A SELF-SUSTAINED ELECTRICAL SOLITON OSCILLATOR

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ABSTRACT

This paper introduces a robust self-sustained electrical soliton oscillator that combines a nonlinear transmission line (NLTL) and a unique amplifier. The amplifier uses a non-linear transfer function and an adaptive bias control to work in cooperation with the soliton dynamics of the NLTL. This system reproducibly self-generates stable soliton pulse trains. Experimental results are presented together with a description of the stability mechanisms.

Index Terms – Nonlinear transmission lines (NLTL), solitons, oscillators, soliton oscillators, mode-locking, soliton mode-locking, pulse generation.

1. INTRODUCTION

Solitons are a unique class of pulse-shape waves that propagate without changing their shape in nonlinear dispersive media [1]. In the electrical domain, a nonlinear transmission line (NLTL) serves as such a medium and supports electrical solitons. Soliton propagation on the NLTL has been actively studied in the past decades, most notably for sharp pulse generation applications, *e.g.*, [2]. In this past research the NLTL has been predominantly used as a 2-port system, which requires an input to generate solitons. A 1-port self-sustained electrical soliton oscillator based on the NLTL, which could self-start by amplifying background noise, is an intriguing idea, but there has not been a robust electrical soliton oscillator reported to date to the best of our knowledge. While Ballantyne *et al* demonstrated a self-sustained NLTL-based soliton oscillator [3] [4], it cannot reproduce stable soliton oscillations, lacking robustness and controllability. This difficulty arises as the soliton dynamics on the NLTL do not easily lend themselves to standard circuit amplification techniques.

Outside the electronics community, however, self-sustained stable soliton oscillators using various nonlinear dispersive media have been reported. In optics the soliton fiber ring laser is indeed a soliton oscillator utilizing an optical fiber as a soliton propagation medium, *e.g.*, [5]. In magnetics YIG or ferrite films have been used as soliton propagation media to achieve self-sustained magnetic soliton oscillation, *e.g.*, [6]. Most of the soliton oscillators in the non-electrical domains commonly exploit a special amplification technique called *saturable absorption*. The invention of the saturable absorption technique dates back to 1954 [7] and surprisingly in the electrical domain, where Cutler used the amplification technique for *non*-soliton electrical pulse generation on a linear transmission line.

In this paper we introduce what is believed to be the first robust self-sustained electrical soliton oscillator that combines the NLTL and a unique amplifier based on Cutler's method including the saturable absorption technique. While several of the principles of our amplifier remain the same as Cutler's, we apply these techniques to achieve a different goal, the establishment of stable soliton oscillations on an NLTL. Additionally, our amplifier implementation is novel, optimized for realization using today's silicon transistors. Self-started by ambient noise, our oscillator reproducibly generates stable soliton pulse trains. A prototype using discrete components is constructed as a proof of concept with the pulse repetition rate ranging from 1 to 10 MHz, while the circuit can be implemented at GHz frequencies. Section 2 reviews the basic properties of the NLTL. In Section 3 we discuss challenges in the design of an NLTL soliton oscillator. Section 4 introduces our soliton oscillator that overcomes the challenges. Experimental results follow in Section 5.

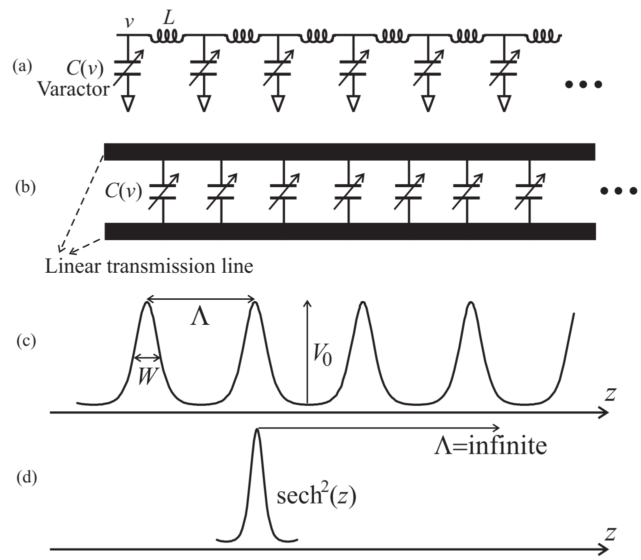

Figure 1: (a) Artificial NLTL consisting of lumped inductors and varactors. (b) NLTL utilizing a linear transmission line. (c) A general soliton pulse train waveform. (d) The mono-pulse case.

2. NLTL AND SOLITONS

A nonlinear transmission line (NLTL) is essentially a linear transmission line periodically loaded with varactors such as *pn* junction diodes or MOS capacitors. The varactors are nonlinear capacitors whose capacitance varies with the voltage across them. Figures 1(a) and (b) illustrate example NLTLs.

The NLTL is a nonlinear dispersive system. The dispersion arises from the structural periodicity of the line. The nonlinearity originates from the varactors. In the NLTL, the nonlinearity can act against the dispersion, and if a proper balance is established between the two mechanisms, certain electrical pulse-shape waves can travel on the line with unchanged waveforms. These unique waves are called solitons [1]. Figure 1(c) illustrates a general soliton pulse train formed on an infinitely long NLTL. This train of pulses is known as a cnoidal wave, which is the solution of the KdV equation describing the NLTL dynamics [1]. There are an infinite number of cnoidal wave solutions to the NLTL resulting from different combinations of pulse spacing, Λ, and the amplitude, V_0. The cnoidal wave pulse width, W, is a function of Λ and V_0. Figure 1(d) shows the special mono-pulse case, a single soliton, with $\Lambda = \infty$.

Among the infinite possible cnoidal wave solutions, initial

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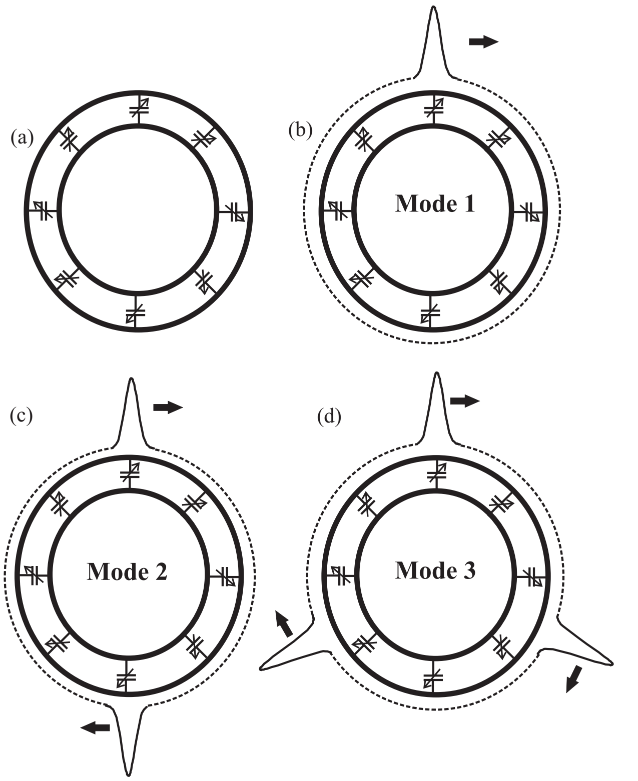

Figure 2: (a) Ring NLTL (b) $l = \Lambda$. (c) $l = 2\Lambda$. (d) $l = 3\Lambda$.

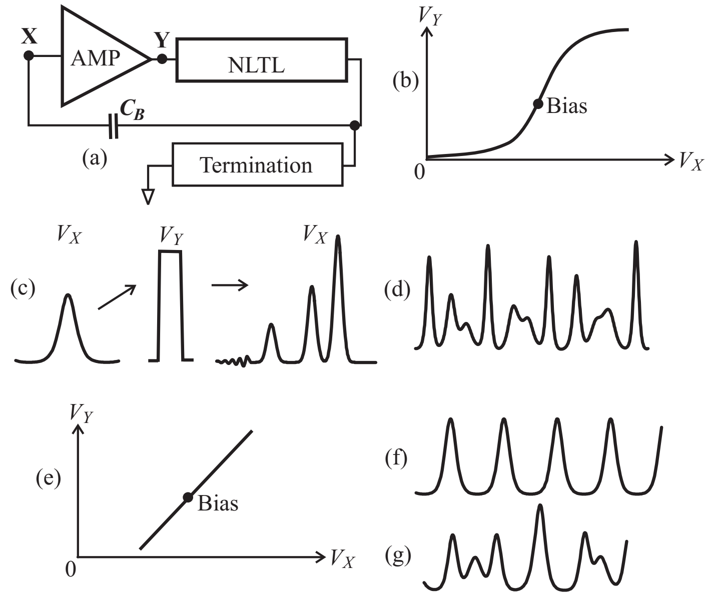

Figure 3: (a) A feasible NLTL soliton oscillator topology. (b) Transfer function of a saturating amplifier. (c) Impact of saturation. (d) Simulated unstable oscillation with the saturating amplifier. (e) Transfer function of a linear amplifier. (f,g) Two possible waveforms with the linear amplifier [3] [4].

and/or boundary conditions will determine the soliton modes that could propagate unchanged on the NLTL. Non-soliton waves can also travel on the NLTL, but change their shape in the course of propagation, often breaking up into several soliton pulses of different amplitudes, accompanied by a dispersive tail (ringings). While this transient behavior has been positively exploited for sharp soliton pulse generation in the 2-port NLTL scheme [2], it makes the soliton oscillator design difficult as seen in Sec. 3.

In addition to maintaining their shapes, solitons on the NLTL have other important properties. First, a taller soliton pulse propagates faster than a shorter one. Second, when two soliton pulses collide, they do not linearly superpose, and their nonlinear interaction results in permanent phase shift in both pulses. These nonlinear behaviors pose a significant challenge in the design of the NLTL soliton oscillator as seen in the following section.

3. NLTL SOLITON OSCILLATOR: DESIGN CHALLENGES

3.1. NLTL Soliton Oscillator Topology

Let us consider a closed-loop (ring) NLTL shown in Fig. 2(a). If only one-direction propagation is considered, the possible soliton propagation modes (cnoidal waves) on the ring are the ones that satisfy $l = n\Lambda$ $(n = 1, 2, 3, ...)$ where l and Λ are the circumference of the ring and the pulse spacing, respectively. The first three soliton propagation modes formed on the ring are shown in Fig. 2.

Figure 3(a) depicts a feasible soliton oscillator topology that could self-generate one of the soliton modes of the ring NLTL. In the system, a non-inverting amplifier is inserted in the NLTL loop in order to initiate startup and compensate for loss in the NLTL. The amplifier allows one-direction wave propagation only. The soliton oscillator also contains a termination to prevent reflections. Since it is difficult to perfectly impedance match the termination to the NLTL, undesired reflections will still occur and are treated as perturbations in this paper.

As will become clear shortly, the amplifier design is a critical task in attaining stable oscillations. The amplifier design, however, is not straightforward since conventional amplifiers will not work harmoniously with the NLTL. In the following, we examine two amplifier cases to elucidate the design challenges. The recognition of these challenges will be helpful in understanding our soliton oscillator presented in Sec. 4.

3.2. Saturating Amplifier

Let us first study the case where a standard saturating amplifier is used for the soliton oscillator. The transfer function of the saturating amplifier is depicted in Fig. 3(b). This amplifier has a fixed operating point and clamps a large signal. To see the impact of this saturation, let us assume that a soliton pulse appears at the input of the amplifier at a certain time [V_X on the left in Fig. 3(c)]. This soliton pulse, after passing through the amplifier, will appear as a square shape pulse due to the saturation [V_Y in Fig. 3(c)]. Since this is no longer a soliton pulse, it will break up into several soliton pulses with different amplitudes that will propagate down the NLTL with different velocities, all of which eventually appear again at the input of the amplifier [V_X on the right in Fig. 3(c)]. This process repeats itself, creating many soliton pulses with various amplitudes in the loop. These soliton pulses propagate with different speeds and nonlinearly interact with one another, making the system tend toward what appears to be a chaotic state. Our simulation of the oscillator with a saturating amplifier supports this reasoning, producing an unstable oscillation shown in Fig. 3(d).

3.3. Linear Amplifier

The previous subsection suggests that one *might* be able to attain a stable soliton oscillation if the signal saturation is mitigated in the amplifier. Ballentyne *et al* in [3][4] implemented such a system, by using a linear amplifier (See Fig. 3(e) for its transfer function.) with externally adjustable gain to eliminate saturation. Ballentyne indeed observed periodic soliton waveforms as shown in Fig. 3(f). However, various different and unstable waveforms occurred as well at different times or with slight changes of circuit parameters [4]. A depiction is shown in Fig. 3(g). While Ballantyne's oscillator overcame the signal saturation, it still does not ensure reproducible, stable soliton oscillations. This suggests that there are critical issues other than signal saturation, which could prevent a stable soliton oscillation.

3.4. Design Issues

While we identified the amplifier saturation as a design obstacle in Subsection 3.2, we overlooked two other important issues to achieve a stable soliton oscillation: *perturbation rejection* and *mode selection*. First, perturbations arise from inherent noise and reflections from the imperfect termination. Additionally, even if the amplifier saturation is reduced, the signal distortion cannot be entirely removed, leading to another source of perturbation. The perturbations can excite various solitons in addition to the existing, desired soliton pulse train. The nonlinear interactions between the perturbing solitons and the existing soliton pulse train result in significant phase and amplitude variations. Second, the oscillator could simultaneously excite several soliton propagation modes of the ring NLTL whose examples were shown in Fig. 2, and nonlinear inter-mode interactions on the NLTL could lead to instability. Hence it is important for the oscillator to have a single mode pulse train in steady-state. The saturating amplifier and the linear amplifier incorporate neither a single mode selection mechanism nor a perturbation rejection mechanism. Summarizing, to obtain a stable soliton oscillation, the amplifier in Fig. 3(a) should possess the following properties/capabilities:

- Reduced saturation,
- Perturbation rejection,
- Single mode selection.

4. NLTL SOLITON OSCILLATOR: DESIGN

Our solution to address the three design issues to achieve a stable soliton oscillation was the development of a unique amplifier utilizing an adaptive bias control, similar to Cutler's method for non-soliton pulse generation on a linear transmission line [7]. In our case, the adaptive bias control simultaneously solves the three problems mentioned above, stabilizing soliton oscillations on the NLTL.

4.1. Operating Principle - Adaptive Bias Control

Figure 4 illustrates our self-sustained NLTL soliton oscillator with a schematic of the new amplifier. The basic structure is the same as the circuit of Fig. 3(a). We will postpone the detailed description of the amplifier to the next subsection, and here describe its overall transfer function to see how the amplifier enables a stable soliton oscillation.

The amplifier is a non-inverting amplifier with a saturating transfer function as shown in Fig. 5, but with a moveable bias point that is adjusted according to the *dc* component of the output waveform (V_Y of Fig. 4). As shown in Fig. 5(a),

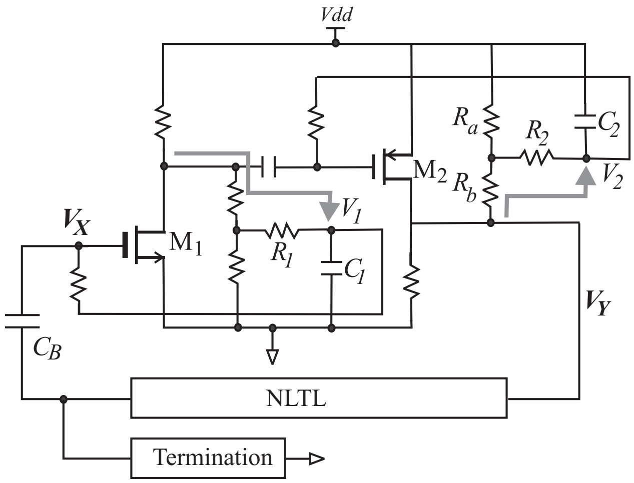

Figure 4: Our NLTL soliton oscillator with the new amplifier.

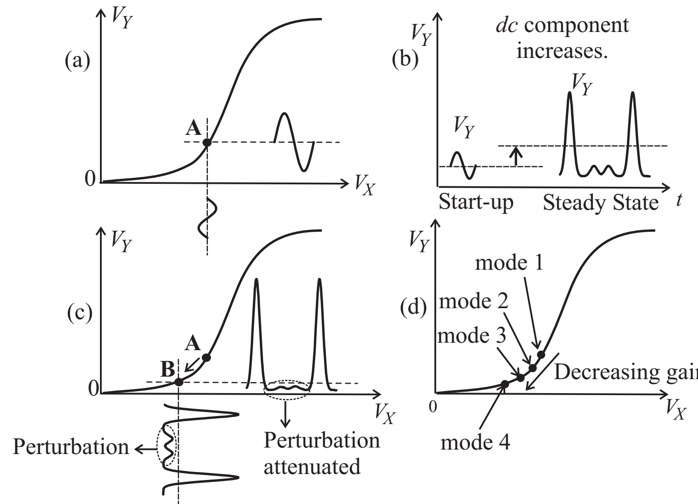

Figure 5: (a) Bias point **A** at the startup. (b) *dc* component of V_Y increases as the oscillation grows into soliton pulses. (c) Reduced bias point **B** as the oscillation grows into soliton pulses. Saturable absorption is shown as well. (d) Mode-dependent gain.

during the initial startup transient, the bias of the amplifier is set at point **A** in the larger gain region to allow startup from ambient noise. As the oscillation grows and forms into pulses, the *dc* component of $V_Y(t)$ increases as shown in Fig. 5(b). This increased *dc* component is then used to lower the input bias as shown with point **B** in Fig. 5(c). The reduced bias corresponds to a net overall gain reduction since less of the signal appears in the larger gain portion of the transfer curve. The bias point moves down the transfer curve reaching steady state when the average gain becomes equal to the average loss in the system. This adaptive bias control together with the nonlinear transfer curve of the amplifier addresses all the three design issues mentioned earlier.

First, in steady-state, the input bias has been sufficiently reduced so that the peak portions of the input and output waveforms remain in the linear region of the amplifier transfer curve, thereby preventing distortion. See Fig. 5(c). Second, perturbations at the input of the amplifier are significantly attenuated at the output, because the perturbations fall below the gain region of the transfer curve as shown in Fig. 5(c). This corresponds to perturbation rejection. The higher portions of the main pulses still receive enough gain to compensate loss. This threshold-dependant gain-attenuation mechanism is the "saturable absorption" that has been widely employed in optical soliton mode-locking, *e.g.* [8]. Third, the selection of a single mode out of the possible modes, *e.g.* Fig. 2, is accomplished with the adaptive bias control. Different soliton modes will have different *dc* components and therefore different overall gain due to the adaptive bias control, Fig. 5(d). Only those modes with sufficient gain to overcome the loss of the system can be sustained in steady-state oscillations. When more than one mode has sufficient gain, only the highest mode is stable since any small perturbation to a lower mode will grow into a soliton resulting in a higher mode oscillation. Consequently, the mode-dependent gain allows only one soliton pulse train mode. In summary, the adaptive bias control and nonlinear transfer function address the three design issues mentioned in Subsection 3.4 and enable a stable soliton oscillation.

4.2. Detailed Operation of the Amplifier

The amplifier shown in Fig. 4 consists of two complementary stages built around MOS transistors, M1 and M2, forming a non-inverting network. The adaptive bias is implemented identically for each stage and functions as follows. The output waveform, V_Y, is sensed by the voltage divider consisting of the two resistors, R_a and R_b, and then is integrated by the R_2-C_2 low pass filter. The voltage, V_2, now represents a scaled *dc* component of the waveform, V_Y, as the result of the integration. This *dc* component 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. The increase in V_2 corresponds to a reduction in the gate-source voltage of M2, effectively lowering its bias. The same argument applies to the first stage, M1, although the waveforms are inverted. Overall, combining the functions of the two stages, the input of the amplifier (V_X) has a reduced bias as the *dc* component of the output of the amplifier (V_Y) increases, performing the adaptive bias control described in the previous subsection.

5. EXPERIMENTAL RESULTS

A proof of concept was implemented with an artificial NLTL consisting of discrete inductors and varactors (*pn* junction diodes) with discrete MOS transistors. The soliton pulse repetition rate of 1 to 10 MHz was chosen to facilitate the proof of concept while the circuit can be implemented at GHz frequencies.

Figure 6(a) shows the oscillation start-up. Ambient noise is amplified creating a small oscillation which then grows into a soliton pulse train. In the start-up phase, another competing mode is observed, but is eventually suppressed by the stabilizing mechanism of the amplifier as seen in Fig. 6(a). In the figure, one can also see a shorter pulse propagates slower than a taller pulse, a key signature of the soliton propagation.

Figure 6(b) shows the steady-state soliton pulse train at one particular node of the NLTL. This waveform corresponds to the $l = \Lambda$ mode where there exists only one pulse propagating in the NLTL. The amplitude and pulse repetition rate are stable, showing no discernable variation. For instance, the variation of the pulse repetition rate remains within 0.1%. The waveform slightly deviates from the ideal cnoidal waveform due to dissipation, minor distortions of the amplifier, and reflections from the non-ideal termination. In this sense the output signals are quasi-solitons. By tuning the bias component, $l = 2\Lambda$ mode of oscillation shown in Fig. 6(c) was obtained. In this mode, two pulses co-propagate in the NLTL. The oscillator was insensitive to large perturbations, always returning to the stable oscillation.

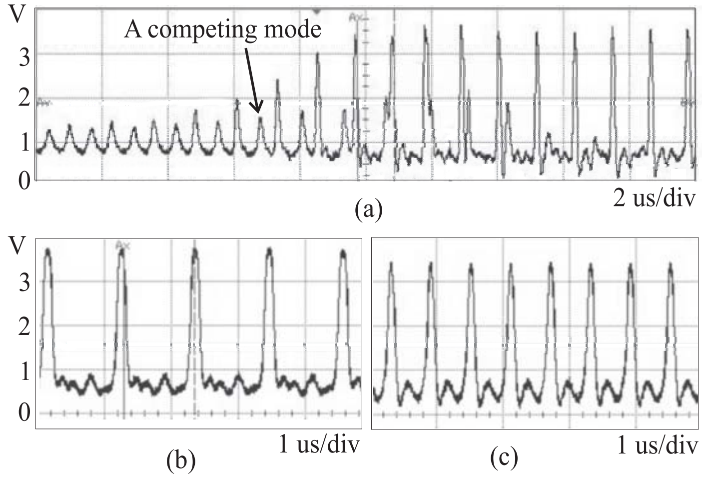

Figure 6: Measured stable soliton oscillation (a) Start-up transient of $l = \Lambda$ mode oscillation. (b) $l = \Lambda$ mode oscillation. (c) $l = 2\Lambda$ mode oscillation.

6. CONCLUSION

We have presented what we believe to be the first robust electrical soliton oscillator. This soliton oscillator derives its stability by coupling the NLTL with the unique amplifier incorporating a non-linear transfer function and an adaptive bias mechanism. This system is a direct analog of optical soliton mode-locking. The experimental results demonstrated a stable, reproducible soliton oscillation. This soliton oscillator offers a new venue to investigate soliton dynamics and electrical soliton mode-locking.

7. ACKNOWLEDGMENT

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