What does the Ashkin-Dziedzic experiment reveal about the electromagnetic force density in matter?

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There are several different expressions for the electromagnetic force density inside a material. In addition to the canonical Lorentz force density, there exist at least four other expressions based on the Abraham, Minkowski, Einstein-Laub, and Chu formulations of electrodynamics. Experiments to distinguish the various expressions are sparse because differences are apparent only under exotic conditions such as inside deformable media or media moving at relativistic speeds. In this work, we carefully examine the seminal 1973 experiment by Ashkin and Dziedzic to look for clues to isolate a single true force density expression. The experiment consisted of high-powered laser pulses directed onto an air-water interface, which caused the interface to bulge upwards (opposing gravity) regardless of the illumination direction. The results have been interpreted using both the Minkowski and Abraham formulations of electrodynamics. What remains is to analyze the results using the other formulations.

We re-visit the Ashkin and Dziedzic experiment using force density expressions derived from five variants of electrodynamic theory (Abraham, Minkowski, Lorentz, Einstein-Laub, and Chu). The experiment is modeled using a coupled electromagnetic–hydrodynamic simulator. Electromagnetic force densities are calculated in space and time by solving Maxwell's equations using the finite-difference-time-domain (FDTD) technique. The force density is used as a driving term in the Navier Stokes equations, which are solved using a front tracking marker and cell scheme (MAC). The simulations reveal striking differences in the force density distributions calculated by the various formulations, which in turn yield different predicted deformations of the air-water interface. We show that the force densities of Abraham, Minkowski, and Einstein-Laub all predict the upward deformation of the interface consistent with the observations by Ashkin and Dziedzic. The Lorentz and Chu force densities predict downward deformation of the interface. This work is important because it highlights a well-studied scenario in which different electrodynamic formulations can potentially be distinguished, an important step towards better understanding how fields and matter exchange momentum.