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The handedness and classification of materials

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ABSTRACT

According to direction relationship among the triplet of vectors of electric field intensity, magnetic field intensity and wave vector of electromagnetic wave, materials have usually been classified as right- and left-handed material. Here, we shall strictly and systematically demonstrate that, in a linear isotropic homogeneous medium, the direction relationship among the triplet of vectors of electric field intensity, magnetic field intensity and wave vector of electromagnetic wave may generally alter between right-handedness and left-handedness with change of time except for the special cases. Thus the further classification of materials according to handedness and corresponding criterion are proposed.

1. Introduction

In free space or a usual lossless linear isotropic homogeneous medium, the triplet of vectors of electric field intensity $\vec{E}(\vec{r},t)$, magnetic field intensity $\vec{H}(\vec{r},t)$ and wave vector k of electromagnetic wave (EMW) form a right-handed orthogonal set [1,2], this medium can be termed as right-handed material (RHM). On the other hand, Veselago predicted that the triplet of vectors of $\vec{E}(\vec{r},t)$, $\vec{H}(\vec{r},t)$ and $\vec{k}$ of EMW in the medium having simultaneously negative permeability and permittivity may form a left-handed orthogonal set [3]. Such material is called as left-handed material (LHM). Apparently, the wave vector $\vec{k}$ of EMW in LHM is anti-parallel to the Poynting vector [4], which associates with various other unique properties of LHM, such as the negative refraction [3–6], the reversals of both Doppler shift and Cherenkov radiation [3], enhancement of evanescent wave [7], etc.

It is stressed that variation of $\vec{E}(\vec{r},t)$ and $\vec{H}(\vec{r},t)$ of EMW in free space is either in step as shown in Fig. 1(a) or anti-phase as shown in Fig. 1(b), the direction of cross product of $\vec{E}(\vec{r},t)\times\vec{H}(\vec{r},t)$, i.e., the time-dependent Poynting vector (TDPV) $\vec{S}(\vec{r},t)$, of the EMW is always parallel to $\vec{k}$. Whereas, in the double negative lossless medium proposed by Veselago [3], $\vec{E}(\vec{r},t)$ and $\vec{H}(\vec{r},t)$ of EMW alter also either in step as shown in Fig. 1(c) or anti-phase as shown in Fig. 1(d), $\vec{S}(\vec{r},t)$ of the EMW is always anti-parallel to $\vec{k}$. However, in a lossy or gain medium, variation of $\vec{E}(\vec{r},t)$ and $\vec{H}(\vec{r},t)$ of EMW is usually non-synchronous (see Fig. 2(a) and (b)), direction of $\vec{S}(\vec{r},t)$ may alter with change of time [1,2], which may alter the direction relationships among vectors of $\vec{E}(\vec{r},t)$, $\vec{H}(\vec{r},t)$ and $\vec{k}$, and then affect the handedness properties of the material. On the other hand, negative refraction associated with energy losses have been observed under different conditions [5,6,8]. At a LHM/vacuum interface, negative refraction obeys the usual Snell's law [5,6], and effects of the slight losses on energy flow propagation direction of transmitted wave are negligible [6]. Further, it is noted that, even if the LHM has significantly large imaginary parts of permeability and permittivity, refraction behavior is still dominated by the negative real part of the refraction index [9–11]. But, it is known early that the usual Snell's law is no longer valid at the lossy interface [12]. As a typical example, negative refraction may also be produced by a heavily lossy wedge without negative refraction index [8,13,14]. In addition, a variety of conditions and phase diagram for negative refraction have been proposed [15–18]. However, it is demonstrated that the different conditions are not equivalent when they are extended to active media [17]. Therefore, systematical investigation on effects of direction alteration of $\vec{S}(\vec{r},t)=\vec{E}(\vec{r},t)\times\vec{H}(\vec{r},t)$ may be helpful for one further understanding the negative refraction observed under

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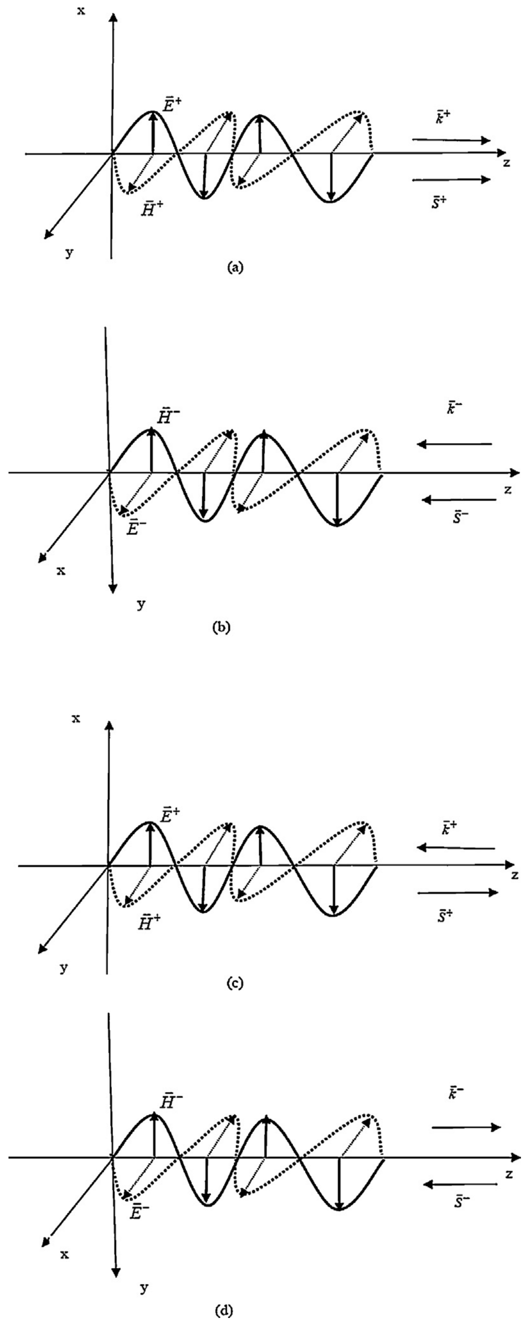

Fig. 1. Sketch of EMW propagating in free space with its Poynting vector along (a) +z axis direction and (b) −z axis direction with their electric and magnetic field vectors oriented in the directions of the x and y axes, respectively. EMW propagating in double negative lossless medium with its Poynting vector along (c) +z axis direction and (d) −z axis direction, respectively.

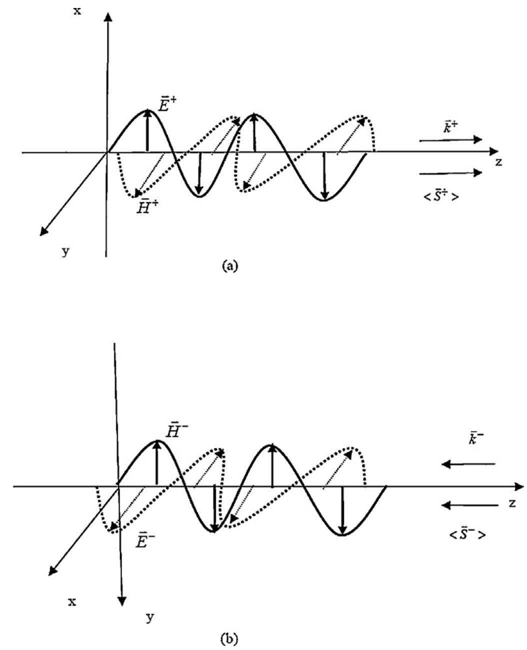

Fig. 2. Sketch of EMW propagating in lossy or gain medium with its TAPV along (a) +z and (b) −z axis direction, respectively, variation of electric field $\vec{E}(\vec{r}, t)$ and magnetic field $\vec{H}(\vec{r}, t)$ is non-synchronous.

different conditions and fully addressing handedness properties of the material and the criterion for LHM.

The remainder of the paper is organized as follows. In Section 2, we shall strictly and systematically demonstrate that, in a lossy or gain medium, direction relationship among the triplet of vectors of electric field intensity, magnetic field intensity and wave vector of EMW may generally alter between right-handedness and left-handedness with change of time except for the special cases. Thus the further classification of materials according to handedness and corresponding criterion are proposed. Finally, some conclusions are drawn in Section 3.

2. Analysis and discussions

Let's consider in detail the properties of varying electric field, varying magnetic field and EMW in a linear isotropic homogeneous medium. For a given angular frequency ω, an $\exp(i\omega t)$ time dependence is implicit. The medium can be characterized by complex permeability and permittivity scalars of $\tilde{\mu} = \mu' - i\mu'' = |\tilde{\mu}| \exp\left(-i\alpha_{\mu}\right)$ and $\tilde{\varepsilon} = \varepsilon' - i\varepsilon'' = |\tilde{\varepsilon}| \exp\left(-i\alpha_{\varepsilon}\right)$, respectively (in this paper, the complex valued parameters are marked with "∼"). Where $\alpha_{\mu(\varepsilon)}$ is the magnetic (electric) damping angle. For the passive medium, the damping angle is in the range of $\alpha_{\mu(\varepsilon)} \in [0, \pi)$ usually; and for the active medium, the damping angle range may be taken as either $\alpha_{\mu(\varepsilon)} \in (\pi, 2\pi)$ (e.g., for two-component system) or $\alpha_{\mu(\varepsilon)} \in (-\pi, 0)$ (for inverted system) [19]. For convenience, the complex valued parameters of EMW are adopted to address the phase difference between $\tilde{\vec{E}}(\vec{r}, t)$ and $\tilde{\vec{H}}(\vec{r}, t)$. The constitutive relations are given as follows, respectively

$$\tilde{\vec{D}}\left(\vec{r}, t\right) = \tilde{\varepsilon}\tilde{\vec{E}}\left(\vec{r}, t\right) \tag{1}$$

$$\tilde{\vec{B}}\left(\vec{r}, t\right) = \tilde{\mu}\tilde{\vec{H}}\left(\vec{r}, t\right) \tag{2}$$

Eq. (1) indicates that variation of electric displacement vector $\tilde{\vec{D}}(\vec{r}, t)$ lags behind that of $\tilde{\vec{E}}\left(\vec{r}, t\right)$ in a phase of α_{ε} and Eq. (2) refers that variation of magnetic flux density vector $\tilde{\vec{B}}(\vec{r}, t)$ lags behind that of $\tilde{\vec{H}}(\vec{r}, t)$ in a phase of α_{μ}, respectively. On the other hand, the source-free complex valued Maxwell's equations may be written as

$$\nabla \cdot \tilde{\vec{D}}\left(\vec{r}, t\right) = 0 \tag{3}$$

$$\nabla \times \tilde{\vec{E}}\left(\vec{r}, t\right) = -\frac{\partial \tilde{\vec{B}}\left(\vec{r}, t\right)}{\partial t} \tag{4}$$

$$\nabla \cdot \tilde{\vec{B}}\left(\vec{r}, t\right) = 0 \tag{5}$$

$$\nabla \times \tilde{\vec{H}}\left(\vec{r}, t\right) = \frac{\partial \tilde{\vec{D}}\left(\vec{r}, t\right)}{\partial t} \tag{6}$$