Investigation of Novel Waveguide Phase Shifters for High Power Applications

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Abstract— High-power phase shifter that can on-line adjust the transmit phase of high-power microwave (HPM) is of great interest. The traditional phase shifters can not satisfy the power capacity requirement. There is a pressing need to come up with new alternative phase shifters. In this paper, two kinds of waveguide phase shifters are investigated. To increase the power capacity, no dielectric is introduced, and they are all mechanical phase shifters. Both the phase shifters are with high transmission efficiency over 99% and high power capacity over 300 MW in the vacuum.

1. INTRODUCTION

High-power phase shifter that can on-line adjust the transmit phase of high-power microwave (HPM) is of great interest [1, 2]. It has an extensive application in mode converter, high power array antenna and others [3–6]. Ferrite phase shifter [7] and PIN diode phase shifter [8] are the two well developed phase shifters that can be applied in above mentioned fields. However, they can not be applied directly for high-power applications because ferrite and semiconductor has limited power handling capacity [9, 10]. In view of such limitation, it is a pressing need to come up with novel phase shifters for high-power applications.

In this paper, two kinds of waveguide phase shifters are investigated. To increase the power capacity, no dielectric is introduced, and they are all mechanical phase shifters. The first one named waveguide-inserting-fin phase shifter. The inserting-fin changes the transmission constant of the microwave. 360 degree phase shift can be obtained by adjusting the length of the inserting metal fin. The advantage of this phase shifter is that the microwave propagation keeps on the same direction but with longer longitudinal length. The second one named narrow side slot-waveguide phase shifter. It is designed based on 3 dB power divider of waveguide Slot Bridge. The difference is using adjustable metal choke piston at the terminal position of the power divider. Then, it can realize 360 degree phase shift by adjusting the choke piston position. Both the phase shifters are with high transmission efficiency over 99% and high power capacity over 300 MW in the vacuum.

2. WAVEGUIDE-INSERTING-FIN PHASE SHIFTER

Figure 1 is the scheme of the waveguide-inserting-fin phase shifter. The rectangular waveguide is divided to four regions by metal fin 1 and fin 2 in the middle of the waveguide perpendicular to the broad wall, the input TE10 mode microwave in region 1 then changes to two TE10 mode in region 2 and region 3, respectively. And the two TE10 modes finally combined again to TE10 mode in region 4. It is known that the transmission constant in region 2 and region 3 is different from that in region 1 and region 4 [11]. Fin 1 is fixed to the waveguide, and fin 2 can be sliding in and out into fin 1 to change the transmission length L of the two TE10 modes, resulting in the phase shift of the microwave. The convex 1 and 2 are used to diminish the reflections.

As an example, a phase shift operates at frequency 9.5 GHz is designed. The wide side dimension a is 40 mm, the narrow side dimension b is 20 mm; thickness of fin 1 and 2 is 5 mm and 1 mm, respectively. The dimensions of the convex 1 and 2 are optimized.

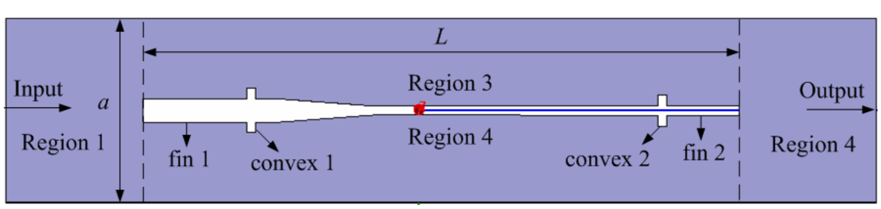

Figure 1: Scheme of the waveguide-inserting-fin phase shifter.

Figure 2 displays the electric field distribution inside the waveguide-inserting-fin phase shifter. It shows the microwave propagation process. Besides, it can be seen that there is no obvious electric field enhancement during the adjustment of the position of fin 2, the maximum field is 3.226 kV/m during the adjustment when the inject power is 1 W. It is known that the breakdown electric field is about 30 kV/cm in the normal condition, however, according to Kilpatrick criterion [12] in the vacuum condition $f = 1.643E^2e^{-8.5/E}$, where f is the frequency (MHz); E is the corresponding breakdown electric field (MV/m), so the breakdown electric field is about 80.178 MV/m for microwave at 9.5 GHz in the vacuum. Then it can be obtained that a waveguide-inserting-fin phase shifter has a power capacity larger than 864.8 kW and 617.8 MW in the atmosphere and vacuum, respectively.

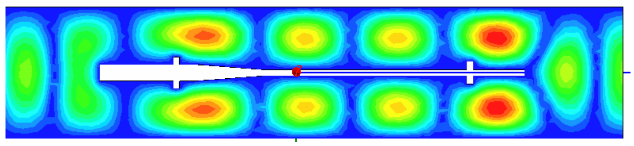

Figure 2: Electric field distribution inside the waveguide-inserting-fin phase shifter.

Figure 3 presents the phase shift and transmission coefficient versus the transmission length L changed by sliding fin 2. From the simulation results by electromagnetism software, the transmission efficiency keeps over 99% when the phase shift reaches 360 deg. The phase shift reaches 4.1 deg per millimeter. The fin 2 need to slide about 87.8 mm to achieve 360 deg phase shift, and the whole length of this phase shift structure need about 200 mm. The advantage of this phase shifter is that the microwave propagation keeps on the same direction but with longer longitudinal length.

3. NARROW SIDE SLOT-WAVEGUIDE PHASE SHIFTER

Figure 4 is the structure of the narrow side slot-waveguide phase shifter. The structure is similar to the 3 dB power divider of the waveguide slot bridge and the operate mechanism is also similar. The microwave is in TE10 mode in port 1, and transforms to TE20 mode in the region of narrow side slot. By designing the length L of the narrow side slot and the wide side dimension of the slot region a, the power can be equally divided to port 2 and port 3. Different from the power divider, here we use the choke piston at the terminal position of the power divider. Then, the microwaves in port 2 and 3 are reflected to port 4. Optimizing the dimension L and a can obtain high transmission efficiency in port 4. Moreover, the output phase in port 4 can be changed by adjusting the length ΔL. It can realize 360 degree phase shift by adjusting the choke piston position.

Taking 14.25 GHz microwave as an example, a narrow side slot-waveguide phase shifter is designed. The wide side dimension and narrow side dimension of port 1, port 2, port 3 and port 4 is 15.8 mm and 10.16 mm, respectively. The length L of the slot is 24.14 mm, the wide side dimension a' is 30.6 mm, the wall thickness h is 2 mm.

Figure 5 displays the electric field distribution inside the narrow side slot-waveguide phase shifter. It also shows the microwave propagation process. The maximum field is 5.501 kV/m

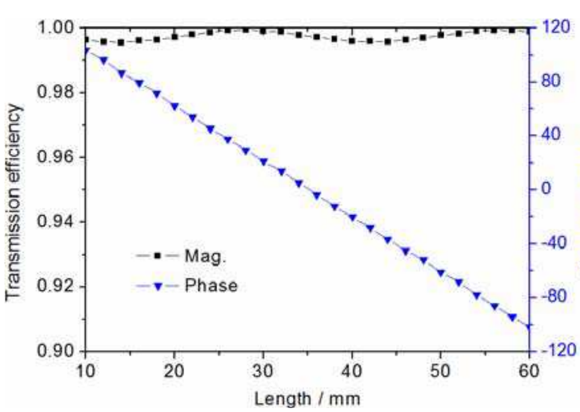

Figure 3: Phase shift and transmission efficiency versus the transmission length L.

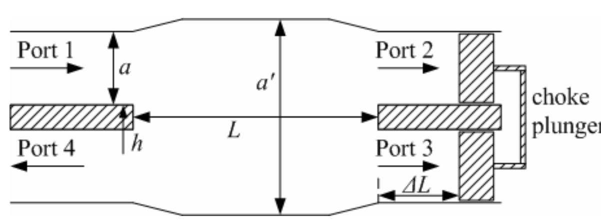

Figure 4: Scheme of the narrow side slot-waveguide phase shifter.

during the adjustment of ΔL when the inject power is 1 W. As calculated above in Section 2, it can be obtained that the breakdown threshold for Ku band 14.25 GHz in the vacuum is 97.3 MV/m. Then, such a narrow side slot-waveguide phase shifter has a power capacity larger than 297.4 kW and 312.8 MW in the atmosphere and vacuum, respectively.

Figure 6 presents the phase shift and transmission coefficient versus the length ΔL adjusted by the choke piston. From the simulation results by electromagnetism software, the transmission efficiency keeps over 99% when the phase shift reaches 360 deg. The phase shift reaches 23.12 deg per millimeter. The choke piston need to slide about 15.6 mm to achieve 360 deg phase shift, and the whole length of this phase shift structure need about 70 mm. The advantage of this phase shifter is that this kind phase shifter has high power handling capacity with relatively small size. And it is easy to be realized in engineering. The choke piston can be drive by stepper motor.

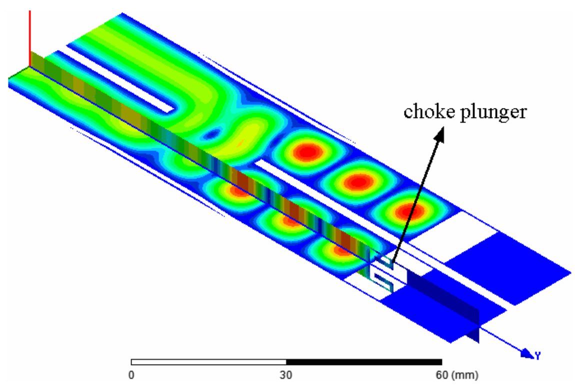

Figure 5: Electric field distribution inside the narrow side slot-waveguide phase shifter.

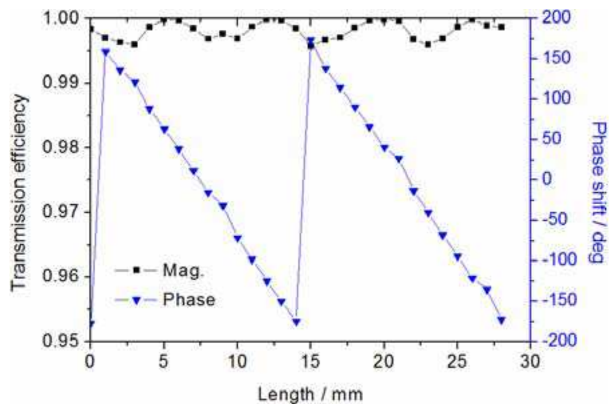

Figure 6: Phase shift and transmission efficiency versus the transmission length L.

4. CONCLUSIONS

Phase shifter, as a key device of array antenna used to adjust the output phase of HPM, is urgently needed to be investigated since the common phase shifter can not satisfy the HPM applications. In this paper, two kinds of phase shifters that adjust the output phase of HPM are put forward. Both the phase shifters are with high transmission efficiency over 99% and high power capacity over 300 MW in the vacuum. Researchers can choose a phase shifter according to their applications.

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