Generation and Radiation of High-Power Mesoband Waveforms using Quarter-Wave Switched Oscillators

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Abstract

In the late 1990s and early 2000s, Carl Baum proposed the idea of generating moderate bandwidth electromagnetic waveforms using quarter-wave switched oscillators. After his initial conceptual proposition, it took several years to realize these systems, and many lessons were learned along the way. This article captures the details of the modeling and design methodologies that we have developed over the years in order to obtain oscillators with specific characteristics. The design methodology consists of a delicate balance among the pulsed power, electrodynamic, and mechanical considerations, each of which often work against each other in practice.

1. Introduction

In Circuits and Electrical System Design Note #45 [1], Carl Baum proposed the use of a simple quarter-wavelength, switched oscillator as a high power microwave (HPM) source that could produce very high peak powers and several cycles of resonant energy, thereby concentrating the energy stored in a capacitive energy storage unit in a moderate microwave bandwidth. His proposal called for a new class of device that was intermediate in bandwidth between ultra-wideband sources like JOLT [2] and more conventional narrow band HPM sources [3]. The key innovation was that these moderate bandwidth, or *mesoband* (MB) sources use the simpler technology of UWB systems to generate waveforms of similar intensity, but have 10 – 20 dB higher peak energy spectral density due to the increase in pulse duration (more energy per pulse) and corresponding reduction in bandwidth (spread out over less bandwidth).

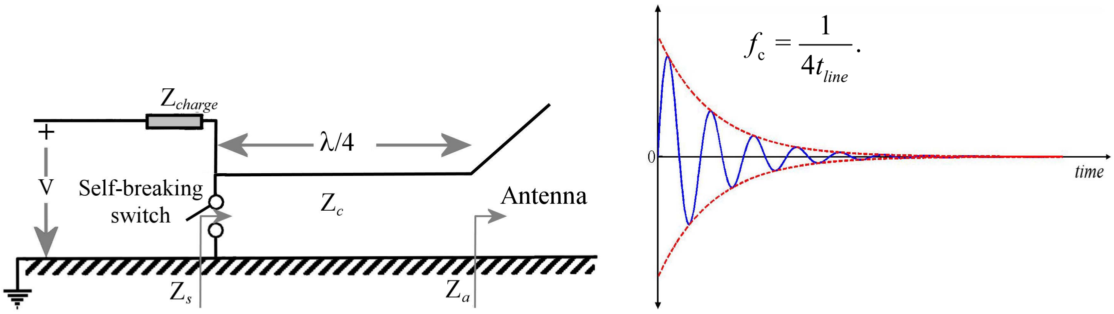

Figure 1: (left) A low-impedance (high capacitance) transmission line is charged up and then switched at one end. A transient waveform bounces back and forth between the switch and a high impedance load (antenna), thus creating a high-*Q* oscillator. (right) A model waveform from such a system

Figure 1 shows the simple circuit schematic of a quarter-wave oscillator. The low-impedance transmission line is charged and serves as the energy storage device during the charge phase. When the voltage on the line reaches the threshold voltage, a switch is closed at one end of the line, and a transient pulse is launched. At the opposite end, the pulse encounters a high input-impedance antenna, and most of the energy is reflected, with a voltage reflection coefficient of nearly unity. This reflected pulse then returns to the switch, where it meets a nearly-short circuit, and is reflected once again, but this time with a reflection coefficient of negative unity. The pulse bounces back and forth between the ends, delivering a little bit of its energy at each round-trip to the antenna.

Figure 2 shows a concept for realizing the idea of Baum in a practical system. The low-impednace transmission line is actually a very large coaxial capacitor, with length approximately equal to the desire quarter-wavelength line. In order to manage the large potentials required in an HPM system, the center conductor of the coax must be relatively large in order to reduce the peak fields during the charge cycle and prevent unintended breakdown in the coax. The switching mechanism is in a nearly-parallel-plate geometry on the central axis of the coax. However, in order to have

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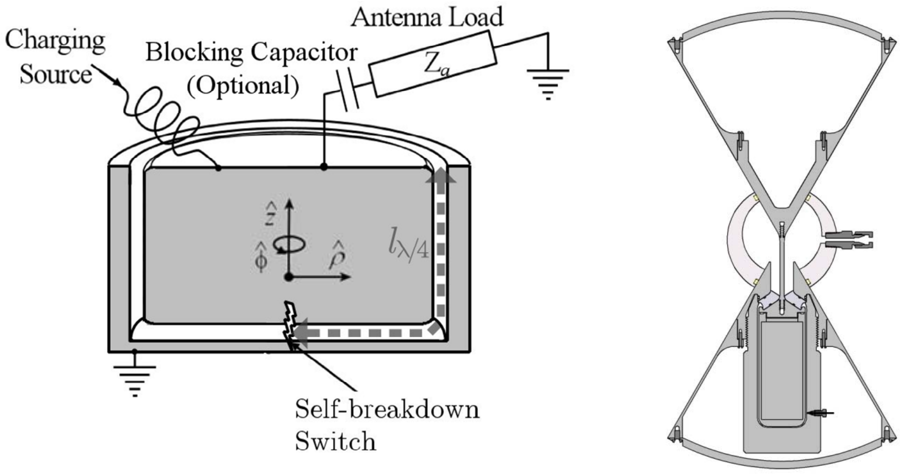

Figure 2: (left) Schematic design for a coaxial SWO. The low-impedance coax is charged up to high voltage, and a self-breakdown switch is located on the axis at the closed end. The currents flow from the switch around the corner, up the coax, and interact with the high-impedance antenna. (right) An actual engineering design (not built) of a system that integrates this concept into a biconical radiator.

excellent switching properties, it is necessary that the shapes of the conductors be precisely controlled and that the gap spacing be extremely small. In order to connect the on-axis switch to the low-impedance coax, a section of radial transmission line is used to guide the currents from the switch to the coaxial pulsed forming line. Since the radial transmission line is a slow-wave structure, it increases the effective length of the oscillator, thereby lowering the resonance below the physical quarter-wavelength frequency.

2. Static Field Management

The first consideration when designing a SWO as shown in Fig. 2 is to ensure that the static field levels are managed in order to guarantee that the switch will close on axis. This is most problematic in the bend region where the radial transmission line meets the coaxial storage section. We have developed an iterative, semi-automated design philosophy that allows us to control the field enhancement in this section and achieve a desired profile [4]. Figure 3 shows how this proceeds. We begin with a relatively crude outline of the desired system, paying little attention to bends and corners. We then obtain equipotential surfaces from the solution to Laplace's equation on our original geometry, and we use two such surfaces as a new set of electrodes for the next iteration. We can control the rate-of-change of the static fields in the bend through our choice of equipotential surfaces using a parameter called the bend factor

$$bf = \frac{V_1 - V_2}{V_1' - V_2'}, \tag{1}$$

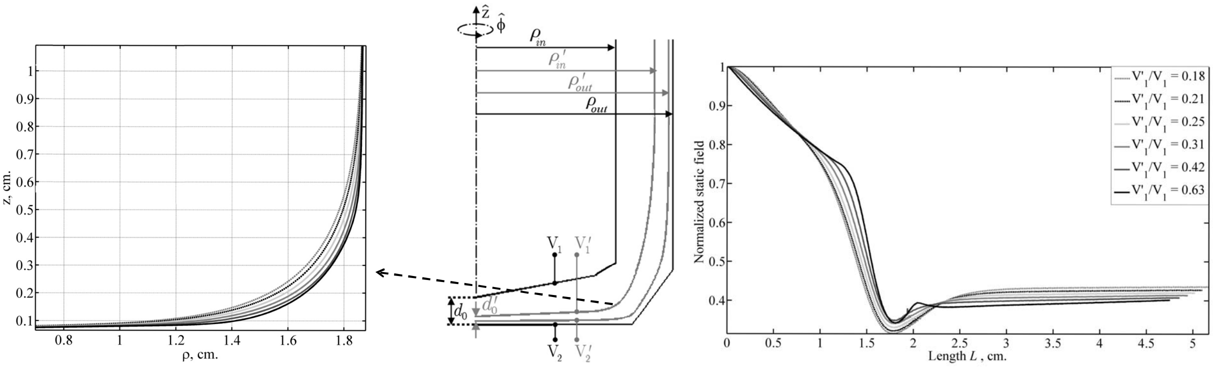

Figure 3: Beginning with a simple model for the system, we solve Laplace's equation and use the equipotential surfaces as a new pair of electrodes. We control the shape of the conductors by using a parameter called the *bend factor*, which guides our selection of surfaces. Increasing the bend factor allows for less field enhancement, as shown at right.

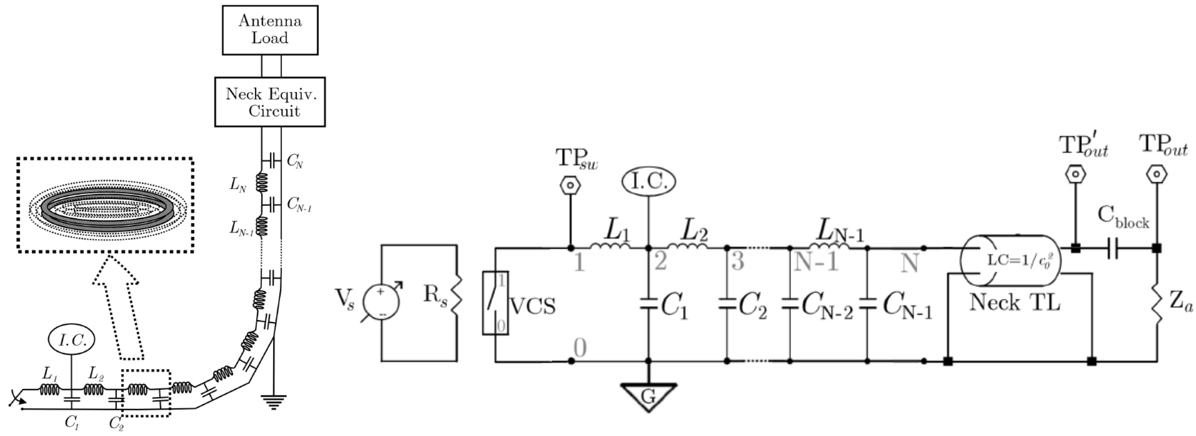

Figure 4: The electrostatic field solution is used to compute equivalent lumped inductances and capacitances that are then output into a SPICE model that predicts the resonant behavior of the oscillator.

which is the ratio between the original potential difference and the potential difference of the equipotential contours chosen for the next iteration.

3. Dynamic Modeling

Once we have satisfied our electrostatic field management requirements, the next step is to understand the tuning capabilities that we have in order to tailor the dynamic output of the system. We use a series of different models, including a simple Spice model and two more complicated Maxwell's equations solvers [4]. As shown in Fig. 4, we can divide the energy storage transmission line into a set of distributed, varying inductances and capacitors. These distributed elements are then modeled as lumped elements and are input into a Spice model of the overall system. If a more detailed electromagnetic model is required, we use either a 2-D FEM code programmed using the Matlab PDE Toolbox [4,5] or a 3-D Finite Volume Time Domain code in CST Microwave Studio. Schematics of the computational domains for each of these models is shown in Figure 5. The three models each have their own assumptions, and they vary most dramatically in terms of how they model the load. The SPICE model uses a resistive load, the FEM model uses a Sommerfeld radiation condition in a bound geometry, while the CST model fully models the antenna, and is the most accurate. A comparison between the computed resonance behavior of the three systems is shown in Figure 6. As can be seen, the two models that have resistive loads match well, but the CST model has a slightly lower resonance frequency because it fully models the antenna, which has an interaction with the SWO.

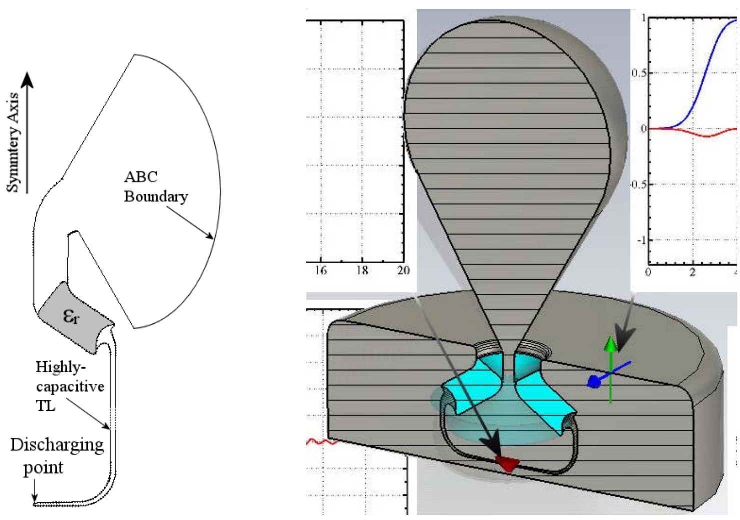

Figure 5: Computational domains for the 2D FEM model (left) and the 3D CST model (right). The 2D model uses an ideal ABC on a bound geometry, while the 3D model includes the antenna.

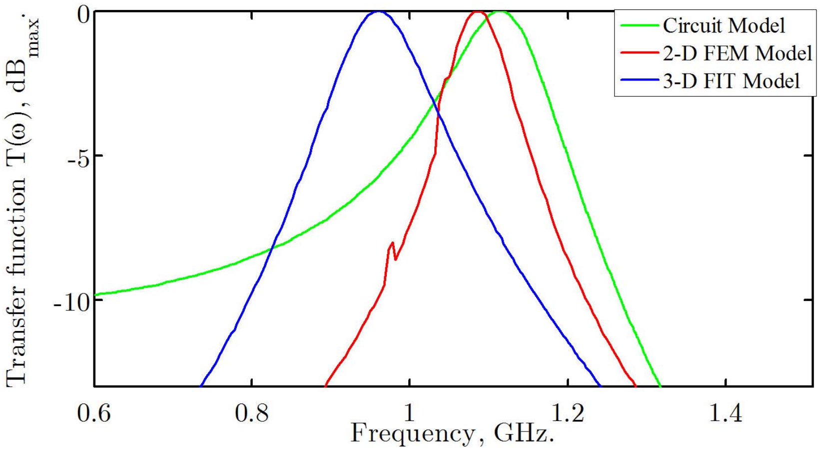

Figure 6: Computed resonance behavior of a particular system using the circuitmodel (Fig. 4) and the two full-wave solvers (Fig. 5).

4. Conclusion

In this paper we describe our design methodology for developing a SWO source under a particular set of constraints. By balancing the static and dynamic properties of the system, the desired frequency can be attained while managing the field levels and realizing maximum power. We rely on a physics-based optimization strategy that chooses the contours for the electrodes in a way that naturally controls the field enhancement, then optimize the resonance behavior using full-wave and circuit models coupled with knowledge of how the geometrical parameters interact with the microwave behavior.

5. Acknowledgments

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