Novel high-frequency, high-power, pulsed oscillator based on a transmission line transformer

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Recent analysis and experiments have demonstrated the potential for transmission line transformers to be employed as compact, high-frequency, high-power, pulsed oscillators with variable rise time, high output impedance, and high operating efficiency. A prototype system was fabricated and tested that generates a damped sinusoidal wave form at a center frequency of 4 MHz into a 200 Ω load, with operating efficiency above 90% and peak power on the order of 10 MW. The initial rise time of the pulse is variable and two experiments were conducted to demonstrate initial rise times of 12 and 3 ns, corresponding to a spectral content from 4–30 and from 4–100 MHz, respectively. A SPICE model has been developed to accurately predict the circuit behavior and scaling laws have been identified to allow for circuit design at higher frequencies and higher peak power. The applications, circuit analysis, test stand, experimental results, circuit modeling, and design of future systems are all discussed. © 2007 American Institute of Physics. [DOI: 10.1063/1.2753833]

I. INTRODUCTION

Numerous applications require pulsed power systems capable of generating high-power, high-frequency pulses into a dynamic, high-impedance load. Applications demanding especially portable, compact, and inexpensive pulsed power drivers are single-shot electromagnetic pulse (EMP) test systems.1–3 Conventionally, magnetic flux compression generators (MFCGs) are employed to generate a low-frequency pulse that is modulated to high frequency and radiated with a dynamic, high-impedance impulse radiating antenna.4,5 However, the low efficiency inherent in the current methods of high-frequency modulation motivates research toward alternatives as a high-efficiency pulsed power oscillator.4 The circuit discussed within has been demonstrated at a peak power and frequency below the range of interest for applications as oscillators for EMP test systems; however, the analysis will be presented for scaling toward peak powers of on the order of 100 GW and frequencies on the order of 100 MHz.6–7 One consensus common to the vast amount of research in the field of pulsed electric field inactivation is that a pulse with a fast rise time on the order of nanoseconds is required to rupture the cell membrane, thereby allowing further damage to the cell nucleus and ultimately cell inactivation.4–7 Accordingly, future work in this field should undoubtedly examine pulses of a single frequency content, similar to the work of Nomura et al. and Akiyama, and with a fast initial rise time on the order of nanoseconds. It is this type of pulsed power driver that will be described in this article.

Transmission line transformers (TLTs) are conventionally employed as low voltage, square-pulse transformers for a variety of electronics applications.8 At higher voltages, several groups have designed TLTs capable of generating square pulses greater than 100 kV into a high-impedance load.9,10 For the vast majority of applications for TLTs, the parasitic mode is suppressed by winding the transmission lines on a ferromagnetic core to raise the inductance of the parasitic transmission lines, thereby increasing their characteristic impedance and negating their effects.9–12 The circuit discussed within, termed the transmission line oscillator (TLO), utilizes the parasitic mode in a TLT to generate a high-power, high-frequency damped sinusoidal wave form with variable rise time, high output impedance, and high operating efficiency. The TLO consists of several primary transmission lines arranged in a linear geometry, connected in parallel at their input side and in series at their output side. Parasitic transmission lines exist between a ground plane positioned along the length of the primary lines and the unshielded conductors in the primary transmission lines. A low-impedance, square-pulse generator, such as a pulse forming line (PFL) or pulse forming network (PFN), is used to drive the input of the TLO and a dynamic, high-impedance load, such as an impulse radiating antenna, is connected at the output of the TLO. In a parameter space characterized by the properties of the para-
sitic lines, primary lines, pulse generator, and load, the TLO will generate damped oscillations at a constant frequency with a fast initial rise time. Standard circuit analysis techniques and simulations can be used to model the behavior of the TLO, where the analysis shows that the frequency of oscillation scales inversely with the physical length of the circuit. Therefore, the potential exists to design compact, pulsed power drivers for several high-frequency applications based on the TLO circuit discussed within.

II. CIRCUIT ANALYSIS

The two-stage TLO with circuit schematic shown in Fig. 1 will be used to explain the basic principles of the circuit. Assuming that coaxial cables are used for the primary lines, one parasitic transmission line exists between the ground plane and the outer conductor of line 1, as labeled on the circuit schematic. In general, parasitic lines will exist between the ground plane and any unshielded conductors that are not grounded at both ends. Parasitic lines can also exist between unshielded conductors of the primary lines, as is the case for TLOs with more than two stages.

Circuit simulations show that for a parameter space where \( Z_{01} = Z_{02} = \frac{1}{2} Z_L \) and \( Z_{03} \gg Z_{01} \), the circuit is an ideal, square-pulse transformer, and in a parameter space where \( Z_{03} = Z_{01} = Z_{02} \), the circuit will generate damped oscillations at a constant frequency with a fast initial rise time. The circuit response may be predicted analytically only in a parameter space where the transit times of the parasitic and primary lines are equal, so that reflections occur in the transmission lines at integer multiples of the transit time, and the lattice diagram method may be applied. In general, though, the transit time of the parasitic line, \( \tau_{\text{ds}} \), is given by

\[
\tau_{\text{ds}} = \tau_{\text{dp}} \sqrt{\frac{\varepsilon_{\text{rs}}}{\varepsilon_{\text{rp}}}},
\]

where \( \tau_{\text{dp}} \) is the transit time of the primary lines, \( \varepsilon_{\text{rs}} \) is the dielectric constant of the parasitic line, and \( \varepsilon_{\text{rp}} \) is the dielectric constant of the primary lines. Accordingly, the transit times of the parasitic and primary lines will be equal only if they share the same dielectric. Since this is not the case in a realistic system, the circuit response cannot be predicted analytically and, therefore, computer simulations are necessary.

An open-source circuit analysis program, LTSpice, was used in the current and subsequent sections to model the circuit response of the TLO.

A simulation of the circuit response for the two-stage TLO is given in Fig. 2 for the realistic parameter space described in Table I. A polyethylene dielectric \( \varepsilon_{\text{rp}} = 2.26 \) (Ref. 14) was assumed for the primary lines and an air dielectric was assumed for the parasitic lines. The simulations demonstrate that the frequency of oscillation varies by 15% for a load impedance that varies by an order of magnitude. Accordingly, the TLO is a suitable pulsed power driver for a dynamic load such as an impulse radiating antenna.

The amplitude of the output pulse decays in an exponential envelope, as characterized by the damping time \( \tau_{\text{damp}} \) and expressed by

\[
V_{\text{out}}(t) \sim \cos(\omega t) \exp(-t/\tau_{\text{damp}}),
\]

where \( V_{\text{out}}(t) \) is the temporal component of the amplitude of the output pulse, \( \omega \) is the center frequency, and the higher-frequency terms corresponding to the initial rise time have been neglected. For the experiments discussed subsequently, the output pulse damps to a negligible amplitude within approximately ten periods, and therefore \( \tau_{\text{damp}} \) is approximately one order of magnitude greater than \( \omega^{-1} \). As the impedance of the parasitic lines increases several orders of magnitude above the impedance of the primary lines, the oscillations are increasingly damped and the voltage gain approaches the value for the ideal square-pulse transformer.

The circuit simulation demonstrates that close to 100% of the input energy is delivered to the load over the pulse width. The sources of energy loss in the circuit include losses in the output switch of the pulse generator and radiation losses in the circuit conductors. Since the latter increases with frequency, it should be expected that efficiency will decrease at higher frequencies.

The rise time of the initial pulse is unaffected by the presence of the parasitic lines as they are grounded at their input side and do not affect the temporal properties of the pulse. The propagation of the energy from the source to the load is given by the ratio of the load impedance, \( Z_L \), to the input impedance, \( Z_0 \) (Fig. 2). The loss in this process is given by the ratio of the load impedance to the input impedance times the total impedance at the load, which may be approximated by

\[
\frac{Z_L}{Z_0} = \frac{R}{Z_0} \approx \frac{R}{Z_0}.
\]

Table I. The parameters of the two-stage TLO circuit simulation are summarized.

<table>
<thead>
<tr>
<th>Pulse generator (PFL) properties</th>
<th>Primary line properties</th>
<th>Parasitic line properties</th>
<th>Load impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_{01} = 25 \Omega )</td>
<td>( Z_{02} = 50 \Omega )</td>
<td>( Z_{03} = 40 \Omega )</td>
<td>( R = 100 \Omega )</td>
</tr>
<tr>
<td>( \tau_{\text{d}} = 50 \text{ ns} )</td>
<td>( \tau_0 = 10 \text{ ns} )</td>
<td>( \tau_{\text{r}} = 6.7 \text{ ns} )</td>
<td>( L_{\text{seal}} = 100 \text{ nH} )</td>
</tr>
</tbody>
</table>
output pulse until two parasitic transit times have elapsed. Therefore, the fast rise times inherent to PFLs can be achieved by minimizing stray circuit inductance and also by including a peaking switch in the circuit. The spectral content of the output pulse includes components corresponding to the primary oscillation frequency and the initial rise time. By adjusting the rise time of the initial pulse, the spectral content can be adjusted to include components from a few megahertz to hundreds of megahertz.

III. EXPERIMENTAL TEST STAND

The transmission line oscillator fabricated and tested at the University of Missouri-Columbia consists of four 50 Ω coaxial transmission lines connected in parallel at their input side and in series at their output side. The pulse generator is a 12.5 Ω, 25 ns, dc-charged PFL and the load resistor is a 200 Ω CuSO₄ aqueous-electrolyte resistor with approximately 100 nH series inductance. A flat copper sheet serving as the ground plane connects the pulse generator to the load resistor and is positioned along the length of the primary transmission lines. Accordingly, three parasitic lines exist that are shorted at their input side and connected from the outer conductor of a coaxial transmission line to the ground plane at their output side. In addition, parasitic lines also exist between unshielded conductors in the primary lines.

A circuit schematic of the experimental TLO is given in Fig. 3 in which the transmission line parameters of the parasitic lines were calculated using Eqs. (3)–(5) and Figs. 7 and 8, discussed subsequently. A diagram detailing the circuit connections and experimental layout is shown in Fig. 4 and explained in the caption.

IV. EXPERIMENTAL RESULTS

Experiments were conducted with the transmission line oscillator to demonstrate the time-domain and frequency-domain characteristics of the output pulse. The experiments were conducted with and without a peaking switch connected before the load in order to demonstrate the variable rise time and variable spectral content of the TLO. For both experiments, the inverse of the damping time was equal to approximately \( \frac{1}{2\pi t} \) of the center frequency.

The plots in Fig. 5 represent the results of the experiments conducted without a peaking switch. The 10%–90% rise time of the initial pulse is 12 ns and the center frequency of the spectral content is at 4.5 MHz. The FWHM bandwidth of the spectral content is 1 MHz and additional spectral content corresponding to the rise time of the initial pulse exists from 20 to 30 MHz. The energy delivered to the load is within 90% of the initial input energy and the peak power delivered to the load exceeds 5 MW.

FIG. 3. A circuit schematic of the four-stage experimental TLO is given.

FIG. 4. (Color online) A diagram of the circuit connections and experimental layout of the system, not to scale. The pulse generator is not shown on the diagram. The transmission line section was supported in a plastic tube that fed into a transformer oil container. The load resistor, diagnostics, removable peaking switch, and series-connected end of the transmission line section were immersed in transformer oil. A Northstar passive RC-compensated voltage probe, and a Pearson current monitor were utilized as the diagnostics. A flat copper sheet was connected to the pulse generator at one end and to the outer conductor of a transmission line and the load resistor at the other end.

FIG. 5. Plot (a) represents the output voltage, plot (b) represents the frequency content, plot (c) represents the input and output energy, and plot (d) represents the output power for the experiments conducted without a peaking switch.
The plots in Fig. 6 represent the results of the experiments conducted with a peaking switch. The peaking switch was fabricated from sharpened electrodes with millimeter gap spacing. The 10%–90% rise time of the initial pulse is 3 ns and the center frequency of the spectral content is at 4.5 MHz. The full width at half maximum (FWHM) bandwidth of the spectral content is 1 MHz and additional spectral content corresponding to the rise time of the initial pulse exceeds 100 MHz. The energy delivered to the load is within 90% of the initial input energy and the peak power delivered to the load exceeds 25 MW. A negatively charged PFL was used to generate the data of Fig. 6 and a positively charged PFL was used to generate the data of Fig. 5; hence the opposite initial voltage as shown in the figures.

V. MODELING AND SCALING

A circuit model of the transmission line oscillator was developed to verify the response of the prototype TLO and also to use as a predictive tool in the design of future TLOs operating at higher frequencies and higher peak power. The two transmission line geometries described in Fig. 7 were utilized to model the parasitic transmission lines of the prototype TLO. Figure 7(a) represents the wire-over-ground geometry and is used to predict the parameters of the parasitic transmission lines between the flat ground plane and outer conductors of the coaxial transmission lines in the prototype TLO. The characteristic impedance of the wire-over-ground geometry is given by

\[ Z_0 = \frac{60 \Omega}{\sqrt{\varepsilon_r}} \ln \left( \frac{4h}{d} \right), \]  

(3)

Figure 7(b) represents the dual-wire geometry and is used to predict the parameters for parasitic transmission lines between the outer conductors of coaxial transmission lines in the prototype TLO. The characteristic impedance of the dual-wire geometry is given by

\[ Z_0 = \frac{60 \Omega}{\sqrt{\varepsilon_r}} \ln \left( \frac{w^2}{r^2} \right), \]  

(4)

and the transit time of both transmission line geometries is given by

\[ \tau_d = \frac{\sqrt{\varepsilon_r}}{c}. \]  

(5)

The dimensions of the transmission line section in the prototype TLO are given in Fig. 8, from which Eqs. (3)–(5) can be applied with the models of Fig. 7 to accurately predict the parameters of the parasitic transmission lines. In order to model the parasitic transmission lines in an arbitrary geometry, a similar analysis could be applied. In addition, the stray inductance in the circuit connections of the TLO can be modeled using equations found in Ref. 16 or measured with an RLC meter. For the experiments discussed, both methods were utilized to accurately model the stray circuit inductance. The results of the model are shown in Fig. 9, demonstrating close agreement with the experimental results.
Accordingly, the circuit model will be utilized in future designs to scale the TLO to higher frequencies and higher peak powers.

VI. DESIGN OF A 30 MHz SYSTEM

The circuit model discussed previously was applied in the design of an eight-stage TLO operating at a center frequency of 33 MHz, approximately one order of magnitude higher than the prototype TLO. The parameter space given by Table II was assumed in the design and the output waveform predicted by the circuit model are given in Fig. 10. The dielectric constant of the primary lines was assumed to be polyethylene and, accordingly, Eq. (5) was used to predict the length of the transmission line section to equal 0.38 m (15 in.). As the length scales inversely with the square root of the dielectric constant, designs utilizing a higher dielectric constant could significantly decrease the physical length of the circuit. The analysis provides the motivation for future experiments to demonstrate the TLO in this parameter space.

VII. DISCUSSION

Experiments and analysis have demonstrated the potential for the TLO circuit to be employed as a compact pulsed power driver for several high-frequency, high-power applications. Eventually, a fundamental limit on the frequency of oscillation will be reached as the transmission lines in the TLO circuit become so short that the connection inductance dominates the circuit response. It is the future goal of this program to demonstrate the TLO circuit at frequencies from tens to hundreds of megahertz, or until the fundamental limit is observed. A 30 MHz system has been designed utilizing the circuit models developed with the prototype system and will be tested near term. Additional research in advanced polymers in our research group will aid in the design of the high energy-density transmission lines required for the design and fabrication of compact TLOs operating at hundreds of megahertz and energies up to 1 kJ.

TABLE II. The parameters of the 30 MHz TLO circuit simulation are summarized.

<table>
<thead>
<tr>
<th>Pulse generator (PFL) properties</th>
<th>Primary line properties</th>
<th>Parasitic line properties</th>
<th>Load impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{charge}}=645$ kV</td>
<td>$Z_0=6.25$ Ω</td>
<td>$Z_{\text{d}}=50$ Ω</td>
<td>$Z_{\text{bias}}=1000$ Ω</td>
</tr>
<tr>
<td>$E_{\text{store}}=100$ J</td>
<td>$\tau_d=3$ ns</td>
<td>$\tau_p=2$ ns</td>
<td>$\tau_d=1.33$ ns</td>
</tr>
</tbody>
</table>

FIG. 9. The results of the circuit model and the experimental data are represented in an overlay plot.

FIG. 10. Plot (a) represents the output voltage vs time and plot (b) represents the output power and energy vs time for the 33 MHz TLO circuit simulation.

7. Hidenori Akiyama (private communication).