On-chip stackable dielectric laser accelerator

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Abstract

In this paper, we propose a novel stacked laser dielectric acceleration structure. This structure is based on the inverse Cherenkov effect and represented by a parametric design formulation. Compared to existing dielectric laser accelerators relying on the inverse Smith–Purcell effect, the proposed structure provides an extended-duration synchronous acceleration field without requiring the pulse front tilting technique. This advantage significantly reduces the required pulse duration. In addition, the easy-to-integrate layered structure facilitates cascade acceleration, and simulations have shown that low-energy electron beams can be cascaded through high gradients over extended distances. These practical advantages demonstrate the potential of this new structure for future chip accelerators.

Full Text

Preamble

On-chip stackable dielectric laser accelerator

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Abstract: In this paper, we propose a novel stacked laser dielectric acceleration structure based on the inverse Cherenkov effect, represented by a parametric design formulation. Compared to existing dielectric laser accelerators relying on the inverse Smith–Purcell effect, the proposed structure provides an extended-duration synchronous acceleration field without requiring the pulse front tilting technique, which significantly reduces the required pulse duration. In addition, the easy-to-integrate layered structure facilitates cascade acceleration, and simulations have shown that low-energy electron beams can be cascaded through high gradients over extended distances. These practical advantages demonstrate the potential of this new structure for future chip accelerators.

Introduction

The industrial applications of modern particle accelerators have extended beyond scientific research [1,2]. However, radio-frequency particle accelerators are typically bulky and heavy, with practical limitations such as the threshold for metallic structure breakdown and restrictions on the power and wavelength of microwave sources [3-6]. In recent decades, researchers have attempted to construct miniature and even benchtop particle accelerators [7-15]. Acceleration mechanisms based on laser-dielectric interactions have recently attracted increased attention due to their promising potential for developing on-chip microscopic accelerators. The inverse Smith–Purcell-effect dielectric laser accelerator (ISP-DLA) [8-15] and the inverse Cherenkov-effect dielectric laser accelerator (ICS-DLA) [16-19] are two laser-dielectric acceleration concepts that have been investigated since the 1960s, shortly after the invention of the laser.

Most dielectric laser accelerator (DLA) schemes are based on the inverse Smith–Purcell effect. In their typical configuration, a periodic dielectric structure is adopted to spatially modulate the incident laser field and synchronize the incident free electrons through the spatial harmonics of the induced waves in the electron beam channel. These previous developments face several challenges [8-15], including: (1) microscale fabrication of accelerator structures, which requires advanced micro- and nano-processing techniques; (2) selection of dielectric materials, some of which have high laser damage thresholds but cannot be fabricated as micro- and nanostructures; (3) reduced laser damage thresholds of dielectric materials after nano-processing; and (4) the pulse front tilting technique, which is required to extend the interaction time between the laser and dielectric to achieve extended acceleration, improve laser energy utilization efficiency, and prevent unnecessary high energy loads on the structure [20]. These challenges limit the acceleration gradient, acceleration distance, energy utilization efficiency, and flexibility of laser dielectric acceleration structures while increasing experimental difficulty.

In this study, we developed a stacked acceleration structure based on the inverse Cherenkov effect to achieve cascade acceleration of nonrelativistic low-energy electrons through a multilayer dielectric. First, the proposed structure is identical to existing inverse Cherenkov-effect accelerators and effectively solves the challenges encountered in inverse Smith–Purcell effect acceleration structures, including: (1) elimination of the requirement for laser frontier technology, and (2) not requiring multiple lasers to achieve cascade acceleration, thereby eliminating the difficulty of coupling multiple lasers. Second, this structure enables higher acceleration gradients and energy gains and has no theoretical upper limit on acceleration energy. In addition, because this stackable structure can be assembled from modular acceleration units, it provides additional configuration flexibility to satisfy specific requirements for different applications. This flexibility makes the current structure a prototype for future chip accelerators in universal application scenarios.

2. Theory and Structural Design

The proposed stacked acceleration structure is depicted in Fig. 1 [Figure 1: see original paper]. A case study of two dielectric layers is presented for demonstration without loss of generality. The line-shaped collimated incident laser was perpendicular to Surface II and the beveled surface of a multilayer dielectric prism with a right-angled triangular cross-section. An evanescent wave is generated at Surface I with a velocity of $v_p = \frac{c}{n \cdot \sin\alpha}$, traveling forward along the surface in the x-direction, where α is the angle between the hypotenuse and the bottom edge, c is the velocity of light in vacuum, and n is the refractive index of the prism. This wave has a longitudinal electric field component E_x, transverse electric field component E_y, and out-of-plane magnetic field component H_z.

Fig. 1. (a) Schematic of stacked acceleration structure. The red arrow line represents the incident laser. The refractive indices of the two dielectric layers are n_1 and n_2. (b) Partial enlargement of Fig. 1(a) showing refraction process occurring at interface. The angles between the bottom edge of the right-angled triangle and the two traversal directions perpendicular to two laser beams (equivalently, the electric field directions) are α_1 and α_2, respectively.

The electrons move in the x-direction in the vacuum below Surface I. Electrons in phase with an accelerating electric field (equivalently, negative phase $\phi < 0$) can then be accelerated by applying the inverse Cherenkov effect. However, the electron velocity v_e must be equal to that of the evanescent wave, that is, $v_e = v_p$, to achieve continuous acceleration.

On Surface I, the first criterion [17-19] for achieving continuous acceleration through the inverse Cherenkov effect is:

$$\sin\alpha = \frac{v_e}{c} = \frac{1}{n\beta} \tag{1}$$

In Equation (1), α is the angle between the hypotenuse and the bottom edge, c and v_e are the velocities of light in vacuum and electrons, respectively, and $\beta = v_e/c$ is the relativistic velocity of the electron. As the electron accelerates and β increases, the electrons move faster than the wave, lose synchronization, and eventually their acceleration ends.

Currently, the solution to this problem is achieved by varying angle α [18-19]. In this study, the electron velocity was matched to the wave velocity by selecting different dielectrics to vary the refractive index. First, the refracted light ray A is analyzed, as shown in Fig. 1. Each time the laser passes through the interface between two adjacent layers with different dielectrics, the light is refracted due to a change in the refractive index. Some of the laser light is reflected, which reduces the laser energy; this reduction is undesirable for energy utilization efficiency and accelerating electric field. Thus, it is necessary to ensure that the light passes through the interface only once so that the laser experiences only one additional reflection and refraction.

A limit was proposed for the dielectric length of each layer to achieve this. Taking the second layer in Fig. 1 as an example, the second-layer thickness d_2 is limited by Rays B and C. The geometric relationship is expressed by $d_2 = L_2 \times (\tan\alpha_2 - \tan\alpha_1)$. Similarly, the recurrence equation for the thickness d_i of each subsequent layer can be derived: $d_i = L_i(\cos\alpha_{i-1} - \cos\alpha_i)$, for $i \geq 2$. By combining these two equations, the relationship between the thickness d_i of each layer and the thickness d_1 of the first layer is expressed by:

$$d_i = d_1 \times \frac{(\tan\alpha_i - \tan\alpha_{i-1})}{(\cos\alpha_{i-1} - \cos\alpha_i)} \prod_{k=1}^{i-1} \frac{\cos\alpha_k}{\cos\alpha_{k-1}}, \quad i \geq 2$$

Second, even when the laser passes through the interface only once, as shown in Fig. 1, the angle of the laser to the bottom surface (Surface I) changes from α_{i-1} to α_i after refraction at the dielectric interface. Equation (1) must still be satisfied to maintain acceleration: $\sin\alpha_i = \frac{1}{n_i\beta_i}$. When refraction occurs at the interface, the law of refraction is expressed by $n_{i-1}\sin\alpha_{i-1} = n_i\sin\alpha_i$. In addition, the trigonometric relationship is $1 = (\sin\alpha_i)^2 + (\cos\alpha_i)^2 = [1/(n_i\beta_i)]^2 + (\sin\alpha_i)^2 = [1/(n_i\beta_i)]^2 + (n_{i-1}\sin\alpha_{i-1}/n_i)^2$.

Solving these equations yields $n_i = \sqrt{(n_{i-1}\sin\alpha_{i-1})^2 + (1/\beta_i)^2}$, where $\beta_i = v_i/c$. A similar derivation holds at each interface, resulting in the recurrence relationship:

$$n_i = \sqrt{(n_{i-1}\sin\alpha_{i-1})^2 + \left(\frac{1}{\beta_i}\right)^2}, \quad i \geq 2$$

In addition, because the incidence angle of the laser is the same for each layer of the dielectric, $\alpha_1 = \alpha_2 = \cdots = \alpha_i = \pi/2 - \theta$, the recurrence relationship can be simplified to:

$$n_i = \sqrt{(n_{i-1}\cos\theta)^2 + \left(\frac{1}{\beta_i}\right)^2}, \quad i \geq 2$$

In summary, the refractive index and thickness of each layer of the dielectric, starting from the second layer, can be derived as a function of the parameters of the first layer:

$$\begin{cases} n_i = \sqrt{(n_{i-1}\cos\theta)^2 + \left(\frac{1}{\beta_i}\right)^2}, & i \geq 2 \\ d_i = d_1 \times \frac{(\tan\alpha_i - \tan\alpha_{i-1})}{(\cos\alpha_{i-1} - \cos\alpha_i)} \prod_{k=1}^{i-1} \frac{\cos\alpha_k}{\cos\alpha_{k-1}}, & i \geq 2 \end{cases} \tag{2}$$

In the first row of Equation (2), n_i is the refractive index of the ith layer, and the label follows the convention in Figs. 1 and 2. β_i is the theoretical design velocity of electrons in the vacuum acceleration region on Surface I below the ith layer of the dielectric, which is also the velocity of light in the x-direction when it is in this dielectric. For this theoretical electron velocity, as the electron beam stream advances longitudinally in the acceleration channel, the electron energy and velocity increase. Electron velocity β_i gradually increases when the electron moves below the surface of each dielectric layer, whereas the velocity v_p of the corresponding laser pulse remains unchanged. Therefore, the phase difference gradually accumulates as the electrons move with the laser during the acceleration phase:

$$\Phi = \left(1 - \frac{v_p}{v_e}\right)\sin\alpha$$

If the electron beam is injected at the maximum amplitude of the laser, it becomes necessary to ensure that the phase difference $|\Phi| \leq \pi/2$ when the electron beam leaves; otherwise, it enters the deceleration phase. This corresponds to two cases: (1) The electron velocity v_e is extremely high, resulting in phase difference $\Phi \leq -\pi/2$, and the electron beam reaches the front deceleration phase; or (2) The electron velocity v_e is extremely low, resulting in phase difference $\Phi \geq \pi/2$, and the electron beam will enter the rear deceleration phase.

A suitable electron beam velocity, as expressed by Equation (3), can be selected to extend the acceleration distance and duration. This is achieved such that (1) the electron beam velocity is lower than the speed of light in the dielectric at the entrance of each dielectric layer, and (2) the electron beam velocity is higher than the speed of light in the dielectric at the exit of each dielectric layer:

$$\begin{cases} v_e < v_p, & x = x_{i,\text{entry}} \\ v_e > v_p, & x = x_{i,\text{exit}} \end{cases} \tag{3}$$

In Equation (3), x is the longitudinal position of the electron, $x_{i,\text{entry}}$ is the entry into the nth layer of the dielectric, and $\sum_{k=1}^{i-1} d_k = 0$ when $i = 1$. Thus, the relative longitudinal displacement of the electron beam stream in the phase is first backward (equivalently, the negative x-direction) and then forward (equivalently, the positive x-direction), extending the duration in the accelerated phase [9,15].

In the second row of Equation (2), d_i is the thickness of the layers, known as d_1 and d_2 in Fig. 1. From recursive formula (2), as long as the prism base angle α, refractive index n_1, and thickness d_1 of the first layer of the dielectric are specified, the remaining refractive index n_i and thickness d_i can be obtained recursively. Moreover, Equation (1) indicates that when the incident electron energy is determined, only one degree of freedom remains between α and n_1. Generally, researchers tend to select quartz and other common materials within the range of refractive indices and make the base angle α as small as possible. A positive correlation exists between the acceleration electric field or acceleration gradient and $\cos\alpha$; hence, a smaller base angle α indicates a higher acceleration gradient [17-19]. In addition, continuous or arbitrary regulation of the dielectric refractive index has led to significant progress in research on optical materials; therefore, a dielectric satisfying Equation (2) can be fabricated [21-23].

Fig. 2 [Figure 2: see original paper]. Schematic of structure for 50 keV electron acceleration. The light blue, purple, and red ellipses represent the injected low-energy (50 keV) electron beam stream, accelerating electron beam stream (schematic), and output high-energy electron beam stream, respectively. The insertions "dec" and "acc" indicate that half of the phases in a laser cycle accelerate the electrons, and the other half decelerate them.

Based on the theoretical analysis above, a two-dimensional numerical simulation study was conducted using the finite element method and the particle-in-cell algorithm. The simulated structure is shown in Fig. 2. The base angle α of the prism was set to 30°, and the refractive index and thickness of each layer were calculated using Equations (2) and (3), respectively. A symmetric double prism was used, in which the transverse forces on both sides of the channel centerline are of equal magnitude but in opposite directions. This configuration prevents beam deflections. The geometric parameters of the simulated structures are listed in Table 1 .

The laser was set as a 10.00- m far-infrared CO_2 laser. Because the timescale of the simulated physical process is similar to the pulse width of widely used CO_2 lasers [24-28], the laser was set as a continuous plane wave with an electric field amplitude of $E_0 = 5.0$ GV/m. The selected value implies that the power density of the laser beam is approximately 6.6×10^{12} W/cm^2, and the energy density of the laser pulse irradiating the prism is approximately 0.2 J/cm^2. These values are consistent with the laser parameters used in a related study [17].

We propose that line-shaped laser pulses collimated by a cylindrical lens be utilized to drive the symmetric prism, enabling long-distance synchronization. With an energy of 50.00 keV, the injected electrons were in the low-energy non-relativistic range ($\beta \ll 1$) typical for monoenergetic electron beams generated from electron guns with no initial energy dispersion and a charge of 9.36 fC. The particles in the bunch followed a KV distribution, which uniformly places the particles in phase space. The distance between the particles was approximately the same throughout the beam. The initially normalized emittance was 10 pm • rad. The initial maximum transverse distance relative to the center of the beam was 0.1 m, and the maximum divergence angle was approximately 23 mrad. The longitudinal beam length was 3.34 fs, and the distance between the center of the electron beam and prism Surface I was 0.5 m. These design parameters are consistent with those of the electron beam generated using the electron gun of the DLA [29-31], and the covered parametric range has not yet been investigated for the inverse Cherenkov-effect particle accelerator [16-19].

Table 1. Simulation parameters of geometric structure

Section	Length (m)	Refractive Index
First		
Second		
Third		
Fourth		
Fifth		
Structural spacing		

3. Simulation Results and Discussion

The energy spectrum of the accelerated electron beam stream is shown in Fig. 3 Figure 3: see original paper, corresponding to the instant at 600.42 fs when the electron beam had completely accelerated. The peak energy was 309.55 keV, and the full-width at half-maximum (FWHM) of the energy dispersion was 2.00 keV, corresponding to a relative ratio of 0.65%. Correspondingly, an electron energy gain of 259.55 keV was achieved with an average acceleration gradient of 2.62 GeV/m and an acceleration factor $\Delta E/E \approx 0.52$. This was obtained by dividing the total energy gain of the electrons by the entire path length of approximately 98.96 m.

The phase-space diagram of the horizontal (y-direction) space is shown in Fig. 3(b), which corresponds to the same moment as in Fig. 3(a). The maximum divergence angle of the electron beam did not exceed 21 mrad. Compared with the initial value of approximately 23 mrad, the divergence angle was reduced, and a weak focusing effect was achieved. Fig. 3(c) shows the spatial (x-direction) distribution of the electron beam and the energy distribution with time, with sampling points separated by $0.25T$ or approximately 8.34 fs. The electron energy increased monotonically, and continuous acceleration was achieved. The curve representing the electron beam energy increased smoothly through the vacuum channel, with only some jitter at the layer interfaces. This smooth increase indicates that the acceleration gradient does not change significantly at each stage; thus, the proposed stacked acceleration structure achieves long-range acceleration with a high acceleration gradient. The electron beam underwent diffusion and recompression in the spatial x-direction, and the energy of the electron beam underwent diffusion and recompression. The stretching and diffusion of the electron beam are caused by inhomogeneous field distribution in the accelerated vacuum channel, as reported in the literature [17-19]. When the diffusion of the electron beam stream becomes very strong, the positive phase ($\phi > 0$), that is, the decelerating phase-electric field in front and behind the electron beam, suppresses it, introducing negative feedback. Consequently, the length of the accelerated electron beam is limited to half of the laser cycle, and the extremely fast electrons slow down, inhibiting their energy increment and minimizing the energy dispersion. This also reduces the speed of the fast-electron beams and concentrates the electrons in the movement direction. This technique facilitates the electron beam to achieve its quasi-monoenergy and compression in the direction of motion after passing through the channel. This property may be valuable in future ultrashort pulse electron beam streams such as attosecond pulses, ultrafast electron diffraction, and other fields.

In addition, the electron charge for the fluctuation of the electron beam current charge was observed (Fig. 3(d)), and the simulation demonstrated that no beam loss occurred during the electron beam current acceleration. This finding is consistent with the earlier analysis that the field generated by this stacked structure does not cause transverse (y-direction) deflection of the electron beam current. Furthermore, the width of such a vacuum channel is adequate.

Fig. 3. (a) Electron energy spectrum at end of acceleration, normalized to peak. (b) Phase-space diagram of horizontal (y-direction) space. The vertical coordinate is the divergence angle, and the horizontal coordinate is the lateral position of the electron. (c) Spatial (x-direction) and energy distribution of electron beam at each moment (difference of $0.25T$ for each data sampling point). (d) Total power variation in electron beam at each moment (difference of $0.25T$ for each data sampling point).

The spatial and temporal variations in the longitudinal electric field E_x along the central axis of the vacuum channel were investigated to further examine the acceleration process of the electron. The path of an electron carrying average energy was adopted to approximate the mean trajectory of the electron beam, as shown in Fig. 4 [Figure 4: see original paper]. This demonstrates how an electric field induces electron acceleration or deceleration. The blue-violet region represents the deceleration field, whereas the orange-red zone represents the acceleration field. The net energy gain of a particle is closely related to the phase ϕ in which the electron beam is placed in the electric field. In the phase of the laser electric field, the solid green line represents the global line of the particle beam with average velocity. The electron beam is synchronized with the laser pulse and is always in the negative phase of the electric field ($\phi < 0$), known as the acceleration phase. This is why a stacked structure can achieve a high acceleration gradient for long-distance acceleration.

Accelerating a single beam does not fully utilize all the acceleration phases. Therefore, in the future, a multibeam cluster acceleration mode similar to modern conventional accelerators, with each pair of neighboring electron beam clusters spaced by a deceleration phase, can be adopted to improve the energy conversion efficiency and electron beam power.

Fig. 4. Electric field E_x (magnitude normalized with respect to E_0) as functions of time and space (x-position). The vector of this field is in the lateral direction of the vacuum channel. The green line indicates the electron trajectory, and the sampling time step is $0.25T$. The color bar on the right represents the normalized field strength, E_x/E_0 ratio.

Moreover, the performance of each layer of the structure was assessed to adapt it to future chip accelerator applications and construct a structure that can be dismantled to alter the electron beam energy to satisfy the needs of various situations. The energy spectrum of the electron beam stream produced by the acceleration of each layer is shown in Fig. 5 [Figure 5: see original paper]. The moments indicated by different colors in Fig. 5 correspond to the electron energy spectra obtained from the first layer to the sixth layer of the dielectric acceleration. The values are listed in Table 2 . The energy dispersion of the intermediate electron beam flow was relatively high. However, none of the energy dispersions exceeded 4.00 keV of the FWHM, and none of the corresponding relative ratio values exceeded 2.00%. The peak energy of the electron beam obtained from the final acceleration was 309.55 keV, and the FWHM of the energy dispersion did not exceed 2.00 keV. This indicates that the intermediate electron beam flow can also be used as the injection step, as discussed in the next section.

Fig. 5. Electron beam energy spectrum corresponding to end of acceleration of each layer of dielectric.

Table 2 presents the results of an investigation of the acceleration efficiency, in which the energy gain in the electron beam stream in each accelerated stage is determined, together with the corresponding average acceleration gradient. This coincided with the case presented in Fig. 3(c).

Table 2. Electron beam profile and acceleration performance for each layer

Section	Electron Energy (keV)	Half-height-width (keV)	Ratio (%)	Electron Gain Energy (keV)	Average Acceleration Gradient (GeV/m)
First					
Second					
Third					
Fourth					
Fifth					
Total					

This section presents the expandability of the proposed structure. First, the acceleration distance required to accelerate a 50 keV electron beam to 1 MeV was approximately 362.60 m using an average acceleration gradient of 2.62 GeV/m for the entire structure. Second, the thickness and refractive index of the dielectric to be added could be obtained using Equations (2) and (3). The length (x-direction or Surface I direction) and height (y-direction or Surface III direction, the highest point of the prism) of each subsequent layer are listed in Table 3 . In this case, the acceleration structure of the first five segments used the above structure.

Furthermore, preliminary estimates were obtained for longer acceleration distances and higher energy gains. The electron relativistic velocity β and dielectric refractive index n changed with increasing electron energy (Fig. 6 Figure 6: see original paper). The pinch angle was based on the same initial angle as used in this study. The refractive index of the dielectric rapidly decreased as the electron energy increased, and the refractive index eventually reached 2.00 and remained constant. Fig. 6(b) shows the variation in the thickness of each section of the dielectric structure. The thickness of each stage increased exponentially as the number increased. Dielectrics of this size are easy to prepare. In addition, the laser could be infinitely extended in one direction (with the focal length or extendable distance significantly longer than the acceleration distance) and tightly focused in the other direction (laser wavelength magnitude) using beam spreading and line-shaped collimation [32]. This implies that on Surfaces I and II (Fig. 1), the passing distance of the laser in the dielectric is significantly longer than the required acceleration distance. In general, the proposed structure can be extended to higher energy targets by adding a new dielectric layer behind the structure.

Table 3 . Size of subsequent structure

Section	Length (m)	Height (m)
Sixth		
Seventh		
Eighth		

Section	Length (m)	Height (m)
Ninth		
Tenth		

Fig. 6. (a) Electron relativistic velocity (blue line) and dielectric refractive index (red line) as functions of electron energy; (b) Length of each section of dielectric structure (The green and brown lines indicate measurements in microns and meters, respectively, while logarithmic coordinates are used.)

4. Conclusion

A laser dielectric accelerator is proposed based on the inverse Cherenkov phenomenon using a multilayer structure. A parametric design approach was applied to this structure and is demonstrated with a design example for accelerating electron beam currents ranging from 50.00 to 309.55 keV. This suggests that the stackable structure enables a high-energy-gain cascade acceleration technique featuring a high acceleration gradient and an extended acceleration distance, as demonstrated via simulation. Furthermore, this stackable accelerating structure has a flexible configuration. Theoretically, the structure can achieve arbitrarily high acceleration under design assumptions by extending the accelerator length following the proposed design procedure. The proposed structure is a promising prototype for use in future chip accelerators.

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Data Availability. The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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