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A Single-Layer Hollow-Waveguide 8-Way Butler Matrix with Modified Phase Shifters

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1 Introduction

The authors proposed a beam-switching antenna consisting of a Butler matrix and a slot array integrated on a single-layer dielectric substrate to reduce the connection loss between them, especially in millimeter-wave bands [1]. The Butler matrix consists of hybrids, cross couplers and phase shifters. For the single-layer configuration, the hybrids and the cross couplers are constructed by short-slot couplers. Length reduction of the short-slot couplers in post-wall waveguides have been proposed [2].

In this paper, the authors apply the similar reduction method to hollow waveguides. The post-wall waveguide is a dielectric-filled waveguide and the measured transmission loss is 0.039 dB/cm at 25.6 GHz. On the other hand, a hollow waveguide has very low loss and the calculated transmission loss is 0.004 dB/cm at 22 GHz. The loss of the full structure of an 8-way Butler matrix using hollow waveguides is estimated to be only 0.2 dB. Figure 1 is the block diagram of the 8-way Butler matrix. The numbers in circles are phase shifters and they correspond to the amount of phase shift in units of $-\pi/8$. In order to realize many divisions in a single layer waveguide, many cross couplers are arranged. The length reduction of the couplers, especially the cross couplers, is important in order to miniaturize the full structure. By the proposed method, the cross coupler is 50% shorter than the conventional design method [2]. The total length of the Butler matrix is also reduced to half by using the length-reduced couplers. Since the frequency characteristics of the phase shifters in the prototype matrix (Fig.2 (a)) are poor, the overall characteristics of the matrix are not good. Then, the structures of the phase shifters is modified as is shown in Fig.2(b). Although the size is slightly larger than the prototype one, the frequency dependencies of the phase difference are suppressed. The design procedure of couplers are discussed in ref.[2], we focus on phase shifters in this paper.

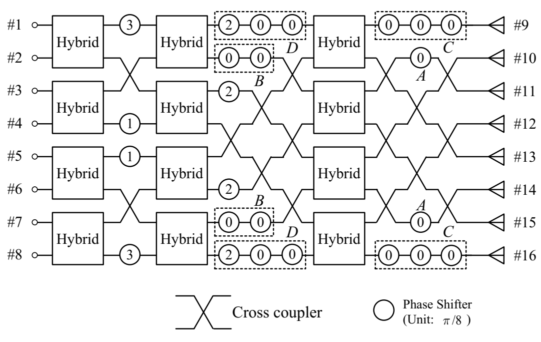

Figure 1: The configuration of an 8-way Butler matrix.

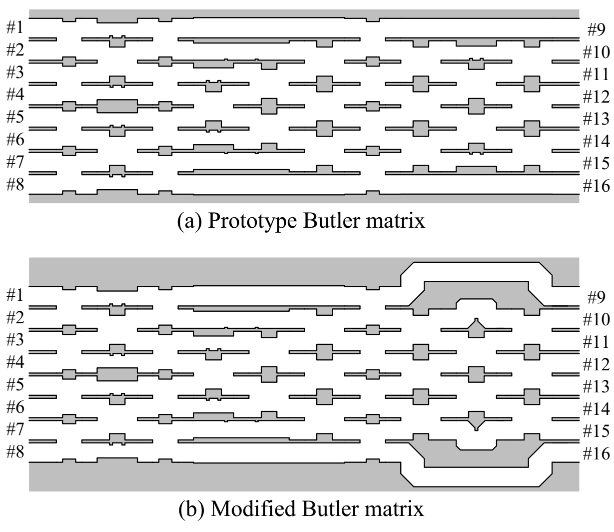

Figure 2: The top view of a single-layer hollow-waveguide 8-way Butler matrix.

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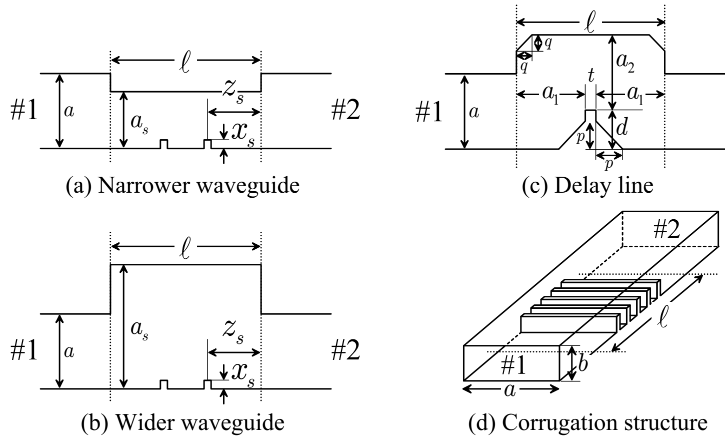

Figure 3: The structures of the phase shifters.

2 Design of the phase shifters

A signal inputted at different input ports in a Butler matrix produces a different phase taper among the output ports [3]. Inputs from the eight ports of an 8-way Butler matrix give eight switching beams. In the matrix, the phase shifters require phase shifts of 0 deg, -22.5 deg, -45 deg and -67.5 deg at proper places shown in Fig.1. The phase shifters are designed by the Method of Moments (MoM) [4]. Two- or three-cascaded phase shifters enclosed by a dashed line in Fig.1 are replaced with one phase shifter in the design.

The phase shift is defined as the difference in transmission phase between a cross coupler and a phase shifter. It is obtained by changing the waveguide width a_s as is shown in Fig.3(a), (b). Reflection is suppressed by two walls near the side wall. A narrower or wider waveguide width a_s of the phase shifter gives phase positive (progression) or negative (delay), respectively. Required phase shifts in the Butler matrix are basically "negative". This negative phase shift is actually realized by a progressive phase shifter adding 360-degree progression. Wider-width phase shifters with delay are difficult to be arrayed due to space limitation in a Butler matrix. The narrower-width phase shifters are adopted except phase shifters D in the prototype Butler matrix even though a wider-width phase shifter (b) has a wider band width than a narrower one (a). Since the waveguide width in the wider-width phase shifter exceeds the cutoff of the higher-order modes, such as the TE_{20} and TE_{30} modes, in order to obtain the required phase shift, the reflection suppression is difficult. The design parameters of the phase shifters are summarized in the left column of Table 1. In the phase shifter C and D, good reflection characteristics are obtained without walls near the side wall. Figure 4 shows the frequency characteristics of the phase shift. The frequency variation is larger in a phase shifter with a smaller amount of phase shift. The frequency tendency of the phase shifters B, C and D are opposite to that of the others.

In the prototype model, the phase shifts are realized by changing the phase constant of the TE_{10} mode. Since the transmission phase is a product of the phase constant β and a path length ℓ. A phase delay is obtained by extending the path length. Figure 3(c) is a phase shifter based on this idea. The a_2 is equal to the waveguide width a. The phase delay is specified by d. Reflection is suppressed by p and q. The 0 deg phase shifter A which has the largest frequency variation of the phase shift is replaced by the structure (c). To arrange the phase shifter A in the single-layer waveguide Butler matrix, the phase shifter C is also modified. The design parameters of the modified phase shifters A and C are shown in the right column of Table 2. Figure 4 shows the frequency characteristic. The modified A and C have similar frequency tendency. The frequency variations of the phase shift in the prototype phase shifter over a 2 GHz band are −86.5 deg and 52.9 deg, respectively. The variations of the modified phase shifters are 22 deg. The corrugation structure, such as Fig.3(d), also causes a phase delay. Since the width of the structure is same as waveguide width a, the modification of adjacent components is not needed.

3 Characteristic of the Butler Matrix

Figure 2 shows the top view of the single-layer hollow-waveguide 8-way Butler matrix. The total size of the matrix is 303.14 mm $\times$ 133.364 mm which corresponds to $17.71\lambda_g \times 7.5\lambda_g$. The whole structure is uniform along its height. The characteristics of the full structure of the matrix calculated by Ansoft HFSS are summarized in Table 2. The ideal dividing characteristics are $1/8 = -9.03$ dB in amplitude and a linear phase taper between adjacent output ports. Reflection to each input port is less than −30 dB. The amplitude error for input port $\#n$ is defined as the difference between the maximum and minimum amplitudes among all the output ports when port $\#n$ is excited. The amplitude error for each port is less than 0.4 dB. The insertion loss for input port $\#n$ due to the conductivity of the metal is estimated by substracting the total output power ($= \sum_{m=9}^{16} |S_{m,n}|^2$, $n = 1, 8$) from the input power (= 1). The insertion loss for each port is less than 0.20 dB. This value is almost equal to the sum of the losses of the components estimated individually: $3 \times Loss_{\mathrm{Hybrid}} + 7 \times Loss_{\mathrm{Cross\ coupler}} + 9 \times Loss_{\mathrm{Spacing}} + 2 \times Loss_{\mathrm{Input}} = 3 \times 0.010\ \mathrm{dB} + 7 \times 0.014\ \mathrm{dB} + 9 \times 0.004\ \mathrm{dB} + 2 \times 0.015\ \mathrm{dB} = 0.17\ \mathrm{dB}$. The phase error for input port $\#n$ is defined as the difference between the ideal and the average of the phase difference between adjacent output ports. The phase error for each port is less than 0.5 deg. Figure 6 shows the frequency characteristics of the phase difference between adjacent output ports. The variation of phase difference depending on the frequency is smaller in the modified matrix than in the prototype one. The directivity for input port $\#n$ is calculated by an 8×16 infinitesimal magnetic dipole array excited by the matrix, where the element spacings in each direction are 12.268 mm and 6.81 mm $= \lambda_0/2$. The amplitude difference between the ports is 3.1 dB due to the element pattern of the magnetic dipole. The differences between this directivity and the directivity calculated from ideal power division are less than 0.02 dB.

4 Conclusions

The authors propose a planar 8-way Butler matrix in a single-layer hollow-waveguide at 22 GHz. The total size of the matrix is $17.1\lambda_g \times 7.5\lambda_g$. The calculated loss of the whole structure is only 0.2 dB. The phase shifter is modified and the phase difference variation is suppressed to 45 deg from 85 deg in the overall characteristics of the Butler matrix. Measured characteristics will be presented.

References

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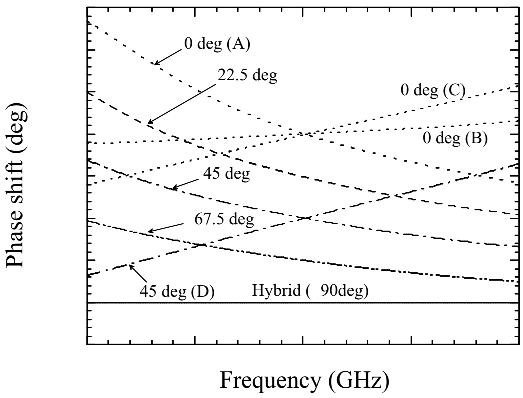

Figure 4: The frequency characteristics of phase shifters (prototype).

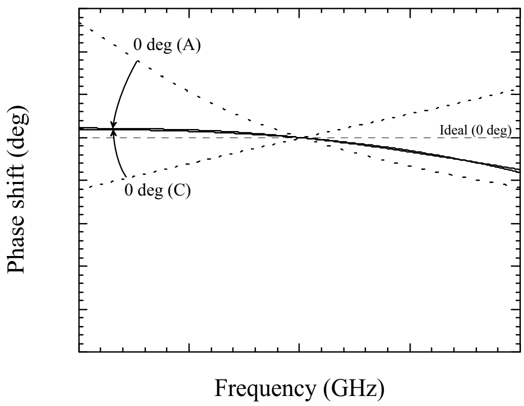

Figure 5: The frequency characteristics of phase shifters (modified).

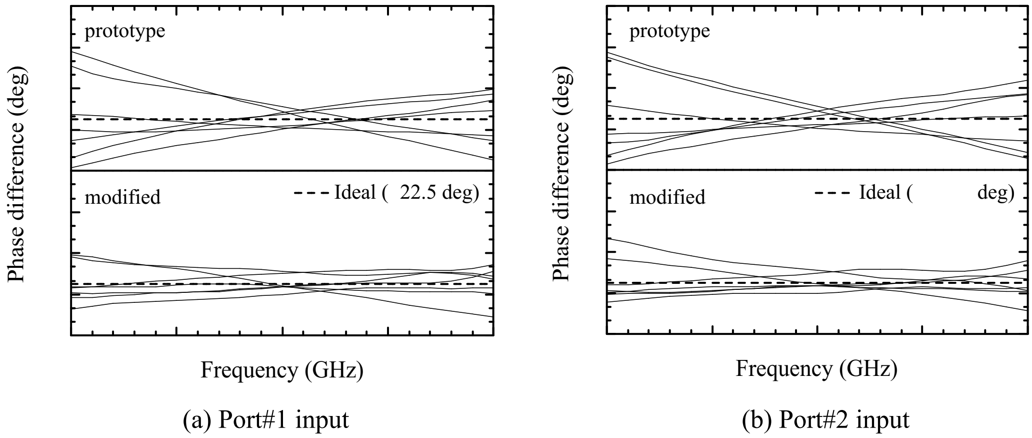

Figure 6: The phase difference between adjacent output ports

Table 1: Design parameters of the phase shifters.
(The corresponding structures are left: Fig.3(a), right: Fig.3(c))

	0 deg (A)	−22.5 deg	−45 deg	−67.5 deg
a_s	7.74 mm	7.90 mm	8.05 mm	8.25 mm
x_s	0.96 mm	1.04 mm	1.07 mm	1.15 mm
z_s	8.17 mm	7.98 mm	7.86 mm	7.68 mm
	0 deg (B)	0 deg (C)	−45 deg (D)	
a_s	9.45 mm	10.64 mm	11.08 mm	
x_s	0.60 mm	–	–	
z_s	17.96 mm	–	–	

	0 deg (A)	0 deg (C)
d	5.51 mm	13.41 mm
a_1	10.295 mm	13.00 mm
a_2	10.668 mm	10.668 mm
t	1.60 mm	57.37 mm
p	2.30 mm	7.17 mm
q	3.99 mm	8.62 mm

Table 2: Characteristics of the 8-way Butler matrix.

Input port #	#1	#2	#3	#4	#5	#6	#7	#8
Reflection (dB)	−33.7	−31.7	−38.9	−30.9	−30.3	−38.7	−35.0	−33.3
Ideal output amplitude (dB)	−9.03	−9.03	−9.03	−9.03	−9.03	−9.03	−9.03	−9.03
Average output amplitude (dB)	−9.22	−9.23	−9.22	−9.23	−9.23	−9.23	−9.22	−9.22
Amplitude error (dB)	−0.20	−0.22	−0.34	−0.20	−0.17	−0.31	−0.22	−0.25
Insertion loss (dB)	0.19	0.19	0.19	0.20	0.20	0.19	0.19	0.19
Ideal phase difference (deg)	−22.5	157.5	−112.5	67.5	−67.5	112.5	−157.5	22.5
Average phase difference (deg)	−22.1	157.8	−112.0	68.0	−67.9	112.1	−158.0	22.0
Phase error (deg)	0.4	0.3	0.5	0.5	−0.4	−0.4	−0.5	−0.5
Directivity (dBi)	28.2	25.2	26.0	26.9	26.9	26.0	25.2	28.2