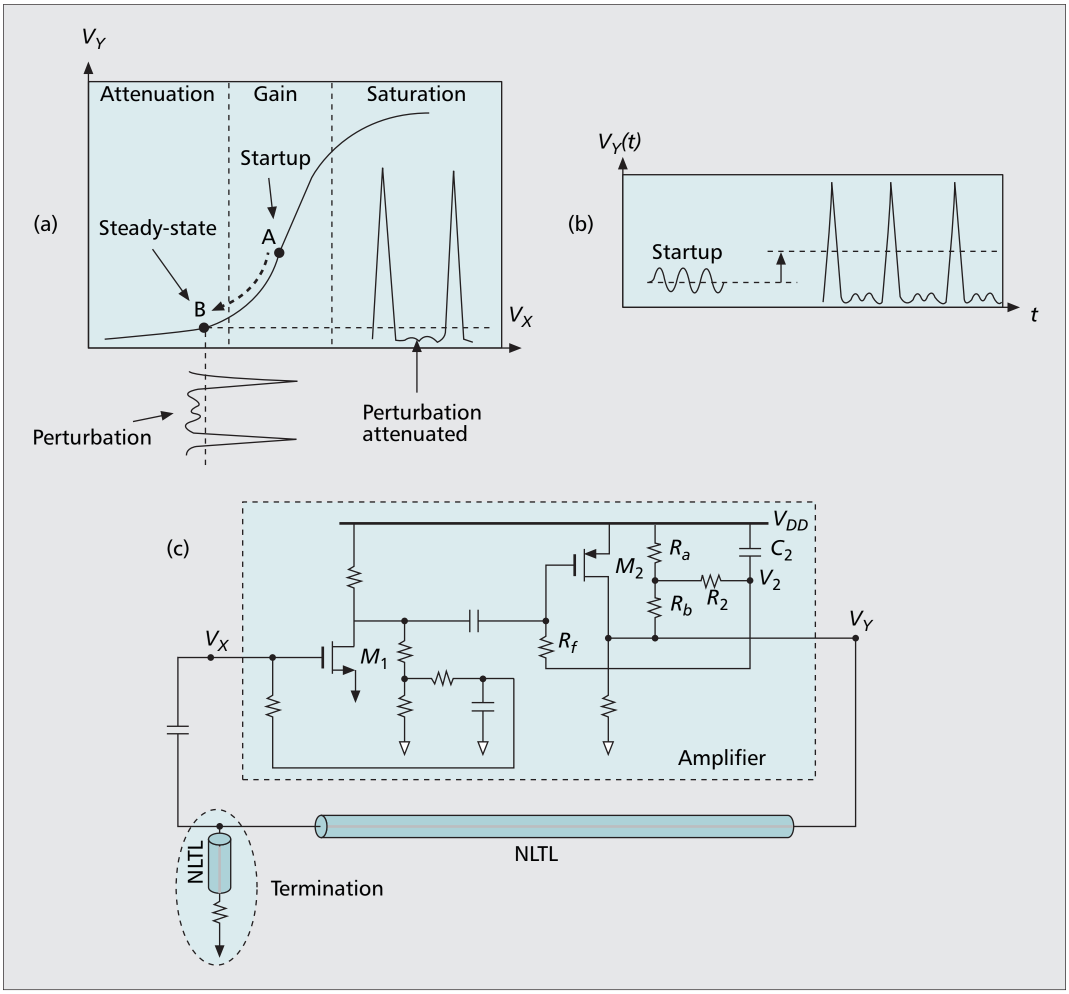
Now with the electrical soliton oscillator concept firmly demonstrated, the oscillator, in either stable or chaotic operation regime, can be quickly extended to a significantly higher speed. This can be done by, for instance, integrating ultrafast GaAs NLTLs.



■ **Figure 5.** *a) Nonlinear transfer curve of the saturating amplifier. In the initial startup, bias point A lies in the gain region. Increased DC component during the transient (Fig. 5b) is used to lower bias of the amplifier, leading to a steady-state bias B; b) DC component of the amplifier output increases as the oscillation grows and forms into a soliton pulse train, c) example oscillator implementation.*

the steady-state bias on the dc component of the amplifier output leads to a mode-dependent gain since each mode has a different dc component. This naturally leads to a single-mode selection, for which details can be found in [5].

Note that to achieve distortion reduction (first stability mechanism), the top portion of the amplifier nonlinearity in the transfer curve, the boundary between the gain and saturation regions, is avoided, while to achieve perturbation rejection (second stability mechanism) while maintaining gain, the bottom portion of the amplifier nonlinearity in the transfer curve, the boundary between the gain and attenuation regions, is exploited.

The adaptive bias-control amplifier concept is general, and can be implemented in a variety of forms. Figure 5c shows an example oscillator implementation [5, 6] with the amplifier inside the dashed box. The amplifier consists of two inverting stages: one built around an nMOS transistor, M1, and the other built around a pMOS transistor, M2. Together they form a noninverting network. The adaptive bias control is implemented for both stages. It functions as follows for the pMOS stage. The output waveform V_Y sensed by the R_a-R_b voltage divider is integrated by the R_2-C_2 low-pass filter. The integrated voltage V_2 represents a scaled dc component of V_Y. Now V_2 is fed back to the gate of M2 to set its bias. As the dc level of V_Y increases, V_2 will rise with respect to ground, which corresponds to a reduction in the gate-source voltage of M2, effectively lowering its bias. A similar scenario applies to the nMOS stage. Combining the two stages, the bias of the amplifier at the input is reduced as the dc component of V_Y increases, thus performing the adaptive bias control.

Three additional points are noteworthy. First, although the adaptive bias control in Fig. 5 uses the signal's dc component, it can be alternatively executed by using the signal's peak to expedite start-up transients. Second, the termination of Fig. 5 is needed to absorb energy. This termination cannot be perfect because NLTL's characteristic impedance is voltage-dependent. However, the resulting small reflections are attenuated by the amplifier's perturbation rejection mechanism, the second stability mechanism. Third, one can implement simple switches to activate and deactivate the bias-feedback net-

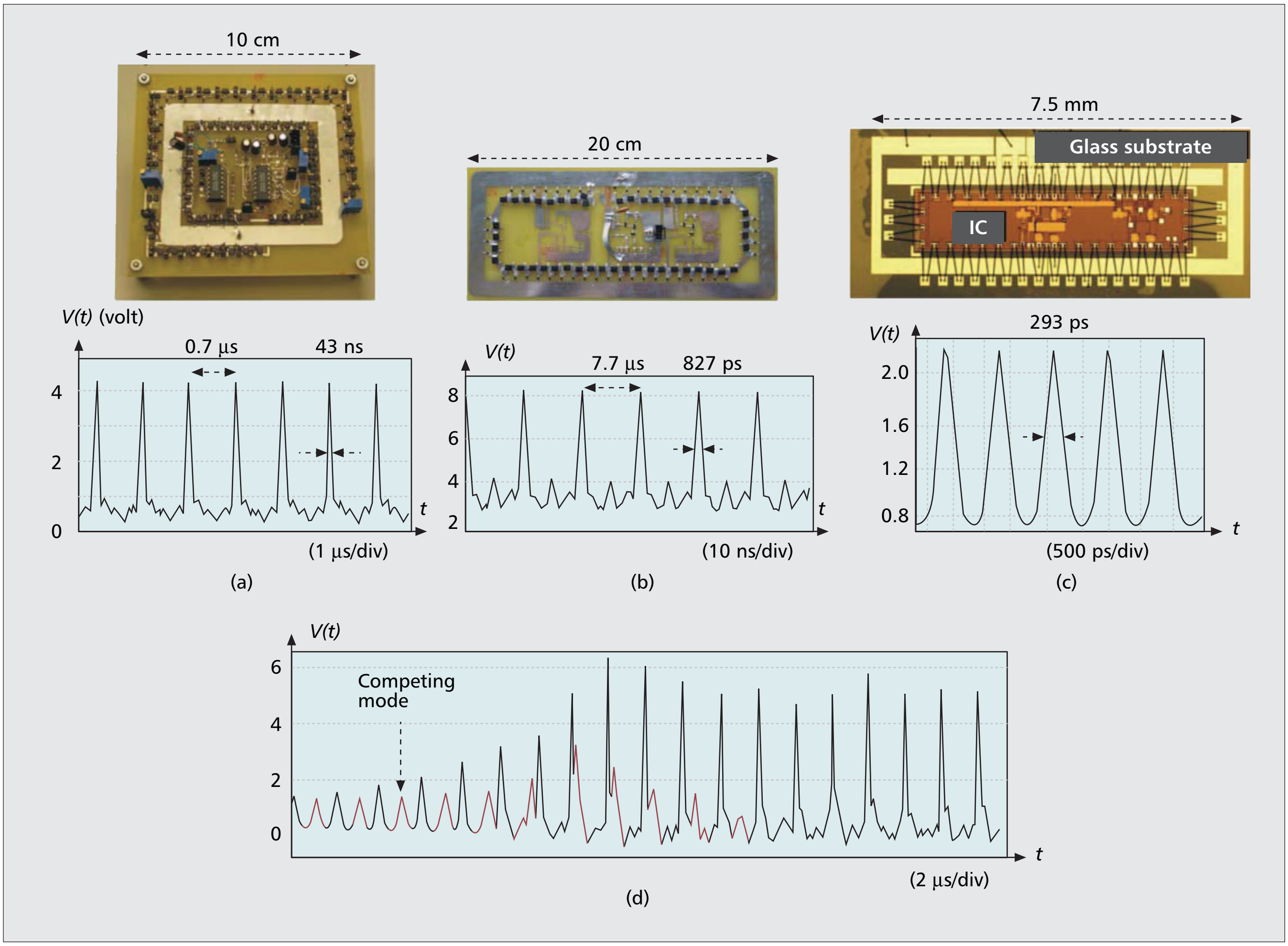


Figure 6. *a) First soliton oscillator prototype, and a measured steady state stable periodic train of soliton pulses; b) second soliton oscillator prototype and a measured steady-state stable periodic train of soliton pulses; c) third chip-scale soliton oscillator prototype with a measured steady-state stable periodic train of solitons; d) measured initial startup transient from the first prototype of Fig. 6a.*

work to toggle between the stable and chaotic oscillation regimes.

Three prototypes confirmed the concept of electrical soliton oscillator [5, 6]. The first two prototypes (Figs. 6a and 6b) were built using discrete components to explicitly examine detailed dynamics of the soliton oscillator. The third prototype (Fig. 6c) was implemented on a CMOS IC to demonstrate a chip-scale operation. Each prototype self-generated a periodic train of solitons pulses.

The lowest frequency prototype (Fig. 6a) allows for a detailed view of the oscillation startup (Fig. 6d). The oscillator self-starts by creating a small oscillation, eventually growing into a steady-state soliton pulse train. During this process, another completing mode is clearly seen (red): it first grows with time, but is eventually suppressed by the stabilizing mechanism of the amplifier. One can also see the shorter pulse (competing mode, red-) propagate at a different speed than the taller pulse (main mode that survives, black): in this time-domain measurement at a fixed point on the NLTL, the shorter pulse originally behind the taller pulse catches up with the taller pulse and eventually moves ahead of it after collision. In the space domain, this corresponds to the taller pulse propagating faster than the shorter pulse, a key signature of solitons. For other fascinating dynamics of the soliton oscillator, readers are referred to [5].

FURTHER DESIGN CONSIDERATIONS

Our work so far has been focused on the demonstration of the stable and chaotic soliton oscillator concepts, the former with confirming experimental results and the latter with simulations. The minimum pulse width of 293 ps in our latest stable soliton oscillator prototype (Fig. 6c) is not a record number, but the prototypes were intentionally made relatively slow in order to explicitly examine signals in a real-time oscilloscope.

Now with the electrical soliton oscillator concept firmly demonstrated, the oscillator, in either stable or chaotic operation regime, can be quickly extended to a significantly higher speed. This can be done by, for instance, integrating ultrafast GaAs NLTLs [10], which were shown to produce picosecond soliton pulses, in our electrical soliton oscillator. The utilization of such ultrafast NLTLs is expected to increase the signal bandwidth up to one terahertz in the chaotic soliton oscillator, and to decrease a pulse width down to one picosecond (and increase pulse repetition

The electrical soliton's superb capability of pulse width compression and resulting large bandwidth give an edge to the electrical soliton oscillator over other impulse and chaotic signal generation circuits.

rate up to about forty gigahertz) in the stable soliton oscillator.

Placing such an ultrafast NLTL in the electrical soliton oscillator raises an important question about the impact of the amplifier bandwidth on the minimum soliton pulse width. While the propagation of a 1-ps-wide pulse on an NLTL is feasible as demonstrated in [10], amplifiers, even in the state-of-the-art solid-state technologies, cannot provide bandwidth for such a sharp pulse. The experimental studies in [5] 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 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.

Finally, in addition to the bandwidth, power consumption, and area, there are also important design considerations. The chip-scale stable soliton oscillator shown in Fig. 6c occupies an area of about 3×7 mm and consumes dc power of about 20 mW. The relatively large area is due to the use of bonding wires as the NLTL inductors, but the size can be significantly reduced by using an on-chip NLTL and operating at higher speeds. How the dc power consumption would scale with the speed remains to be studied. The original soliton oscillator topology shown in Fig. 3a uses lumped voltage amplification, and is not energy efficient. A distributed soliton oscillator where power gain is distributed all along the NLTL could enhance the energy efficiency as well as the speed.

CONCLUSION

While a sinusoidal signaling of information is a powerful paradigm that communication engineers have matured over nearly a century, the past decades have also seen possibilities in communications using nonsinusoidal signals such as impulses and chaotic signals. If they prove useful in real-world communication, the electrical soliton oscillator may serve as the heartbeat of these unorthodox communication systems. The electrical soliton's superb capability of pulse width compression and resulting large bandwidth give an edge to the electrical soliton oscillator over other impulse and chaotic signal generation circuits. This prospect is brightened by the fact that nature's most intricate and brilliant communication network, the human brain, utilizes soliton-like neuron impulses and, often, their chaotic behaviors.

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BIOGRAPHIES

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SCOTT DENENBERG (denenber@fas.harvard.edu) is in his senior year at Harvard University. He is expected to graduate in the spring of 2007 with an S.B. in electrical engineering. He is just beginning the process of applying to graduate programs in electrical engineering, hoping to begin in the fall of 2007. This past summer he joined Donhee Ham's group in researching the soliton damping process in the stable soliton oscillator. He will be continuing his work as part of a senior thesis project, looking into chaotic soliton oscillators and their synchronizations. He has been on the Harvard Men's Tennis team during his entire college career. He earned Varsity letters in his sophomore and junior years, and was elected Captain of the team at the beginning of his senior year. He and his doubles partner were elected to the All-Ivy team at the end of their junior year.

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