Four-Element Planar Butler Matrix Using Half-Wavelength Open Stubs

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***Abstract*—A simple design of a four-element planar Butler matrix is presented, comprising half-wavelength open stubs to improve relative-phase characteristics between output ports. Over the frequency range from 0.85 to 0.90 GHz, the experimental matrix exhibits phase errors (in the desired phase differences between output ports) and couplings of within 2° and -6.45 ± 0.25 dB, respectively.**

***Index Terms*—Butler matrix, microwave circuits, open stubs.**

I. Introduction

MULTIPLE-BEAM antennas for mobile and satellite communication systems have been studied [1], [2]. A Butler matrix, which uses a combination of 90° hybrids and fixed phase shifters, is useful for beam forming because of its simplicity and easy fabrication [3]. Uehara *et al.* have proposed a four-element planar Butler matrix using a novel layout with branch-line hybrids and eighth-wavelength delay lines without any crossing [4]. Experimental results demonstrate that measured average phase errors are within 11° [5]. Since practical problems associated with manufacturing would introduce unexpected phase errors, inherent transmission-phase variations as a function of frequency caused by the delay lines (of which electrical lengths are in proportion to operating frequency) must be compensated in order to obtain correct operation of the antennas. Schiffman phase shifters [6], [7] can be used to achieve flat relative-phase differences between output ports, but these require implementing long reference lines and couplers with precise even and odd-mode characteristic impedances on a thick microstrip substrate.

This letter proposes a simple design of four-element planar Butler matrix to improve relative-phase characteristics between output ports and presents the experimental results of the fabricated Butler matrix.

II. Design Approach and Fabrication

Fig. 1 shows the circuit configuration of the proposed four-element planar Butler matrix. A signal incident at input port (#1, #2, #3, or #4) is divided into four output ports (#5, #6, #7, and #8) with equal amplitude and specified relative-phase differences. We inserted half-wavelength open stubs on the side opposite the eighth-wavelength delay lines. In this case, input impedances of the open stubs are infinite at the center frequency f_0. Then, by determining characteristic impedances of the open stubs so that transmission-phase variations of the delay lines and the open stubs are almost the same near the center frequency f_0, it is possible to obtain flat relative-phase differences between output ports.

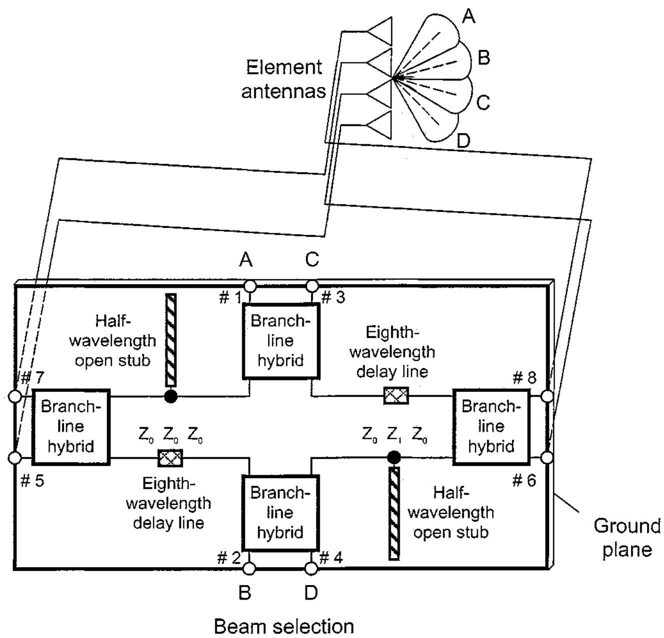

Fig. 1. Circuit configuration of proposed four-element planar Butler matrix.

The necessary characteristic impedances of the open stubs are determined as follows. Assuming that the characteristic impedances of input, output, and the delay line are the same (Z_0), and the length of the delay line is d, the derivative of the phase of the delay line transmission coefficient, $phase(S_d)$, at a center angular frequency ω_0, is expressed as follows.

$$\left.\frac{\partial\, phase(S_d)}{\partial\omega}\right|_{\omega_0} = -d\left.\frac{\partial\beta(\omega)}{\partial\omega}\right|_{\omega_0} \tag{1}$$

where angular frequency and phase constant are expressed as ω and $\beta(\omega)$, respectively. Next, assuming that the characteristic impedances of the input and output of the open stub are Z_0, and the characteristic impedance and length of the open stub are Z_1 and d_1, respectively, the phase of transmission coefficient of the

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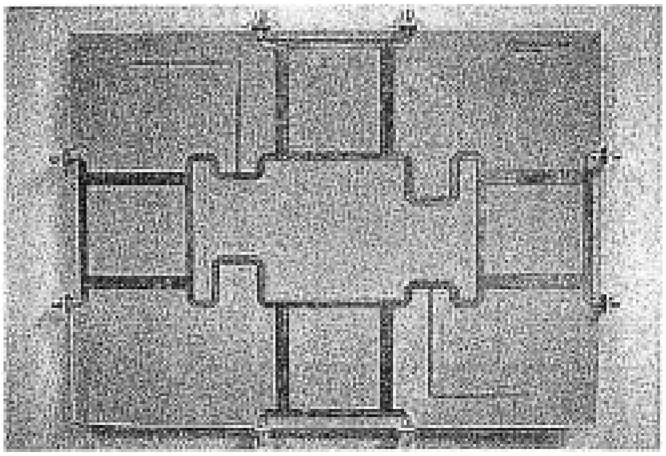


Fig. 2. Photograph of the fabricated Butler matrix.

open stub, $phase(S_o)$, at an angular frequency ω near ω_0, is expressed by

$$phase(S_o) = \arctan\left\{-\frac{Z_0}{2Z_1}\tan\beta(\omega)\,d_1\right\} \cong -\frac{Z_0}{2Z_1}\tan\beta(\omega)\,d_1. \quad (2)$$

Thus, the derivative of $phase(S_o)$ at a center angular frequency ω_0 is expressed as follows.

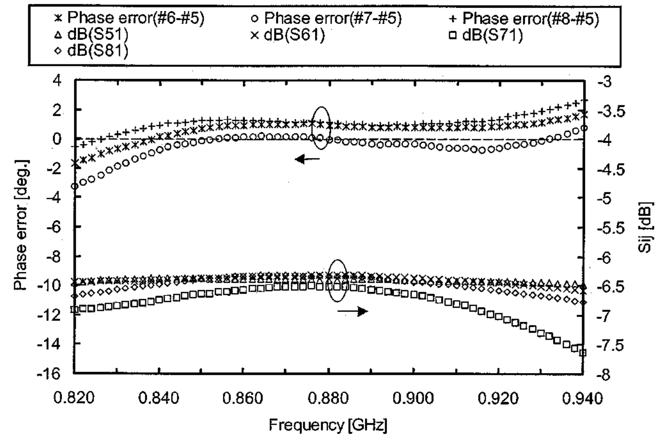
$$\left.\frac{\partial\, phase(S_o)}{\partial\omega}\right|_{\omega_0} = -\frac{Z_0}{2Z_1}\,d_1\left.\frac{\partial\beta(\omega)}{\partial\omega}\right|_{\omega_0}. \quad (3)$$

The condition of the same transmission-phase variations of the delay line and the open stub at the center frequency f_0 is that (1) and (3) become equal, i.e., the following equation holds true:

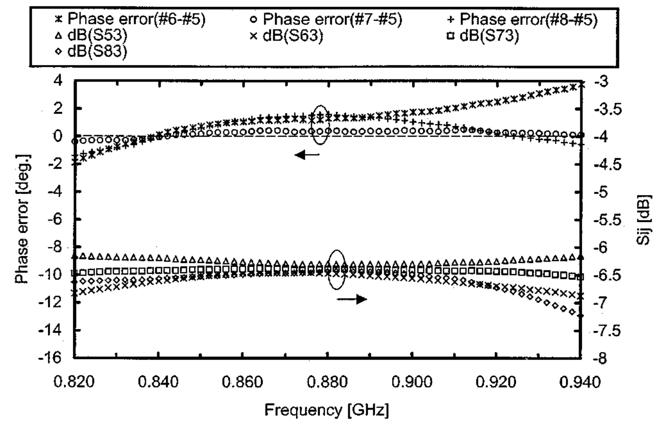
$$Z_1 = 2Z_0. \quad (4)$$

This value is twice as large as in the case of using quarter-wavelength short stubs [8], which must use via-holes to a ground plane and is not preferable for a thick microstrip substrate. This is because the phase rotation effect of half-wavelength open stubs is twice as large as with quarter-wavelength short stubs.

We designed a UHF-band four-element planar Butler matrix and manufactured it on double-sided copper-clad high-frequency substrate, with a thickness of 1.52 mm. Typical dielectric constant and loss tangent of the substrate at 0.90 GHz are 3.05 and 0.003, respectively. Fig. 2 shows a photograph of the fabricated Butler matrix. The size is 20.8 cm × 28.4 cm. The number of bends in the microstrip lines is the same in all paths in order to reduce the effects of amplitude and phase differences between paths at the bends. We measured frequency performance of the fabricated Butler matrix in the cases of generating beams A through D. For example, measured results in the case of generating beam A and C are shown in Fig. 3. The device works well and has good performance in the cases of generating beams A through D: the phase errors are within 2°, the power splits are -6.45 ± 0.25 dB, and the return losses are greater than 17 dB over the frequency range from 0.85 to 0.90 GHz. For comparison, we fabricated a four-element planar Butler matrix without using half-wavelength open stubs. Measured phase errors are within 4° over the frequency range from 0.85 to 0.90 GHz, which corresponds to twice as large as that using half-wavelength open stubs. If the operating frequency range is wider, the difference of phase errors is much bigger because the electrical lengths of delay lines are proportional to the operating frequency.



(a)



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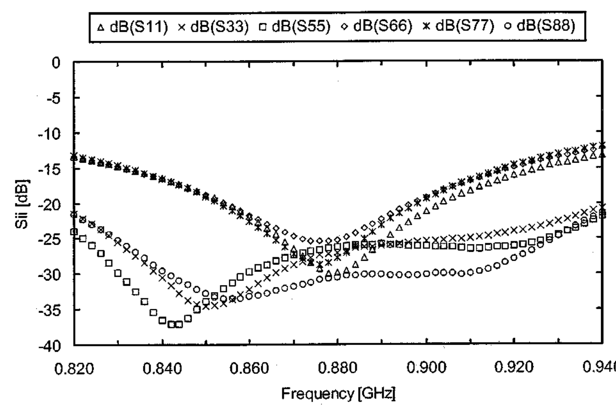

(c)

Fig. 3. Measured frequency performance of the fabricated Butler matrix in the case of generating beam A and C. (a) Phase errors in the desired relative-phase differences between output ports and magnitudes of transmission coefficients, S_{ij}, in the case of generating beam A; (b) phase errors in the desired relative-phase differences between output ports and magnitudes of transmission coefficients, S_{ij}, in the case of generating beam C; (c) magnitudes of reflection coefficients, S_{ii}.

III. Conclusion

We have proposed a four-element planar Butler matrix using half-wavelength open stubs. Over the frequency range from 0.85 to 0.90 GHz, a fabricated UHF-band Butler matrix exhibited phase errors (in the desired relative-phase differences between output ports) of within 2°, couplings of -6.45 ± 0.25 dB, and return losses greater than 17 dB.

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