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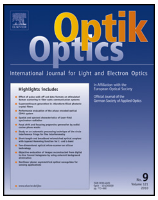

Original research article

Physical nature and magnitude of optically induced forces derived from laws of mechanics

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ABSTRACT

We derive the true magnitude of the optically induced force (OIF) in a linear transparent optical medium where $\varepsilon \geq 1$ and $\mu \geq 1$ from unambiguous but contradictory results of two known thought experiments where no preliminary assumption about phenomena connected with electrical and magnetic fields are used. The analysis is based on laws of mechanics only. By means of comparing these forces with known types of forces we conclude that there are four kinds of force. First, this is the Coulomb force known in electrostatics. Second, this is the magnetic force known in magneto statics. Third, this is Ampere-like force arising at an interaction between the alternate polarization current and the alternate magnetic field of the light wave. Fourth, this is the force arising at an interaction between alternate magnetization current and the alternate electrical field of the light wave studied by Einstein and Laub in 1908. A sum of the third and fourth kinds of force in a field of an electromagnetic wave averaged over time is equal to zero at a steady state. We show that the existing formulas for third and fourth kinds need to be corrected for the medium where $\varepsilon > 1$ and $\mu > 1$.

1. Introduction

The notion of the force is used for a long time in the mechanics. In the early 20th century, it has been proven that light exerts pressure upon reflection from the reflector and therefore has momentum as usual moving bodies with non-zero mass. In this case the density of optically induced force in matter could be calculated by using known method in mechanics as a difference between input and output momentum density fluxes (MDF). Unfortunately, there is no the generally accepted notion about a magnitude of the momentum of light in matter till now. However, the second way for calculation of OIF can be used. Since forces in the electricity are known since time when laws of Coulomb and Ampere was discovered, on one hand, and the light wave is a combination of alternate electrical and magnetic fields, on the other hand, one can used these laws for calculation of OIF. In accordance with this approach, Gordon in 1973 proposed to calculate optically induced forces applied to the optical medium by using the Lorentz law for density force [1]. Since then several hundreds of works have been published where OIFs are derived by a direct application of the Lorentz density force. For example, we can mention publications of Loudon and Barnett [2], Barnett and Loudon [3], Mansuripur [4], Boyd [5], Kemp et al. [6], Zakharian et al. [7]. This approach is used widely till now and authors point out that they have used an approach based on the Lorentz force as the dignity of their work.

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As is pointed out [3], “traditionally, the electromagnetic stress tensor has been used to derive the mechanical force exerted by the radiation field on ponderable media. This approach, while having the advantage of generality, tends to obscure behind complicated mathematics the physical origin of the forces. It is possible, however, to calculate the force of the electromagnetic radiation in various media by direct invocation of the Lorentz law of force. The derivation is especially straightforward in the case of solid metals and solid dielectrics, where the mass density and the optical constants of the media may be assumed to remain constant under internal and external pressures, and where material flow and deformation can be ignored” Loudon [2] has emphasized “the simplicity and safety of calculations based on the Lorentz force and the dangers of calculations based on derived expressions involving elements of the Maxwell stress tensor, whose contributions may vanish in some situations but not in others.” Indeed, the physical origin of the Lorentz force is evident. This is an interaction between bounded charges in dielectric and the electric field of the light wave as well as an interaction between polarization currents in dielectric and the magnetic field of the light. However, as was shown by Hirose [8] in 2010, the Lorentz force approach is incorrect. This conclusion was confirmed in 2014 [9].

Last time another approach to calculation of OIF is used [10] that was proposed by Einstein and Laub in 1908 [11]. In this case additional bounded magnetic charges and currents of magnetization are taken into account. This testifies that a search of a correct expression for calculation of OIF continues and a generally accepted safe method for calculation of OIF is absent at present. As a result, it is unknown what kinds of force are responsible for arising OIF. Are these the known kinds of forces? Possibly, there are unknown kinds.

2. Our approach to the analysis of optically induced forces

We believe that the most correct way to analyze OIF is to abandon a search for the right formula and to come back to analyze a change of the momentum density flux (MDF) of light in matter. For this purpose, the exact knowledge about a magnitude of the MDF in matter is required. At the same time, any assumptions about the physical effects responsible for arising of OIF are unacceptable. It is turn out that a knowledge about kinds and magnitude of OIF can be obtained from laws of mechanics. In this case, the knowledge is independent on all proposed in last century electrodynamical theories that try to explain arising OIF. The conservation laws and the interrelation between a force and momentum are the main ground for the analysis. We have used the following unambiguous, in our opinion, facts to derive a notion about a magnitude of MDF in matter.

First, there is the Balazs thought experiment known since 1953 [12]. It is shown theoretically that an initially motionless transparent block, where a light pulse enters from free space without reflection and is propagating without absorption, should be displaced in a direction of a propagation of the light pulse. As a result, the block is moving along the light pulse direction when the pulse is propagating inside the block. In this case, a part of the momentum of the pulse is transferred to the block. Therefore, the momentum of light inside the block becomes smaller than that of the same pulse propagating in free space. Thus, the momentum of light inside the block corresponds to the Abraham form. Only the law of conservation of the position of the center of mass in a closed system was used for deriving this conclusion. As is pointed in review [3], “If argument advanced in favor of the Abraham momentum were to be incorrect, than that would bring into question uniform motion of an isolated body as expressed in the Newton’s first law of motion”. A description of this experiment is presented in many recent publications [13–15].

Second, there is another thought experiment [16–20] based on the energetic approach where no assumption about kinds of OIF is also made. Unlike the Balazs thought experiment where the law of conservation of the momentum is used, the law of conservation of the energy is used in the thought experiment. Processes in a plane optical resonator are analyzed. A continuous light wave is reflecting in serial from two parallel reflectors of a plane optical resonator. The resonator is filled by a liquid dielectric. Forces applied to the reflector are calculated by means of analysis of a change of the total energy stored in the oscillating system at displacement of the reflector. Adiabatic invariant Σ/ω is taken into account where Σ and ω are the energy stored in the oscillating system and its eigen frequency, respectively. Thus, we can judge about a change of Σ by means of an analysis of a change of ω. Well-known methods developed in optics for planes resonators are used for calculation of the change of ω. There is no mention about OIF.

It is known that the eigen frequency ω increases if the distance between reflector decreases. Therefore, the energy stored in the system increases also. Comparing an increase of the eigen frequency ω in the resonator filled by the liquid dielectric and in the resonator located in free space at decreasing the distance between reflectors, we have concluded that ω increases in the first case by n times greater than in the second one. The same is valid for the energy Σ. Then the pressure applied to the reflector is greater by n times in the first case than that in the second one. Thus, a change of MDFs in the first case is greater by n times than that in the second one and, therefore, the MDF in matter increases by n times.

Repeating the same consideration for the optical medium where $\varepsilon > 1$, $\mu > 1$, we obtain that the pressure applied to the reflector is greater by $(\varepsilon\mu)^{1/2}$ times in the first case than that in the second one. Therefore, the MDF in matter increases by $(\varepsilon\mu)^{1/2}$ times.

The same result has been obtained for continuous light wave by means of analysis of the tangential pressure produced by the wave at an incline incident on a plane boundary between free space and an optical medium. Only the law of the conservation of the momentum has been used [18].

A resolution of the contradiction between these two rival experiments is presented in Refs. [19,20]. It is shown that the contradiction can be overcome if additional types of OIF in the regions of the optical medium were leading and trailing edges