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Photon and physical phenomena responsible for its momentum

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ABSTRACT

We derive a magnitude of the momentum of light in matter by means of matching two irrefutable not contradictory thought experiments where no preliminary assumptions about kinds of optically induced forces responsible for a change of the momentum of light in matter are made. The total momentum increases in the matter by n times due to the Coulomb kind of force in a dielectric investigated by Maxwell. There are two different component of the total momentum. These are the mechanical component arising due to a motion of conventional material objects, mass of whose is non-zero and the electromagnetic component produced by a travelling electromagnetic wave, mass of which is equal to zero. The following types of optically induced forces provide a redistribution of the total momentum between these components. These are the kind of the Abraham-like force produced in matter by an electromagnetic wave, intensity of which is changed in time and the Helmholtz-like force arising in a field of an electromagnetic wave due to an inhomogeneity of the electrostriction pressure produced by the light wave. The mechanical component of the momentum of the light is negative and the electromagnetic component is greater than the total momentum.

1. Introduction

In the early 20th century, it has been shown that objects, mass of which is equal to zero can have momentum. These objects are waves, in particular, light waves and photons. The term "photon" is commonly used to refer to optical pulses. Perhaps this is one of the reasons, which did not allow to establish the magnitude of its moment in the matter. Photon viewed as indivisible, while the optical pulse has a structure defined by such parameters as the duration, leading and trailing edges. We will use the term "optical pulse". It has been found that a direction of the momentum of the optical pulse of energy $\mathcal{E}$ that propagates in a free space at the speed of light c coincides with the direction of the pulse and a magnitude of the momentum is given by $p = \mathcal{E}/c$. The same magnitude can be obtained on assumption that the mass of the optical pulse is equal to the known expression $m = \mathcal{E}/c^2$. Since then two types of the momentum are known. This is the Newton mechanical momentum and the electromagnetic momentum of the light propagating in free space.

As far as the momentum of light in matter is concerned, there are no general accepted notion till now. There is no doubt that the energy of the optical pulse that enters the optical medium from free space without reflection is preserved and its speed decreases from c to c/n. On assumption that the kind of the momentum of light in matter is electromagnetic, we obtain

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that $\mathcal{E}/(c/n)$ increases by n times and, therefore, the momentum of light in matter corresponds to the Minkowski form. On the contrary, on assumption that the kind of the momentum of light in matter is mechanical and the expression for the mass $\mathcal{E}/c^2$ is universal, we obtain the momentum is equal to $(\mathcal{E}/c^2)(c/n)$ and, therefore the momentum decreases by n times.

These two contradictory approaches are supported by contradictory unambiguous thought experiments. There is an opinion that the so-called "Einstein box theories", first used by Balazs [1] as a modified Einstein thought experiment, uniquely select the Abraham momentum as a momentum of the field. The importance of this experiment is connected with the fact that neither preliminary notions about optically induced forces (OIF), no notions about their physical nature and phenomena responsible for their arising are used. A behavior of a transparent block of an optical medium is considered when the photon propagating in free space in positive direction enters the block and propagates through it. Parameters of the photon in free space is known and is characterized by the energy $\mathcal{E}$, momentum $\mathcal{E}/c$, and duration τ_P. It is shown that the block should be displaced in the positive direction when the pulse leaves the block. In this case the block is mowing in positive direction when the pulse is propagating in the block. As a result, a part of the pulse momentum is transmitted to the block and, therefore, the momentum of the pulse within the block is smaller than that in free space. As a result, the force that acts on the block when the pulse is entering into the block without reflection is positive.

Most recently, Barnett and Loudon reanalyzed the controversy and argued that both momenta are "correct" because both can be measured, but in different situations [2]. Following the analysis of Balazs and repeating arguments of the thought experiment, they concluded that "it is difficult to see how any component of our derivation could seriously be open to question". "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".

However, the arguments that open to question has been pointed out recently [3]. The mass of the optical pulse in free space is questionable because any mass cannot move at optical speed c. To overcome these doubts, we will consider a modification of the Balazs thought experiment where the notion about the mass of the optical pulse is not used. We show that the conclusion derived from the Balazs thought experiment is correct.

On the other hand, in accordance with another thought experiments [4,5] where no assumption about the nature of physical processes is made also, the momentum density flux (the momentum of the electromagnetic wave that passes though unit area per unit time) of a plane continuous electromagnetic wave in matter increases by n times. This conclusion is confirmed by experiments [6,7] as well as calculations based on the Maxwell equations [8]. In this case, the force that acts on the optical medium when the wave is entering into the medium without reflection is negative.

It is shown that the contradictory between these results can be resolved [9] if the following difference between conditions of these thought experiments is taken into account. An optical pulse is considered in the first thought experiment whereas a continuous optical wave is considered in the second one. Unlike the continuous optical wave, there are leading and trailing edges in the optical pulse. If optically induced forces (OIF) that arises in the regions where the leading and trailing edges of the optical pulse are propagating are taken into account, we obtain that the pressure on the block in the Balazs thought experiment is positive due to these forces but the total momentum of the optical pulse in matter increases by n times. At the same time, OIFs produce splitting of the total momentum between electromagnetic and mechanical components.

At present it is recognized that the momentum of light in matter consists of the electromagnetic and mechanical components [10–16]. An example of the electromagnetic component is the momentum of optical wave in free space where the mechanical component is absent. Since optically induced forces (OIF) arise at propagation of light in matter, these force produce the mechanical momentum at expensive of the electromagnetic one. A reciprocal conversion is also possible. However there is no generally accepted conception about both a magnitude of the mechanical momentum and its properties.

Since our approach is based on assertion that no preliminary assumption about kinds of OIF, their physical nature of arising, reasons of their arising, and only well-known laws of mechanics should be used, we present initially the modified version of the Balazs thought experiment where a notion about mass of the photon is not used. Next, we describe the second thought experiment that contradicts the first one. Further an elimination of contradictions and analysis of properties of the photon are presented.

2. Modified version of the Balazs thought experiment

Recently, description of the Balazs thought experiment is presented in many publications. In the same time, the following doubts in its correctness is put forward in [3]: "We find that an optical pulse and a single photon in the medium-box thought experiment both have the pulling effect". Besides the notion of "mass of an optical pulse" is questionable because this mass moves at light speed in free space. We will show that the results of the Balazs thought experiment are correct and the same results can be obtained from a modification of this experiment where the notion about the "mass of a optical pulse" is not used.

Let four reflectors 1, 2, 3, 4 be mounted on a cart, as is shown in Fig. 1. A photon emanated by a laser 6, reflects in serial from the reflectors and is absorbed by absorber 7.

Let us first consider case 1 where block 5 of a transparent optical medium that is considered in the classical Balazs thought experiment is absent. The photon in a form of a wave train radiated by source of photons 6 reflects in serial from reflectors 1, 2, 3, 4, and absorbs absorber 7. Let us assume for the sake of simplicity that $\tau_E \ll \tau_P \ll T$ where τ_E, τ_P, T are durations of edges of the wave train, duration of the wave train and the time of propagation of the wave train inside the block, respectively. In this case the time of transient processes connected with entering the wave train into the transparent block 5 can be neglected.