Visualizing Time-Domain Distributed Electromagnetic Fields Using Sonnet

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Abstract: In this paper, we present a methodology that allows spatially distributed time-domain behaviour of an electromagnetic circuit to be plotted. The process is fully automated and implemented in Matlab using the SonnetLab interface to *em* and *emvu*. The technique permits the visualization of circuits operating in harmonically rich environments, for example high-speed digital circuits and power amplifiers, through a straight-forward application of the Fourier coefficients of the voltages impressed upon all circuit nodes. We demonstrate how to plot the time dependent surface currents and tangential electric fields due to any periodic, band-limited signal. The technique is demonstrated by animating the response of a transmission line due to a voltage square-wave and by computing the large-signal time-domain currents on the matching circuit of a 80-W LDMOS RF power amplifier operating at 2.6 GHz. Three dimensional surface plots of the currents and the tangential electrical fields surrounding these circuits are rendered.

Keywords: Time-domain visualization, signal integrity, power amplifier, Sonnet

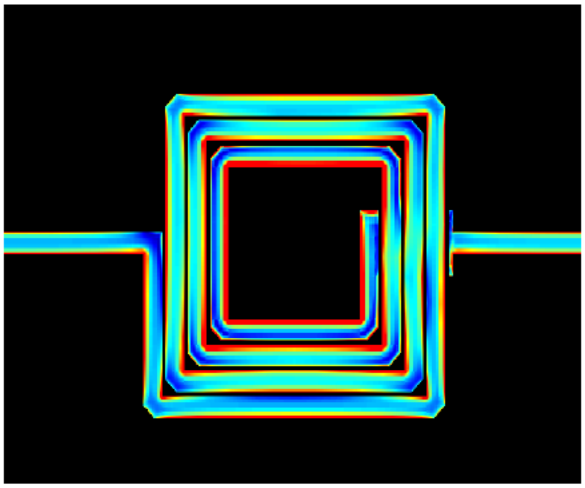
1. Introduction

Within virtually all modern electromagnetic software packages there are post-processing options to view the electromagnetic fields and surface currents of a circuit. Surpassing the description of the electrical behaviour at the ports, field visualization often provides significant insight into the circuit's internal operation. The resulting detailed renderings can show locations of current crowding, sources of adverse coupling and its effects, quality of transistor bias line decoupling, and even un-intended ground paths. Currents and fields, may also be animated by successively increasing the phase, and the behaviour over a period, or several periods, is often plotted. These type of frequency domain analysis and time-domain simulations and animations due to various input pulses have are commonplace [1], [2]. Visualizing these effects and the subsequent analysis often indicates where the circuit should be modified for optimal performance.

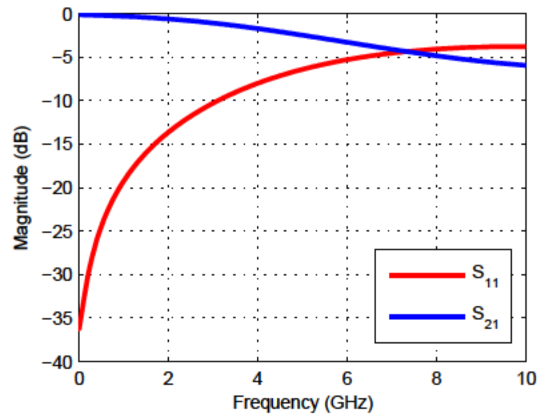
Illustrating this point, the current density within a square spiral inductor reveals current crowding as indicated in in Fig. 1(a). The simulated S-parameters, or the computed quality-factor, may show the performance limitations resulting from the current crowding but they do not offer any insight to diagnose circuit limitations nor optimize its performance. The current crowding at the corners suggest that circular spiral will provide a high quality factor. This information is not readily discernible from the S-parameters.

In addition to the obvious interest from the electromagnetic simulation community, there has been a significant interest to obtain measured fields from near-field probing systems. These systems employ miniaturized antennas [3], or complex electro-optic probing systems [4] that are scanned above an operating circuit. The measurements allow the detection and elimination of spurious radiated emissions [5], to understand MMIC operation [6], or examine the feeding to arrays of amplifiers [7]. These measurement techniques are designed to view subtle aspects of a circuit while operating under its intended electrical and environmental conditions.

The aforementioned simulation and measurement techniques obtain results at a single frequency, or in the case of time-domain responses, pulses that may be different than those seen by the circuit. Many circuits operate in



(a) Surface current density



(b) Reflected and transmitted S-parameters

Figure 1. Current crowding within a 3.5 turn square-spiral inductor with a line width of 20 μm and a spacing of $5\mu m$. The current density at 5.0 GHz is shown and crowding of the current in the corners and near adjacent lines is evident (darker colours indicate areas of low current density).

environments rich in harmonic content, where many frequencies are simultaneously propagating throughout the circuit. For high-speed digital systems, where signal integrity concerns are paramount, the response of a circuit due to various digital signals propagating is of interest. For power-amplifiers it is very useful to view spatially distributed currents at the fundamental frequency of operation but efficient operation demands control over the harmonics and the resulting waveforms. As such it is of keen interest to view the voltage and current waveforms [8]. For these applications, visualization of the steady-state time-domain responses are beneficial.

In this paper we present an automated methodology using the method-of-moments based simulator *em* to view the time domain currents and tangential electric fields of circuits while excited with realistic multi-harmonic signals. In the Sections that follow we present the background theory and outline the simulation process. We conclude by showing the time-domain fields surrounding a microstrip transmission line due to to a pulsed excitation and we plot the large signal currents within a high-power RF transistor amplifier.

2. Background

Sonnet's *em* uses the method-of-moments (MoM) during the electromagnetic simulation of a circuit. During this process the currents on the metalic portions of the circuit are computed and from this the S-parameters are then derived. For different port impedances and applied voltages the currents can be recomputed and exported.

Once the currents are obtained the time-domain response at any harmonic, N is

$$J(t) = J_N e^{j\omega t} \tag{1}$$

where J_N is a two-dimensional vector containing the currents over the entire layer, and $J(t)$ is the current density at a particular time, t. The currents are computed at different time steps and each frame is rendered to generate the time-domain currents. Within *emvu* the magnitude of $J_N(t)$ is plotted. We can extend this method for circuits with multi-harmonic content where the total time-domain response surface for each harmonic are summed,

$$J(t) = J_0 + J_1 e^{j\omega_o t} + J_2 e^{j\omega_1 t} + \ldots + J_N e^{j\omega_N t} \tag{2}$$

The methodology used to obtain the time-domain currents is outlined in Fig. 2. The first step in the process is to obtain the S-parameters the circuit component on which the currents are to be plotted. A circuit-theory based simulation of the full circuit is performed and the voltages at all harmonics are saved to a text file. These voltages are impressed upon the structure in *emvu* and the field or current is obtained at DC and all of the harmonics.

To simplify the repetitive and time consuming tasks of reading the node voltages, impressing this on the ports, generating and animating the field plots we have automated this process using the SonnetLab v5.0 toolbox. This toolbox allows us to drive the EM simulation directly from Matlab and we can export the current density matrix and operate on it from within Matlab.

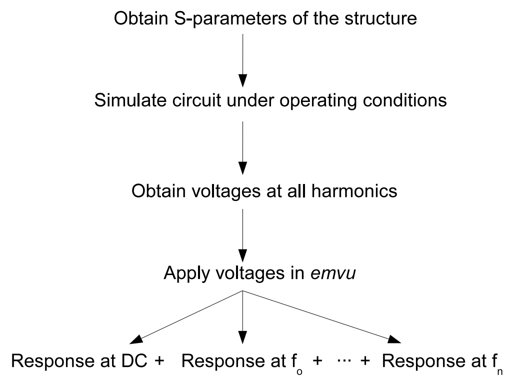


Figure 2. A flow chart showing how the time-domain response of the circuit is obtained

3. Application Examples

A. 50-Ω Transmission line

We first demonstrate this technique by plotting the time-domain currents and the tangential electric fields surrounding a microstrip transmission line which is excited with a periodic square-wave voltage source. The transmission line is suspended in air 20 mil above a ground plane, is 30 inches long, and is 100 mil wide; with a characteristic impedance of 50 Ω. The voltage source, connected to port 1 has a period of 1 ns and a duty cycle of 25%, while port 2 is terminated in a 50-Ω load.

To view the tangential electric fields a sense layer is place 1 mil above the top metal of the transmission line. This 'metal' has a surface resistance equal to zero and a surface reactance equal to 1e6 ohms per square. With such a large surface reactance this layer has little influence on the original fields but allows us to plot currents that are directly proportional to them [9].

The Fourier coefficients of the input signal are obtained for the first 10 coefficients. Sonnet simulations are performed near DC (where currents can be generated) and at each integer multiple of the fundamental frequency; $\frac{1}{Period}$. Once the simulations are completed the currents need to be extracted from *emvu*, the input voltages at each frequency are used along with the voltages present on the other ports. These are obtained by multiplying the Fourier coefficients of the incident signal by the S_{21}. These voltages are then loaded into *emvu* and the complex current density is output at each frequency for the top metal of the transmission line and for the sense layer.

In Fig. 3(a) the tangential electric field surrounding the microstrip is plotted along with the current on the transmission line. This plot is one frame of the animation. Positive and negative voltage pulses on either side of the transmission line are in sync with the rising and falling edges of the current pulse.

The high currents at the edges of the transmission line also are seen. This is further demonstrated by plotting the currents traveling down the transmission line at various cut-lines within the microstrip as shown in Fig. 3(b). High current densities are seen traveling down the edges of the line while the current density within the transmission line is significantly less. Similar behaviour is shown for the tangential electric fields. Surface plots of the currents and voltages are shown in Fig 4.

B. A Class-AB Power Transistor

In this sub-section we demonstrate the techniques through the calculation and visualization of the large-signal time-domain currents on the matching networks of a class-AB amplifier operating at 2.6 GHz. The amplifier uses a LDMOS RF power transistor capable of 80-W output power, P_{1dB}, at 2.6 GHz.

To obtain the surface currents on the matching networks at each frequency the voltages at all of the 7 points identified within the circuit as illustrated Fig. 5. These are obtained through a harmonic balance (HB) simulation where the S-parameters distributed PCB matching networks have already been run and are included in the schematic as an S-parameter file represented by the 'look-alike artwork' symbol.

The HB simulation was performed at P_{1dB} and all of the port voltages up to the 5^{th} harmonics are recorded in a text file. A Matlab script reads these and via the SonnetLab toolbox the voltages at each port are applied within *emvu* and the current matrix is returned for each harmonic. The surface currents at each frequency are generated and

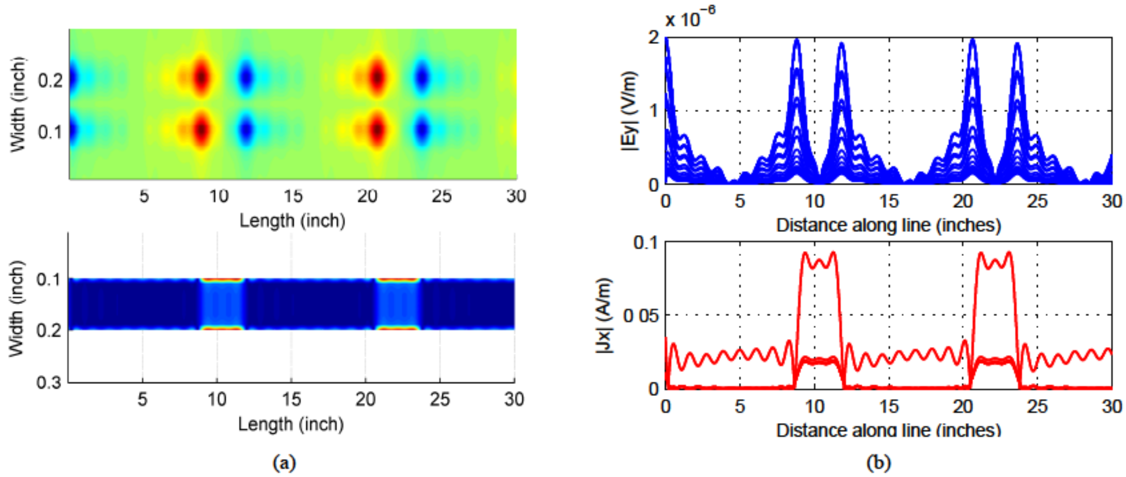


Figure 3. Plots of the current density and the tangential electric field along the 50-Ω transmission line. In (a) surface plots showing the intensity of the current density traveling down the microstrip line (Jx) and the tangential electric field (Jy) are plotted. In (b) plots are show at various cuts parallel to the transmission line indicating the relative intensity.

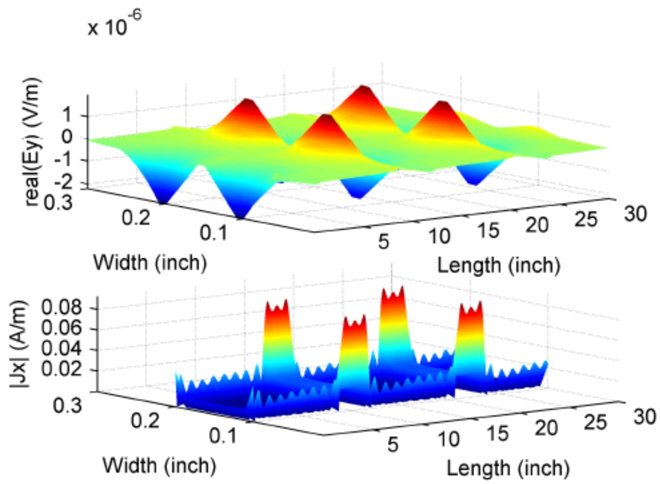


Figure 4. A perspective view of the current and tangential electric fields propagating down the long transmission line.

then summed together. Co-simulating and linking the electromagnetic simulator with the nonlinear circuit simulator allows us to view the full large-signal currents on the transistor as plotted in Fig. 6.

This technique provides a detailed look at the internal operation of the power amplifier beyond what is possible from the examination of the terminal properties typically measured e.g. gain, efficiency. In Fig. 6 the higher magnitude currents at the drain are expected due to the gain of the transistor. The asymmetrical influence of the bias line and the matching capacitors on the output are clear and indicate that a more symmetrical application of the bias and output matching capacitor could improve the overall transistor performance. This technique is applicable and can easily provide more information for the operation of the transistor for different bias conditions and impedance terminations, providing the designer with additional information that can be useful during the optimization of the transistors performance.

4. Conclusions

In this paper we have shown how it is possible using Sonnet and the SonnetLab toolbox to animate the surface currents and the tangential electric fields surrounding a circuit. In contrast to the standard visualization methods available in most moment-method simulators, where only the fields or currents for a single frequency can be plotted, this technique allows the circuit to be excited by any arbitrary, band-limited, periodic waveform. Allowing the circuit

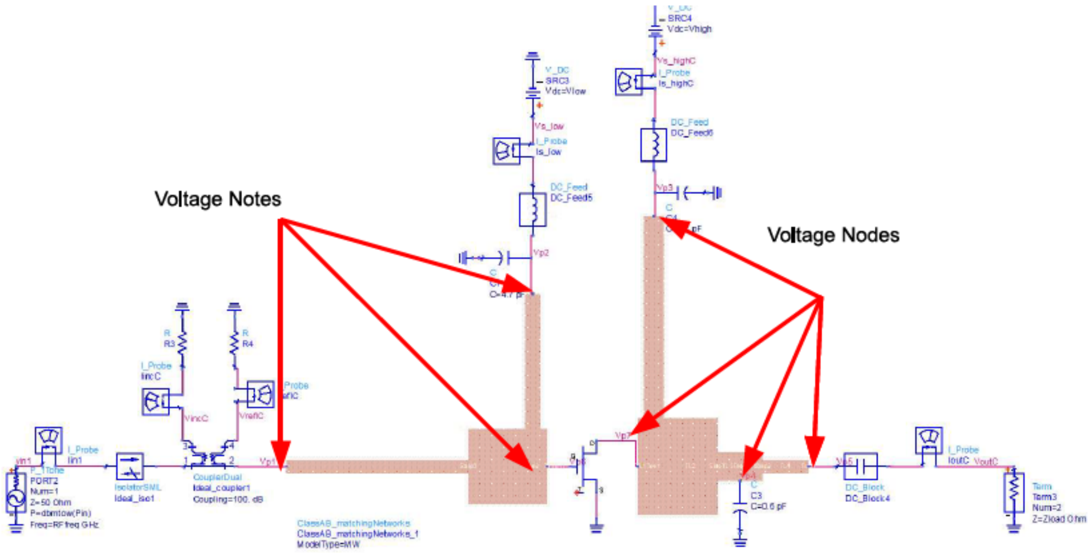


Figure 5. The schematics simulation of the 2.6 GHz 80-Watt LDMOS transistor. Note the locations of the locations port locations where the voltages are captured. These voltages are used as the port excitations to obtain the current waveforms.

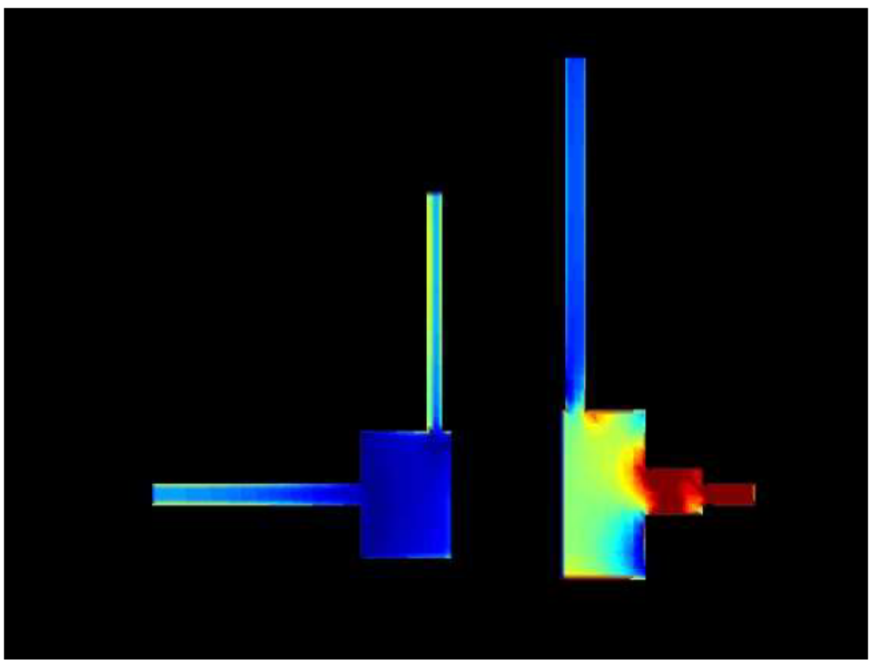


Figure 6. The large-signal currents present on the matching networks of the power amplifier. This plot is a single frame at one instant of the time-domain animation. Note the high currents on the drain of the transistor

designer to gain significant insight into the electromagnetic behaviour of their circuit in realistic environment and examining the circuit under different time-domain signals.

5. Acknowledgments

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