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ANALYSIS OF CHARGED PARTICLE ACCELERATION STRUCTURES ON CHIPS

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Recently, one of the promising methods of acceleration on diffracted electromagnetic waves is the method of laser acceleration of charged particles on periodic chip structures. The article analyzes the influence of various changes and sizes of chips on the rate of acceleration. Electromagnetic fields formed by dielectric chip structures when irradiated with a laser pulse were calculated using a numerical method. Recommendations are given for choosing the profile of dielectric structures for the purpose of effective acceleration of charged particles.

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INTRODUCTION

Recent experimental studies on the acceleration of nonrelativistic [4] and relativistic electrons [5], with the development of numerical simulation techniques, it became possible to analyze in detail the methods of accelerating charged particles on a laser pulse without setting up an experiment. Along with theoretical developments [6], work is being actively carried out on numerical simulation of new methods of acceleration, in particular, on the action of a laser pulse on chips [2, 3]. The relevance of such developments will be determined by the maximum miniaturization of the device, as well as its optimization of this type of production of accelerators for fundamental and applied research. Works on CHIP-structures served as the beginning for further comprehensive development of this direction. As an accelerating force acting on a charged particle, in this case, is a component of the electric vector of the laser pulse. The design of the structure is chosen such that when the laser pulse leaves the surface of the dielectric, there are electromagnetic waves. They are formed as a result of the passage of an electromagnetic wave (light) in a dielectric. In this case, small fluctuations in dielectric polarization (permeability) occur in individual atoms, as a result of which each particle radiates secondary waves in all directions. At the boundary of different optical media (on the dielectric surface), these secondary waves go beyond the interface.

According to the Huygens-Fresnel principle, a mutual amplification or attenuation of the amplitude of two or more coherent waves simultaneously propagating in space occurs above the surface layer of a dielectric (interference pattern). The result of the interference depends on the phase difference of the superimposed waves.

Due to the low losses of an electromagnetic wave passing through a dielectric (in this case, quartz), diffraction waves have low energy and quickly decay. The condition for the formation of Fresnel diffraction interference is the expression:

$$b^2/D\lambda \sim 1,$$

where b is the width of the obstacle, D is the distance from the obstacle to the place of observation, λ is the length of the electromagnetic wave.

In works [2, 3] dielectric CHIP structures of various profiles (meaning different shapes of obstacles c) of chips were studied in order to determine the optimal shape of the CHIP structure for synchronous action on a charged particle.

1. GOAL OF THE WORK

The purpose of this work is to describe the mechanism of action of the formed electric field on a moving charge in the zone where conditions (1) are satisfied and to give recommendations for simplifying the setting of the experiment on the CHIP structure.

2. STATEMENT OF THE PROBLEM AND DISCUSSION

On Fig. 1 [2, 3] presents the types of profiles of CHIP structures. which were used in numerical simulations as diffraction gratings. Profile 1 is used in real experiments in laboratories [1 - 4], while profile 2 is easily produced by etching. At all stages of modeling the structure, the length is L = 16 μm, which is 20 optical periods of the wavelength.

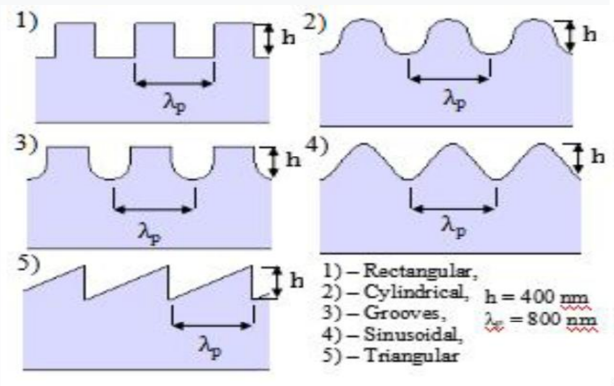


Fig. 1. Profiles of the CHIP structure

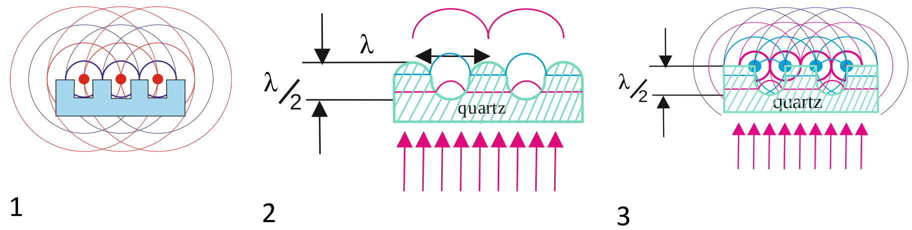


Fig. 2. Fragments of diffraction waves 1 and 3 correspond to profiles 1 and 3 in Fig. 1, and 2 – profile 2 Fig. 1

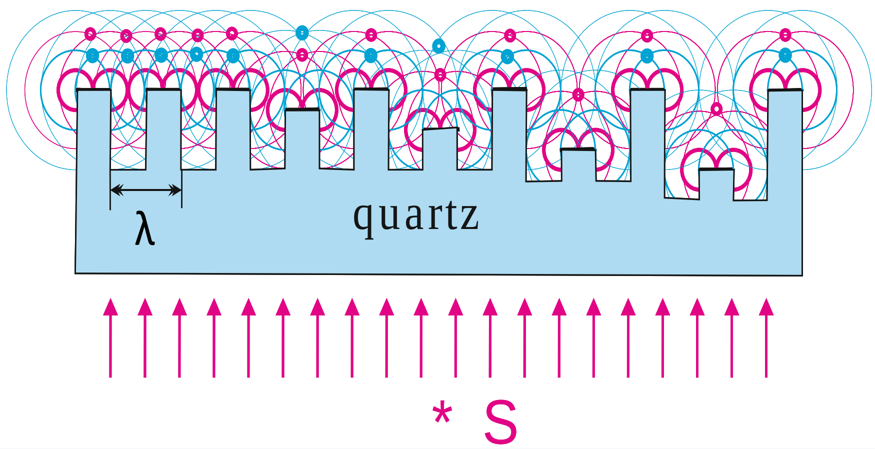


Fig. 3. Interference of diffraction waves over chips of different heights with the same period. The thickness of the lines is proportional to the intensity of the wave amplitude. Solid circles are antinodes and nodes. The blue color of the lines and circles are the minimum wave fronts and nodes, the red color is the maximum wave fronts and antinodes

On Fig. 2 shows fragment 1 with a chip period less than λ. Antinodes (red circles) are formed near the surface of the chips, of low intensity (the intersection of red circles) at a distance greater than λ. The rest of the field has a mixture of maximum and minimum fronts of diffraction waves, which does not satisfy the conditions for the acceleration of charged particles. As noted above, diffraction waves are low-energy (the intensity of the wave front is inversely proportional to D2) and, as can be seen from the figure, only in the pre-surface layer there are conditions (in this case, D = b2 / λ at b = λ / 2, D =λ/4) to accelerate a charged particle. On fragment 2 of Fig. 2 shows the fronts of diffraction waves, the rest of the space is filled with a set of wave fronts of different intensity, and the conditions for accelerating a charged particle are unlikely. The same conclusion can be drawn for the profile of chips 3, a fragment of which is shown in Fig. 2. In Fig. 3 shows the diffraction pattern on chips with the period λ recommended in [6], showing the modified chip heights. In the structure (see Fig. 3, left) with chips of equal height, favorable conditions for accelerating charged particles can be seen. There are a number of antinodes - accelerations (red circles) of particles and nodes - decelerations (blue circles) even at some distance from the chip surface.

Small distances between antinodes and nodes can be characterized as an increase in the rate of acceleration (deceleration) of such a structure. With a decrease in the size of the chips (see Fig. 3 on the right), the distance between antinodes and nodes increases, which should be reflected in a decrease in the rate of acceleration (deceleration) of charged particles. But the density of diffraction waves decreases, and the effect of extraneous forces on the acceleration process decreases.

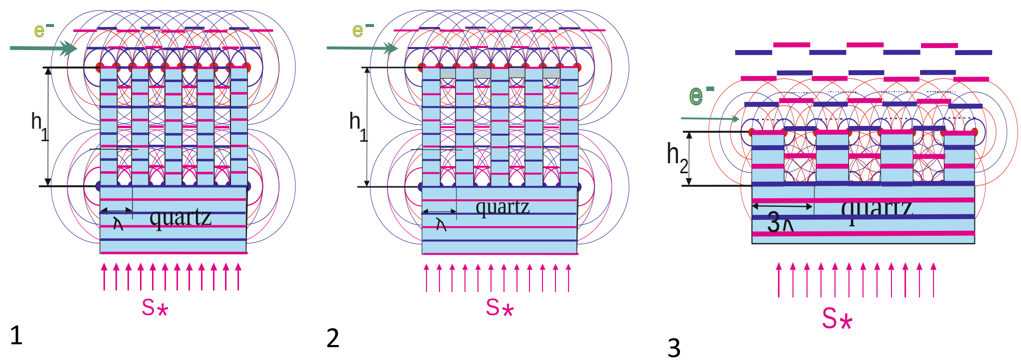


Fig. 4. Chip structures of different profiles 1 and 3, Fragment 2 Chip structure with inserts in the gaps

On Fig. 4 shows fragments of CHIP structures of different profiles. Red circles and straight lines-fronts, blue circles and straight lines-fronts are the positive and negative components of the electric vector of an electromagnetic wave. The design of the structure was calculated so that the number of laser pulse periods in the chip and in the gap between them was an integer number of half-wavelengths.

This condition is due to the fact that at the level of the edge of the chips there is a positive component of the electromagnetic wave (crest), and in the gap there is a negative component of the electromagnetic wave (trough). This is achieved by different speeds of the electromagnetic wave in the dielectric (chip) and in the gap between them. So on fragment 1 there is a ratio of 9/2 λ to 6/2 λ, on fragment 2 – 9/2 λ to 6/2 λ, with an insert (see Fig. 4, fragment 2), on fragment 3 – 3/2 λ to 2/2λ. This design of the CHIP structure satisfies the condition: while the charged particle flies over the chip (clearance), the electric vector component changes sign over the clearance (chip). To fulfill this condition, there are two parameters: the first is h and the second is the refractive index n. In this case, n=1.5 was taken for the graphical construction of the above structures.

Failure to comply with this condition (as an example, fragment 2 of Fig. 4) disrupts the uniformity of the acceleration process on the CHIP structure.

On Fig. 4 fragment 2, an additional delay is inserted into the gap (in the upper part of the chips), which led to some non-uniformity of the acceleration graph (non-linearity of the levels of the electromagnetic wave fronts is observed on the trajectory of the movement of charged particles).

It should be added that the intensity of the electric field formed by the front of the laser pulse wave is several orders of magnitude greater than the intensity of the Fresnel interference fields. To enhance the Fresnel fields, a CHIP structure of complex design is designed [4] (Fig. 5).

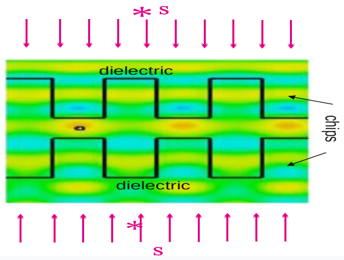


Fig. 5. Complex chip structure

Fig. 1 shows the dimensions of the chips and the gaps between them. As noted in the above-mentioned works, their production involves a rather complex technology, especially to make deep gaps between them. We propose the following construction. It was shown in [6] that a quartz plate can be made with a thickness of about 1 μm and a length of up to 10 mm. N pairs of blanks of the required dimensions are made, for example $1x5x1 \cdot 10^{-3}$ mm 100 pcs. and $1x2x1 \cdot 10^{-3}$ mm 100 pcs. A CHIP structure is assembled from this set (Fig. 6, 1). Similar parts can be made from rolled gold with a thickness of $0.4 \cdot 10^{-3}$ mm.

The complexity in making a CHIP structure, as well as in conducting a focused electron beam with a diameter of 10^{-3} mm, can be simplified as follows.

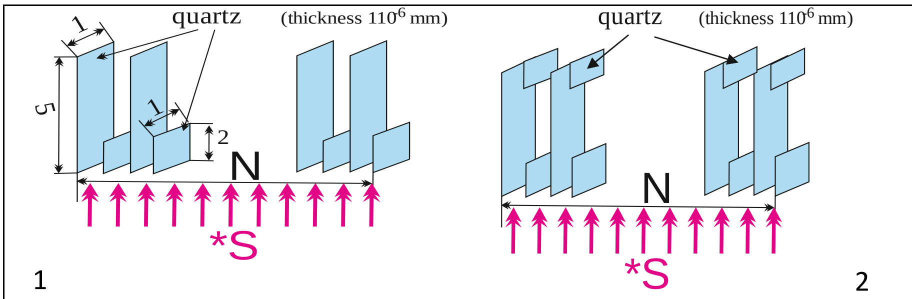
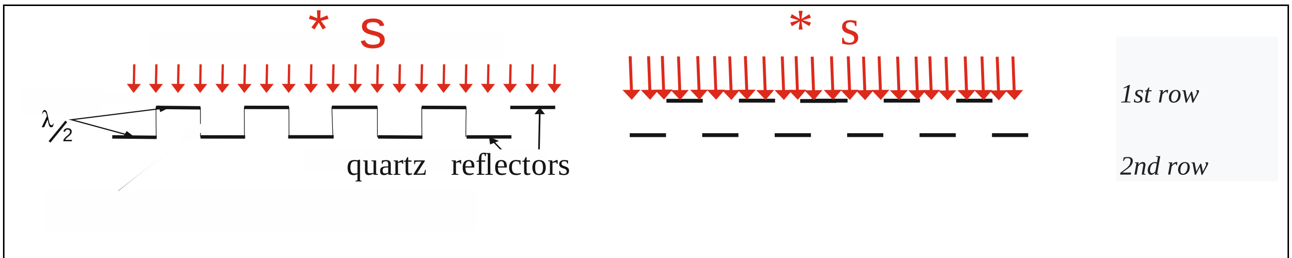


Fig. 6. Chip structures samples from quartz: 1 without top gasket, 2 with gasket



A *B*

Fig.7. A – shows the chips covered with reflectors at the ends; B – a structure of two rows of reflectors and gaps, the reflectors of the 2nd row are located opposite the gaps of the 1st row, the linear dimensions of the structure elements are equal to the dimensions of the reflectors on the chips

Let's consider one more construction. Cover the ends of the CHIP structure with a reflective layer (Fig. 7,A), direct the laser pulse flow from the vacuum side. On Fig. 7,B shows an analogue of Fig. 7,A without dielectric substrate.

On Fig. 8 shows the fields of numerical simulation by an incident plane electromagnetic wave of a laser pulse over chips A and B and structure C and D. Red arrows indicate the direction of the laser pulse during irradiation of prototypes in Fig. 7. Designations of blue and red circles are the same as described above.

At first glance, in Fig. 8 shows the analogy of the fields both on chips in this design (see Fig. 7,A) and on the proposed structure (see Fig. 7,B). It should be noted that for a sufficiently large cross section of the laser pulse above the chips (proposed structure) (proposed structure) Fig. 8,B and C, a uniform field of antinodes and nodes of the electromagnetic field is formed, which may affect the rate of acceleration.

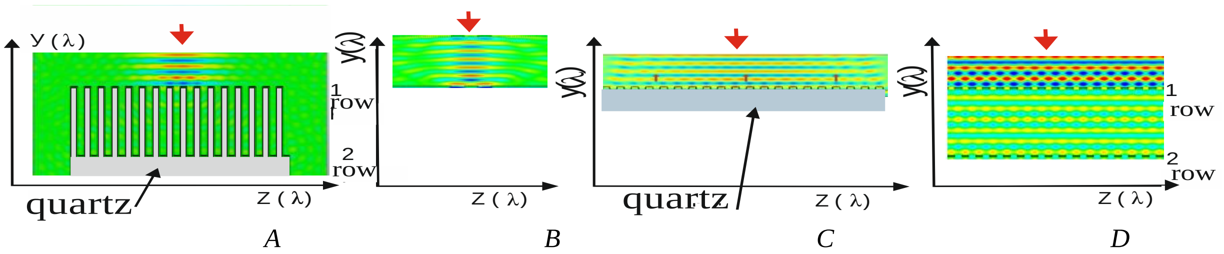


Fig. 8. For comparison, the drawings of the fields are shown, calculated by numerical simulation for the model of Fig. 7,A with different cross sections of the laser pulse C and D. For the fragment of Fig. 7,B similarly – fragments D and F

CONCLUSIONS

Thanks to the increase in the height of the chip structure column shown in Fig. 4,1, it is possible to achieve the formation of a more homogeneous accelerating field. However, due to the complexity of the production process of the structure, it is proposed to use the technology presented in Fig. 6,1. However, this technology has certain design features associated with the fragility of the structure. Therefore, it is proposed to use the technology depicted in Fig. 6,2, which is intended to increase the strength characteristics of the accelerating structure.

Fig. 4,3 shows a diagram of the diffraction wave propagation, which allows for interference of diffraction waves with increasing chip structure period, resulting in a smaller effect on the uniformity of the accelerating field. This in turn affects the acceleration rate, making it possible to accelerate at a greater distance from the chip structure, which significantly facilitates the positioning of the structure relative to the electron flight path.

Thus, the modification of the chip structure significantly facilitates the experimental setup, making it possible to use the chip structure in a simplified form (Fig. 8,B and D), providing a simple alignment technology, which will allow for the acceleration of electron beams of larger diameter.

Thus, the alteration of the CHIP structure greatly facilitates the setting of the experiment, it will be possible to use the CHIP structure in a simplified form (see Fig. 8,B and D), it will provide a simple adjustment technology, which will make it possible to increase the cross section of the laser pulse.

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АНАЛІЗ СТРУКТУР ПРИСКОРЕННЯ ЗАРЯДЖЕНИХ ЧАСТИНОК НА ЧІПАХ

Г.О. Кривоносов, А.В. Васильєв

Одним з перспективних методів прискорення на дифракційних електромагнітних хвилях останнім часом є метод лазерного прискорення заряджених частинок на періодичних чіп-структурах. У статті проведено аналіз впливу різних змін та розмірів чіпів на темп прискорення. Чисельним методом прораховані електромагнітні поля, що утворені діелектричними чіп-структурами при опроміненні їх лазерним імпульсом. Надаються рекомендації щодо вибору профілю діелектричних структур з метою ефективного прискорення заряджених частинок.