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# Optical pressure applied to a semi-infinitive dielectric

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ABSTRACT

The generally accepted notion about a magnitude of the optical pressure produced by a light wave on the boundary between free space and optical medium is absent at present. Moreover, it does not even know the direction of this pressure. We show that three kinds of pressures should be taken into account. This is the pressure arising due to a change of the momentum of the light wave on the boundary. This is the electrostriction pressure that does not change the momentum of the light wave. At last, these are the pressures arising in the regions of the optical medium where leading and trailing edges of a light pulse are propagating. The net pressure on the boundary is positive unlike zero pressure in accordance with the approach based on the Lorentz density force. Our consideration is based on grounds derived from unambiguous but contradictory results of two thought experiments. No advance assumption about types and a physical origin of optically induced forces responsible for the optical pressure is made. We have shown that the pressure produced by the continuous light wave at a steady state is negative. The total pressure produced by the light pulse on the boundary and on the optical medium is positive.



## 1. Introduction

It is known since time of Maxwell that the light produces the pressure on the reflector at reflection from it and, therefore, has the momentum. The pressure exerted by the light wave on the mirror in free space is well-known and is equal to $2W_0$ where $W_0$ is the energy density of the light wave. In the same time a magnitude of the pressure in the simplest case where the reflector is replaced by a plane boundary between free space and dielectric is debated to date. It is explained by the fact that a general accepted notion about a magnitude of the momentum of light in the dielectric is absent at present. Since a magnitude of the momentum penetrating into the dielectric is unknown, the pressure on the boundary cannot be calculated by means of an analysis of a change of the momentums at reflection from the boundary.

There are age-old debates about a magnitude of the momentum of light in matter. In accordance with Minkowski, the momentum in matter increases by $n$ times as compared with the momentum of the same light in free space where $n$ is the refractive index of the matter. On the contrary, in accordance with Abraham, the momentum of light in matter decreases by $n$ times. In 2010 various arguments in favor of Abraham and Minkowski theories were presented in the review [1] devoted to the 100-year anniversary of this problem.

If the Abraham form of the momentum is used, the pressure on the boundary is positive. On the contrary, if the Minkowski form is used, the pressure on the boundary is negative. In 1973 Gordon proposed an alternative approach based on a belief that

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the Lorentz density force is responsible for the light pressure [2]. In this case the pressure on the boundary can be calculated directly and the question about the momentum of light in matter can be bypasses. Since then, dozens of publications have published where optical pressures have been calculated for various configurations of an optical medium. Several reviews have recently appeared [3–6]. In accordance with the Lorentz force approach, the pressure produced by a continuous light wave on the boundary is equal to zero.

Last time another approach to calculation of optically induced forces (OIF) is used [7] that was proposed by Einstein and Laub in 1908. In this case additional bounded magnetic charges and currents are taken into account. Again, the pressure is equal to zero. This testifies that the search of the correct expression for calculation of the pressure is not terminated.

Thomson was the first who calculated the optical pressure on the plane boundary in 1904 [8]. His calculation predicts an outward force normal to the boundary. This result agrees with Poynting calculations in 1905 [9,10]. In more recent work, including the Loudon work [11], the corresponding force for an incident plane wave is expected to point inwards. As is pointed out in [11], “it is clearly unsatisfactory that even the direction of the force is uncertain for the simplest form of light beam with a plane wave front”. In accordance with the Lorentz force approach, the momentum of light in matter is the arithmetic average between the Minkowski and Abraham momentums. In our opinion, the most convincing is work [12] where it is shown that the pressure on the dielectric surface produced by the continuous wave in the steady state is negative and corresponds to the results of Poynting. Thus, the circle is closed.

## 2. Grounds for calculation of optically induced forces

We believe that the most correct way is to abandon the search for the right expression for calculation of OIF and to take unambiguous known results based on the conservation laws as a ground. There are two thought experiments based on such laws.

First, Balazs showed theoretically in 1953 that an initially motionless transparent block through which a light pulse is propagating without reflection should be displaced in a direction of a propagation of the light pulse if the light pulse enters the block from free space [13]. As a result, the block is moving along the light pulse motion 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 is smaller than that of the same pulse propagating in free space. Thus, the momentum of light inside the block corresponds to the Abraham. Only the law of conservation of the position of the center of mass in a closed system consisting of the block and the light pulse is used. As is pointed in review [1], “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 [1,3,4,6,13,14].

Second, we showed in 2012 that a continuous light wave circulating in a plane optical resonator filled by an optical medium produces the pressure on the reflector that is greater by $n$ times than the pressure produced by the same light wave in the resonator located in free space. As a result, the momentum of the light in the first case is greater by $n$ times than that in the second one [15]. No previous assumption about reasons responsible for arising pressure on the reflector is made. An availability of adiabatic invariant $E/\omega$ is used where $E$ is the energy stored in the resonator, $\omega$ is its eigen frequency. A change of $\omega$ at a change of the distance between reflectors can be calculated without any mentions about optically induced forces. If the distance between the reflectors decreases, the frequency $\omega$ increases. Therefore the energy $E$ stored in the resonator increases also. This means that the force applied to the reflector is directed opposite its motion. Therefore, the force tends to increase the distance between the reflectors. Besides, we have shown that a change of the stored electromagnetic energy in the resonator with matter at displacement of the reflector is greater by $n$ times in the resonator filled by matter than a change of the same energy in the resonator located in free space. This means that the pressure on the first resonator is greater by $n$ times than the pressure on the second one. In this case the momentum density flux in the first resonator is greater by $n$ times than that in the second one.

We have shown that the contradiction between these two thought experiments can be matched on assumption that the momentum of light in matter corresponds to the Minkowski form. In the same time there are the Abraham density force arising in the regions of the optical medium where leading and trailing edges of the light pulse are propagating.

In the present paper, we take into account the electrostriction pressure that arises in the regions where the light pulse is propagating. This pressure also has an impact on the pressure at the boundary between free space and matter at the time when the light pulse is entering the matter. However, this pressure is produced by inner forces and, therefore, does not change the momentum of light.

## 3. Pressures produced by a light on a plane boundary between an optical medium and free-space

Let us first consider the simplest case when a plane continuous light wave enters normally from free space a homogeneous optical medium with the reflective index $n$ through the plane boundary between free space and the optical medium. Let the momentum density flux (MDF) (the momentum of light which intersects unit area per unit time) in free space be equal to $W_0$, where $W_0$ is the energy density of the light wave in free space. In accordance with the presented conception, MDF of the light wave penetrating in the medium increases by $n$ times. Let us calculate the pressure produced by the light wave on the boundary of the optical medium by means of analysis of a change of the MDF.