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Mobile Teaching and Learning of Coupled Line Structures Using M1-D CL-FDTD Method

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Abstract—In this article, mobile teaching and learning of coupled line structures using multiple one-dimensional coupled line finite-difference time-domain (M1-D CL-FDTD) method are presented. The formulation of M1-D CL-FDTD method applicable for coupled line structures is provided. The method bypasses the more computationally intensive full-wave 3-D method and it is well-suited for implementation on mobile devices. Several mobile apps are developed to provide interactive visualization of EM wave propagation in coupled line structures. Such visualization allows the underlying resonating and coupling mechanisms to be elucidated clearly and improves students' understanding of coupled line theories. Mobile teaching and learning of various coupled line structures including coupled transmission lines, coupled line bandpass filter, directional coupler and branch line coupler are demonstrated and discussed.

Index Terms—Mobile teaching and learning, coupled line structures, multiple 1-D CL-FDTD method, electromagnetics education, wave propagation

I. INTRODUCTION

Teaching and learning of engineering electromagnetics (EM) has been receiving much attention over the years. Educators within the EM community have been seeking innovative ways to improve students' understanding on the rather challenging subject. Many previous efforts have been focused on providing visualizations through computer-based softwares and simulation tools [1]-[11]. While these computer softwares and simulation tools are effective to help students better understand the concepts of various EM topics, they generally lack touch-based interactivity and inefficiency for ubiquitous, seamless teaching and learning. With the rapid technological advancement and wide availability of mobile devices, it is a good opportunity to capitalize on their affordances among the current and next generations of mobile-savvy students for EM education. Compared to computer-based softwares, mobile devices such as phones and pads provide touch-based interactivity and allow seamless teaching and learning anytime, anywhere.

In line with our continued efforts, we have capitalized on the usage of mobile devices for teaching and learning of various EM topics, including microwave circuit design [12], EM polarization [13], plane wave reflection and transmission [14]

and transmission line theory [15]. To enhance visualization of field vectors in 3-D space, the 3-D TV is further exploited in [14] to provide the necessary depth perception to students in classroom. In [15], EM computation on mobile devices allows interactive visualization of wave propagation in user-configurable transmission line circuits to reinforce various transmission line concepts. This has been made possible using our multiple one-dimensional finite-difference time-domain (M1-D FDTD) method [12], [16], which bypasses the more computationally intensive full-wave 3-D or 2-D FDTD method [17]. Furthermore, it is unlike previous purely 1-D FDTD method that may be over simplistic and not too practical. Instead, our M1-D FDTD method could accommodate common practical transmission line structures with stubs and even parallel/series lumped elements, by incorporating novel concepts of magnetic current and effective permittivity. However, the method thus far is only applicable for uncoupled transmission lines, and it is not suitable for coupled ones found in common coupled line structures. Most computer-based softwares on the topic of transmission lines theory [7], [8], [11] are also targeted at uncoupled transmission lines only. In EM engineering curricula, coupled line structures such as coupled line filters and directional couplers still form an important part of syllabi. Thus, visualization of EM wave propagation in coupled transmission lines is highly desirable to help improve students' understanding of coupled line theories.

The M1-D FDTD method has been extended for coupled transmission lines [18], which is hereby aptly referred as M1-D coupled line (CL)-FDTD method. We shall present the mobile teaching and learning of coupled line structures using M1-D CL-FDTD method. The formulation of M1-D CL-FDTD method applicable for coupled line structures will be provided. The method bypasses the more computationally intensive full-wave 3-D method and it is well-suited for implementation on mobile devices. Several mobile apps are developed to provide interactive visualization of EM wave propagation in coupled line structures. Various topics including coupled transmission lines, coupled line bandpass filter, directional coupler and branch line coupler will be demonstrated and discussed. Survey feedback gathered from the students to gauge their response towards the mobile apps will also be presented.

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Fig. 1. Electric and magnetic fields on coupled transmission lines using M1-D CL-FDTD method.

II. M1-D CL-FDTD METHOD

To facilitate the computation of EM wave propagation on mobile devices, the M1-D CL-FDTD method is adopted. Based on the even- and odd-mode approach, the coupled transmission line parameters can be incorporated directly into the method. Fig. 1 shows the electric and magnetic fields on coupled transmission lines using M1-D CL-FDTD method. The coupled transmission lines are aligned along the z -axis. E_{x1} , H_{y1} are the electric and magnetic fields along line 1, while E_{x2} , H_{y2} are the electric and magnetic fields along line 2. The EM wave propagation in coupled transmission lines can be described using the following differential equations [18]:

$$\frac{\partial E_{x1}}{\partial t} = -\frac{1}{\epsilon_s} \frac{\partial H_{y1}}{\partial z} - \frac{1}{\epsilon_m} \frac{\partial H_{y2}}{\partial z} \quad (1a)$$

$$\frac{\partial E_{x2}}{\partial t} = -\frac{1}{\epsilon_s} \frac{\partial H_{y2}}{\partial z} - \frac{1}{\epsilon_m} \frac{\partial H_{y1}}{\partial z} \quad (1b)$$

$$\frac{\partial H_{y1}}{\partial t} = -\frac{1}{\mu_s} \frac{\partial E_{x1}}{\partial z} + \frac{1}{\mu_m} \frac{\partial E_{x2}}{\partial z} \quad (1c)$$

$$\frac{\partial H_{y2}}{\partial t} = -\frac{1}{\mu_s} \frac{\partial E_{x2}}{\partial z} + \frac{1}{\mu_m} \frac{\partial E_{x1}}{\partial z} \quad (1d)$$

where

$$\frac{1}{\epsilon_s} = \frac{v_e Z_{0e} + v_o Z_{0o}}{2}, \quad \frac{1}{\epsilon_m} = \frac{v_e Z_{0e} - v_o Z_{0o}}{2}, \quad (2a)$$

$$\frac{1}{\mu_s} = \frac{1}{2} \left(\frac{v_o}{Z_{0o}} + \frac{v_e}{Z_{0e}} \right), \quad \frac{1}{\mu_m} = \frac{1}{2} \left(\frac{v_o}{Z_{0o}} - \frac{v_e}{Z_{0e}} \right). \quad (2b)$$

ϵ_s , ϵ_m , μ_s and μ_m are the self and mutual permittivities and permeabilities, in terms of even- and odd-mode characteristic impedances Z_{0e} , Z_{0o} and phase velocities v_e , v_o . In turn, the phase velocities are related to the even- and odd-mode effective permittivities ϵ_{eff}^e , ϵ_{eff}^o as

$$v_e = c/\sqrt{\epsilon_{eff}^e}, \quad v_o = c/\sqrt{\epsilon_{eff}^o}. \quad (3)$$

Note that the differential equations in (1) are different and not reducible from the 3-D, 2-D or 1-D Maxwell's equations. They are also different from the equations used for uncoupled transmission lines in [12], [15], [16].

Based on (1), the formulation of M1-D CL-FDTD method is provided as

$$E_{x1}|_k^{n+1} = E_{x1}|_k^n - \frac{\Delta t}{\epsilon_s|_k \Delta z} \left(H_{y1}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_{y1}|_{k-\frac{1}{2}}^{n+\frac{1}{2}} \right) - \frac{\Delta t}{\epsilon_m|_k \Delta z} \left(H_{y2}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_{y2}|_{k-\frac{1}{2}}^{n+\frac{1}{2}} \right) \quad (4a)$$

$$E_{x2}|_k^{n+1} = E_{x2}|_k^n - \frac{\Delta t}{\epsilon_s|_k \Delta z} \left(H_{y2}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_{y2}|_{k-\frac{1}{2}}^{n+\frac{1}{2}} \right) - \frac{\Delta t}{\epsilon_m|_k \Delta z} \left(H_{y1}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - H_{y1}|_{k-\frac{1}{2}}^{n+\frac{1}{2}} \right) \quad (4b)$$

$$H_{y1}|_{k+\frac{3}{2}}^{n+\frac{3}{2}} = H_{y1}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - \frac{\Delta t}{\mu_s|_{k+\frac{1}{2}} \Delta z} (E_{x1}|_{k+1}^{n+1} - E_{x1}|_k^{n+1}) + \frac{\Delta t}{\mu_m|_{k+\frac{1}{2}} \Delta z} (E_{x2}|_{k+1}^{n+1} - E_{x2}|_k^{n+1}) \quad (4c)$$

$$H_{y2}|_{k+\frac{3}{2}}^{n+\frac{3}{2}} = H_{y2}|_{k+\frac{1}{2}}^{n+\frac{1}{2}} - \frac{\Delta t}{\mu_s|_{k+\frac{1}{2}} \Delta z} (E_{x2}|_{k+1}^{n+1} - E_{x2}|_k^{n+1}) + \frac{\Delta t}{\mu_m|_{k+\frac{1}{2}} \Delta z} (E_{x1}|_{k+1}^{n+1} - E_{x1}|_k^{n+1}) \quad (4d)$$

where n is the time index and k is the position index along z -direction. Note that the M1-D CL-FDTD method requires only spatial discretization along the z -direction. This obviates the need for fine meshing of line width and spacing of the coupled transmission lines. Hence, the method is able to bypass the more computationally intensive full-wave 3-D method. It is well-suited for implementation on mobile devices platform with limited computing resources.

III. MOBILE TEACHING AND LEARNING OF COUPLED LINE STRUCTURES

In this section, mobile teaching and learning of coupled line structures including coupled transmission lines, coupled line bandpass filter, directional coupler and branch line coupler are demonstrated and discussed.

A. Teaching and Learning of Coupled Transmission Lines

We first demonstrate the teaching and learning of coupled transmission lines. Fig. 2 shows the time series snapshot of E or voltage wave propagation in coupled transmission lines on iPad. The left and right sides of line 2 are terminated with open and short circuits, respectively. A Gaussian pulse is excited on line 1 and the evolution of transient E fields along the coupled transmission lines can be demonstrated. As shown in Fig. 2(a), the Gaussian pulse is incident from the left side of line 1. Upon reaching the coupled transmission lines, the Gaussian pulse begins to couple from line 1 to line 2, as seen in Fig. 2(b). As the wave propagates down the coupled transmission lines, it can be observed that the coupled pulse in line 2 gradually evolves into non-Gaussian pulse, as seen in Fig. 2(c).

Besides the time evolution of pulse coupling, we are also able to demonstrate the pulse reflection from open or short circuit terminations from either side of line 2. Upon reflection

Fig. 2. Time series snapshot of E or voltage wave propagation in coupled transmission lines on iPad.

from the short circuit termination on the right, Fig. 2(d) shows that the pulse has the opposite polarity compared to the incident pulse in Fig. 2(c). The pulse then travels back from right to left in Fig. 2(e) and undergoes reflection again upon reaching the open circuit termination on the left. In this case, the reflected pulse in Fig. 2(f) has the same polarity compared to the incident pulse in Fig. 2(e). Throughout the simulations, the animations can be paused or continued whenever needed to allow clearer visualization by the students. Besides Gaussian pulse, other excitation sources such as modulated Gaussian or sinusoidal source are also available. Through these visualizations, the students can understand better the dynamics of EM wave being coupled from one line to another, as well as the wave reflection at open or short circuit termination in coupled transmission lines.

B. Teaching and Learning of Coupled Line Bandpass Filter

Next, we demonstrate the teaching and learning of coupled line bandpass filter. The bandpass filter is constructed by cascading multiple coupled line sections. For each coupled line section, two of the four ports are terminated with open circuit. In this example, we choose the filter specification as third-order Chebyshev response with passband ripple 0.5 dB, center frequency 2 GHz and fractional bandwidth 0.1. Fig. 3 shows the schematic of the coupled line bandpass filter on iPad. The filter is realized by four coupled line sections with parameters calculated from standard design equations [19]. The length of each section is quarter-wavelength, i.e. $\lambda/4$. A Gaussian pulse is exemplified as excitation at the input port.

To reinforce the concept of bandpass filter, we shall demonstrate the excitation of sinusoidal wave with different frequencies into the coupled line filter. First, the frequency is chosen as 2 GHz, which is the center frequency of the passband. Fig. 4 shows the snapshot of wave propagation in coupled line

Fig. 3. Schematic of the coupled line bandpass filter on iPad.

Fig. 4. Snapshot of wave propagation in coupled line bandpass filter on iPad, excited by a 2 GHz sinusoidal wave.

bandpass filter on iPad. As depicted in the figure, the waves are resonating constructively in the coupled lines, while allowing most of the waves to pass through the coupled line filter. The students are able to visualize clearly the dynamics of wave propagation being coupled from one section to another in the filter. Next, the sinusoidal frequency is changed to 3 GHz, which is a frequency outside the passband. As observed in Fig. 5, the waves can no longer resonate properly and most of the waves are unable to pass through the coupled line filter. Such visualization allows the resonating and coupling mechanisms to be elucidated clearly and improve students' understanding of coupled line theories. To plot the frequency response, the S parameters can also be computed right on mobile devices like the previous app [12]. For independent verification, the students may be asked to construct the coupled line bandpass filter using Advanced Design System (ADS) during hands-on design class and plot the S parameters as

Fig. 5. Snapshot of wave propagation in coupled line bandpass filter on iPad, excited by a 3 GHz sinusoidal wave.

Fig. 6. S parameters of the coupled line bandpass filter.

in Fig. 6. Through the S parameters plot, we can clearly see that the input signal around the center frequency 2 GHz is transmitted while the rest are blocked. From here, they can relate better the frequency-domain response of the filter to its time-domain response demonstrated earlier. It is worth noting that the ADS software does not facilitate time-domain visualization of wave propagation, resonating and coupling mechanisms.

We shall briefly mention about the computational requirements of M1-D CL-FDTD method and compare them with full-wave 3-D FDTD method. Note that each cell in M1-D CL-FDTD method involves only four field components, i.e. E_{x1} , E_{x2} , H_{y1} and H_{y2} , while each cell in 3-D FDTD method involves all six field components. This is because the M1-D CL-FDTD method requires only spatial discretization along the propagation z -direction, c.f. (4), while the 3-D FDTD method requires spatial discretization for the whole 3-D domain. Furthermore, the computational domain of the 3-D FDTD method often includes some free space surrounding simulation structures as well as absorbing boundary condi-

Fig. 7. Snapshot of wave propagation in directional coupler at steady-state on iPad, excited by a 5 GHz sinusoidal wave.

Fig. 8. Snapshot of wave propagation in directional coupler at steady-state on iPad, excited by a 3.5 GHz sinusoidal wave.

tions, e.g. perfectly matched layers (PML) in all directions. This can be illustrated using the popular full-wave commercial software, Computer Simulation Technology (CST) Microwave Studio. For the coupled line bandpass filter example, the M1-D CL-FDTD method requires only ~ 260 cells, while a setup in CST (with minimum cell per wavelength set to 30) requires $\sim 150k$ ($16 \times 71 \times 134$) cells in the computational domain. Therefore, it can be seen that the M1-D CL-FDTD method is more resource-efficient than the full-wave method and well-suited for implementation on mobile devices.

C. Teaching and Learning of Directional Coupler

We proceed to demonstrate the teaching and learning of directional coupler. The coupling coefficient C is set to be $1/\sqrt{2}$ (i.e. 3 dB) at design frequency 1 GHz and the length of the coupled line section is again quarter-wavelength. A 5 GHz sinusoidal wave is excited into the directional coupler from port 1 (input). Due to the periodic nature of its frequency response, the directional coupler has the same response at 5 GHz. Fig. 7 shows the snapshot of wave propagation in the directional coupler at steady-state, excited by a 5 GHz sinusoidal wave. It can be observed that at steady-state, there is no reflection from port 1 (matched) and no wave is present at port 4 (isolated). With $C = 1/\sqrt{2}$, we also observe that the wave amplitudes at ports 2 (through) and 3 (coupled) are both equal. Furthermore, it can be seen that there is also a phase difference of 90° between ports 2 and 3.

To demonstrate the response of the directional coupler at other frequencies, we shall modify the frequency of the sinusoidal wave to 3.5 GHz. Fig. 8 shows the snapshot of wave propagation in the directional coupler at steady-state, excited by a 3.5 GHz sinusoidal wave. It can be observed that the wave amplitudes of ports 2 and 3 are no longer equal. However, it

Fig. 9. S parameters of the directional coupler.

is interesting to note that port 1 and port 4 are still matched and isolated, respectively. In fact, it can be demonstrated that given any input excitation at port 1, such as narrow band sinusoidal source or wide band Gaussian pulse, modulated Gaussian, etc., there will be no reflection at port 1 and no wave present at port 4. Thus, the students can learn that the directional coupler is matched at port 1 and isolated at port 4 at any frequency. Although such characteristics have been pointed out in [19, Section 7.6, pp. 354], they may not be appreciated well only with text. This is because most would often think that the matching and isolation can only work at design frequency. On the other hand, the visualizations through self exploration with various excitation frequencies greatly convince the students on such characteristics of a directional coupler. To verify its frequency response, the students may be asked to construct the directional coupler in ADS again and plot the S parameters as in Fig. 9. It can be seen that all the S parameters are periodic with a frequency interval of 2

Fig. 10. Snapshot of wave propagation in branch line coupler at steady-state on iPad, excited by a 5 GHz sinusoidal wave.

Fig. 11. Snapshot of wave propagation in branch line coupler at steady-state on iPad, excited by a 3.5 GHz sinusoidal wave.

GHz. As the frequencies depart from the design frequency and its odd harmonics, the S_{21} and S_{31} parameters deviate from 3 dB. On the other hand, the S_{11} and S_{41} parameters are very low throughout the whole frequency band. Hence, the students are able to validate themselves the frequency-domain response against the time-domain response of a directional coupler. They can also learn about the periodicity of the frequency response due to the trigonometric functions present in the S parameter expressions of coupled line structures.

D. Teaching and Learning of Branch Line Coupler

Finally, we demonstrate an example of branch line coupler, comprising four sections of quarter-wavelength transmission lines at design frequency 1 GHz. While the branch line coupler involves direct coupling through interconnected transmission lines, there are many similarities between the responses of a branch line coupler and a directional coupler. Hence, it is worth demonstrated to students for comparison with the directional coupler. For branch line coupler, the EM wave propagation can be simulated using the conventional explicit M1-D FDTD method for multiple (uncoupled) transmission lines and/or stubs [12], [16]. To further enhance its efficiency, the unconditionally stable fundamental alternating direction implicit (FADI) FDTD method [20] is adopted to allow time step larger than the stability constraint. Fig. 10 shows the snapshot of wave propagation in the branch line coupler at steady-state, excited by a 5 GHz sinusoidal wave. Using the FADI-FDTD method, the simulation may be “fast-forwarded” to allow quicker visualization. This can be done by adjusting the slider provided to increase the time step. The time step is specified in terms of $CFLN = \Delta t / \Delta t_{CFL}$, where Δt_{CFL} is the Courant-Friedrichs-Lewy (CFL) time step of the explicit M1-D FDTD method. Here, CFLN is chosen as 10. From Fig. 10, we observe that there is no reflection from port 1 (matched) and no wave is present at port 4 (isolated), as in the directional coupler case earlier. The wave amplitudes at ports 2 (through)

Fig. 12. S parameters of the branch line coupler.

and 3 (coupled) are equal. A phase difference of 90° is also present between ports 2 and 3. It should be pointed out to the students that in the branch line coupler, the locations of ports 3 and 4 are opposite to those of the directional coupler.

For other frequencies, Fig. 11 shows the snapshot of wave propagation in the branch line coupler at steady-state, excited by a 3.5 GHz sinusoidal wave. Unlike the directional coupler, it can be observed that port 1 and port 4 are no longer matched and isolated, respectively. Therefore, the branch line coupler cannot maintain the matching and isolation at any frequency. The wave amplitudes of ports 2 and 3 are also not equal. The S parameters of the directional coupler are again plotted using ADS in Fig. 12 to verify its frequency response. They are still periodic with a frequency interval of 2 GHz. However, it can be clearly seen that all S parameters deviate as the frequencies depart from the design frequency and its odd harmonics. Thus, the students are able to clearly distinguish between the responses of branch line coupler and directional coupler.

E. Survey Feedback from Students

Some examples of mobile apps were demonstrated to 74 postgraduate students in two RF circuit design classes at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. Following the demonstrations, we conducted survey among the students to gather feedback on their reception towards the mobile apps. The students were asked if the apps are useful and motivate them to learn more actively on transmission lines. They are given the likert scale listed as: (5) Strongly agree, (4) Agree, (3) Moderate, (2) Disagree, and (1) Strongly disagree. 97% of the students provided the response of (5) Strongly agree or (4) Agree. On the scale of 0 to 10, they were then asked to rate the apps in helping them to understand the concepts of transmission lines. The students provided an average rating of 9.3 out of 10. In addition, it had been more convenient for the students to use mobile apps rather than to access the workstations in the computing laboratory for ADS or CST software. From the survey feedback, the mobiles apps were generally well received by the students. Most of them were more interested to observe various wave dynamics as compared to reading plain text in lecture notes only. As seeing is believing, they could appreciate better the coupled line theories through visualization on mobile devices.

IV. CONCLUSION

This article has presented the mobile teaching and learning of coupled line structures using M1-D CL-FDTD method. The formulation of M1-D CL-FDTD method applicable for coupled line structures has been provided. The method bypasses the more computationally intensive full-wave 3-D method and it is well-suited for implementation on mobile devices. Several mobile apps have been developed to provide interactive visualization of EM wave propagation in coupled line structures. Such visualization allows the underlying resonating and coupling mechanisms to be elucidated clearly and improves students' understanding of coupled line theories. Various topics including coupled transmission lines, coupled line bandpass filter, directional coupler and branch line coupler have been demonstrated and discussed. From the survey feedback, the mobiles apps were generally well received by the students. In the near future, the unconditionally stable M1-D FDTD methods based on the alternating direction implicit (ADI) scheme [21] for coupled line structures will be implemented on mobile devices to further enhance the efficiency.

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