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A Microstrip Circuit Toolkit App with FDTD Analysis Including Lumped Elements

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I. INTRODUCTION

In 2014 IEEE Microwave Theory and Techniques Society (MTT-S) International Microwave Symposium (IMS2014), a student design contest on Apps for Microwave Theory and Techniques was held which was sponsored by Microwave Field Theory (MTT-15) technical committee. One objective of the design contest is to take advantage of the growing computing capacity of smart handheld and mobile devices to promote their use for computer-aided analysis and design of microwave components and circuits. With the rapid development of recent iOS and Android smart phones or pads, some advanced scientific computation programs are now feasible to be executed on these portable devices. These handy devices can also deal with microwave circuit calculations if the apps are well designed. Since these devices are always accessible at almost anytime, it may be more convenient for engineers and students to analyze and design microwave circuits on the phones or pads directly. Note however that 3-D full wave simulations for complicated microwave circuits usually require large amount of memory and CPU with high performance. Thus, it is still difficult to run 3-D full wave simulations on the portable smart devices.

Another objective of the design contest is to exploit the pervasiveness of smart handheld and mobile devices to facilitate the learning of microwave field theory principles and phenomena in a visual and interactive way, which elucidates the underlying physics or basic principles. If an intriguing app on the phones or pads could help analyze and design microwave circuits visually and interactively, students and engineers would be more willing to learn about microwave circuits. Otherwise, it is often not easy for them to understand and appreciate the microwave circuit theory and techniques from the textbooks alone.

In this contest, a versatile toolkit app is developed for microstrip circuit analysis and design on iOS devices. This app realizes various functions including microstrip line analysis and synthesis, calculations of input impedance, reflection coefficient and frequency response in terms of S-parameters. Smith chart tool is also provided to aid in designing microstrip circuit. In addition, a novel multiple 1-D finite-difference time-domain (FDTD) method is proposed to simulate microstrip circuits incorporated with lumped elements (resistor, capacitor and inductor) in parallel as well as series connections. These functions can be a handy assistant for students and engineers to test their simple design ideas without complicated derivations or simulations using a bulky computer. Moreover, friendly intuitive user interface is fully considered in designing the

app. So there is no real need for one to be trained to learn how to use this app. Several educational circuit examples are provided to help students gain a better understanding of the electromagnetic wave propagation in the microstrip circuit in a visual way. Our developed microstrip toolkit app is called μ StripKit.

II. MICROSTRIP CIRCUIT TOOLKIT APP: μ STRIPKIT

Once the app μ StripKit is launched, users are required to set up the microstrip parameters shown in Fig. 1. The parameters include the substrate relative dielectric constant ϵ_r , the thickness h and the center operating frequency of the microstrip circuit to be designed or analyzed. These parameters can be changed or set using the sliders or keyboard.

Fig. 1. Set up the microstrip parameters.

Next, users need to choose the circuit components to form microstrip circuit by swiping around the component selection panel, as shown in Fig. 2. The available components are listed in Fig. 3 comprising microstrip line, shorted or open stubs and lumped elements including resistor, capacitor and inductor. Both series and parallel connections of the lumped elements are provided. The parameters of all components can be changed or set by using the sliders or keyboard in the parameters panel in Fig. 2. Once the users add one component with properly set parameters, the component will be shown in the circuit schematic panel below. The input impedance, reflection coefficient, return loss and insertion loss will all be

calculated simultaneously. If desired, the parameters of each component in the circuit schematic panel can be changed if the component is selected and it can be deleted as well. Moreover, the sequence of the components in the circuit schematic panel can also be altered by long press and drag.

For microstrip lines and stubs, the microstrip line analysis and synthesis [1] function is provided. The upper textfields in the parameters panel are used to change the parameters of the microstrip line width (for analysis) and the corresponding characteristic impedance Z_0 (for synthesis). If the microstrip line width is changed or set using the slider or keyboard, the characteristic impedance Z_0 will be calculated simultaneously. Likewise, the width will be calculated once the characteristic impedance Z_0 is changed. Spontaneous calculation is implemented so that no button is needed to trigger the microstrip line analysis and synthesis function. Similar arguments apply for the lower textfields in the parameters panel pertaining to the microstrip line physical and electrical lengths.

Fig. 2. Component selection panel, parameters panel and circuit schematic panel.

As shown in Fig. 4, Smith chart tool is provided to aid engineers and students in designing microstrip circuit. Blue line shows the input impedance looking into every component of microstrip circuit sequentially. If the parameter of any component in the circuit schematic panel is changed, the blue line on the Smith chart will be changed simultaneously. Furthermore, users can plot constant resistance, reactance, conductance, susceptance and VSWR circles [1] (in grey color) on the Smith chart. These circles can be useful reference for students and engineers to adjust the parameters of components in designing the matching circuit. Additionally, the input impedance, reflection coefficient, return loss and insertion loss will all be calculated simultaneously next to Smith chart.

The S-parameters S_{11} and S_{21} of a microstrip circuit from 0 to 20 GHz are shown in Fig. 5. These S-parameters are derived as follows: The ABCD matrix of each component in the circuit

Fig. 3. Circuits components provided to form microstrip circuit: (a) microstrip line (b) series resistor (c) series inductor (d) series capacitor (e) microstrip stub with open end (f) microstrip stub with shorted end (g) parallel resistor (h) parallel capacitor (i) parallel inductor.

Fig. 4. Smith chart tool to aid designing microstrip circuit (e.g. bottom right inset).

is firstly calculated and the overall ABCD matrix of the whole two-port network is derived by multiplying the ABCD matrix of each component sequentially. The S-parameters are then obtained from the overall ABCD matrix at every frequency [2].

Time domain analysis of the microstrip circuit is given for students and engineers to have a better understanding of how electromagnetic waves propagate in the circuit. The microstrip circuit that users built in the previous step will be automatically meshed. Two kinds of sources are provided to show different propagation phenomena. One kind of source is sinusoidal wave and the other is Gaussian pulse. The source is excited at the input port. If the electromagnetic waves pass through a stub, the waves will enter the stub and the reflected waves will return from the stub to the main microstrip line circuit. A snapshot of the animation of electromagnetic wave propagation in the

Fig. 5. S-parameters of a microstrip circuit.

microstrip circuit (with stubs) is shown in Fig. 6.

Fig. 6. Animation of electromagnetic wave propagation in the microstrip circuit (with stubs).

III. MULTIPLE 1-D FDTD ANALYSIS INCLUDING LUMPED ELEMENTS

A. Simplification of microstrip circuit model

Given that the animated simulation will be implemented on the portable iOS devices, we propose a novel multiple 1-D

FDTD method for microstrip circuit analysis to save memory and computational time. Since microstrip circuit is actually a 3-D structure, it is necessary to simplify the microstrip circuit model so as to conform to the proposed multiple 1-D FDTD method.

Every microstrip line has its own characteristic impedance Z_0 according to its width and substrate height [1]. In our simplification, we consider that the characteristic impedance Z_0 corresponds to a wave impedance η as if the electromagnetic wave is prorogating in a medium with electric permittivity ϵ and magnetic permeability μ . Thus, the characteristic impedance can be expressed in terms of wave impedance as [3]

$$Z_0 = \eta = \sqrt{\frac{\mu}{\epsilon}}. \quad (1)$$

Meanwhile, the phase velocity along a microstrip line with effective dielectric constant ϵ_{eff} can be expressed as

$$v_p = \frac{c}{\sqrt{\epsilon_{eff}}} = \frac{1}{\sqrt{\epsilon\mu}}, \quad (2)$$

where c is the speed of light in free space. Again, we have assumed that the electromagnetic wave is going through a medium with electric permittivity ϵ and magnetic permeability μ .

By combining (1) and (2), the electric permittivity ϵ and magnetic permeability μ can be determined as

$$\epsilon = \frac{\sqrt{\epsilon_{eff}}}{Z_0 c}, \quad \mu = \frac{Z_0 \sqrt{\epsilon_{eff}}}{c}. \quad (3)$$

This approximation can also be applied for microstrip stubs with open or shorted ends.

Fig. 7. Parallel and series connected lumped elements (LE) in 1-D FDTD mesh.

B. Derivation for lumped elements in series connection

In 1-D FDTD mesh, there are only E_x and H_y components for electromagnetic waves propagating along the Z-axis. Referring to Fig. 7, it is feasible to compute the current density J through the parallel connected lumped element readily [4]-[6]. This is because the current density J is along the X-axis

and it can be expressed in terms of E_x component directly in the electrical field E_x update equation. However, this is not applicable for series connected lumped element owing to the lack of E_z component in 1-D FDTD mesh and there is no E_z update equation.

To resolve the above problem, we propose a novel method by introducing magnetic current density M (instead of J) to be used in the magnetic field H_y (instead of E_x) update equation. The magnetic current density M is defined as

$$\iint \vec{M}_{LE} \cdot d\vec{S} = \iint [-\nabla \times \vec{E}_{LE}] \cdot d\vec{S} = - \oint \vec{E}_{LE} \cdot d\vec{l}. \quad (4)$$

Since there is no E_z component in 1-D FDTD mesh, the values of $E_{z,i+1}$ and $E_{z,i}$ are equal to zero as indicated in Fig. 7. The closed loop integral of the four E components then becomes simply the corresponding voltage V_{LE} in terms of E_x component (without E_z):

$$\begin{aligned} - \oint \vec{E}_{LE} \cdot d\vec{l} &= (E_{x,k} - E_{x,k+1})\Delta x \\ &= V_{x,k} - V_{x,k+1} = V_{LE}. \end{aligned} \quad (5)$$

In this way, the voltages of series connected lumped elements in 1-D FDTD mesh can be determined.

C. Courant-Friedrichs-Lewy (CFL) condition

Although it is seemingly "1-D" FDTD scheme for the above microstrip circuit analysis, the 1-D FDTD CFL condition [4] is not applicable actually. In fact, the CFL condition for the proposed multiple 1-D FDTD method should be

$$\Delta t \leq \frac{\Delta x}{c\sqrt{2}}, \quad (6)$$

where $\Delta x(=\Delta y=\Delta z)$ is the mesh size. Such CFL limitation for the proposed multiple 1-D FDTD method actually corresponds to the 2-D CFL condition. If the 1-D CFL time step size is used, the method will become unstable especially for the microstrip circuit with stubs. This is mainly due to the stubs that are included in the simulation. The excitations of the stubs come from the main microstrip circuit and the reflected electromagnetic waves go back to the main circuit causing instability.

Although the microstrip circuit with stubs make up a 2-D planar circuit, we still implement essentially 1-D computations for the stubs. The occupied memory of each stub is a 1-D array and depends on its own physical length and meshing. Compared to 2-D simulation with 2-D arrays, the proposed method saves considerable computational time and memory. It is noted that if there is no stub in the microstrip circuit, the 1-D CFL condition with larger time step size could be adopted to save computational time.

To further circumvent the CFL limitation, unconditionally stable FDTD method may be employed which keeps the algorithm stable regardless of the time step size. In particular, the alternating-direction-implicit (ADI) FDTD method including lumped elements has been presented in [7]. This method and its efficient fundamental alternatives [8], [9] may be implemented in the future version of this app.

D. Update equations including lumped elements in parallel and series connections

The updating equations for the proposed multiple 1-D FDTD method including lumped elements in parallel and series connections are given as follows. Note that the equations for lumped elements in parallel connection are different from those in series one.

The updating equations for resistor with resistance R in parallel connection are ($V = IR$)

$$\left[\frac{1}{2}(E_x|_k^{n+\frac{1}{2}} + E_x|_k^{n-\frac{1}{2}})\Delta x \right] = [\Delta y \Delta z J_x|_k^n] R \quad (7a)$$

$$\begin{aligned} \left(1 + \frac{\Delta t \Delta x}{2\epsilon R \Delta y \Delta z}\right) E_x|_k^{n+\frac{1}{2}} &= \left(1 - \frac{\Delta t \Delta x}{2\epsilon R \Delta y \Delta z}\right) E_x|_k^{n-\frac{1}{2}} \\ &\quad - \frac{\Delta t}{\epsilon \Delta z} (H_y|_{k+\frac{1}{2}}^n - H_y|_{k-\frac{1}{2}}^n). \end{aligned} \quad (7b)$$

The updating equations for resistor with resistance R in series connection read

$$\left[M_y^{n+\frac{1}{2}} \Delta x \Delta z \right] = \left[\frac{\Delta y (H_y|_{k+\frac{1}{2}}^{n+1} + H_y|_{k+\frac{1}{2}}^n)}{2} \right] R \quad (8a)$$

$$\begin{aligned} \left(1 + \frac{\Delta t R \Delta x}{2\mu \Delta y \Delta z}\right) H_y|_{k+\frac{1}{2}}^{n+1} &= \left(1 - \frac{\Delta t R \Delta x}{2\mu \Delta y \Delta z}\right) H_y|_{k+\frac{1}{2}}^n \\ &\quad - \frac{\Delta t}{\mu \Delta z} (E_x|_{k+1}^{n+\frac{1}{2}} - E_x|_k^{n+\frac{1}{2}}). \end{aligned} \quad (8b)$$

The updating equations for capacitor with capacitance C in parallel connection are ($I = C \frac{dV}{dt}$)

$$[J_x|_k^n \Delta y \Delta z] = C \frac{(E_x|_k^{n+\frac{1}{2}} - E_x|_k^{n-\frac{1}{2}})\Delta x}{\Delta t} \quad (9a)$$

$$\begin{aligned} \left(1 + \frac{C \Delta x}{\epsilon \Delta y \Delta z}\right) E_x|_k^{n+\frac{1}{2}} &= \left(1 + \frac{C \Delta x}{\epsilon \Delta y \Delta z}\right) E_x|_k^{n-\frac{1}{2}} \\ &\quad - \frac{\Delta t}{\epsilon \Delta z} (H_y|_{k+\frac{1}{2}}^n - H_y|_{k-\frac{1}{2}}^n). \end{aligned} \quad (9b)$$

The updating equations for capacitor with capacitance C in series connection read

$$\left[H_y|_{k+\frac{1}{2}}^n \Delta y \right] = C \frac{(M_y|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - M_y|_{k+\frac{1}{2}}^{n-\frac{1}{2}})\Delta x \Delta z}{\Delta t} \quad (10a)$$

$$\begin{aligned} H_y|_{k+\frac{1}{2}}^{n+1} &= \left(1 - \frac{\Delta y \Delta t^2}{\mu C \Delta x \Delta z}\right) H_y|_{k+\frac{1}{2}}^n \\ &\quad - \frac{\Delta t}{\mu \Delta z} (E_x|_{k+1}^{n+\frac{1}{2}} - E_x|_k^{n+\frac{1}{2}}) - \frac{\Delta t}{\mu} M_y|_{k+\frac{1}{2}}^{n-\frac{1}{2}} \end{aligned} \quad (10b)$$

$$M_y|_{k+\frac{1}{2}}^{n+\frac{1}{2}} = M_y|_{k+\frac{1}{2}}^{n-\frac{1}{2}} + \frac{\Delta y \Delta t}{C \Delta x \Delta z} H_y|_{k+\frac{1}{2}}^n. \quad (10c)$$

The updating equations for inductor with inductance L in parallel connection are ($V = L \frac{dI}{dt}$)

$$\left[E_x|_k^{n-\frac{1}{2}} \Delta x \right] = L \frac{(J_x|_k^n - J_x|_k^{n-1})\Delta y \Delta z}{\Delta t} \quad (11a)$$

$$\begin{aligned} E_x|_k^{n+\frac{1}{2}} &= \left(1 - \frac{\Delta x \Delta t^2}{\epsilon L \Delta y \Delta z}\right) E_x|_k^{n-\frac{1}{2}} \\ &\quad - \frac{\Delta t}{\epsilon \Delta z} (H_y|_{k+\frac{1}{2}}^n - H_y|_{k-\frac{1}{2}}^n) - \frac{\Delta t}{\epsilon} J_x|_k^{n-1} \end{aligned} \quad (11b)$$

$$J_x|_k^n = J_x|_k^{n-1} + \frac{\Delta x \Delta t}{L \Delta y \Delta z} E_x|_k^{n-\frac{1}{2}}. \quad (11c)$$

The updating equations for inductor with inductance L in series connection read

$$\left[M_y|_{k+\frac{1}{2}}^{n+\frac{1}{2}} \Delta y \Delta z \right] = L \frac{(H_y|_{k+\frac{1}{2}}^{n+1} - H_y|_{k+\frac{1}{2}}^n) \Delta x}{\Delta t} \quad (12a)$$

$$\left(1 + \frac{L \Delta x}{\mu \Delta y \Delta z} \right) H_y|_{k+\frac{1}{2}}^{n+1} = \left(1 + \frac{L \Delta x}{\mu \Delta y \Delta z} \right) H_y|_{k+\frac{1}{2}}^n - \frac{\Delta t}{\mu \Delta z} (E_x|_{k+1}^{n+\frac{1}{2}} - E_x|_k^{n+\frac{1}{2}}). \quad (12b)$$

It is noted from the above that for series capacitor and parallel inductor, one extra step is necessary to update the current density J and the magnetic current density M respectively.

IV. EDUCATIONAL CIRCUIT EXAMPLES

To demonstrate the proposed method in the app, three animated FDTD simulation examples are used as educational illustrations to teach students about the microstrip circuit principles in a visual way.

Fig. 8. Microstrip circuit with a termination.

The first example is about standing wave. A microstrip line with characteristic impedance of 50Ω is connected to a termination with unity reflection coefficient, as shown in Fig. 8. A sinusoidal wave is excited at the input port. When the wave propagates to the termination, the wave will be reflected totally. After the reflected wave and the incident wave from the source are superimposed, the phenomenon of standing wave will show up.

The second example is about matched load where the schematic is similar to the above but with a 50Ω resistor termination. A Gaussian pulse is excited at the input port. In this example, we observe that there is no reflected wave when the pulse arrives at the termination. It should be noted that there is no absorbing boundary condition implemented at the end of the circuit, but the wave could still be absorbed (by the resistor). If we change the resistance of the termination (no longer 50Ω), we will see reflection from the resistor. If the difference between the resistance and the characteristic impedance of the microstrip line is larger, more reflected wave will be observed.

The third example is about electromagnetic wave interaction with stub which shows how the wave enters a stub and how it is reflected back to the main microstrip circuit. As shown in Fig. 6, two microstrip stubs are connected to the main microstrip line. The first one is a shorted stub and the second one is an open stub. Students can observe that the pulse will be

totally reflected in phase in the open stub and out of phase in the shorted stub. The animation helps students visualize how electromagnetic wave propagates in the microstrip circuit with various stubs.

V. CONCLUSION

A versatile toolkit app μ StripKit has been developed for microstrip circuit analysis and design on iOS devices. This app realizes various functions including microstrip line analysis and synthesis, calculations of input impedance, reflection coefficient and frequency response in terms of S-parameters. Smith chart tool has also been provided to aid in designing microstrip circuit. In addition, a novel multiple 1-D FDTD method has been proposed to simulate microstrip circuits incorporated with lumped elements in parallel as well as series connections. Several educational circuit examples have been provided to help students gain a better understanding of the electromagnetic wave propagation in the microstrip circuit in a visual way.

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