Four-Way Butler Matrix of Double-Layer Rectangular Waveguides using Broad-Wall Slit Coupling

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Abstract

The authors design and fabricate a full double-layer structure of rectangular waveguides for a four-way Butler matrix for a band from 3.9GHz to 4.1GHz. The waveguide Butler matrix is expected to be used for a multi-beam antenna in mobile communications at high frequencies. Use of slits in the hybrids and the phase shifters enhances the bandwidth of the dividing characteristics of Butler matrix in comparison with use of slots. The maximum of the amplitude difference among the output port is 3.1dB and the phase deviation from the desired value is 5.2 deg over the 200MHz bandwidth.

1. INTRODUCTION

Multibeam antennas have been discussed for base station antennas in mobile communications at high frequencies in order to enhance antenna gain and to reduce interferences at the same frequency. The Butler matrix [1] is one of feed circuits for forming multibeams. In principle, a power from one of the input ports is equally distributed into all the output ports and no power is reflected to all the input ports. Phase differences among the output ports are different for each input port and a main beam is effectively formed in a different direction. The Butler matrix includes some line crossovers in conventional configurations. Double-layer configuration using microstrip lines were proposed to dispense with the crossovers [2][3]. However the transmission loss of a microstrip line is so large at high frequencies that the Butler matrix using microstrip lines cannot be used. Hollow waveguides have to be used at such high frequencies because of negligibly small transmission loss. Conventionally crossovers using waveguides were so complicated that simple configuration should be invented.

The authors proposed a novel double-layer configuration using rectangular waveguides [4]. The double-layer structure is constructed by use of hybrids with broad-wall coupling and change of layers at places for phase shifters. The phase shifters are also realized with broad-wall coupling between two shorted waveguides. In [4], a four-way matrix was designed and manufactured at 8.45GHz. However, the broad-wall coupling in was obtained by slots, so that the frequency bandwidth was narrow due to the resonance of the slots. In this paper, the authors design and manufacture a four-way matrix using the broad-wall coupling by slits, which are cut in the transverse direction all over the broad-wall, both in the hybrids [5] and the phase shifters [6] to enhance the bandwidth for a band from 3.9Ghz to 4.1GHz.

2. DOUBLE-LAYER CONFIGURATION OF BUTLER MATRIX

Fig.1 shows the block diagram of the eight-way Butler matrix as an example. The input ports are at the bottom and the outputs are at the top in the figure. The names of the input ports correspond to the beam direction (L: left, R: right, 1: smaller tilting angle ˜ 4: larger one) (1). The Butler matrix consists of 3dB hybrids and phase shifters. The numbers in the circles for the phase shifters are required an amount of phase shift in degrees. Both the hybrids and the phase shifters are composed in double layers. Then the Butler matrix is realized fully in double layers where the solid lines are on the upper layer and the dotted lines are on the lower layer as shown in Fig.1. Change of layers occurs only at places for the phase shifters. No crossings exist on the same layer. The four-way configuration consists of four hybrids and two phase shifters (the required amount is 45 degrees in the both), which are the right-bottom or left-bottom part of the eight-way one. The four-way structure is also in double layers on the whole. The configuration of 2^n beams is realized in double layers in the same manner.

Fig.2 shows the waveguide layout for eight beams using hybrids and phase shifters with broad-wall coupling. Waveguides in the upper layer are presented in grey. The lower-layer waveguides are turned over right and left with respect to the upper-layer ones as shown by dashed lines in the figure. Bends are inserted equally in all the waveguides so that no phase difference occurs among the output ports due to them. Fig.3 shows the structure of the hybrid. The structure is symmetrical with respect to the center. Slits are cut all over the common broad-wall of two waveguides. The height of the narrow-wall width should be less than a quarter of the free-space wavelength so that the height of the coupled region should be smaller than a half of the wavelength not to propagate the higher modes there. The number of the slits should be determined for required bandwidth. The slit widths and the distances between adjacent slits are designed to get –3dB coupling with 90-degree difference in the two output ports and to suppress reflection to the two input ports. Fig.4 presents the structure of the phase shifter. Slits are cut all over the common broad-wall of two shorted waveguides. The structure is symmetrical with respect to the center. The number of the slits should be determined for required bandwidth. The slit width is controlled to get required phase shift. The slit position from the shorted plate is determined to suppress reflection. The phase shifter as well as the hybrid is analyzed by the mode matching method. The dimensions are determined by the genetic algorithm and the modified Powell's method [7].

3. EXPERIMENTAL RESULTS

The hybrid is designed to suppress the reflection below -30dB, the amplitude difference between the two output ports less than 1.25dB and the phase difference within 89.5-90.5 deg. for a band from 3.9GHz to 4.1GHz. The number of the slits is three for these specifications. The broad-wall width a is 58.17mm, the narrow-wall width b is 14.5mm and the wall thickness t is 1.6mm. The slit widths l_1 and l_2 are 1.77mm 5.34mm and the slit spacing s_1 is 29.80mm. Fig.5 shows the reflection S_{11}, Fig.6 shows the amplitude at the output ports and Fig.7 shows the phase difference between the output posts. The calculated results satisfy the above-mentioned specifications. The measured reflection is below -17.5dB over 3.9-4.1GHz as shown in Fig.5. The too thin slits could make the reflection worse in the fabrication. The isolation is not measured but it is expected to be almost equal to the reflection. In the measurement, the amplitudes to the two output ports are equal at 4.05GHz, which is shifted from the center frequency, as shown in Fig.6. In the band of 3.9GHz - 4.1GHz, the maximum of the amplitude difference is 2.0dB. As for the phase difference, it is -89.2deg – -89.5deg over 3.9GHz-4.1GHz as shown in Fig.7. The phase deviation for frequency is very small.

The 45-degree phase shifter is designed to suppress the reflection below -30dB, the phase difference within 42deg – 48deg for the band from 3.9GHz to 4.1GHz. The number of slits is two. Fig.8 presents the reflection and the transmission phase for the slit width l_1 of 4.38mm and the slit positions s_0 and s_1 of 0.80mm and 1.05mm. These are calculated results because the phase shifter has not been fabricated yet. The shift of 45 degrees is obtained at 4.05GHz, which is a bit moved from the center frequency of 4.0GHz. The reflection is below -30dB and the transmission phase is -41.5deg - -46.0deg over the above bandwidth.

The four-way Butler matrix is designed to suppress the amplitude difference among the output ports below 2.5dB and the phase deviation smaller than 6 deg. from the desired phase difference (135deg) between adjacent output ports for each input over 3.9GHz – 4.1GHz. The total size of the Butler matrix is 453mm long, 205mm width and 38mm height. The length of the bends is about 55mm and the spacing between the elements is about 30mm. Fig.9 shows the measured reflections at all the input ports. The reflections are below -25dB over 3.9GHz-4.1GHz. The isolation would be equal to the reflection. Fig.10 and Fig.11 present the amplitude at the output ports and the phase difference between the adjacent output ports, respectively. The calculated results are obtained by cascading those of the two hybrids and the phase shifter. They satisfy the above-mentioned specifications. In Fig.10, the measured amplitudes at the output ports are almost equal at 4.03GHz. This frequency is almost same to that for the uniform division of the hybrid in Fig.6. The maximum of the amplitude difference is 3.1dB at 3.9GHz in the measurement. In Fig.11, the desired phase difference of 135 deg is obtained at 3.9GHz in the measurement. The phase difference becomes 130.1 deg in S_{81}/S_{51} and 140.2deg in S_{71}/S_{81} and S_{51}/S_{61} at 4.1GHz. The change of 5 deg over the 200MHz bandwidth is almost equal to that in the phase shifter in Fig.8.

4. CONCLUSIONS

The authors have designed and fabricated a four-way Butler matrix of double-layer rectangular waveguides using coupling of slits on the broad walls for a band from 3.9GHz to 4.1GHz. In the measurements, the uniform division in amplitude is obtained at 4.03GHz and the desired phase difference between the adjacent output ports is realized at 3.9GHz. This discrepancy could come from too thin slit width. The adjustment of the center frequency to 4.0GHz should be required in the future study.

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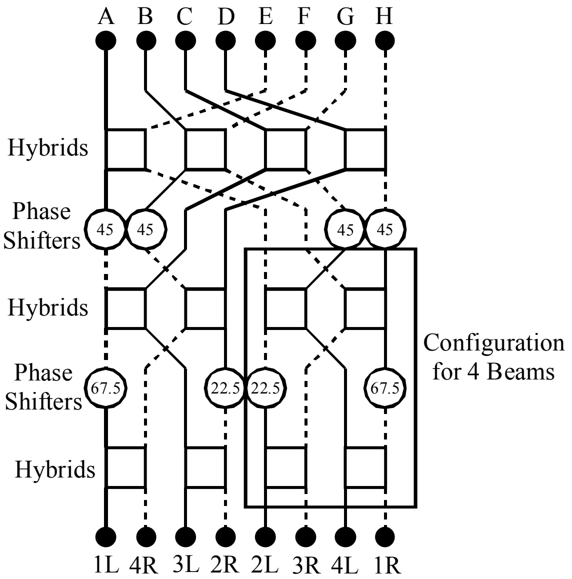

Fig.1: Block Diagram for an Eight-Way Butler Matrix

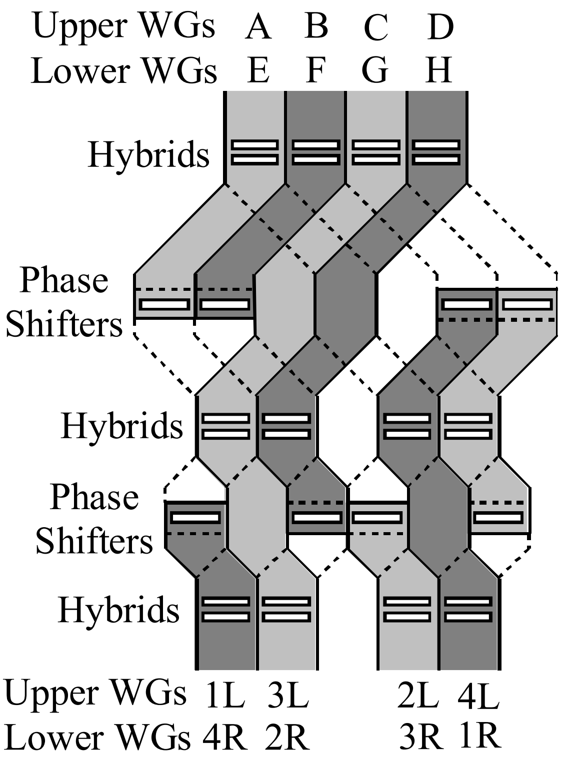

Fig.2: Waveguide Layout for the Eight-Way Butler Matrix

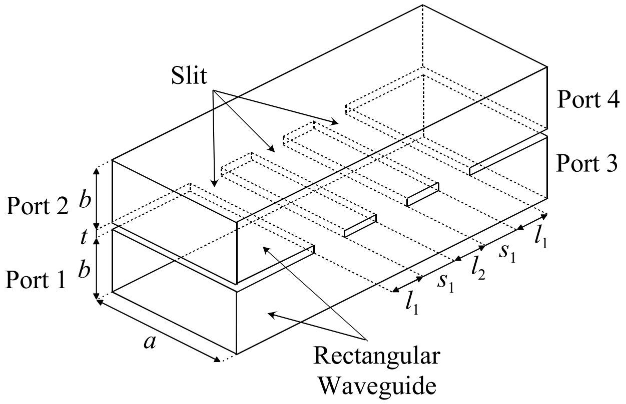

Fig.3: Structure of the Hybrid

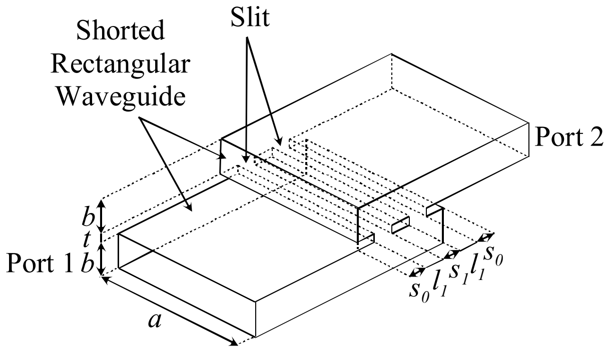

Fig.4: Structure of the Phase Shifter

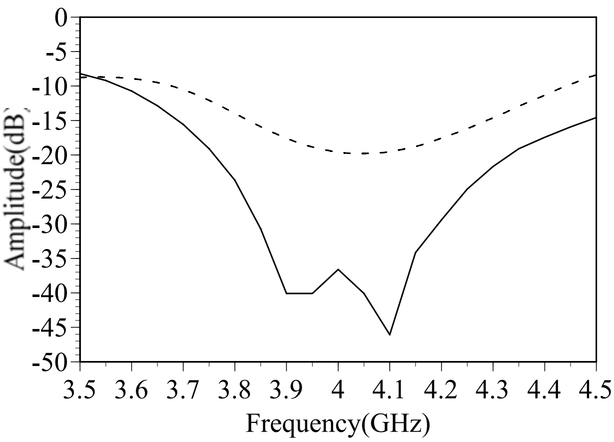

Fig.5: Reflection of the Hybrid
(Solid: Calculated, Dotted: Measured)

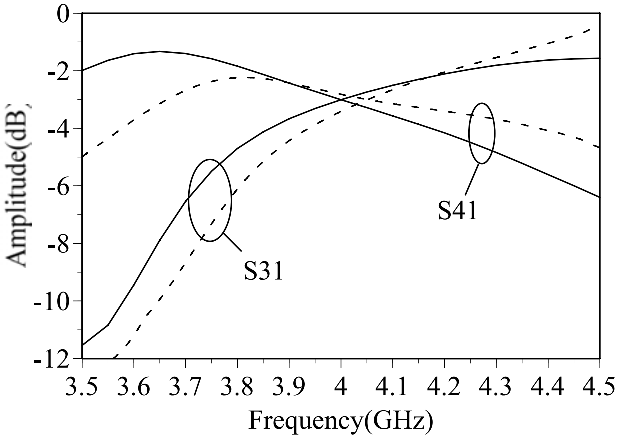

Fig.6: Amplitude at the Output Ports of the Hybrid
(Solid: Calculated, Dotted: Measured)

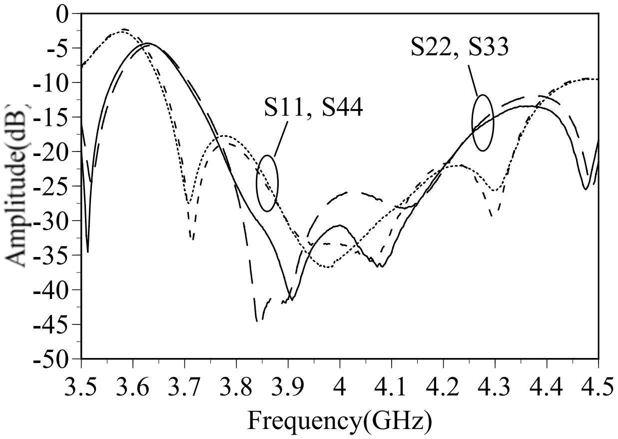

Fig.9: Reflection of the Four-Way Butler Matrix
(Measurements only)

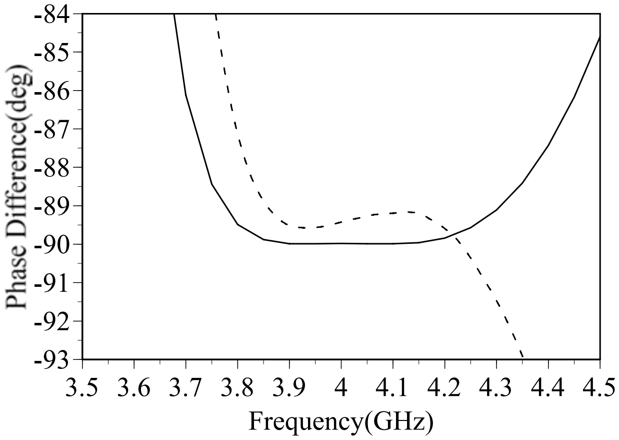

Fig.7: Phase Difference between the Output Ports of the Hybrid
(Solid: Calculated, Dotted: Measured)

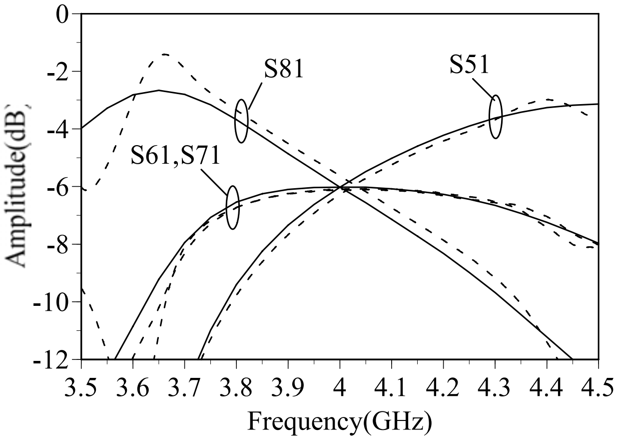

Fig.10: Amplitude at the Output Ports
in the Four-Way Butler Matrix
(Solid lines: Calculated, Dotted lines: Measured)

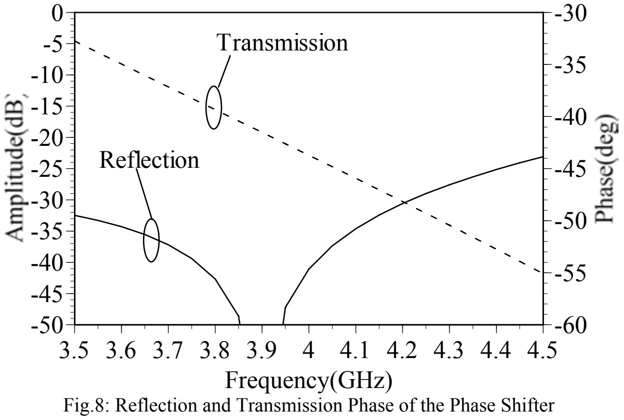

Fig.8: Reflection and Transmission Phase of the Phase Shifter
(Calculations only)

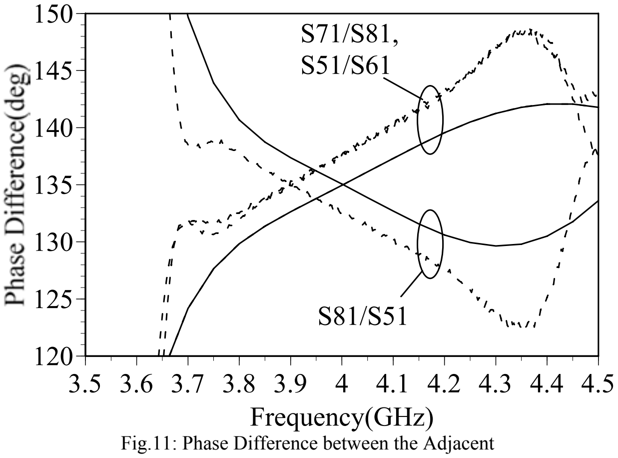

Fig.11: Phase Difference between the Adjacent
Output Ports in the Four-Way Butler Matrix
(Solid lines: Calculated, Dotted lines: Measured)