Photon mass drag and the momentum of light in a medium

Conventional theories of electromagnetic waves in a medium assume that the energy propagating with the light pulse in the medium is entirely carried by the field. Thus, the possibility that the optical force field of the light pulse would drive forward an atomic mass density wave (MDW) and the related kinetic and elastic energies is neglected. In this work, we present foundations of a covariant theory of light propagation in a medium by considering a light wave simultaneously with the dynamics of the medium atoms driven by optoelastic forces between the induced dipoles and the electromagnetic field. We show that a light pulse having a total electromagnetic energy $\hbar \omega$ over bar propagating in a nondispersive medium transfers a mass equal to $\Delta m = (n^2 - 1) \hbar \omega / c^2$, where $n$ is the refractive index. MDW, which carries this mass, consists of atoms, which are more densely spaced inside the light pulse as a result of the field-dipole interaction. We also prove that the transfer of mass with the light pulse, the photon mass drag effect, gives an essential contribution to the total momentum of the light pulse, which becomes equal to the Minkowski momentum $p(M) = n \hbar \omega / c$. The field's share of the momentum is the Abraham momentum $p(A) = \hbar \omega / (nc)$, while the difference $p(M) - p(A)$ is carried by MDW. Due to the coupling of the field and matter, only the total momentum of the light pulse and the transferred mass $\Delta m$ can be directly measured. Thus, our theory gives an unambiguous physical meaning to the Abraham and Minkowski momenta. We also show that to solve the centenary Abraham-Minkowski controversy of the momentum of light in a nondispersive medium in a way that is consistent with Newton's first law, one must account for the mass transfer effect. We derive the photon mass drag effect using two independent but complementary covariant models. In the mass-polariton (MP) quasiparticle approach, we consider the light pulse as a coupled state between the photon and matter, isolated from the rest of the medium. The momentum and the transferred mass of MP follow unambiguously from the Lorentz invariance and the fundamental conservation laws of nature. To enable the calculation of the mass and momentum distribution of a light pulse, we have also generalized the electrodynamics of continuous media to account for the space- and time-dependent optoelastic dynamics of the medium driven by the field-dipole forces. In this optoelastic continuum dynamics (OCD) approach, we obtain with an appropriate space-time discretization a numerically accurate solution of the Newtonian continuum dynamics of the medium when the light pulse is propagating in it. The OCD simulations of a Gaussian light pulse propagating in a diamond crystal give the same momentum $p(M)$ and the transferred mass $\Delta m$ for the light pulse as the MP quasiparticle approach. Our simulations also show that, after photon transmission, some nonequilibrium of the mass distribution is left in the medium. Since the elastic forces are included in our simulations on equal footing with the optical forces, our simulations also depict how the mass and thermal equilibria are reestablished by elastic waves. In the relaxation process, a small amount of photon energy is dissipated into lattice heat. We finally discuss a possibility of an optical waveguide setup for experimental measurement of the transferred mass of the light pulse. Our main result that a light pulse is inevitably associated with an experimentally measurable mass is a fundamental change in our understanding of light propagation in a medium.

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