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Propagation of a light pulse inside matter in a context of the Abraham–Minkowski dilemma

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ABSTRACT

It is shown that a light pulse propagating in an optical medium exerts the optical pressure on the medium in the regions where leading and trailing edges are propagating. This effect is derived from analysis of unambiguous thought experiments which results contradict one other. It is shown that a magnitude of the pressure is equal to $(n - 1/n)W_0$, where n and W_0 is the refractive index of the medium and the momentum flux density of the same pulse in free space, respectively. The Abraham form of the momentum of light is redundant if the optical pressure is taken into account. In this case the dilemma disappears because one of the rival alternatives disappears.

1. Introduction

There have been extensive debates about the correct expression of the momentum density of electromagnetic waves in linear media for more than 100 years since the original papers of Minkowski [1] and Abraham [2], and even so there is still some confusion or at least disagreement among authors. In 2010 various arguments in favor of Abraham and Minkowski theories were presented in review [3] devoted to the 100 year anniversary of this problem. This is not the place to review the large literature devoted to this problem. The interested reader can study the recent review by Pfeifer et al. [4].

There is an opinion that the Balazs thought experiment [5] uniquely select the Abraham momentum as a momentum of the field in matter. A behavior of a transparent block of an optical medium through which a light pulse is propagating is considered. The main argument in favor of the Abraham momentum is that the behavior of the block is explained correctly on assumption that the Abraham momentum takes place within the block. Minkowski momentum would predict a motion of the block in the opposite direction to the incident pulse. Most recently, Barnett and Loudon reanalyzed the controversy and argued that both momenta are "correct" because both can be measured, but in different situations [3]. 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".

Other thought experiments can be used to clear up a situation about kinds of optically induced forces (OIF) and their interaction. One of them is considered in [6] on the basis of the energetic approach where no previous assumption about a number and kinds of OIF is done. It is shown that the momentum flux density of a continuous light wave in an optical medium increases by n times as compared with that of the same wave in vacuum. This corresponds to the Minkowski approach.

An assumption is advanced that the difference between magnitudes of the momentum is connected with a difference between properties of a light pulse with leading and trailing edges and continuous light wave. For example, the wavelength of a light pulse is decreasing gradually because the electrostriction pressure is produced by a light pulse and a part of its energy is transmitted to the medium in a form of elastic energy [7]. Besides, it is shown that additional density forces applied in the regions where leading and trailing edges of the pulse are propagating should arise. This

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conclusion is derived from an attempt to coordinate rival results of thought experiments which are based only on laws of conservation of the momentum and energy. The additional forces are equal to the known Abraham density force the existence of which is debated for a long time.

2. Momentums of light in an optical medium based on thought experiments

Pros and cons of the Minkowski and Abraham forms of the momentum of light are analyzed in [3]. A single decisive argument in favor of the Abraham form is the Balazs thought experiment [5]. It is believed that the most direct way to calculate the momentum of a photon in a medium is to use the Newtonian idea that the center of mass (or more precisely the center of mass-energy) of an isolated system undergoes uniform motion. For this purpose a situation presented in Fig. 1 is considered. Here light pulse 1 propagates in vacuum at speed of light c and its momentum is equal to p_0. When the light pulse enters the transparent medium in a form of a block 2, its speed slows to c/n and, as a result, it takes the time $T = nL/c$ to travel through the block, where L and n are the thickness and refractive index of the block, respectively. It is supposed that the block begins to move to the right when the pulse enters the block and stops its motion when the pulse exits the block. Actually, a sum of the momentums of the light pulse and block is preserved and, as a result, the momentum of the light pulse within the block decreases. When the light pulse exits the block, the momentum of the light pulse is recovered and the momentum of the block becomes equal to zero. As a result, the block stops. It is shown that the light pulse should transmit to the block momentum $p_0(1-1/n)$ [3].

Denoting the momentum of light inside the block by x, we have, from the law of conservation of the momentum, $x + p_0(1-1/n) = p_0$ or $x = p_0/n$. As was noted, only the conservation of momentum and the uniform motion of the center mass-energy in deriving this result is used and it is difficult to see how any component of this derivation could seriously be open to question. If the momentum flux density of the same light pulse propagating in free space is equal to W_0, the pressure (force per unit area) produced by the light pulse on the block is given by

$$P_A = W_0\left(1 - \frac{1}{n}\right). \tag{1}$$

The same result we obtain on assumption that the momentum flux density of the light pulse within the block is equal to W_0/n

On the other hand, there is a thought experiment based on the energetic approach where no assumption is done about kinds of optically induced force applied to the block [6]. In accordance with the thought experiment the pressure produced on the block by a continuous light wave is given by

$$P_M = -W_0(n-1) \tag{2}$$

The same result we have on assumption that the momentum flux density of the wave within the block is equal to $W_0 n$

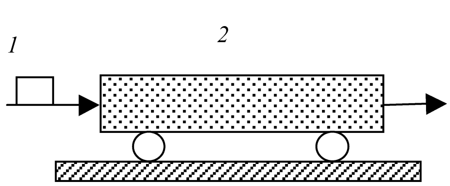

Fig. 1. Propagation of light pulse 1 through block 2 of optical medium with the reflective index n.

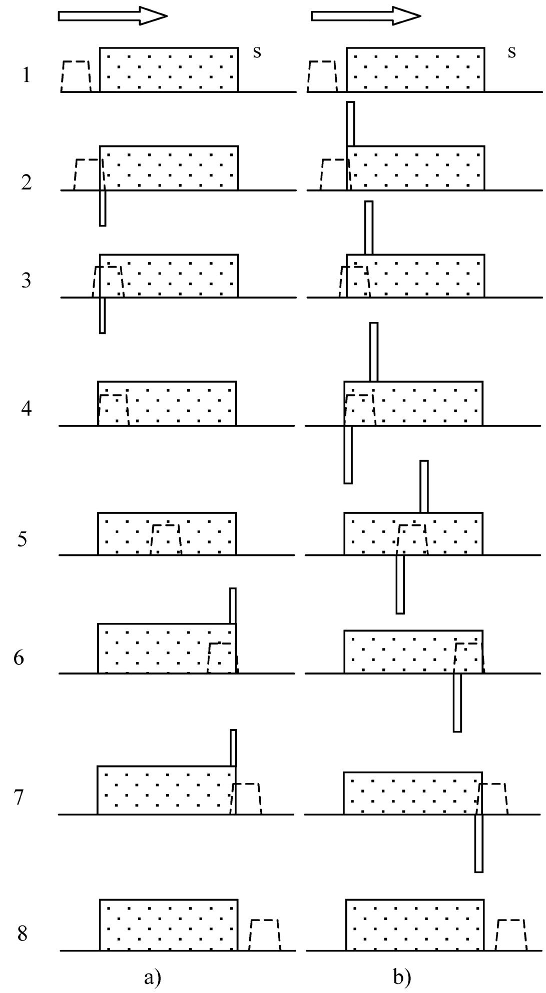

Fig. 2. Serial stages of propagation of a light pulse (dashed trapeze) through optical block (dotted rectangular). (a) Pressures P_M arising on the front and faces of the block; (b) pressures P_{add} arising at leading and trailing edges of the light pulse.

3. Elimination of contradictions between thought experiments

Thus, the momentum of the light pulse in the block corresponds to the Abraham form and is smaller by n times than that in free space. The momentum of a continuous light wave in the block corresponds to the Minkowski form and is greater by n times than that in free space. A reason of a discrepancy is required to disclose. The reason should be connected with properties of a light pulse that are different from that of a continuous light wave. Unlike a continuous light wave, there are leading and trailing edges in a light pulse. Let us assume that additional pressure should arise at these edges at a propagation of a light pulse in a homogeneous optical medium. Two pressures should be applied to the regions of the block where the leading and trailing edges are located at given time instants. Besides, these pressures should provide zero net force applied to the optical medium if the pulse is propagating in a homogeneous optical medium. A net pressure is different from zero when the light pulse enters or exits the block. In this case only one pressure is applied to the block. The pressure is applied in a time interval equaled to the duration of the light pulse. Thus, these two additional pressures P_{add} on the edges of the light pulse can produce the pressure that overcome the negative pressure given by Eq. (2) and provide a positive displacement of the block. An action of the additional pressures P_{add} is shown in Fig. 2(b) along with action of the main pressures P_M given by Eq. (2) and is shown in Fig. 2(a).