Electromagnetic forces on the dielectric layers of the planar optical Bragg acceleration structure

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Optical Bragg acceleration structures are waveguides with a vacuum core and dielectric layers as a cladding, designed to guide laser light at the speed-of-light TM mode and accelerate charged particles. In this study, we analyze the electromagnetic forces exerted on the dielectric layers of a planar structure by both the guided laser light and the wake-field of moving charges. The distribution of the volume force densities, as well as the surface force densities, in the interfaces between the layers as a result of the laser propagation is given, and analytic scaling laws for the maximal values are obtained. Separation of the wake-field into the structure’s eigenmodes is essential in order to determine the different contributions of the wake-field to the total impulse that acts on the structure. It is shown that the impact of the wake-field on the structure results almost entirely from the fundamental TM mode. While the total force on the dielectric layers may be significantly stronger than the gravitational force, we show that for typical structures, the pressures that develop are orders of magnitude below the damage threshold.

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I. INTRODUCTION

Optical acceleration of charged particles, where particles are accelerated by laser light rather than by microwave radiation, is a subject of increasing interest. Due to the high loss of metals at optical wavelengths, optical acceleration structures are likely to be made of dielectric materials, which are also less susceptible to breakdown. One type of structure that may be used is an open optical structure, as in the LEAP [1] crossed laser beam experiment, where the interaction between the crossed laser beams and the particles is limited by slits to satisfy the Lawson-Woodward theorem [2,3]. Another type of structure is the dielectric waveguide, an example of which is the two-dimensional photonic band-gap structure with a vacuum tunnel bored in its center [4]. In such a configuration, a laser pulse propagates at the speed-of-light mode (phase velocity $v_{ph}=c$) while accelerating a bunch of charged particles in the vacuum tunnel. Alternatively, one-dimensional photonic band-gap structures, namely, Bragg reflection waveguides [5–7] specifically designed for the speed-of-light mode, were suggested as acceleration structures [8]. A possible coupling scheme to this acceleration structure was recently proposed [9].

Optical Bragg acceleration structures, either planar or cylindrical, having typical transverse dimensions of a few microns, exhibit high performance as acceleration structures and therefore seem to be promising candidates for future optical accelerators. In the present study, we focus on the planar optical Bragg acceleration structure illustrated in Fig. 1. The laser light is guided between two mirrors separated by a distance $2D_{int}$, so that the wave propagates along the $z$ axis, and no variations are assumed along the $y$ axis ($\partial / \partial y = 0$). The mirrors consist of dielectric layers with alternating permittivity, having transverse quarter-wave width with the exception of the innermost layer. This first layer is a matching layer whose width is determined so that the structure supports the speed-of-light TM mode required for the acceleration process [8]. It was shown that, generally, Bragg waveguides may be designed for a given symmetric field distribution [10].

It is evident that if accelerators are to work at optical wavelengths, then the acceleration structures will be about three orders of magnitude smaller in the narrow transverse dimension of the cross section than current structures driven by microwave sources, as the structures will be made of micron-scale dielectrics instead of centimeter-size metallic walls. At the same time, the electromagnetic fields due to the traveling wave will be significantly stronger. Moreover, since the overall amount of charge is expected to remain similar to that of current accelerators, the electromagnetic wake-field resulting from the motion of these charges will be stronger as well. These intense electromagnetic fields exert forces on the dielectric structure, commonly referred to as “radiation pressure.” Electromagnetic forces were previously investigated in photonic crystals [11], and the total pressure on the mirrors of Bragg reflection waveguides was demonstrated to be of great appeal subject to proper design [12,13]. It is the purpose of this study to evaluate these forces as they may impose constraints on future optical acceleration structures. Specifically, strong enough forces may deform the dielectric layers, change their width, and consequently detune the waveguide from the transverse resonance of the synchronized speed-of-light mode. Moreover, high pressures may cause crack formation and damage to the structure.

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FIG. 1. Configuration of the planar optical Bragg accelerator.