PHASE TUNING SYSTEM FOR TRAVELLING WAVE RESONATOR

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The article describes the system of phase tuning based on waveguide phase shifter. Phase shifter is represented by the dielectric plate with low dielectric permittivity placed inside a travelling wave resonator waveguide ring close to the narrow wall. Phase shift is defined by the plate displacement relative to the waveguide wall. Plate displacement is introduced by the stepping motor providing high precision of the positioning or manually. Graphs of electrodynamic characteristics dependences from the plate position and its parameters are listed. Several variants of motion input into the vacuum volume are described.

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INTRODUCTION

Travelling wave accelerating systems for electron beams acceleration are widespread because of high values of shunt impedances. Despite this fact travelling wave systems have large disadvantage concerning low amplitude of accelerating field amplitude that is several times lower that in standing wave accelerators [1]. To increase the intensity of accelerating fields in the travelling wave accelerators without amplifying the input RF power the travelling wave resonator (TWR) system was proposed [2].

Principal scheme of the TWR is depicted on the Fig. 1 (1 – accelerating section, 2 – directional coupler, 3 – TWR ring, 4 – vacuum ports). Power input is organized with the directional coupler inside the ring of the travelling wave resonator formed of the accelerating structure and the rectangular waveguide short-circuiting the power input and output of the accelerating structure.

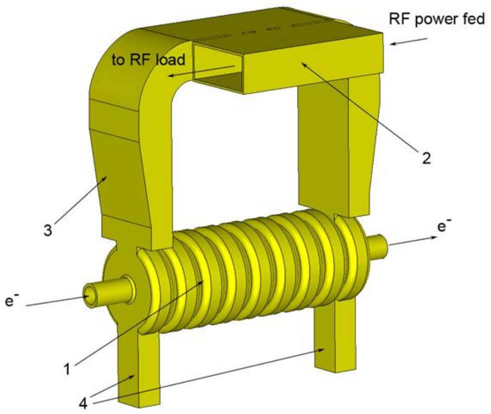


Fig. 1. General scheme of the TWR

The power circulates multiple times in the TRW ring and accumulates there. The TWR ring length for this must be equal to even number of the wavelengths. Electrical field amplitude increase in such a scheme of power input can reach 5 times or more compared to the conventional power input scheme in case of low reflection values of power from the accelerating system and low values of power attenuation coefficient in the walls of the ring. However the TWR structure assumes strict co-phased composition of the wave on each turn of the ring. This condition cannot be satisfied without the exploitation of the phase shifter. The high values of the circulating power in the ring supposes the application of the high-power waveguide phase shifters that must provide precision phase tuning in wide phase band and low power reflection coefficient.

1. WAVEGUIDE PHASE SHIFTER CALCULATION

The waveguide phase shifter was calculated to provide required level of phase tuning in the TWR. It is proposed to place the phase shifter inside the TWR ring (Figs. 2-4). The ring length the phase shifter placed in the waveguide transition before the power input or power output from the structure. Geometrical sizes of the waveguide transition were chosen for the accelerator working in π/2 mode, frequency 3000 MHz and relative phase velocity β=0.999. In case of choosing for the investigation case of accelerating structure working on 2π/3 mode of other value of phase velocity only the width of the waveguide narrow wall will differ though so the results of investigation will not differ much from each other. Phase shift in the unit is provided by the bringing in the waveguide volume dielectric object that disturbs the electromagnetic field. In this particular case disturbing object is chosen to be the plates fabricated from quartz glass (ε=3.8 at 20°C) or fluoroplastic (ε=2.1 at 20°C). Both materials have high strength and stability to high microwave fields. Plate has length equal to generators wavelength (100 mm at 3000 MHz) and length is varied along the longitudinal position in the waveguide transition and in each point is 2 mm distant from the waveguide wall. From two sides plate has chamfer edges that equals quarter of the generators wavelength that are made to minimize the reflections of the power from the phase shifter.

Plate is brought in the waveguide and is fixed on two bars placed on the half of the waveguide width. Distance between these two bars equals quarter of generators wavelength that allows to annihilate the field disturbance by the first bar with the second bar field disturbance. Bars can be fabricated of the fluoroplastic with the dialectical permittivity 2.1. Fixation of the bars inside the body of the plate can be realized using the vacuum glue or with the grooved slots inside the plate.

Phase shift in the unit at the certain position of the plate can be estimated using the theorem of small perturbations that defines the variation of the electromagnetic fields characteristics in case of perturbation body insertion [1].

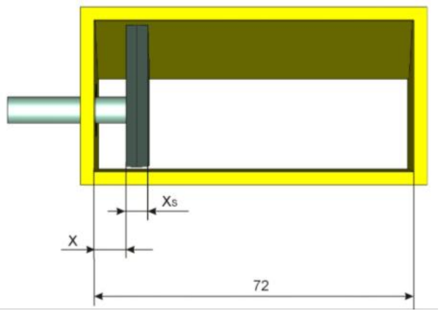


Fig. 2. Phase shifter front view

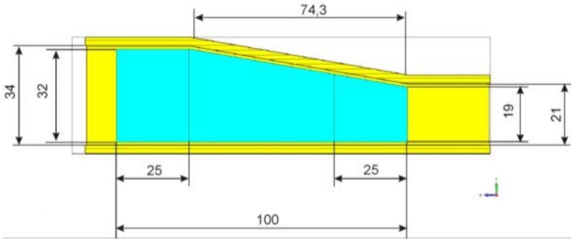


Fig. 3. Phase shifter left cut view

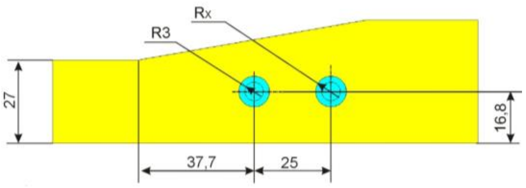


Fig. 4. Right view of the phase shifter

Using this theorem phase shift resulting from the inserted dielectric plate with the length *l* and width equal to the width of the narrow wall of the waveguide can be estimated by:

$$\Delta\psi = (k_z - k_{z0})l = \frac{\omega l}{4P}\varepsilon_0(\varepsilon - 1)\int_{\Delta S} \vec{E}\vec{E}_0^{*} ds, \qquad (1)$$

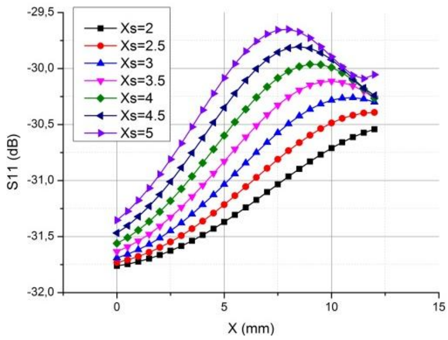
where ψ is a microwave field phase; ω is an angular frequency of the microwave field; *P* is a waveguide power loss; ε_0 is a relative dielectric permittivity of the free space; ε is a relative dielectric permittivity of the plate; $\vec{E}_0^{*}$ is a magnitude of the electrical field in the hollow waveguide; $\vec{E}$ is a magnitude of the electrical field in the system with perturbation object.

For approximate results the equation that links the field phase shift with the thin dielectric plate position that is placed parallel to the narrow wall can be written as:

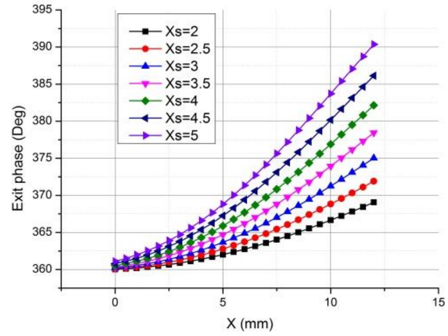
$$\Delta\psi = (\varepsilon - 1)l \frac{k_z}{\sqrt{1-(\lambda/\lambda_{кр})}} \frac{hd}{ab} \sin^2\left(\frac{\pi}{a}x_0\right), \quad (2)$$

where k_z is a longitudinal wave number; λ is a microwave wavelength; $\lambda_{кр}$ is a critical wavelength of the waveguide; *h* is a thickness of the dielectric plate; *d* is a length of the plate; *a* and *b* are transverse sizes of the waveguide; x_0 is a distance between the plate and the narrow waveguide wall.

However more certain data were required for the TWR modeling that would include the variable cross-section of the waveguide, presence of fluoroplastic plate holding bars and variable plate thickness. CST Studio Suite [3] modeling was held to investigate the 3D EM modeling of the phase shifter model depicted on the Figs. 2-4. The power reflection coefficients from the phase shifter power input and EM field phase on the exit of the phase shifter were calculated to estimate the effect of the inserted dielectric plate and bars on the EM fields in the waveguide. The variation of the plate input depth and thickness of the plate were considered (letters X and Xs on the Fig. 1. Thickness was varied from 2 to 5 mm with half millimeter step, position of the plate vs. the waveguide wall – from 0 to 5 mm. Results of investigation are shown of the Figs. 5, 6.

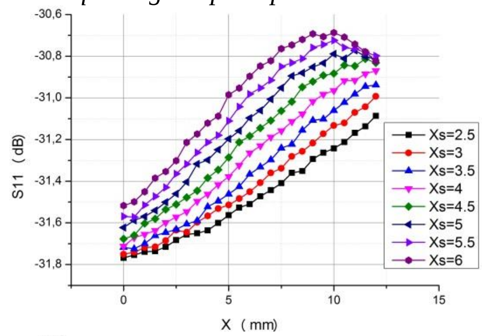


a

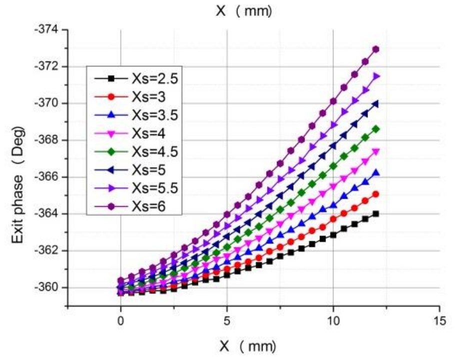


b

Fig. 5. Dependences of the phase shifter reflection coefficient (a) and EM field phase on the phase shifter exit (b) from the quartz glass plate position and thickness



a



b

Fig. 6. Dependences of the phase shifter reflection coefficient (a) and EM field phase on the phase shifter exit (b) from the fluoroplastic plate position and thickness

Graphs 5 a,b shows that increase of the quartz glass plate thickness greatly enlarge the phase shift angle of the propagating wave. Difference between the phase shift for the 5 and 2 mm plates equals 22 degrees at maximum plate input depth (12 mm). Herewith the increase of the plate thickness also increases the reflection coefficient of the phase shifter. However the difference between reflection coefficients for 2 and 5 mm plates in whole band of considered parameter values lies within 1.5 dB.

Applying the fluoroplastic plate doesn't change the dependence's characters. As fluoroplastic has lower dielectric permittivity than glass, to reach the same values of phase shift larger plates thickness are required. For instance, the 6 mm fluoroplastic plate with 6 mm thickness 12 mm depth of the plate position provide 12 degrees phase shift. The same shift can be acquired with the quarts glass plate with 2.5 mm thickness. And reflection coefficients of the phase shifter in both cases are approximately the same within 0.5 dB limit.

It is important to notice that without any dielectric objects in the waveguide the reflection coefficient from the power input equals -31.8 dB. It means that dielectric plate and bars have not much impact on the propagating wave and will not affect the performance of the TWR.

2. MOTION INLET

Two schemes of plate depth variation were proposed. Schematic views of the constructions are depicted on the Figs. 7 and 8. Construction is based on the application of the stepping motor. As the total weight of the phase shifter plate including the bars is less than 100 g (density of the fluoroplastic is $2.20 \cdot 10^3$ kg/m^3, quartz glass – $2.20 \cdot 10^3$ kg/m^3) it is possible to use low power stepping motors. Using the 40 mm diameter cog wheel for setting in motion the dielectric plate the stepping motors with quasi static synchronizing moment equal or larger than 0.2 kg·cm. Two discussed schemes are varied from each other by the method of setting in motion the cog wheel by the stepping motor.

Construction of the first type motion inlet is shown on the Fig. 7. On the figure plate 2 that is attached to the fluoroplastic bars 1 is set in motion with the cog wheel 3 that is connected to the stepping motor 4 [4]. At the rotation inlet cog wheel rotates and moves the metal plate along the rail runner 7. Case of the stepping motor is not vacuum-tight so it has to be placed outside the vacuum chamber 8. Axle is inserted inside the vacuum chamber through the vacuum-tight rotation movement input 9.

Second type of the plate movement is based on the stepping motor with vacuum-tight case 4 (see Fig. 8) [5]. This motor can be placed inside the vacuum volume because it doesn't cause pollution of the vacuum with the motor oil vapors.

Thus instead of rotating motion input inside the vacuum chamber it is enough to use vacuum-tight electrical wire input 8 inside of the chamber that simplifies the construction.

Both variants of stepping motors have possibility to operate in the mode of minimal angle step equal 1.8 degrees. In case of using the 4 cm diameter cogwheel gives the plate motion step equal 0.628 mm. So the phase tuning in the phase shifter reaches the accuracy of 1 degree/step within all phase shifter geometrical parameter values take in consideration.

At small values of plate disposition from the waveguide wall the accuracy reaches the values of around 0.2 degrees/step.

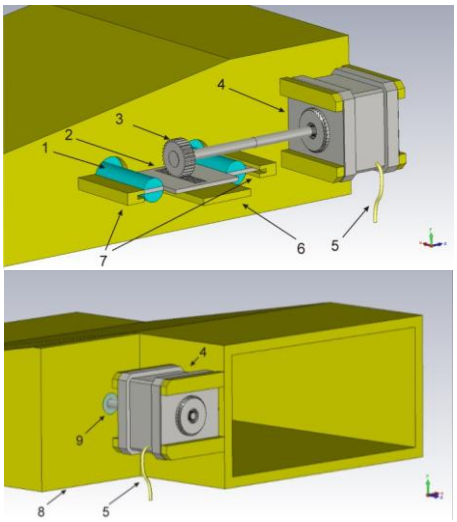


Fig. 7. Elements of the phase shifter based on conventional stepper motor: 1 – dielectric plate with bars; 2 – metal plate with grooves for motion transmission; 3 – shaft of the motor with cog wheel; 4 – stepper motor; 5 – electrical wires; 6 – supporting plate; 7 – guiding slots; 8 – vacuum casing; 9 – vacuum-tight inlet of the rotating motion

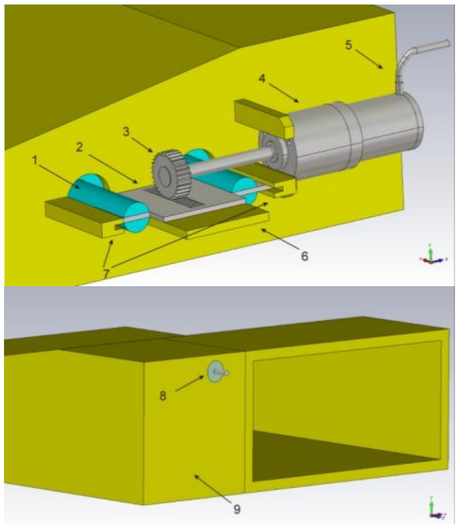


Fig. 8. Elements of the phase shifter based on vacuum-tight stepper motor: 1 – dielectric plate with bars; 2 – metal plate with grooves for motion transmission; 3 – shaft of the motor with cog wheel; 4 – stepper motor; 5 – electrical wires; 6 – supporting plate; 7 – guiding slots; 8 – vacuum-tight inlet of electrical wires; 9 – vacuum casing

Another important investigation is to analyze the part of the power from the waveguide that penetrates the motor section of the phase shifter through the circular holes for the holding bars. The power transmitting coefficient was measured for different values of plate disposition and different holes diameters. The results are show on the Fig. 9. Additionally the distribution of the electrical field distribution is presented on the Fig. 10. The figure depicts the case of 3.5 mm holes radii and disposition of the plate equal 7 mm (see Fig. 9). As it can be seen from the picture the part of the picture 9 the power branched into the motor section of the phase shifter doesn't exceed -40 dB for practically all values of holes radii. It can also be noticed from the Fig. 10 that amplitude of the electrical field is close to 0 in the motor section.

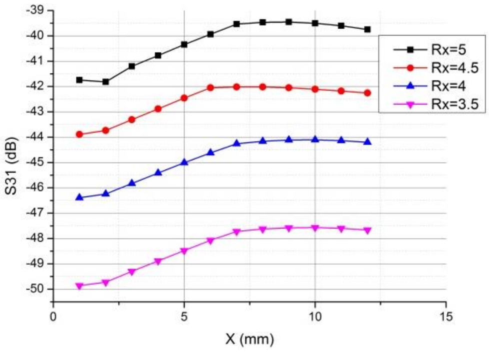


Fig. 9. Power branching coefficient from waveguide to the motor section of the phase shifter vs. Plate disposition and holes radii

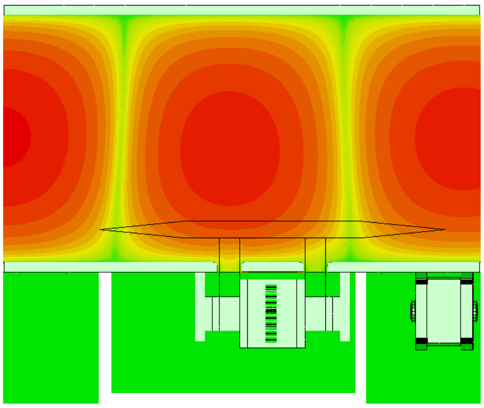


Fig. 10. Electrical field magnitude distribution

These results allow declaring that the motor section of the phase shifter doesn’t expose the action of the microwave radiation from the waveguide.

CONCLUSIONS

Waveguide phase shifter based on the dielectric material plate (quartz glass or fluoroplastic) seems out to be a good candidate for implementation of the phase shift of the microwave power circuating inside the travelling waveguide resonator. Due to optimized geometry of the phase shifter it provides low level of reflected power – 30 dB and provides enough width of phase shifting. This phase shifter also allows tuning the microwave field phase at MW values of power that is highly important in TWR application. Maximal phase shift on the exit of the phase shifter is reached on the plate displacement appeared to be 30 degrees at 5 mm plate thickness and 13 degrees at the 6 mm plate thickness. Two principal schemes of phase shifter elements arrangement were proposed. Motion input of perturbation plate is proceeded by conventional or vacuum-tight stepper motor.

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СИСТЕМА ФАЗОВОЙ ПОДСТРОЙКИ РЕЗОНАТОРА БЕГУЩЕЙ ВОЛНЫ

Т.В. Бондаренко, И.С. Щедрин

Описывается система фазовой подстройки в кольце резонатора бегущей волны (РБВ), основанная на волноводном фазовращателе. Фазовращатель представляет собой диэлектрическую пластину с низким уровнем диэлектрической проницаемости, располагающуюся внутри волноводного кольца РБВ вблизи узкой стенки волновода. Сдвиг фазы распространяющейся волны варьируется положением пластины относительно стенки волновода. Изменение положения диэлектрической пластины производится с помощью шагового двигателя, обеспечивающего высокую точность установки фазы, либо вручную. Приведены графики зависимостей электродинамических параметров фазовращателя в зависимости от положения диэлектрической пластины и ее параметров. Описаны несколько вариантов ввода движения в вакуумный объем.

СИСТЕМА ФАЗОВОЇ ПІДСТРОЙКИ РЕЗОНАТОРА БІГУЧОЇ ХВИЛІ

Т.В. Бондаренко, І.С. Щедрін

Описується система фазового підстроювання в кільці резонатора бігучої хвилі (РБХ), що заснована на хвилеводному фазообертачі. Фазообертач являє собою діелектричну пластину з низьким рівнем діелектричної проникності, що розташовується в середині хвилеводного кільця РБХ поблизу вузької стінки хвилеводу. Зсув фази хвилі, що поширюється, варіюється становищем пластини щодо стінки хвилеводу. Зміна положення діелектричної пластини проводиться за допомогою крокового двигуна, що забезпечує високу точність установки фази, або вручну. Наведено графіки залежностей електродинамічних параметрів фазообертача залежно від положення діелектричної пластини і її параметрів. Описано кілька варіантів введення руху у вакуумний об’єм.