NEW HIGH POWER VARIABLE-ATTENUATOR / PHASE-SHIFTER SYSTEMS

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Abstract

For the prebuncher and buncher of the electron linac, two kinds of waveguide systems were newly designed which can be used not only as a variable attenuator but also as a phase shifter. Either of the two systems has the distinctive feature that it does not introduce an rf phase shift as the attenuation is varied. This feature greatly speeds up the process of converging on optimum phase and power settings for both the prebuncher and buncher. The principles of the new systems are described.

Introduction

In the electron linac electron bunches are produced by the prebuncher and buncher. Since the characteristics of the beam are mainly determined by the bunches, it is very important to optimize the rf powers and phases in these devices. For the optimizing process, a system consisting of an attenuator and a phase shifter is necessary for each of these devices. However, the existing high-power variable attenuators have a problem in that a phase shift is introduced as the attenuation is varied. This fact makes it complicated to search for optimum parameters of the prebuncher and buncher. New systems were designed in order to solve this problem.

Presently, the new systems are under production for renewing the systems now in use in the Photon Factory 2.5-GeV electron linac. The system in use for the buncher is pressurized with SF_6, so that it requires rf windows which part the gas from a vacuum. Bored holes with small cracks were found on the vacuum sides of the windows this Spring. Fortunately, the holes still did not reach to the other side. In order to avoid this kind of problem, the new systems were designed so as to be used under vacuum, as are those of the positron generator in KEK.

Although the new systems are essentially very similar they look quite different at first glance. It might therefore be better to explain them separately.

Medium power system

In this section the system for medium power is discussed. The rf power required in the prebuncher is usually less than 10 kW. In this power range a dielectric substance is usually used for varying the power or phase. The attenuation can be altered by changing the position of a loss dielectrics in the waveguide: The attenuation becomes larger when the substance is moved toward the rectangular waveguide center where the field strength of the TE_{10} mode becomes maximum. Another type of attenuator has a rotary vane in a circular waveguide. In any case, the rf phase is inevitably shifted as the attenuator is changed.

On the other hand, the new system has the configuration illustrated schematically in Fig. 1. It is composed of a 20-dB directional coupler as a power divider, a 3-dB directional coupler with two short plungers which move independently and a dummy load for termination. The power for the prebuncher is provided from the main line for the buncher by the 20-dB power divider. Then, the power is divided again by a 3-dB directional coupler into two parts, each of which is reflected by a short plunger at a different position (Fig. 2); the two fields are then mixed by the same 3-dB coupler.

Let us consider a determination of the output power and the phase of the system. For simplicity, power losses in the waveguides or by reflections owing to imperfect devices are neglected in the discussions below. Let the input rf field be $2A\exp(i\omega t)$ at plane A as written in Fig. 1. The field is divided by the 3-dB directional coupler into two fields, as mentioned above, each of which is given at the upper short plunger after reflection by

$$\sqrt{2}A\exp[i(\omega t+\theta_1/2+\pi)] \tag{1}$$

and at the lower short plunger after reflection by

$$\sqrt{2}A\exp[i(\omega t+\theta_2/2+\pi+\pi/2)] \tag{2}$$

respectively, where

$$\begin{aligned} \theta_1 &= (l_c + \Delta l) / l_g, \\ \theta_2 &= (l_c - \Delta l) / l_g, \\ \theta &= (\theta_1 + \theta_2) / 2 = l_c / l_g, \\ \text{and} \quad \phi &= (\theta_1 - \theta_2) / 2 = \Delta l / l_g. \end{aligned} \tag{3}$$

Here, l_g is the wavelength in the waveguide. The phase difference $\pi/2$ in Eq. (2) comes from the 3-dB coupler and π in Eqs. (1) and (2) indicates the phase shift as the fields are reflected at the short plungers. Each amplitude is reduced to $\sqrt{2}A$ since the input power is equally divided into two. The fields reflected by the short plungers are mixed by the same 3-dB coupler and become at plane A in the input port as

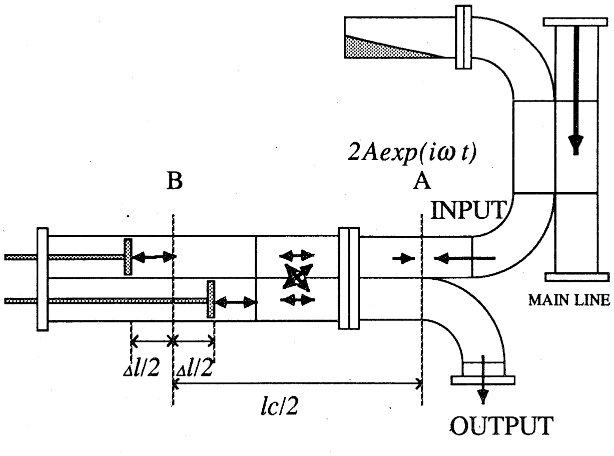

Fig. 1 The attenuator/phase-shifter system for medium power. Bold arrows indicate directions of field flows.

$$Re[A\exp\{i(\omega t+\theta_1+\pi)\} + A\exp\{i(\omega t+\theta_2+2\pi)\}]$$
$$= 2A\sin\phi\ \sin(\omega t+\theta) \qquad (4)$$

and at the same plane A in the output port as

$$Re[A\exp\{i(\omega t+\theta_1+3\pi/2)\} + A\exp\{i(\omega t+\theta_2+3\pi/2)\}]$$
$$= 2A\cos\phi\ \sin(\omega t+\theta), \qquad (5)$$

respectively.

It can be seen from Eq. (3) that ϕ and θ depend only on Δl and l_c, respectively. This means that the output power or phase can be adjusted independently by means of moving the plungers in the opposite or the same direction by equal amounts, respectively. The output power is changed without shifting the output phase in the full range from zero to the input power according to ϕ; on the other hand, the output phase θ is given by the average phase of the two fields before being added. Thus, the new system has functions both of an attenuator and a phase shifter, as mentioned before.

The backward power returned to the input port is mainly absorbed by the dummy load connected at a port of 20-dB directional coupler. The part of the power turns back to the source through the 20-dB directional coupler. This is, however, less than - 40 dB of the main line power, because the returning power to the source passes through the 20-dB coupler two times. Hence, this becomes negligibly small in practical use.

Although the plunger control becomes complex, because it is necessary to shift two plungers independently and simultaneously, the new system becomes simpler and more compact since it requires no additional phase shifter.

High-power system

Let us next consider the system for high rf power. The medium-power system mentioned above has a simple configuration. However, this system is not suitable for use under high power, because in the high-power system it might usually be impossible to use a very weakly coupled power divider as the 20-dB coupler in the medium-power system. Without a weak coupler, high power might turn back to the source and destroy it. Even if a circulator is adopted, the transient part of the pulsed power might be turned back to the source.

Accordingly, another new attenuator/phase-shifter system was designed for high power, so that the reflected power is perfectly absorbed by a dummy load, at least in principle, and does not turn back to the source. The new system is illustrated schematically in Fig. 2. It consists of four 3-dB directional couplers combined in a body, two of which have short plungers, and two dummy loads. In this case, the short plungers at a 3-dB coupler are joined and move together, but each of the joined plungers move independently. The system consisted of a 3-dB coupler and joined short plungers is the well-known phase shifter.

Let us now see how works the new system. Let the input rf field be $2A\exp(i\omega t)$ at the plane A in Fig. 2 as same as the previous case. The input power is divided at the first 3-dB coupler into two parts, each of which is given at the plane B as

$$\sqrt{2}A\exp[i(\omega t+\delta)] \qquad (6)$$

and at the plane B' as

$$\sqrt{2}A\exp[i(\omega t+\delta+\pi/2)], \qquad (7)$$

respectively. The phase δ corresponds to the electrical length between planes A and B. It has been assumed for simplicity that planes B and B' or C and C' are symmetric with respect to the central plane of the system. After

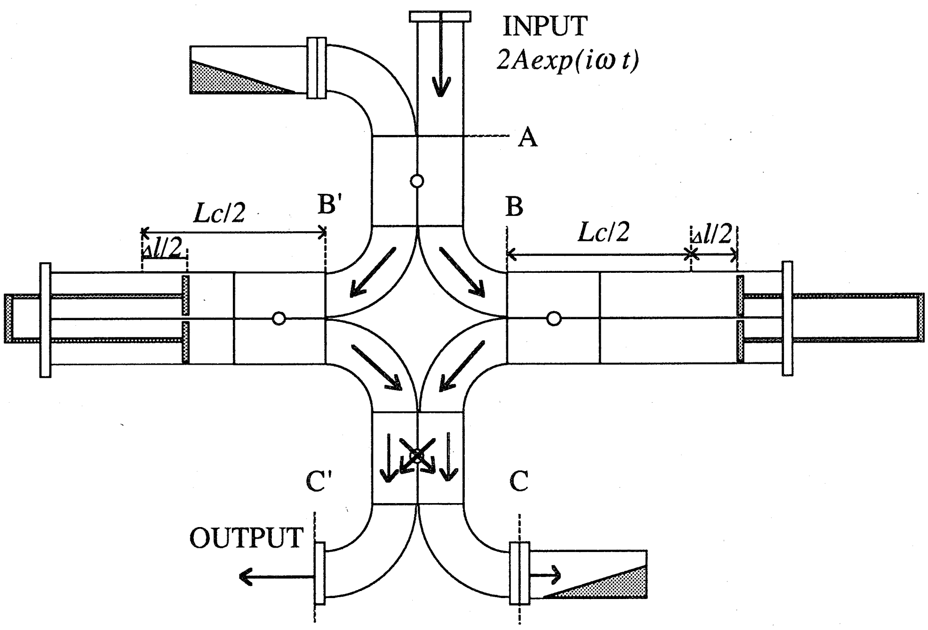

Fig. 2 The attenuator/phase-shifter system for high power. Bold arrows indicate directions of field flows.

passing through the corresponding phase shifter, each field becomes at the exit plane B of the right phase shifter as

$$\sqrt{2}A\exp[i(\omega t+\theta_1'+\pi)] \tag{8}$$

and at the exit plane B' of the left phase shifter as

$$\sqrt{2}A\exp[i(\omega t+\theta_2'+3\pi/2)], \tag{9}$$

respectively, where

$$\theta_1' = (l_c + \Delta l) / l_g + \delta + \pi/2$$

and

$$\theta_2' = (l_c - \Delta l) / l_g + \delta + \pi/2. \tag{10}$$

The phase θ_1' corresponds to the electrical length from plane A to exit-plane B of the phase shifter. The fields given above by (8) and (9) are mixed by the next 3-dB directional coupler. Then, the final fields are given by equations at the plane C as

$$\begin{aligned}&Re[A\exp\{i(\omega t+\theta_1+\pi)\} + A\exp\{i(\omega t+\theta_2+2\pi)\}]\\&= 2A\sin\phi\,\sin(\omega t+\theta)\end{aligned} \tag{11}$$

and at the plane C' in the output port as

$$\begin{aligned}&Re[A\exp\{i(\omega t+\theta_1+3\pi/2)\} + A\exp\{i(\omega t+\theta_2+3\pi/2)\}]\\&= 2A\cos\phi\,\sin(\omega t+\theta),\end{aligned} \tag{12}$$

where

$$\begin{aligned}\theta_1 &= \theta_1' + \delta' = (l_c+\Delta l) / l_g + \delta + \delta',\\ \theta_2 &= \theta_2' + \delta' = (l_c-\Delta l) / l_g + \delta + \delta',\\ \theta &= (\theta_1 + \theta_2) / 2 = l_c / l_g + \delta + \delta',\end{aligned} \tag{13}$$

and $\phi = (\theta_1 - \theta_2) / 2 = \Delta l / l_g.$

The phase δ' corresponds to the electrical length between planes B and C, or B' and C'.

Equations (11) and (12) are exactly the same as (4) and (5), respectively. Although phases θ_1, θ_2 and θ defined by Eq. (13) are slightly different from those of Eq. (3), the difference $\delta+\delta'$ is not important since it is the constant phase. Therefore, the two new systems are equivalent. Owing to the equations obtained above, it is concluded that this system has the same functions explained in the previous section. The difference is that as the two plungers shift in the same direction the attenuation changes, and as they move in the opposite direction the output phase shifts. Of course it is possible to change both the output power and the phase simultaneously by means of shifting the two plungers independently (by moving the short plungers to the different amounts). This operation mode is useful when the rf optimum settings are different, but are determined in every beam, because it becomes easier to switch over one setting to another. This feature also holds for the medium-power system.

Now let us compare the characteristics of the new high-power system with those of the high-power variable attenuator now in use which has a straight waveguide instead of the phase shifter shown on the right-hand side in Fig. 2. In this case, only the phase of one field is changed; then, the output field is given by

$$\begin{aligned}&Re[A\exp\{i(\omega t+\theta_1+\pi/2)\} + A\exp\{i(\omega t+\theta_2+3\pi/2)\}]\\&= 2A\sin\phi\,\cos(\omega t+\theta),\end{aligned} \tag{14}$$

where

$$\begin{aligned}\theta_1 &= \delta'',\\ \theta_2 &= \theta_2' + \delta' = (l_c-\Delta l) / l_g +\delta+\delta'+ \pi/2,\\ \theta &= (\theta_1 +\theta_2) / 2 = [(l_c-\Delta l) / l_g +\delta +\delta'+\delta''+\pi/2]/2,\end{aligned} \tag{15}$$

and

$$\phi = (\theta_1 -\theta_2) / 2 = - [(l_c-\Delta l) / l_g +\delta +\delta'-\delta''+\pi/2]/2.$$

The phases θ and ϕ both depend on $(l_c-\Delta l)/2$, as indicated in Eq. (15). It is therefore impossible to keep the output phase constant as the attenuation is varied. Figure 3a clearly shows this feature in the case that the phase of a field is shifted by $\pi/2$. The added fields before and after the shift are shown by arrows A and B, respectively. Not only the resultant amplitude is changed from 2 to $\sqrt{2}$, but the phase also shifts by as much as $\pi/4$. For a comparison, the corresponding figure for the new system is illustrated in Fig. 3b. In this case, the resultant field is changed from A to B without any phase shift.

Summary

Two waveguide systems which can be used as a variable attenuator and a phase shifter are newly designed. Either of the two systems has the distinctive feature that it does not introduce an rf phase shift as the attenuation is varied. Hence, it is expected that the process of converging on optimum phase and power settings for the prebuncher and buncher will be greatly speeded up by the new systems.

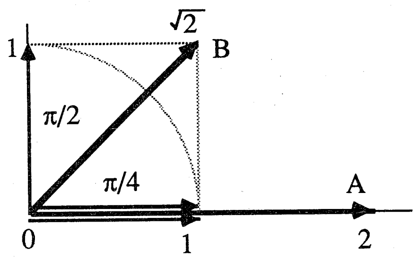

Fig. 3a Addition of two fields in the attenuator now in use. The resultant field changes from A to B.

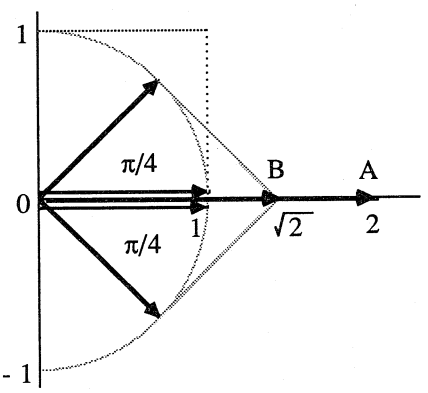

Fig. 3b Addition of two fields in the new system. The resultant field changes from A to B.