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Simulation and Fabrication Research on X-Band Photonic Band Gap Accelerating Structure

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Abstract Numerical simulation of X-band metallic photonic band gap (PBG) accelerating structure based on a 3D electro-magnetic program is presented. The design of 11.42GHz traveling-wave accelerator has been successfully completed, including the RF-coupler design. At last, the electroforming technique is investigated here, with mechanical tolerances given by simulation.

Key words PBG accelerating structure, numerical simulation, coupler design, electroforming

1 Introduction

In order to improve the energy efficiency, the operating frequency of linear accelerators has been greatly increased. Nevertheless, the wakefields, excited by the interaction between the beam and accelerating cavities, are intensified at the same time, producing negative effect on beam transportation. The PBG accelerating structure could effectively suppress these higher-order modes (HOM), achieving single mode acceleration.

The PBG structure was first proposed by Yablonovitch in the 1980s. Beginning in the 1990s, some research institutes started to investigate the metallic PBG structure as a novel accelerating structure, acquiring lots of achievements. However, this research revealed many problems, such as the great difficulties in machining and tuning the small and highly complex PBG structure.

Many scientific institutes have greatly contributed to the research of PBG structures. Studying the wakefields, researchers at UCSD successfully designed and fabricated the first superconducting PBG accelerator[1]. At MIT, an X-band PBG resonator and a 6-cell Ku-band PBG traveling wave accelerating cavity have been completely designed and fabricated, followed by cold tests and high power tests. Finally, the actual acceleration of electron beams was achieved[2]. Research at SLAC mainly focused on PBG fiber accelerators. This structure can be used at much higher frequencies than metallic structures, with high accelerating gradient and low loss[3]. The DULY research center presented the application of PBG structure in multi-beam devices, and they introduced the conceptual design of a 6-beam rod-loaded compact klystron[4].

We have done researches on X-band PBG accelerator cavities such as numerical simulation and machining techniques. 3D electro-magnetic software has been used in our simulation. The characteristics of HOM damping were verified by simulating PBG accelerating cavities with different dimensions. Based on Eigenmode analysis, the traveling wave accelerator was devised, working at 11.42GHz and in $2\pi/3$ mode. Transit analysis was utilized in the design of input and output couplers. In addition, the electroforming technique was investigated in order to manufacture PBG cavities, while the dependence of the

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cell frequency on the deviation of mechanical tolerances was studied with numerical simulation.

2 Characteristic of PBG structure

Two-dimensional triangular array of metallic rods is an ordinary PBG structure in the research of PBG accelerator. Certain global frequency band gaps exist in such a structure, and by appropriately adjusting the ratio of the rod radius a and lattice vector b, we could confine the main accelerating mode in the forbidden band, while allowing higher-order modes to propagate along all directions, namely, distributing in the whole cavity[5]. By removing the central rod of the periodic structure, the PBG accelerating cavity is formed, localizing the main accelerating mode around the defect, actually achieving single mode propagation.

The characteristic of single mode propagation is verified by simulating PBG resonators with different dimensions. In Fig. 1, the blank circles represent metallic rods, and the other parts are vacuum area. The saturated areas represent the electric field distribution of different modes. From Fig. 1(a), where a/b is set to 0.15, we can tell that only the lowest mode is primarily confined in the central part of the cavity. However, in Fig. 1(b), where a/b is set to 0.3, the dipole mode also exists in the center. The ratio of a/b is finally set to 0.15 in the following simulation and fabrication for single mode propagation.

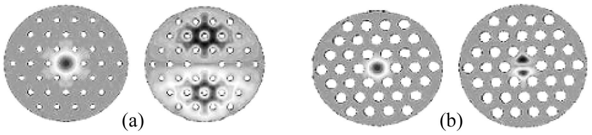

Fig. 1. The lowest order mode and dipole mode of PBG resonators with different ratios of a/b. (a) a/b=0.15; (b) a/b=0.3.

3 PBG traveling-wave accelerator design

The proposed PBG accelerator consists of several traveling-wave cells, the input and output couplers. The simulation model of the designed X-band traveling wave accelerator is shown in Fig. 2. To save simulation time, only two traveling-wave cavities are presented. Three rods between the center of the cavity and the waveguide are removed from both the input and output couplers, in order to effectively couple the microwave power into the PBG cavity. The other dimensions of the coupler cells are the same as those for the accelerating cells.

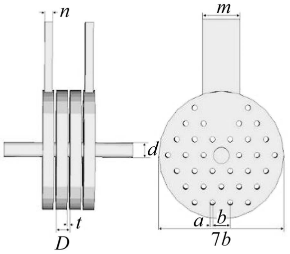

Fig. 2. The model of the PBG accelerator.

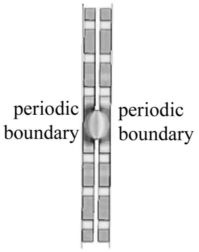

Fig. 3. The single accelerating period.

3.1 Design of the accelerating cavity

The field distribution of accelerating cavities was acquired by Eigenmode analysis. Fig. 3 displays a cross-section of an accelerating period, consisting of two half-cells and a beam hole. Both of the half-cells are ended by a periodic boundary. The dispersive curve was obtained by scanning the phase shift.

The length of a single period section, D, is determined by the operating frequency of the accelerator, f,

$$D=c\frac{\theta}{2\pi f}=\frac{c}{3f}\ , \tag{1}$$

where c is the speed of light, and the θ represents the operating mode.

Keeping the ratio a/b equal to 0.15, while changing the rod radius, a, and the distance between the rods, b, the frequency of $2\pi/3$ mode was adjusted to 11.42GHz. By changing the thickness, t, and diameter, d, of the iris the group velocity was tuned to $0.05c$, in order to achieve effective acceleration in the long cavities.

From the dispersive curve, we could calculate the coupling coefficient between two cavities, k, and the group velocity, $v_{\rm g}$, from Eqs. (2) and (3).

$$k=\frac{f_{\pi}^2-f_0^2}{2f_{\pi/2}^2}\ , \tag{2}$$

$$v_{\rm g}=\frac{{\rm d}\omega}{{\rm d}\beta}\approx\pi Df_{\pi/2}k\sin\theta\ . \tag{3}$$

In these formulas, f_{φ} represents the frequency of the φ mode and ω=$2\pi f$.

The calculation of the accelerating gradient, G, and r/Q, is based on the electric field distribution along the longitudinal axis, $\boldsymbol{E}$.

$$G=\frac{\int_0^D \boldsymbol{E}\cdot \mathrm{d}\boldsymbol{l}}{D}\ , \tag{4}$$

$$r/Q=\frac{G^2}{\omega U}\ , \tag{5}$$

where U represents the stored energy per unit length.

Table 1 lists the final geometrical and microwave parameters, which satisfy the design goal.

Table 1. The final geometrical and microwave parameters of the PBG accelerating cavities.

rod radius a/mm	1.64
distance between the rods b/mm	10.96
iris diameter d/mm	9.61
iris thickness t/mm	1.71
the length of single period D/mm	8.75
operating frequency f/GHz	11.42
phase shift per cell θ	2π/3
coupling coefficient between two cavities k	0.0556
group velocity v_{g}	0.050c
quality factor Q	5461
r/Q/kΩm^{-1}	10.5
accelerating gradient G/MVm^{-1}	$7.1\sqrt{P(MW)}$

3.2 Design of the couplers

Due to the complex structure, it is difficult to match the PBG cavity. The initial dimensions of the input and output PBG couplers were almost the same as the accelerating cavity, with the longer side of the waveguide set to the standard value of WR90. The shorter side of the waveguide could be adjusted according to the length of the cavity. Three rods between the center of the coupler cell and waveguide were removed, in order to effectively couple the microwave power into the PBG cavity. However, the dimensions of the couplers still need future adjustment, and the following calculation and simulation are applied to tune and match the PBG cavity.

3.2.1 Introduction of principles

From the equivalent circuit model, we could calculate the frequency, f_{cs}, and external quality factor, Q_{es}, of the couplers, which match the accelerating cavities[6].

$$f_{\mathrm{cs}}=\frac{f_{\pi/2}+f_{\theta}}{2}\qquad Q_{\mathrm{es}}\approx\frac{2}{k\sin\theta}\ . \tag{6}$$

Thus, f_{cs}=11.344GHz, $Q_{\mathrm{es}}\approx$41.5

On the other hand, f_{c} and Q_{e} of the coupler could be acquired by transient analysis. The simulation model consists of the input or output coupler, an accelerator half-cell and the beam transporting pipe, with a magnetic boundary applied on the side of the half-cell (Fig. 4(a)). The external quality factor was calculated from Eq. (7)

$$Q_{\mathrm{load}}=-\frac{10\lg e\cdot\omega}{k_{\mathrm{energy}}}\ , \tag{7}$$

where k_{energy} is the slope of the energy degradation curve obtained from simulation[7]. The ideal conductor material was adopted in the simulation, and therefore,

$$Q_{\mathrm{load}}=Q_{\mathrm{e}}=-\frac{20\pi\lg e\cdot f_{\mathrm{c}}}{k_{\mathrm{energy}}}\ . \tag{8}$$

3.2.2 Two variables for tuning and matching

The electro-magnetic fields of the main accelerating mode are confined in the inner rods of the PBG cavities. As a result, the dimensions and positions of the inner rods greatly affect the resonating frequency and coupling of the couplers, while the outer rods have such little effect that they cannot be efficiently used for tuning and matching. Two different parameters should be adopted as variables. As shown in Fig. 4, rods1 are located between the rectangular waveguide and the center of the coupler, so that we could adjust the position of rods1 to change the coupling. Rods2 are relatively far from the waveguide, which induce less effect on the coupling between the coupler and the waveguide. However, the position of rods2 will greatly influence the operating frequency of the coupler, and therefore could be utilized for tuning.

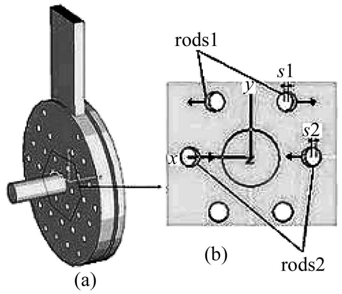

Fig. 4. (a) The model of the coupler and a half traveling-wave cell; (b) Shift of rods1 and rods2.

The rods1 move $s1$ along the x and $-x$ axis respectively departing from the center, and the rods2 move $s2$, approaching the center (Fig. 4(b)). Dependence of $f_{\rm c}$ and $Q_{\rm e}$ on the shift of rods1 or rods2 is shown in Fig. 5.

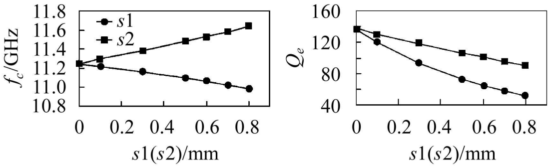

Fig. 5. The dependence of $f_{\rm c}$ and $Q_{\rm e}$ on the shift of rods1 or rods2.

When rods1 were moved, both $f_{\rm c}$ and $Q_{\rm e}$ of the coupler decreased; when rods2 were moved, $Q_{\rm e}$ decreased while $f_{\rm c}$ increased at the same time. Selecting proper values of $s1$ and $s2$, $f_{\rm c}$ and $Q_{\rm e}$ could be adjusted to the theoretical values. When $s1$=0.675mm and $s2$=0.68mm,

$$f_{\rm c}=11.344{\rm GHz}=f_{\rm cs},\quad Q_{\rm e}=41.7\approx Q_{\rm es},$$

which approximately satisfy the requirement.

Accordingly, the final dimensions of the couplers after adjustment are listed in Table 2.

Table 2. The geometrical parameters of the coupler.

rod radius a/mm	1.64
distance between the rods b/mm	10.96
shift of rods1 $s1$/mm	0.675
shift of rods2 $s2$/mm	0.68
length of wide side of waveguide m/mm	22.86
length of narrow side of waveguide n/mm	5.04
diameter of beam pipe d/mm	9.61

3.3 Simulation of the whole PBG accelerator

After all the geometrical parameters have been decided, the distribution and the phase shift of the electric field along the axis in PBG cavity (Fig. 6) could be simulated by transient analysis. Fig. 2 shows the simulation mode.

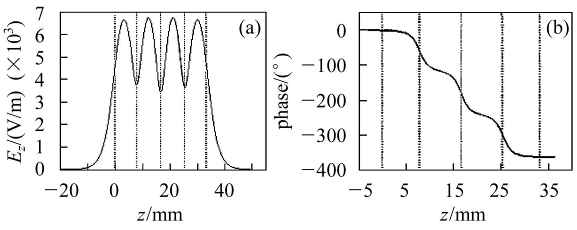

Fig. 6. (a) The electric field distribution along axis; (b) Phase shift of electric field along axis.

The dot lines are the boundaries between cavities. The deviation of the electric field distribution is only about 1%, while the phase shift per accelerating cell is 120°, with a deviation less than 0.5°. The half cell of the coupler, linking to the beam pipe, could be recognized as a standing wave cell, with approximately invariable phase, and the phase shift for the whole coupler cell is approximately 61°—62°.

4 Tolerances and electroforming

4.1 Mechanical tolerances

A model of a 1+1/2 cavity was simulated through Eigenmode analysis. The simulation results showed that the frequency deviation produced by the tolerance of outer rods is much smaller than the inner rods and the middle rods, and thus could be neglected. The tolerances of several important parameters are listed in Table 3.

Table 3. Tolerances of important parameters.

dimensional parameter	tolerance/μm	frequency deviation/MHz
all inner rods	±5	±8.6
all middle rods	±10	±0.5
iris thickness	±10	∓1
iris diameter	±10	±2.5

positional parameter	tolerance/μm	frequency deviation/MHz
all inner rods deviate along radial direction	±5	∓5.9
all inner rods deviate along angular direction	±5	±1.5
all middle rods deviate along radial direction	±10	∓0.6
all middle rods deviate along angular direction	±10	±1.1

4.2 Electroforming

Due to the complex structure, the traditional machining technique and brazing process are not suitable to fabricate X-band PBG cavities. Electroforming and the linear cut technique serve as the promising machining methods. The linear cut technique can be employed to produce the hexagonal column PBG structures. We can get the whole accelerator cavities by omitting the brazing procedure in this way, but it is rather expensive. Therefore, we choose electroforming. The procedures of electroforming are as follows. First, an aluminum mold with holes in the position of the rods is fabricated and is then placed in a copper solution, enabling it to serve as the negative pole. When the voltage is supplied, the copper is deposited on the surface of the aluminum mold, until the thickness of the rods and the two plates reaches a sufficient magnitude. Then, we reduce the thickness of the copper plates to half of the iris through machining. Lastly, the aluminum mold is dissolved in an acid solution, and a single PBG cell is formed (Fig. 7).

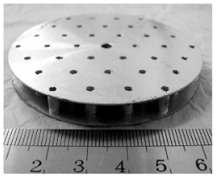

Fig. 7. A single PBG cell.

5 Conclusion

PBG structures have many applications in various fields, such as condensed matter physics, electronics and accelerator physics. Due to its characteristic of high suppression of wakefields, the PBG structure is a promising accelerating structure.

In this paper, an X-band metallic traveling wave PBG accelerating cavity was designed, including the tuning and matching of couplers. The manufacturing technique of electroforming was investigated in order to bypass the difficulties of traditional machining in producing such complex and intricate cavities. Further research to be conducted in the near future will focus on: 1. Conducting cold tests and developing appropriate methods of tuning. 2. Improving the process of the electroforming technique, in order to get a better quality factor of the PBG cavities.

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X波段PBG加速结构的数值模拟和加工研究

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摘要 利用3D电磁场模拟计算软件, 对X波段的金属PBG加速结构进行了模拟计算. 设计了11.42GHz的光速段行波加速腔, 并进行了耦合器调配的计算和模拟. 最后, 研究了电铸加工的方法, 并通过模拟计算给出了加工公差.

关键词 PBG加速结构 数值模拟 耦合器设计 电铸

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