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Teaching and Learning Electromagnetic Polarization using Mobile Devices

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Abstract—The wide availability of smart handheld and mobile devices has provided educators another opportunity to aid teaching of electromagnetic (EM) courses with touch-based interactivity, allowing seamless teaching and learning. This paper presents teaching and learning of EM polarization using mobile devices. The EM polarization app is designed to provide interactive visualization to help students better understand wave polarization concepts. It also enables the professor to illustrate many wave polarization topics effectively through various interactive features. By using the app, various polarizations could be explained better with the aid of 2D and 3D animations. Users are allowed to input various wave parameters to see the change in real time in the polarization ellipse and/or handedness. More advanced topics such as polarization ellipse, Poincaré sphere and Stokes parameters are also discussed and presented. For more graphical interaction with fun, the polarization state is further presented as a coordinate located on Poincaré sphere that coincides with an earth globe. All these features are explained in more detail with clear time-series snapshots supported by concise mathematical equations.

Index Terms—Teaching and learning EM, EM education, mobile devices, polarization.

I. INTRODUCTION

Electromagnetics (EM) form an important branch of physics that is indispensable to electrical and electronic engineers. Many applications of electrical engineering rely on EM theory, especially in the areas of antennas and propagation. Therefore, teaching EM courses in tertiary level electrical engineering is essential to equip students with relevant physical insights and analytical skills. Unfortunately, teaching EM courses in tertiary level remains challenging to date due to its abstract nature. Many EM theories also require high mathematical finesse and involve vectorial analysis in three dimensional (3D) space, which are very difficult to be visualized and grasped by most students. Over the years, computer-based softwares and simulation tools have been developed to provide visualizations to the students in aiding EM teaching [1]–[12]. Certain web-based applications have also been developed [13], [14] to be used as teaching and learning tools. While computer softwares and web-based applications can provide visualization and interaction to a certain extent, it is still deemed insufficient due to limited touch-based interactivity. Furthermore, the reliance on computer is also inefficient and inhibits seamless teaching and learning at anytime, anywhere.

Recently, the wide availability of smart handheld and mobile devices has provided educators another opportunity to aid

teaching of EM courses with touch-based interactivity. The use of mobile devices allows seamless teaching and learning as they are available almost ubiquitously. However, most apps (e.g. [15], [16]) provide very limited visualization and lack interactive features and they are often replicas of web-based apps on phones and pads. Moreover, they lack the features for which the professor and students can use for their teaching and learning purposes. Previously, we have developed a microstrip circuit tool kit app on mobile devices for educational courseware [17], [18]. It realizes an efficient real-time simulation of microwave transmission line circuit on mobile devices. In this paper, we shall present teaching and learning of EM polarization using mobile devices. Our mobile app, called *EMPolarization* on App Store, is designed to provide interactive visualization to help students better understand wave polarization concepts. It also enables the professor to illustrate many wave polarization topics effectively through various interactive features. In our preliminary work, the app has been demonstrated to feature 2D visualization of wave polarization [19]. Hereby, it has been extended to include 3D visualization, where various polarizations could now be explained better with the aid of both 2D and 3D animations. Users are allowed to input various wave parameters to see the change in real time in the polarization ellipse and/or handedness. Besides that, more advanced topics such as polarization ellipse parameters, Poincaré sphere and Stokes parameters will also be discussed and presented. For more graphical interaction with fun, the polarization state will be further presented as a coordinate located on Poincaré sphere that coincides with an earth globe. All these features shall be explained in more detail with clear time-series snapshots supported by concise mathematical equations.

The outline of the paper is as follows. Section II presents the EM polarization along with its 2D and 3D animations on the app. Various interactive visualizations of orthogonal field components, projection and resultant E vectors, handedness, propagation direction, etc. are provided clearly. In Section III, more advanced topics such as polarization ellipse, Poincaré sphere and Stokes parameters are presented, along with their visualizations on the app. How the app can be used to aid teaching and learning of EM polarization is also discussed in both sections.

II. EM POLARIZATION

Fig. 1 shows the overview of the EM polarization app on Apple's iPad. The electric field consists of two orthogonal x and y components, while the wave is assumed to propagate

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Fig. 1. Overview of the EM polarization app on Apple's iPad.

in $+z$ direction. The electric field expressions in time domain and phasor form are provided. The time domain expression reads

$$\tilde{\mathbf{E}}(t) = \mathbf{a}_x E_{0x} \cos(\omega t - \beta z + \phi_x) + \mathbf{a}_y E_{0y} \cos(\omega t - \beta z + \phi_y) \quad (1)$$

where $\mathbf{a}_x$ and $\mathbf{a}_y$ are the unit vectors in x and y directions, E_{0x} , ϕ_x and E_{0y} , ϕ_y are the magnitudes and phase angles of electric field x and y components, ω is the angular frequency, and β is the phase constant. The corresponding electric field expression in phasor domain is given by

$$\mathbf{E} = (\mathbf{a}_x E_{0x} \angle \phi_x + \mathbf{a}_y E_{0y} \angle \phi_y) \exp(-j\beta z). \quad (2)$$

The parameters that can be input by the users are the magnitudes and phase angles of both components, i.e. E_{0x} , E_{0y} , ϕ_x and ϕ_y . These parameters can either be directly keyed in or modified interactively using the slider provided. The propagation direction can also be changed from $+z$ to $-z$ by tapping on the sign before β . Note that the $\cos$ function in (1) can also be switched to $\sin$ function. In doing so, ϕ_x and ϕ_y of the phasor form in (2) are automatically adjusted.

Based on the input parameters, various interactive visualization are provided with 2D and 3D animations. At the top of the app in Fig. 1, one can visualize the time domain waveforms of x and y components of electric field, $E_x(t)$ and $E_y(t)$. The projection vectors of these individual components are animated by green arrows on xy plane, and can be traced from the time

domain waveforms via dashed green lines. The resultant $\mathbf{E}$ field vector is animated by red arrow, along with the trace of $\mathbf{E}$ vector extremity (tip). The type of polarization can then be deduced from the trace of $\mathbf{E}$ vector tip. For instance, in Fig. 1, the $\mathbf{E}$ vector tip traces out an ellipse, indicating that the EM wave is of elliptical polarization. To illustrate the animation of the $\mathbf{E}$ vector, Fig. 2 shows the 2D time-series snapshot of the $\mathbf{E}$ vector, trace of $\mathbf{E}$ vector tip and time domain waveforms for a left-handed elliptically polarized wave at time instant (a) $t = 0$, (b) $t = (1/6)T$, (c) $t = (2/6)T$, (d) $t = (3/6)T$, (e) $t = (4/6)T$ and (f) $t = (5/6)T$, where T is the EM wave period. The speed of animations can be further controlled via slider, or even paused and continued. Through the animation and trace, the professor can explain clearly to the students the polarization state by referring to the shape of the locus traced out by the resultant $\mathbf{E}$ vector tip. The students are also able to visualize clearly how the two orthogonal field components combine to result in certain polarization as time marches.

To determine the sense of polarization (handedness) for elliptically or circularly polarized wave, the IEEE standard defines that when the plane of polarization is viewed looking in the direction of propagation (receding wave), if the extremity of the field vector rotates clockwise [counterclockwise] the sense is right-handed [left-handed] [20]. It is worth mentioning here that the sense of polarization of the optics standard is defined when the plane of polarization is viewed looking in the direction of an approaching wave [21], [22]. Therefore, its sense of polarization is opposite to that of IEEE standard. Henceforth, the IEEE standard shall be adopted throughout the paper, which should not be confused with the optics standard. Alternatively, a more convenient way of determining the sense of polarization of a field vector (consistent with IEEE standard) would be to align one's thumb to point along the direction of propagation, while the other four fingers curl in the direction of rotation. If the direction of rotation aligns with one's right hand [left hand], the sense of polarization is right-handed [left-handed]. For instance, in Fig. 2, based on the directions of rotation and propagation ($+z$, out of the page), it is easily observed that they align with one's left hand, thus deducible as left-handed elliptical polarization. Note that if the propagation direction is reversed from $+z$ to $-z$, the handedness will also be reversed from left-handed to right-handed polarization accordingly. Through the rotation animation, the professor is able to elucidate the handedness effectively while providing clear visualization to the students. The app also provides the visualization of other polarizations. For example, Fig. 3 shows the 2D time-series snapshot for a right-handed circularly polarized wave. In this case, the $\mathbf{E}$ vector extremity traces out a circle, while its rotation and propagation are aligned with one's right hand.

To facilitate determination of each polarization type, the conditions to be checked are provided as well. Several polarization examples and conditions displayed by the app are shown in Table I, along with visualization of their respective $\mathbf{E}$ vector tip. The professor can reiterate these conditions to determine various polarization types. These conditions also enable real-time interactive checking by the students according to the definition of each EM polarization type. For convenience,

Fig. 2. 2D time-series snapshot of E vector, trace of E vector tip and time domain waveforms for a left-handed elliptically polarized wave at time instant (a) $t = 0$, (b) $t = (1/6)T$, (c) $t = (2/6)T$, (d) $t = (3/6)T$, (e) $t = (4/6)T$ and (f) $t = (5/6)T$. T is the EM wave period.

Fig. 3. Same as Fig. 2, but for a right-handed circularly polarized wave.

several examples of linear, circular and elliptical polarizations are available for quick demonstration. Simply tapping on the buttons below the slider will automatically change the input parameters to illustrate the desired polarizations.

While the previous 2D animation depicts electric field vector at $z = 0$ in the xy plane, the app also provides 3D animation, which includes the electric field vector along the propagation z -axis. The 3D animation is shown at the bottom of Fig. 1, which is in complete synchronization with the previous 2D animation. Fig. 4 shows the 3D time-series snapshot of the E vector for a left-handed elliptically polarized wave, which now includes visualization along the z -axis. It can be observed that

the crests (or troughs, marked by red ovals) of the E vector wave are traveling towards the right (propagation along $+z$ direction), while remaining left-handed elliptically polarized throughout. The view can also be zoomed in and rotated conveniently for different view angles. For other example, Fig. 5 shows the 3D time-series snapshot of a right-handed circularly polarized wave traveling towards the same $+z$ direction. The professor can use it to demonstrate wave propagation of various polarization states. These animations further provide the students with clear 3D visualization to better understand the concepts of EM polarization and propagation.

TABLE I
POLARIZATION EXAMPLE, CONDITIONS AND E VECTOR TIP.

Polarization Example	Conditions and E Vector Tip
Linear $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=0$	<p>Check phase angle: $\phi_y - \phi_x = 0.00^\circ$</p> <p>Check magnitude: $E_{0x} \neq E_{0y}$</p> <p>Polarization type: Linear</p>
Circular (Left) $E_{0x}=1, E_{0y}=1, \phi_x=0, \phi_y=90$	<p>Check phase angle: $\phi_y - \phi_x = 90.00^\circ$</p> <p>Check magnitude: $E_{0x} = E_{0y}$</p> <p>Polarization type: Circular (Left)</p>
Circular (Right) $E_{0x}=1, E_{0y}=1, \phi_x=0, \phi_y=-90$	<p>Check phase angle: $\phi_y - \phi_x = -90.00^\circ$</p> <p>Check magnitude: $E_{0x} = E_{0y}$</p> <p>Polarization type: Circular (Right)</p>
Elliptical (Left) $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=50$	<p>Check phase angle: $\phi_y - \phi_x = 50.00^\circ$</p> <p>Check magnitude: $E_{0x} \neq E_{0y}$</p> <p>Polarization type: Elliptical (Left)</p>
Elliptical (Right) $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=-50$	<p>Check phase angle: $\phi_y - \phi_x = -50.00^\circ$</p> <p>Check magnitude: $E_{0x} \neq E_{0y}$</p> <p>Polarization type: Elliptical (Right)</p>

III. POLARIZATION ELLIPSE, POINCARÉ SPHERE AND STOKES PARAMETERS

By tapping on the “more” button on the top right corner in Fig. 1, one will arrive at another part of the EM polarization app as depicted in Fig. 6. The same time domain and phasor form of electric field expressions are carried forward from the previous part, where the input parameters such as magnitudes and phase angles could be changed here as well. The 3D animation of EM polarization is also replicated so that one is able to visualize it at all times. Additionally, more advanced topics are covered in this part of the app. Refer to the top of Fig. 6, the polarization ellipse (trace of E vector tip from the earlier part) is now displayed with various color labeled angles. The red arrow representing the resultant E field vector is also animated here. The corresponding values of the color labeled angles are shown next to the polarization ellipse in the same shadow color symbols or text. The mathematical expressions of these angles are as follows [21]-[23]:

Fig. 4. 3D time-series snapshot of E vector for a left-handed elliptically polarized wave.

– Arctan of E_{0y} over E_{0x} ratio, γ ($0 \leq \gamma \leq 90^\circ$), represented by magenta color

$$\gamma = \tan^{-1}(E_{0y}/E_{0x}) \quad (3)$$

– Difference of phasor angles, δ

$$\delta = \phi_y - \phi_x \quad (4)$$

assuming propagation direction is in $+z$. (For propagation direction in $-z$, $\delta = \phi_x - \phi_y$)

– Ellipticity angle, ϵ ($-45^\circ \leq \epsilon \leq 45^\circ$), represented by yellow color

$$\epsilon = \frac{1}{2} \sin^{-1} \left(\frac{2E_{0x}E_{0y}}{E_{0x}^2 + E_{0y}^2} \sin \delta \right) \quad (5)$$

– Tilt or orientation angle, τ ($-90^\circ \leq \tau \leq 90^\circ$), represented by cyan color

$$\tau = \frac{1}{2} \tan^{-1} \left(\frac{2E_{0x}E_{0y}}{E_{0x}^2 - E_{0y}^2} \cos \delta \right) \quad (6)$$

Fig. 5. Same as Fig. 4, but for a right-handed circularly polarized wave.

– Axial ratio, AR , defined as the ratio of major axis to minor axis of polarization ellipse

$$AR = -\cot \epsilon \quad (7a)$$

$$AR \text{ (dB)} = 20 \log_{10} |\cot \epsilon| \quad (7b)$$

Note that the axial ratio sign is also consistent with that of the IEEE definition, which states that the sign is taken as plus if the sense of polarization is right-handed and minus if it is left-handed [20].

The professor can describe clearly various color labeled angles in the ellipse and the students can observe to understand how these angles change with different input parameters. The geometric relations among various angles are given by [21], [23]

$$\cos 2\gamma = \cos 2\epsilon \cos 2\tau \quad (8a)$$

$$\tan \delta = \frac{\tan 2\epsilon}{\sin 2\tau} \quad (8b)$$

$$\tan 2\tau = \tan 2\gamma \cos \delta \quad (8c)$$

$$\sin 2\epsilon = \sin 2\gamma \sin \delta \quad (8d)$$

The ϵ and τ pair can be converted to γ and δ pair conveniently or vice versa through (8).

Fig. 6. Overview of another part of the EM polarization app.

The polarization state can be further described by a point on Poincaré sphere where the latitude and longitude of the point are related to polarization ellipse parameters as follows [21], [23], [24]:

$$\text{Latitude} = 2\epsilon \quad (9a)$$

$$\text{Longitude} = 2\tau \quad (9b)$$

For more graphical interaction with fun, the Poincaré sphere is designed such that it coincides with an earth globe, where the latitude = 0 and longitude = 0 lines are properly aligned with the equator and prime meridian (Greenwich), respectively. Depending on the input parameters, the coordinate of the polarization state is illustrated by a red mini ball on the earth surface (c.f. Fig. 6). The earth globe can also be interactively rotated and zoomed in by the user. It can be easily shown from (5) that the coordinates of all left-handed polarizations are located on the northern hemisphere ($2\epsilon > 0^\circ$), while the coordinates of all right-handed polarizations are located on the southern hemisphere ($2\epsilon < 0^\circ$). For linear polarization, the coordinate is located along the equator ($2\epsilon = 0^\circ$). For left-handed circular polarization, the coordinate is located at the north pole ($2\epsilon = 90^\circ$) while for right-handed circular polarization, the coordinate is located at the south pole ($2\epsilon = -90^\circ$). Furthermore, the coordinates of all polarizations with $\tau > 0^\circ$ (positive tilt angle) are located on the east of prime meridian ($2\tau > 0^\circ$), while the coordinates of all polarizations with $\tau < 0^\circ$ (negative tilt angle) are located on the west ($2\tau < 0^\circ$), regardless of the polarization type (excluding

TABLE II
POLARIZATION EXAMPLE, POINCARÉ SPHERE AND STOKES PARAMETERS

Polarization Example	Poincaré Sphere and Stokes Parameters	
Linear $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=0$	(lat, long) = (0.00°, 96.03°) $I = S_0 = E_{0x} ^2 + E_{0y} ^2 = 1.81$ $Q/I = S_1/S_0 = -0.10$ $U/I = S_2/S_0 = 0.99$ $V/I = S_3/S_0 = 0.00$	
Circular (Left) $E_{0x}=1, E_{0y}=1, \phi_x=0, \phi_y=90$	(lat, long) = (90.00°, 0.00°) $I = S_0 = E_{0x} ^2 + E_{0y} ^2 = 2.00$ $Q/I = S_1/S_0 = 0.00$ $U/I = S_2/S_0 = 0.00$ $V/I = S_3/S_0 = 1.00$	
Circular (Right) $E_{0x}=1, E_{0y}=1, \phi_x=0, \phi_y=-90$	(lat, long) = (-90.00°, 0.00°) $I = S_0 = E_{0x} ^2 + E_{0y} ^2 = 2.00$ $Q/I = S_1/S_0 = 0.00$ $U/I = S_2/S_0 = 0.00$ $V/I = S_3/S_0 = -1.00$	
Elliptical (Left) $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=50$	(lat, long) = (49.62°, 99.33°) $I = S_0 = E_{0x} ^2 + E_{0y} ^2 = 1.81$ $Q/I = S_1/S_0 = -0.10$ $U/I = S_2/S_0 = 0.64$ $V/I = S_3/S_0 = 0.76$	
Elliptical (Right) $E_{0x}=0.9, E_{0y}=1, \phi_x=0, \phi_y=-50$	(lat, long) = (-49.62°, 99.33°) $I = S_0 = E_{0x} ^2 + E_{0y} ^2 = 1.81$ $Q/I = S_1/S_0 = -0.10$ $U/I = S_2/S_0 = 0.64$ $V/I = S_3/S_0 = -0.76$	

circular polarization, which has no tilt angle) and handedness. Table II shows several polarization examples displayed in the app and their associated Poincaré sphere. The coordinate in (latitude, longitude) is also provided. It can be seen that for all left-handed and right-handed polarizations, the locations are portrayed on the northern and southern hemispheres, respectively. For linear, left-handed and right-handed circular polarizations, they are located on the equator, north and south poles, respectively.

As an application of the Poincaré sphere, it can be used to determine the voltage response of an antenna to an incident wave of arbitrary polarization as [23], [24]

$$V = C \cos \frac{P_w P_a}{2} \quad (10)$$

where C is a constant that is a function of the antenna size and field strength of the wave, $P_w P_a$ is the angle subtended by a great-circle arc from polarization state P_w to P_a , P_w is the polarization state of the wave and P_a is the polarization state of the antenna. From (10), it can be seen that maximum voltage occurs when $P_w P_a = 0$, i.e. the polarization states

P_w and P_w are located at the same point on the Poincaré sphere. On the other hand, minimum voltage ($V = 0$) occurs when $P_w P_a = 180^\circ$, i.e. the polarization states P_w and P_w are located at the opposite ends of each other on the Poincaré sphere. The nearer the two points are on the Poincaré sphere, the lesser the polarization mismatch, and vice versa. Through Poincaré sphere, the professor can explain polarization mismatch between a receiving antenna and an incoming EM wave better. The students are also able to grasp the measure of such polarization mismatch, given their polarization states.

The Stokes parameters can also be used to describe a polarization state. They are determined as [22]

$$I = S_0 = E_{0x}^2 + E_{0y}^2 \quad (11a)$$

$$Q = S_1 = E_{0x}^2 - E_{0y}^2 \quad (11b)$$

$$U = S_2 = 2E_{0x}E_{0y} \cos \delta \quad (11c)$$

$$V = S_3 = 2E_{0x}E_{0y} \sin \delta. \quad (11d)$$

These parameters are provided in the app as seen in Fig. 6. I (or S_0) is related to the intensity of the EM wave and its actual value is provided. For Q (or S_1), U (or S_2) and V (or S_3), they are often normalized by I . Furthermore, the Stokes parameters in (11) satisfy the following relation:

$$I^2 = Q^2 + U^2 + V^2 \quad (12)$$

The polarization state is then described by a set of the Stokes parameters in (11). In fact, it can be further shown that the following relations hold [21]:

$$S_1 = S_0 \cos 2\epsilon \cos 2\tau \quad (13a)$$

$$S_2 = S_0 \cos 2\epsilon \sin 2\tau \quad (13b)$$

$$S_3 = S_0 \sin 2\epsilon \quad (13c)$$

It is evident from (13) that the values for normalized S_1/S_0 , S_2/S_0 and S_3/S_0 may vary from -1 to 1 . The normalized Stokes parameters of different polarization states can be shown below as:

Polarization State	$\frac{S_1}{S_0}$	$\frac{S_2}{S_0}$	$\frac{S_3}{S_0}$
<u>Linear</u>			
$E_{0y} = 0, E_{0x} \neq 0$	1	0	0
$E_{0x} = 0, E_{0y} \neq 0$	-1	0	0
$E_{0x} \neq 0, E_{0y} \neq 0$ for all below:			
$E_{0x} = E_{0y}, \delta = 0^\circ$	0	1	0
$E_{0x} = E_{0y}, \delta = 180^\circ$	0	-1	0
<u>Circular (Left)</u>			
$E_{0x} = E_{0y}, \delta = 90^\circ$	0	0	1
<u>Circular (Right)</u>			
$E_{0x} = E_{0y}, \delta = -90^\circ$	0	0	-1

For other polarization states (e.g., elliptically polarized waves), the normalized Stokes parameters lie between -1 and 1 . The Stokes parameters of several polarization examples as displayed by the app are further shown in Table II. These parameters can be further explained by the professor, while the students are able to learn and visualize.

Some preliminary feedback data is sought from the students to gauge their response and general reception of the app. To

Fig. 7. Overview of app on Apple's iPhone.

that end, the app is used to teach 106 undergraduate students in Nanyang Technological University, Singapore on the topic of wave polarization and their feedback is gathered through questionnaires. According to the feedback, 87% of the students find the app interesting and intriguing. Furthermore, 78% of the students think their understanding of wave polarization has improved after being taught using the app. Overall, positive response has been shown among the students.

IV. CONCLUSION

This paper has presented teaching and learning of EM polarization using mobile devices. The EM polarization app has been designed to provide an interactive visualization to help students better understand wave polarization concepts. It has also enabled the professor to illustrate many wave polarization topics effectively through various interactive features. By using the app, various polarizations could be explained better with the aid of 2D and 3D animations. Users are allowed to input various wave parameters to see the change in real time in the polarization ellipse and/or handedness. More advanced topics such as polarization ellipse, Poincaré sphere and Stokes parameters have also been discussed and presented. For more graphical interaction with fun, the polarization state has been further presented as a coordinate located on Poincaré sphere that coincides with an earth globe. All these features have been explained in more detail with clear time-series snapshots supported by concise mathematical equations. While the presentation of the app thus far is mainly based on Apple's iPad, the app has also been developed for iPhone devices. Fig. 7 shows the overview of the app on Apple's iPhone with similar features. Due to the smaller screen size of iPhones, most features of the app can be further zoomed in and scrolled up/down or left/right for better viewing. The app may also be developed for Android-based mobile devices to reach more users. Besides EM polarization, teaching and learning EM using mobile devices can also be extended to many other EM

topics such as wave reflection and transmission, waveguides, transmission lines, Smith charts and antennas, etc.

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