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DIFFERENT APPROACH TO THE ROTATION OF ELECTRIC FIELD VECTOR OF CIRCULARLY POLARIZED EM WAVES. A REVIEW

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Abstract. In circular (and elliptical) polarization the electric E and magnetic H fields rotate, *i.e.* are in motion at a constant rate in the appropriate plane as the electromagnetic (EM) wave propagates. In technical literature there is a dual approach to the rotation of the vector E for circularly polarized waves, depending on the position of an "observer's eye" in relation to the direction of the wave propagation. There are non-identical traditions and agreements regarding right-hand and left-hand polarization between specialists from different area of knowledge as well as the preferences of individual scientists. For example, in radar astronomy, the "observer's eye" is positioned against EM waves spreading from a wave source towards the "observer's eye". In optics the "observer's eye" may be located on the side of the wave source and sees the wave propagating away from the "observer's side". The contrast approach can be partly explained by differences in measurement techniques in separate areas of science. This ambiguity in the approach to the circular polarization definitions may also complicate the educational process. Here we analyse the definitions of terms related to the circularly polarized waves which are recommended for use in IEEE standards and definitions applying in scientific papers. It should be noted that usually approaches are correct, the problem arises only when the location of the observer's eye is not fixed in space.

Key words: engineering fields, engineering graphics, engineering standards, physics, electromagnetic propagation, circular (elliptical) polarization, left-hand circular polarization, right-hand circular polarization.

1. INTRODUCTION

The word polarization generally means a geometrical orientation. The term "pole" originated from the ancient Greek word "polos", which means the continually shifted point, *e.g.* pole of rotation or spin pole.

Polarization (also polarisation) of an electromagnetic (EM) wave is a very important characteristic of the wave. We will consider here only the EM waves with the circular (elliptical) polarization.

The electric (also magnetic) field vector of the EM wave rotates at a constant rate in an orthogonal plane xOy to the direction of the wave propagation that is along the Oz axis. It should be noted that the polarization of EM waves is always determined by the use of the vector **E** (not the vector **H**). Electric **E** and magnetic **H** fields are perpendicular to each other.

Mathematical description of EM waves' polarization is detailed in books [1–5]. Circular polarization is a special case of elliptical polarization, *i.e.* elliptical polarization is the most general case by IEEE standard [6], and the essence of both polarizations is similar.

The rotation of vectors can have two possible directions, the electric **E** (and magnetic **H)** field vector can rotate in the right-hand or left-hand direction with respect to the direction of the wave propagation. The Pointing vector **P** = [**EH**] describes the direction of the EM wave propagation.

Our article is dedicated to considering the importance of fixing the observer's position in relation to the direction of spreading EM wave on the base of [6–8].

2. DEFINITIONS FROM IEEE STANDARDS

The definitions of a circularly polarized EM wave according to IEEE standard (std) 211–2018 [6] are: "An electromagnetic wave for which the locus of the tip of the instantaneous electric field vector is a circle in a plane orthogonal to the wave normal. This circle is traced at a rate equal to the angular frequency of the wave with a left-hand or right-hand sense of rotation".

In the IEEE std is also definitions relating to **right-hand circular polarized (RHCP) wave**: "A circularly or an elliptically polarized electromagnetic wave for which the electric field vector, when viewed with the wave approaching the observer, rotates **counterclockwise** in space". NOTE 1 – *This definition is consistent with observing* ***a clockwise*** *rotation when the electric field vector is viewed in the direction of propagation.*

In IEEE std [6] is also presented definitions relating to the left-hand circular polarized (LHCP) wave. The definition for RHCP given above and the definition for LHCP from the IEEE std are similar and only have to be replaced such words "counterclockwise" on "clockwise" and *vice versa*.

So we see that the IEEE std **presents both for the right-hand polarized wave and also for the left-hand polarized wave two definitions**: the basic (main) definition of the vector **E** rotation (it is typed in direct font) and the additional definition that is given in NOTE 1 (here *in italic*), see, above-mentioned text.

For more understanding the definitions of **right-hand sense of rotation** we compare the definitions for the right-handed coordinate system (which the axes satisfy the *right-hand rule*) and **right-hand polarized wave.** When we use the right-handed coordinate system then the right thumb points along the *z*-axis in positive direction (in this context can be a direction of EM wave propagation) and the curl of four fingers represents a motion (rotation) from the *x*-axis to the *y*-axis.

When viewed from the top of *z*-axis the system is **counterclockwise**. We see that this definition of the right-handed system rotation coincides with the basic definition in the standard about right-hand polarized wave.

When viewed from the bottom of *z*-axis (from the coordinate system origin) then the system is **clockwise**. We see that last definition of the right-handed system rotation in positive direction (rotation from O*x* axis to O*y* axis) coincides with the additional definition given in NOTE 1 of the IEEE std about the right-hand polarized wave. Therefore the direction of the vector rotation depends on the location of an observer.

Similar reasoning will be for the left-handed coordinate system and left-hand polarized wave. It is also very important to note that many definitions for circularly polarized waves in an earlier IEEE std 211–1997 coincide with the definitions in the present IEEE std 211–2018.

There are plenty books and articles mentioning RHCP and LHCP where authors use the basic or additional (given in NOTE 1 of the IEEE std) definitions related to one of the polarizations.

3. APPLICATION OF RHCP AND LHCP

We want to emphasize that circular (elliptical) polarization of EM waves (light) is extremely important because the one are exploited in scientific investigations and a tremendous number of devices, *e.g.* antennas, polarization beam splitters, polarization-based wavefront-controllers, filters, absorbers, polarization converters, modulators, sensors and other techniques to control and manipulate polarization of EM waves, which are used for many scientific areas as Radio and Radar Astronomy, Radar Polarimetry, Spectroscopy, Spectropolarimetry, Microscopy [3].

Radio astronomy is *a passive observation* of objects emitting EM waves (light) by using radio antennas that form a radio telescope or radio interferometers (an array of separate telescopes, mirror segments). The emitting objects can be some astronomical sources of EM wave radiation. Results of detecting of the circular polarization with circularly polarized antenna feeds from the large scale circular polarization survey made at Very Long Baseline Interferometry is presented in [9]. The technique for studying the performance of the radio telescope and comparison of measurements with calculations are given in [10].

Radar astronomy is *an active observation* of astronomical objects, the object is initially irradiated by EM waves and after that the analysis of the reflected waves is carried out. Radar astronomy has used circular polarization radar signals to explore the surfaces of different solar system and Earth geologic targets [11, 12].

Radar Polarimetry ("Polar" is from "Polarization" and "Metry" is from "the process of measuring") is the science of data collection, analyse and interpretation concerning the polarization state of EM waves. By the definition of IEEE std [6]: "Polarimetry is the study of EM propagation, scattering, and emission that considers the complete polarization state of any arbitrarily polarized wave." Polarimetry data based on the EM wave propagation through a material object to estimate the fine texture and optical activity of this material, as well as on the wave reflection, refraction and diffraction from the object in order to characterize the one. Polarimetry is used in remote sensing applications, such as geoscience, planetary science, and atmospheric sciences [13–16].

Spectroscopy is the science concerned with the examination and measurement of EM spectra produced when the substance of a physical object interacts with EM waves or the object itself emits an EM radiation. Spectroscopy is the study of the *absorption and emission* of an EM wave by substance dependent on the wave frequency (wavelength). There are different kinds of spectroscopy as atomic, molecular, nuclear, circular dichroism (based on the differential absorption of left and right circularly polarized light), photoemission (photoelectric effect is the emission of electrons or other free carriers when EM radiation hits a material) etc. Spectral measurement devices are referred to as spectrometers, spectral analysers, spectrographs and spectrophotometers [17, 18].

Spectropolarimetry is the science of measuring of both the total flux and the polarization state of EM wave (light) as a function of the wave frequency (wavelength). Spectro-polarimetry is a very powerful tool for remote sensing of the thermodynamic and magnetic properties of astrophysical plasmas as well as for the characterization of aerosol, clouds and (tropospheric) ozone [19–22].

Microscopy is the technical area of using microscopes to view extremely small objects. Optical and electron microscopy involve the reflection, refraction or diffraction of EM radiation or electron beams interacting with a study object and the collection of the scattered radiation or another signal in order to create an image [23, 24].

Promising branches of science research are: polarimetric imaging systems for target detection and recognition, imaging of optically active structures (the rotation of the plane of light along the propagation through optically active medium) and metasurfaces (an artificial nanostructured surface) [25–28].

It has been discovered that numerous marine species and terrestrial animals may perceive circular polarization [29–34].

We come to the conclusion after reading the literature concerning to circular polarization that some authors use the basic definition of RHCP and LHCP polarization from IEEE standards [6, 7], others use an additional definition given in NOTE 1 of the same standards. The misconception occur only when the author do not specify a position of an "observer's eye" in relation to the direction of the wave propagation.

In books [1], page 418 and [5], page 334 are given the RHCP and LHCP definitions that correspond for the basic definitions of terms presented in the IEEE std. At the same time the opposite definitions are given in page 15 of book [3], *i.e.* the definitions coincide with the one presented in NOTE 1 of [6] and [7]. In p. 374 of book [4] is written "In optics, the clockwise case is called right circular polarization, and the counter clockwise, left circular polarization”, *i.e.* the definitions as in NOTE 1 of the IEEE std.

Authors note in section 6.2 of [11] that Radio astronomers usually use the IEEE convention for the sense of circular polarization: “If the electric field is rotating counterclockwise around the direction of propagation – your thumb – then your right hand describes the circular polarization state of IEEE RCP. The IEEE logo even has a drawing of the right-hand rule, in case you ever forget which sense is RCP. This is opposite to the definition used by some physicists and optical astronomers”.

In [13] are presented illustrations for explaining RHCP and LHCP when the left-handed Cartesian coordinate system, the origin of coordinates and a propagating EM wave are located in the same side. We see here for the LHCP wave that the rotation of the vector **E** occurs counterclockwise when we observe from the origin of the coordinate. So in [13] is used the additional definition as in NOTE 1 of the IEEE std.

In the first picture of [35] are shown as an EM wave propagates from a horn antenna towards a building while the vector **E** rotates counter clockwise for RHCP. When we assume that a “reader’s eye” is located on the side of the antenna then RHCP meaning coincides with the additional definition of the IEEE std. Papers [14], [15] describe RHCP and LHCP in accordance with the basic definition of the IEEE std.

Therefore, there is some confusion about the rotation of the electric field vector **E** clockwise or counterclockwise in some literature sources, in cases where the position of the observer’s eye is not indicated.

4. DISCUSSION ON CIRCULAR POLARIZATIONS

Comment about RHCP is demonstrated in Fig. 1. Here is shown a single transparent film which is visible from two sides, *i.e.* from the side of a “red eye” and the side of a “blue eye” that is close to sources of EM wave, *i.e.* antennas A_1 and A_2. For convenience, the transparent film is cut and turned to see at the same time both sides of the film with a blue circle and a red one. We see a red circle with the rotation of the vector **E** counterclockwise (also known in some articles as the right-hand, counter-clockwise or anti-clockwise), when we are looking at the red circle from the side of the “red eye”. The “red eye” sees a tip of the Pointing vector **P = [EH]**, *i.e.* when the EM wave approaches to the “red eye”. This description corresponds to the basic definition is presented in the IEEE std for RHCP [6].

When we look on the same transparency film from the side of the “blue eye” then we see the blue circle with a clockwise rotation of the vector **E** in the plane xOy. The “blue eye” sees a tail of the Pointing vector **P**. In this case the EM wave propagates away from the “blue eye” and the tip of the vector **E**, draws the blue circle. We see in Fig. 1 that the direction of rotation in the blue circular is the opposite compared to the red circle. The “blue-eye” view corresponds the additional RHCP definition presented in NOTE 1 of the IEEE std [6].

Similar reasoning would be for the EM wave with LHCP if an observer's eye placed on both sides of the spreading EM wave.

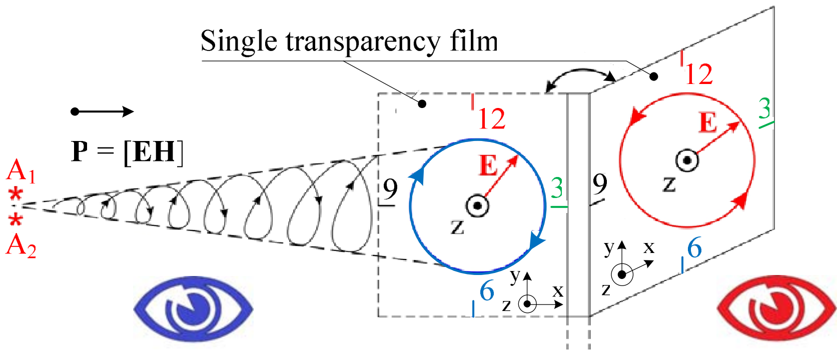


Fig. 1 – The "blue eye" on the left side of the illustration is next to EM wave sources, the "blue eye" sees a tail of the Pointing vector **P** (this definition of RHCP coincides with NOTE 1 of the IEEE std) and the "red eye" is located in the opposite side of the wave sources and the film, the "red eye" sees a tip of the vector **P**, *i.e.* when the EM wave approaches the "red eye". This is in line with the basic definition of RHCP in the IEEE std (Color online).

In Radar astronomy an "eye" of an observer is usually located in the opposite direction from the EM wave source (as the "red eye" in Fig. 1). In the last case EM waves are propagating towards the observer's eye. In optics, an "eye" of an observer and a source of an EM wave can be adjacent, that is, on the same side (the "blue eye" in Fig. 1). You can imagine an optical microscope (for research of a material) with a light source which can be on the same side as the eye of the observer. In optics the EM wave "spreads away" from the side of the observer.

In Figs. 2 and 3 are presented three dimensional (3D) image of RHCP wave (counterclockwise, right-hand rotation) and LHCP wave (clockwise, left-hand rotation).

Figure 2a demonstrates the location of the O*x*, O*y*, O*z* axes of the right-handed Cartesian coordinate system: the right thumb points along the O*z* axis in the positive direction of the axis and the curl of the four fingers represents a motion from the O*x* axis to the O*y* axis. When viewed from the tip of the O*z* axis the system is counterclockwise.

Figure 2b is presented the propagation of the RHCP wave when is using the right-handed coordinate system. We see a black circular helix that is drawn by the tip of vector **E** in 3D space as the EM wave propagates. The direction of the helix's axis matches with the direction of the Pointing vector **P** and the positive direction of O*z* axis. Here is depicted the right-handed helix because, according to the description of helix curves in space, a sight with the "blue eye" along the helix's axis indicates a clockwise screwing motion which is imprinted on the blue circle and the helix is moving away from the observer's "blue eye".

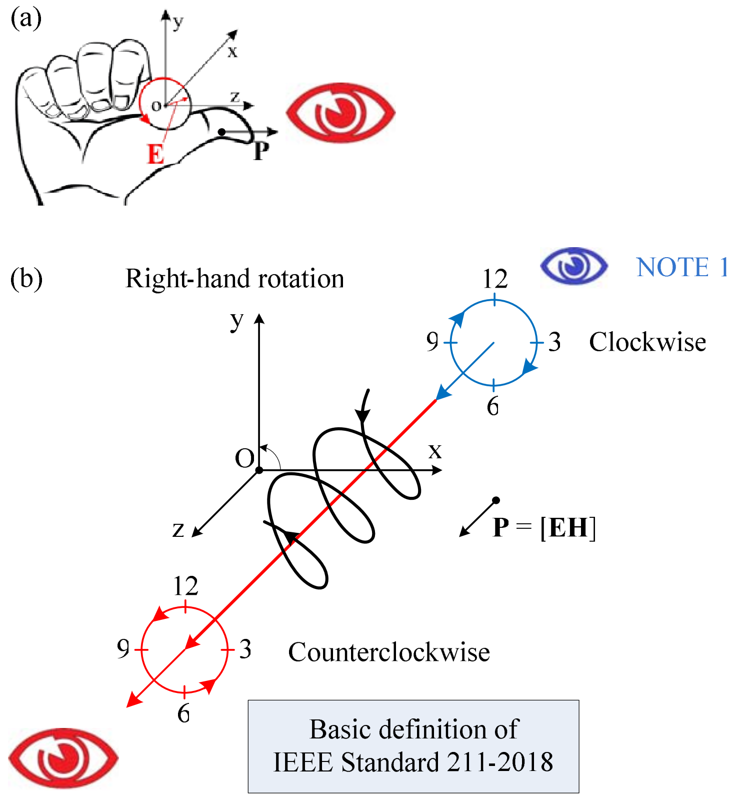


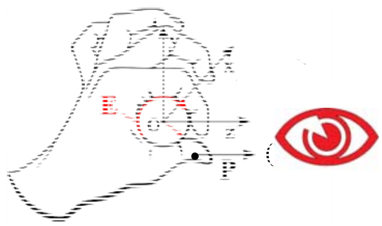
Fig. 2 – a) To the right-hand rule: four right hand fingers curled in the direction of rotation and the right hand thumb pointing in the positive direction of Oz axis; b) – 3D image of RHCP wave which is depicted as a black helix and a rotation of the **E**-vector tip from the observer's "blue eye" and the observer's "red eye" (Color online).

When the observer's eye is the red one and the tip of the Pointing vector **P** is directed towards the "red eye" then this definition coincides with the basic definition of the IEEE std [6] for RHCP wave. We see that the direction of four right hand fingers represents the rotation of the electric field vector **E** from O*x* axis to O*y* axis for the right-handed coordinates. This definition for RHCP wave is also given in our section II of the present work.

When the observer's eye is the blue one and the tail of the Pointing vector is directed away of the observer's "blue eye" then this description is consistent with the additional definitions that is given in NOTE 1 of the IEEE std [6] for RHCP wave. This definition for RHCP wave is also in the Section II of the present work.

Figure 3a demonstrates the location of the O*x*, O*y*, O*z* axes of the left-handed Cartesian coordinate system. For left-handed coordinates the left hand thumb points along the O*z* axis in the positive direction and the curled fingers of the left hand represent a motion from the O*x* axis to the O*y* axis.

(a)



(b)

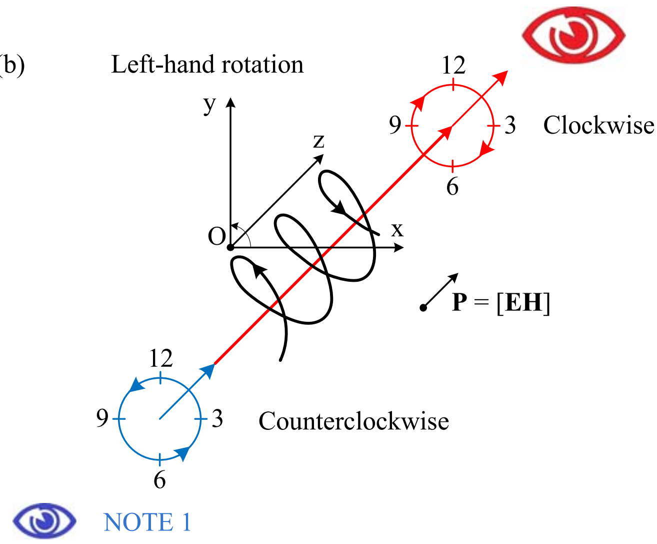


Fig. 3 – a) To the left-handed coordinate system: the left hand thumb points along the O*z* axis in the positive direction and the curled four fingers of the left hand represent a motion from the O*x* axis to the O*y* axis; b) – 3D image of LHCP wave which is depicted as a black helix with a rotation of the **E**-vector tip from the observer's "blue eye" and also from the observer's "red eye".

Figure 3b is presented the propagation of the LHCP wave when is using the left-handed coordinate system. We see a black circular helix that is drawn by the tip of vector **E** in 3D space as the EM wave propagates. The direction of the helix's axis matches with the direction of the Pointing vector **P** and with the direction of the positive O*z* axis. Here is depicted the left-handed helix because if a clockwise screwing motion moves the helix towards the observer ("red eye"), then it is a left-handed helix.

When the observer's eye is the red one and the tip of the Pointing vector is directed towards the "red eye" then this definition coincides with the basic definition of the IEEE std [6] for LHCP wave.

We see (Fig. 3) that the direction of four left hand fingers represents the rotation of the electric field vector **E** from O*x* axis to O*y* axis for the left-handed coordinates.

When the observer's eye is the blue one and the tail of the Pointing vector is directed away of the observer's "blue eye" then this definition coincides with the additional definition that is given in NOTE 1 of the IEEE std [6] for LHCP wave.

As previously noted, the authors of some technical articles do not always indicate the direction of the EM wave propagation along the *z*-axis nor do they indicate the position of an eye of an observer with respect to the source of EM waves. For this reason the electric field vector **E** can rotate clockwise or counterclockwise in the RHCP wave. The same uncertainty is with the left-hand polarized wave.

5. CONCLUSION

Since there are old well-established traditions and agreements in different areas of knowledge regarding the direction of the rotation of the electric field vector relating to the right-hand and left-hand circular polarized EM waves and for that reason, it is necessary to indicate which of the two definitions were used in a scientific paper, *i.e.* the basic definition of IEEE Std 211–2018 or the additional one from the NOTE 1.

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