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A possible mechanism of current in medium under electromagnetic wave*

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In this paper a possible mechanism of current in medium is presented. Comparison between this current and the magnetization current was made. Expression for this current was derived. This work is helpful to understanding the interaction between medium and electromagnetic wave.

Keywords: medium, electromagnetic wave, current, electromagnetism
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Research on the interaction between a medium and an electromagnetic wave has been an important and active field.[1−3] New concepts, phenomena and applications in this field have kept appearing over the past decades. Various explanations and theories for these new concepts and phenomena (such as negative refractive index and negative group velocity and so on[4−9]) have been presented. The contradiction between the existing theory and the new experimental results[10−13] indicates that the interaction between a medium and an electromagnetic wave is a very complicated subject, about which we know very little yet. In this paper we investigate the reaction of a medium to electromagnetic wave to try to understand this interaction from a fundamental point of view.

It has been believed that there are macroscopic charges and macroscopic currents in a medium under the action of electromagnetic wave, and that the total macroscopic charge density ρ and the total macroscopic current density $\boldsymbol{j}$ are[14]

$$\rho = \rho_0 + \rho', \tag{1}$$

$$\boldsymbol{j} = \boldsymbol{j}_0 + \boldsymbol{j}_{\mathrm{P}} + \boldsymbol{j}_{\mathrm{M}}, \tag{2}$$

where ρ_0 is the free charge density, ρ' the polarization charge density, $\boldsymbol{j}_0$ the free charge current density, $\boldsymbol{j}_{\mathrm{P}}$ the polarization current density, and $\boldsymbol{j}_{\mathrm{M}}$ the magnetization current density. As is known, the free current results from the directional motion of electrons (or other charge carriers) between the molecules in the medium, while the polarization charge current and the magnetization current result from the directional motion of the electrons within their molecules under the action of electromagnetic wave of light frequency.[14]

Recently, the electron-cloud-conductor model was presented[15]: when interacting with light, the electron cloud of each electron in the medium can be seen as a conductor, and Faraday's Law applies to this conductor; thus an alternating magnetic field of light existing in the electron cloud can induce a current in the electron cloud. This model has shown good rationality when it is used to deal with refractive phenomena, and verified the refractive index with the diamagnetic susceptibility of He gas.[15] By the electron cloud conductor we mean that the electron may behave as a free electron in its electron cloud space under some condition. In fact, the oscillator model has treated the electron under an alternating electric field as a free electron in the molecule.[14,16,17] This indicates that although the electron cannot move freely between the molecules in a dielectric medium, it can move freely to some extent within its electron cloud. So the electron-cloud-conductor model is reasonable.

Maxwell's theory believes that an alternating magnetic field will induce an electric field around it whether there is a conductor loop around it or not. According to the Faraday's Law, the alternating mag-

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netic field of light existed in the electron cloud space will induce an electromotance, which will cause an additive motion of the electron along the circumference direction in the electron cloud (Fig.1). This additive motion is actually a statistical result of the electron motion, and is superposed on the original motion of the electron in its electron cloud. All the electrons' additive motions along the circumference directions of the electron clouds combine into a current loop (bound current) on the molecule, as shown in Fig.2. For clarity in the following text, we call this current loop the 'induced current loop of molecule'. Then the induced current loops of molecules combine into a macroscopic current (also bound current), as shown in Fig.3. We call this macroscopic current the 'combining induced current', and it is denoted by $\boldsymbol{j}_{\mathrm{F}}$.

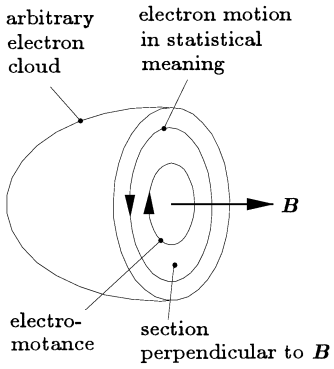


Fig.1. Section of the electron cloud of one electron. The normal of this section is in the direction of $\boldsymbol{B}$. The electron has an additive motion along the circumference direction in its electron cloud under the electromotance produced by $\partial\boldsymbol{B}/\partial t$ of light.

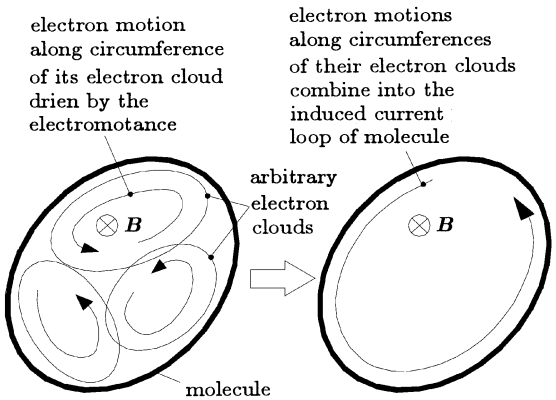


Fig.2. Section of a molecule. The normal of this section is in the direction of $\boldsymbol{B}$. The thick line stands for the molecule and the thin line stands for the electron cloud.

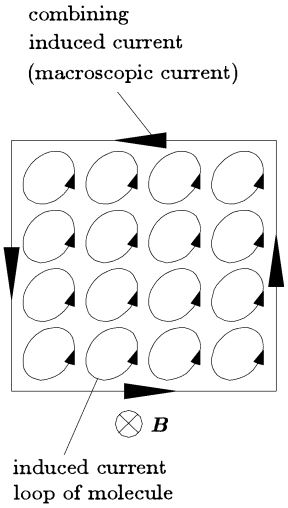


Fig.3. The induced current loops of molecules combine into a macroscopic current, i.e. the combining induced current.

It is well known that the magnetization current results from the current loops in the molecules. The combining induced current results from current loops in the molecules also. But their mechanisms are not the same. The mechanism for the combining induced current is Faraday's Law. So the combining induced current is caused by $\partial\boldsymbol{B}/\partial t$, and $\boldsymbol{j}_{\mathrm{F}}$=0 when $\partial\boldsymbol{B}/\partial t$=0, where $\boldsymbol{B}$ is the magnetic induction of light. $\boldsymbol{j}_{\mathrm{F}}$ has a different phase relative to $\boldsymbol{B}$ of light. While the magnetization current results from the interaction between magnetic field and magnetism of the molecules.[14] $\boldsymbol{j}_{\mathrm{M}} \neq 0$ when this magnetic field is not zero, whether this magnetic field is a static or alternating magnetic induction (such as $\boldsymbol{B}$ of light). $\boldsymbol{j}_{\mathrm{M}}$ has the same phase as $\boldsymbol{B}$ of light. For example, the magnetization current can be produced by the diamagnetism of medium. The diamagnetism results from Larmor precession of electron under external magnetic field $\boldsymbol{B}_{\mathrm{EX}}$ ($\boldsymbol{B}_{\mathrm{EX}}$ may be a static or alternating magnetic induction). The diamagnetism has its own magnetic field. The absolute value of the magnetic field of the diamagnetism is proportional to the absolute value of $\boldsymbol{B}_{\mathrm{EX}}$, and the direction of the magnetic field of the diamagnetism is always opposite to that of $\boldsymbol{B}_{\mathrm{EX}}$. While the combining induced current results from Faraday electromagnetic induction. The absolute value of the magnetic field of the combining induced current is proportional to the absolute value of $\partial\boldsymbol{B}_{\mathrm{EX}}/\partial t$, and the direction of the magnetic field of the combining induced current is not always opposite to that of $\boldsymbol{B}_{\mathrm{EX}}$.

Now we consider the expression for $\boldsymbol{j}_{\mathrm{F}}$. We shall restrict ourselves to homogeneous and isotropic medium for simplicity. Similar to the statistical treat-

ment for the magnetization current, we assume that all the induced current loops of molecules have the same intensity and size when they are under the same action of $\partial \boldsymbol{B}/\partial t$. The intensity $\boldsymbol{i}$ of the induced current loop of molecule is proportional to the electromotance, i.e.

$$\boldsymbol{i} = \sigma U = -\sigma S_{\mathrm{F}} \frac{\partial \boldsymbol{B}}{\partial t}, \tag{3}$$

where $U = -S_{\mathrm{F}}(\partial \boldsymbol{B}/\partial t)$ is electromotance (Faraday's Law), S_{F} is the area of the induced current loop of molecule, σ is a factor. The magnetic moment of each the induced current loop of molecule is

$$\boldsymbol{m}_{\mathrm{F}} = iS_{\mathrm{F}} = -\sigma S_{\mathrm{F}}^2 \frac{\partial \boldsymbol{B}}{\partial t}, \tag{4}$$

which is called the 'induced magnetic moment of molecule'. The direction of $\boldsymbol{m}_{\mathrm{F}}$ is opposite to $\partial \boldsymbol{B}/\partial t$. To distinguish from 'magnetization', the magnetization resulted from the induced magnetic moments of molecules is called the 'induced magnetization', which is

$$\boldsymbol{M}_{\mathrm{F}} = \boldsymbol{N}\boldsymbol{m}_{\mathrm{F}} = -N\sigma S_{\mathrm{F}}^2 \frac{\partial \boldsymbol{B}}{\partial t} = -\beta \frac{\partial \boldsymbol{B}}{\partial t}, \tag{5}$$

where N is molecule density of the medium, β is a factor, which is $\beta = N\sigma S_{\mathrm{F}}^2$. N, σ and S_{F} are related to the properties of the medium and affected by external conditions. We called β the 'induced susceptibility'. Its unit is S·m. Similar to the relationship between the magnetization current density and its magnetization,[14] we have the relationship between the combining induced current density $\boldsymbol{j}_{\mathrm{F}}$ and the induced magnetization $\boldsymbol{M}_{\mathrm{F}}$

$$j_{\mathrm{F}} = \nabla \times \boldsymbol{M}_{\mathrm{F}} = \nabla \times \left(-\beta \frac{\partial \boldsymbol{B}}{\partial t} \right). \tag{6}$$

$\boldsymbol{j}_{\mathrm{F}}$ is the current through unit area in the medium. The density of the combining induced current on the surface of the medium is

$$\phi = \boldsymbol{M}_{\mathrm{F}} \times \boldsymbol{n} = -\beta \frac{\partial \boldsymbol{B}}{\partial t} \times \boldsymbol{n}, \tag{7}$$

where $\boldsymbol{n}$ is the unit vector along the outer normal of the surface. The combining induced current does not cause an accumulation of electric charges. So it does not contribute to the total macroscopic charge density ρ. Hence, Eq.(1) remains unchanged, while Eq.(2) becomes

$$\boldsymbol{j} = \boldsymbol{j}_0 + \boldsymbol{j}_{\mathrm{P}} + \boldsymbol{j}_{\mathrm{M}} + \boldsymbol{j}_{\mathrm{F}}. \tag{8}$$

In summary, it is possible that the combining induced current exists in the medium under electromagnetic wave. Similar to the polarization charge current and the magnetization current in the medium, the combining induced current results from the directional motion of the electrons within their electron clouds under the action of electromagnetic wave. The mechanism for the induced current loop of molecule works as long as there are electron clouds. So the combining induced current should be a universal phenomenon in the medium under the action of light.

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