A Half-Sized Post-Wall Short-Slot Directional Coupler with Hollow Rectangular Holes in a Dielectric Substrate

Shin-ichi YAMAMOTO, Student Member, Jiro HIROKAWA, and Makoto ANDO, Members

SUMMARY The authors realize a 50% length reduction of short-slot couplers in a post-wall dielectric substrate by two techniques. One is to introduce hollow rectangular holes near the side walls of the coupled region. The difference of phase constant between the TE_{10} and TE_{20} propagating modes increases and the required length to realize a desired dividing ratio is reduced. Another is to remove two reflection-suppressing posts in the coupled region. The length of the coupled region is determined to cancel the reflections at both ends of the coupled region. The total length of a 4-way Butler matrix can be reduced to 48% in comparison with the conventional one and the couplers still maintain good dividing characteristics; the dividing ratio of the hybrid is less than 0.1 dB and the isolations of the couplers are more than 20 dB.

key words: short-slot coupler, length reduction, Butler matrix, post-wall waveguide, dielectric substrate, rectangular hole

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 [1], which dispenses with the connector and reduces the loss as well as the total size of the antenna as shown in Fig. 1. The configuration of a 4-way Butler matrix is shown in Fig. 2 [2]. The matrix consists of hybrids and cross couplers. The total length of the Butler matrix is dominated by the length of the couplers, and size reduction of the couplers is important for miniaturization of the full structure.

Metallic waveguide hybrids comprised of quarter-wavelength couplers are widely used with very low loss performance [3]. Since the loss of a hollow waveguide is very small, the losses of the waveguide couplers are negligible. There are hybrids coupled by branch guides [4] or slots [5] on the common broad-wall of hollow rectangular waveguides. These couplers are not suitable for our specific design of single-layer integrated arrays. Short-slot couplers [6] are promising for single-layer structures.

Arbitrary coupling ratio including very strong coupling, high isolation, low VSWR and accurate 90 degree phasing over a 15% bandwidth are advantages of the short-slot coupler. Reference [7] shows an example of size reduction of the short-slot coupler. The coupler length of 1.25\lambda_g is realized by use of a multi-stepped coupled region.

Further size reduction of hybrids and the cross couplers in the post-wall waveguide is discussed in this paper, where the length of the proposed hybrid is 56% of that in Ref. [7]. The insertion loss is slightly larger due to dielectric filling the post-wall waveguides.

The length of the short-slot coupler is generally determined by the difference of the phase constants of the lowest two modes. If there are no reflection-suppressing posts in the conventional structure of Fig. 3(a), the coupled length \ell is 0.92\lambda_g for the hybrid and \ell = 1.77\lambda_g for the cross coupler where the waveguide width \(a = 0.69\lambda\). It is depending only on the difference of phase constants between the two propagating modes in the coupled region. Since the reflections at the ends of the coupled region are generally large, two posts are placed in the coupled region. The posts make the coupled region longer. In the case of two posts with a diameter of 0.1\lambda, the coupled length is \ell = 1.36\lambda_g (0.44\lambda_g increase) for the hybrid and \ell = 1.94\lambda_g (0.17\lambda_g increase) for the cross coupler.

In this paper, we halve the length of short-slot couplers by two techniques. One is to make hollow rectangular holes near the side walls. The difference of phase constant between the TE_{10} and TE_{20} propagating modes in the coupled region becomes large so that the required length to obtain a desired dividing ratio into the two output ports is reduced. Another technique is to select the length of the coupled region to cancel the reflection and to remove the two posts in the coupling region which prevent coupling. In the Butler matrix, the waveguides interconnecting components such as couplers and phase shifters also should be as short as possible provided that higher-mode coupling does not occur. The total length of the matrix becomes 5.11\lambda_g, which is 48% of the conventional one [8].

In Sect.2, the proper ratio of the phase constant between two propagating modes in the coupled region is derived to obtain a desired dividing ratio into the two output ports in the couplers with reflection suppression. The length of the coupled region is properly determined to suppress the reflection. Section 3 discusses the phase constant as a function of the width of the rectangular holes. Experimental results of the hybrid (3 dB coupler) and the cross coupler (0 dB coupler) at 26 GHz band are shown in Sect. 4. The characteristics of phase shifters, the overall structure of the matrix, and an antenna integrated with the matrix are presented in Sect. 5. The conclusions are summarized in Sect. 6.
two propagating modes and the reflection cancellation that dispenses with the posts in the coupling region.

First, the condition for a desired coupling ratio is considered. In the short-slot coupler [6], the coupling is controlled by the accumulated phase difference between the TE$_{10}$ and TE$_{20}$ modes that can propagate in the coupled region, as shown in Fig. 3. The power to Port#2 and #4 from Port#1 are proportional to $\cos((\beta_1 - \beta_2) \ell/2)$ and $\sin((\beta_1 - \beta_2) \ell/2)$, respectively, where $\beta_1$ and $\beta_2$ are the phase constants of the TE$_{10}$ and TE$_{20}$ modes in the coupled region. The $\ell$ is the length of the coupled region. The following relation between the phase constants of the two modes and the coupled length $\ell$ is required for a desired coupling.

$$
\begin{cases}
(\beta_1 - \beta_2) \ell/2 = \pi/4 \quad \text{(for Hybrid)} \\
(\beta_1 - \beta_2) \ell/2 = \pi/2 \quad \text{(for Cross coupler)}
\end{cases}
$$

Secondly, the condition of the reflection cancellation is discussed. Let us consider an incident wave from Port#1. The incident wave is transferred to the TE$_{10}$ and TE$_{20}$ modes at the left end of the coupled region. The transformation to the TE$_{10}$ mode gives remarkable reflection of about −10 dB but that to TE$_{20}$ mode gives negligible reflection of about −20 dB. Similarly, reflection only by the TE$_{10}$ mode occurs at the right end. The two reflections at both ends by the TE$_{10}$ modes should be canceled out. An approximate, simple condition is given by

$$
1 + e^{-j2\beta_1 \ell} = 0.
$$

The coupled length $\ell$ is expressed by

$$
\ell = \frac{2n + 1}{2\beta_1} \frac{\pi}{\lambda_g} = \frac{2n + 1}{4} \lambda_g
$$

where $\lambda_g$ is the guide wavelength of the TE$_{10}$ mode. Here, $\ell$ should be an odd multiple of a quarter wavelength. The ratio of the phase constants between the two propagating modes for both the desired coupling ratio and the reflection cancellation can be derived to satisfy Eqs.(1) and (3) as follows:

$$
\begin{cases}
\frac{\beta_2}{\beta_1} = \frac{2n}{2n + 1} = \frac{2}{3}, \frac{4}{5}, \ldots \quad \text{(for Hybrid)} \\
\frac{\beta_2}{\beta_1} = \frac{2n - 1}{2n + 1} = \frac{1}{3}, \frac{3}{5}, \ldots \quad \text{(for Cross coupler)}
\end{cases}
$$
Under the conditions of Eq. (3), \( \ell \) in Eq. (1) should be as short as possible. The realizable phase constant ratio is limited as is explained in the next section. In this paper, it takes \( \beta_2/\beta_1 = 2/3 \) (\( n = 1 \)) for the hybrid and \( \beta_2/\beta_1 = 3/5 \) (\( n = 2 \)) for the cross coupler. It corresponds to \( \ell = 3\lambda_g/4 \) and \( 5\lambda_g/4 \), respectively.

### 3. Phase Constants Depending on Hole Width

In this paper, the phase constants of the two propagating modes in the coupled region are selectively designed by the width of the rectangular holes near the side walls. Figure 4(a) shows the cross-section of a waveguide to estimate the phase constants in the coupled region. All the walls are Perfect Electric Conductors (PECs). Two hollow rectangular holes are made near the side walls. Figure 4(b) shows the phase constant versus the width \( w \) of the holes calculated by a two-dimensional Finite Element Method code [9]. The increase of the hole width near the side walls produces a large decrease in \( \beta \) since the TE\(_{20} \) field is strong there while it produces only a small decrease in \( \beta \) since the TE\(_{10} \) field is weak there. The difference in the phase constant \( \beta_1 - \beta_2 \) can be enlarged, and the coupled length becomes small. Figure 4(c) shows the ratio of \( \beta_1 \) and \( \beta_2 \) in Fig. 4(b). The width \( w \) is chosen by Fig. 4(c) so that the ratio of the phase constants described in the previous section are satisfied. The coupled length \( \ell \) is determined according to Eq. (1).

The side walls are realized by post-walls in fabrication, and the distance \( d \) from the side wall to the hole should be more than \( d = 1.0 \text{ mm} \). The above-mentioned ratio of the phase constants for a hybrid is obtained by \( w = 1.21 \text{ mm} \) and \( d = 1.5 \text{ mm} \) from Fig. 4(b), where the phase constants are \( \beta_1 = 0.720 \text{ rad/mm} \) and \( \beta_2 = 0.480 \text{ rad/mm} \) and the coupled length \( \ell \) is 6.52 mm. The ratio for a cross coupler is obtained by \( w = 2.01 \text{ mm} \) and \( d = 1.0 \text{ mm} \) where the phase constants are \( \beta_1 = 0.709 \text{ rad/mm} \) and \( \beta_2 = 0.426 \text{ rad/mm} \), and \( \ell \) is 11.10 mm.

### 4. Design and Characteristics of Couplers

The couplers are designed by the following steps. At first, initial values of the length \( \ell \) of the coupled region and the width \( w \) of the rectangular holes are determined by the method described in the previous two sections. Secondly, their values are modified by FEM code [9] and FEM simulator Ansoft HFSS to include roundness of the hole ends in fabrication as shown in Fig. 3(b). The coupled length \( \ell \) is defined as the distance between the center of the wall-edge posts.

The couplers are manufactured by post-wall waveguide technique [10]. The post-wall waveguides are manufactured by the following processes. Via-holes are densely made in a dielectric substrate. Slots as radiating elements are etched on the top plate of the substrate. The technique was applied by the authors for low-cost mass-producible millimeter-wave planar antennas. The design frequency is 25.6 GHz. The dielectric constant of a PTFE substrate is \( \varepsilon_r = 2.17 \). The thickness is 3.2 mm. Via-holes with a diameter of 0.8 mm are arrayed with an interval of 1.6 mm. The waveguide width \( a \) is 5.5 mm. The wall thickness \( t \) corresponds to 0.61 mm, as is shown in Fig. 3(b).

The design parameters of the couplers are summarized in Table 1. In the hybrid, the coupled length \( \ell \) is 8.02 mm = 0.70\( \lambda_g \), which is 51% of the value in the conventional structure. In the cross coupler, \( \ell \) is 12.70 mm = 1.1\( \lambda_g \), which is 57%. Figure 5 shows the photo of the manufactured hybrid. A thick dashed line covers the coupled region.

The transmission loss of the post-wall waveguide is 0.039 dB/cm at 25.6 GHz in measurements. The calculated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hybrid</th>
<th>Cross coupler</th>
</tr>
</thead>
<tbody>
<tr>
<td>coupled length ( \ell )</td>
<td>8.02 mm</td>
<td>12.70 mm</td>
</tr>
<tr>
<td>hole width ( w )</td>
<td>1.30 mm</td>
<td>1.82 mm</td>
</tr>
<tr>
<td>offset ( d )</td>
<td>1.5 mm</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>
transmission loss is 0.038 dB/cm in a dielectric-filled metal-wall waveguide with an equal guide wavelength, where it is assumed that the conductivity of copper is \( \sigma = 5.8 \times 10^7 \) S/m, and the dielectric loss \( \tan \delta = 0.0006 \) measured at 10 GHz. Aluminum tapes cover the rectangular holes on both sides of the substrate in order to prevent radiation from there. Each post-wall waveguide is fed through an aperture as shown in Fig. 5. A coaxial cable is connected together with a transformer. The structure and the performance of the transformer are described in Ref. [11]. The measured insertion loss at each port is 0.20 dB including the losses of the transformer.

Figure 6 shows the measured characteristics of the hybrid and the cross coupler. They are measured by a vector network analyzer with TRL calibration [12], [13]. The reference planes are located at the boundaries of the coupled region by the calibration. Waveguide loads are connected at the dummy ports through the waveguide transformer. The transformers used in the measurements are not well matched in the range greater than 25.9 GHz where the reflection is more than \(-15\) dB. This especially affects the reflection of the two couplers and the isolation of the hybrid. As a result, experiment results other than these and calculated results are in good agreement. The dividing ratio of the hybrid defined as the ratio of \( S_{21} \) over \( S_{41} \) is \(-0.08\) dB. The isolation of the hybrid (\( S_{31} \)) and the cross coupler (\( S_{21} \) and \( S_{31} \)) are 34.0 dB and 18.7 dB, respectively. The insertion losses of the hybrid and the cross coupler are 0.17 dB and 0.45 dB, respectively. It corresponds to the loss in the coupled region. The cross coupler has a loss of 0.2 dB due to the imperfect isolation. The insertion loss and the frequency bandwidth are almost the same when compared with the conventional couplers.

5. Characteristic of the Butler Matrix

An input from each port in a Butler matrix provides a different phase taper among the output ports [2]. In an antenna integrated with a 4-way matrix in this paper, inputs from the four ports gives four switching beams. The matrix requires −45 degree and 0 degree phase shifters as is shown Fig. 2. The phase shifts are realized by changing the phase constant of the TE10 mode as is shown in Fig. 8. Reflection is suppressed by two posts near the side wall. The phase shifters are designed by the Method of Moments (MoM) [14].

The actual required amount of the phase shift \( \phi_p \) in the phase shifters is determined by including the difference between the phase shift in the coupled region and that in a single-mode waveguide, as shown in Fig. 7. The transmission phase \( \phi_c \) of the cross coupler is \(-503.9\) degree in the coupled region. The transmission phase of a 5.5 mm-width single-mode post-wall waveguide with a 12.7 mm-length (\( \ell \)) is \(-397.6\) degree. The phase shifters should give the difference between these transmission phases. Therefore, the required amounts of phase delay are 151.3 (= 503.9 – 379.6 + 45.0) degree for the −45 degree phase shifter and 106.3 (= 503.9 – 379.6) degree for the 0 degree phase shifter.

![Fig. 5](image)

**Fig. 5** Photo of manufactured coupler (hybrid).

![Fig. 6](image)

**Fig. 6** Characteristics of manufactured cross coupler (25.6 GHz).

![Fig. 7](image)

**Fig. 7** Phase shifter.
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Table 2  Design parameters of the phase shifters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>-45 degree</th>
<th>0 degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>waveguide width</td>
<td>4.53 mm</td>
<td>8.57 mm</td>
</tr>
<tr>
<td>post spacing</td>
<td>5.20 mm</td>
<td>3.16 mm</td>
</tr>
<tr>
<td>post position</td>
<td>0.50 mm</td>
<td>0.50 mm</td>
</tr>
</tbody>
</table>

The design parameters of the phase shifters are summarized in Table 2, where post diameter $d_p$ is 0.8 mm. The average of 10 measurements are shown in Fig. 9. The distance between input and output ports of the cross couplers and those of the phase shifters are equal. Phase shift is defined as the difference from transmission phase of the cross coupler. In the -45 degree phase shifter, the phase error is -0.5 degree and the reflection is -23.4 dB at 25.6 GHz. In the 0 degree phase shifter, the phase error is -0.6 degree and the reflection is -20.6 dB at 25.6 GHz. Since the 0 degree phase shifter has frequency characteristics similar to the cross coupler, the phase shift remains unchanged over a wide frequency range. Since the length of the 0 degree phase shifter is equal to the half-wavelength of the TE$_{20}$ mode near 25.8 GHz, remarkable reflection of -9 dB is produced at that frequency. The frequency shifts to a lower frequency by 0.1 GHz due to the difference between the metal walls in the calculation and the post-walls in the experiment.

A distance $s$ between adjacent couplers should be small for reduction of the total length of the Butler matrix. The definition of $s$ is given by the distance between the post centers at the ends of adjacent couplers as is shown in Fig. 10. It is conventionally set the 6.0 mm for 40 dB attenuation of TE$_{20}$ mode. The scattering matrix of the whole Butler matrix with various distance $s$ is calculated by Ansoft HFSS. For $s$ larger than 2.5 mm, the values of the scattering matrix converges within ±0.25 dB in amplitude and ±3.0 degree in phase. In the present design, $s$ is 2.5 mm. Figure 11 shows the proposed and conventional Butler matrices in the same scale. The total length of the proposed matrix is 58.8 mm and is shortened to 48% of the length of the conventional matrix on the whole.

The power dividing characteristics of the Butler matrix are shown in Fig. 12 for an input from Port#2. They are measured with coaxial cables. The measured results include the characteristics of the transformers and feed waveguides. The ideal dividing characteristics are -6 dB in amplitude and phase difference of +135 degree between adjacent output ports. The measured values include measurement error of ±0.3 dB in amplitude and 5 degree in phase at the maxi-
The transmission is about $-7.6\,\text{dB}$ with excessive loss around $1.6\,\text{dB}$. This loss includes $0.56\,\text{dB}$ of the two transmission lines ($7.2\,\text{cm} \times 2$) extending to the input and the output ports and $0.20\,\text{dB} \times 2$ for the insertion loss of transducers used in the measurements. Therefore, the insertion loss of the Butler matrix is effectively $0.64\,\text{dB}$, which includes $0.23\,\text{dB}$ for the loss of the $58.8\,\text{mm}$-post-wall waveguide in the matrix. The amplitude differences between the output ports are less than $0.75\,\text{dB}$ at the design frequency. The phase difference between the adjacent ports is $+134.1$ degree in average. The maximum phase error is $6.9$ degree. For an input from other ports, the difference in amplitude is within $2\,\text{dB}$ while the phase error is of the same degree. The radiation pattern is more sensitive to the phase error than to the amplitude difference. These above-mentioned errors in amplitude do not degrade the pattern seriously.

Although the characteristics of the couplers are improved, the frequency dependence of the phase shifters, especially the $-45$ degree phase shifter, becomes large. Hence, the amplitude characteristics of the Butler matrix are good, but the phase characteristics of the matrix are poor.

As an example, slot arrays which synthesize a null-filled cosecant pattern in the $E$-plane are connected to the four output ports of the Butler matrix. The slot arrays would be designed for base stations in fixed wireless access systems (FWA), which produce uniform illumination over a coverage area [15]. The slot array has 16 elements of reflection-canceling slot pairs in each of the four radiating waveguides. The structure and the operation principle are described in Ref. [16]. One radiating waveguide has a $-3\,\text{dB}$ beam width of $84$ degree in the $H$-plane and a gain of $15.8\,\text{dBi}$. Figure 1 is the photo of the integrated antenna consisting of the Butler matrix and the slot array, where the size of the ground plane is $270\,\text{mm} \times 120\,\text{mm}$. It was confirmed that the size of the ground plane can be reduced to $240\,\text{mm} \times 40\,\text{mm}$ without degrading the radiating pattern due to diffraction effects.

Figure 13 shows the beam switching in the $H$-plane. The amplitude for each beam is normalized by its gain. The main beam direction is switched for each input port as predicted. The interval and the $-3\,\text{dB}$ beamwidth of the four
beams are almost equal. The four beams cover a 115-degree sector, equally. The measured gain is 18.9 dBi for Port #1 and #4 inputs, while it is 19.8 dBi for Port #2 and #3 inputs. The difference is produced by the pattern in the E-plane.

Figure 14 shows the radiation pattern for each of the beams in the E-plane. The amplitude of each beam is normalized by its maximum. The cosecant beams are observed in an angle range of 0 degree to −30 degree. All the beams have almost identical patterns as that of the linear slot array and the differences among the beams are negligible.

Figures 15 and 16 show the main beam directions depending on the frequency in the H- and E-plane, respectively. The beam squint in the H-plane, which reflects the frequency characteristics of the Butler matrix, is about 10 degree or 0.4 times the beamwidth over the 2 GHz band. Reasonable bandwidths are observed. The main beam direction in the E-plane, on the other hand, is considerably squinted with the frequency toward the end of the array as is usual the case with traveling wave arrays. The variation of the direction over a 2 GHz band is 25 degrees which corresponds to 4.2 times the beamwidth. This defect is general and unavoidable for arrays with the length specified for desired gain or beam shape. Figure 17 shows the antenna gain measured in the main beam direction at each frequency. The beam shape distortion and the side lobe level increase account for the gain reduction at the frequencies higher than 25.6 GHz.

6. Conclusions

The authors have succeeded in halving the size of short-slot couplers by making hollow rectangular holes near the side walls and removing the posts in the coupling region to cancel the reflection at its end. A proper ratio of the phase constants as well as the length of the coupled region is analytically derived to obtain a desired dividing ratio into the two output ports in the couplers with reflection suppression. The phase constant ratio is obtained as a function of the width of the rectangular holes.
The coupled length in the proposed type is reduced to 51% for the hybrid and to 57% for the cross coupler, respectively, in comparison with the conventional type. The characteristics of the hybrid and the cross coupler have been confirmed by experiments at 26 GHz band. The dividing ratio of the hybrid is ~0.08 dB. The isolation of the couplers is more than 19 dB. The insertion losses of the hybrid and the cross coupler are 0.2 dB and 0.5 dB, respectively. The distance between the couplers is also shortened, so that the total size of a 4-way Butler matrix is reduced to 48%. The measured insertion loss of the Butler matrix is 0.64 dB. Experiments in 26 GHz band have confirmed the key operation of this antenna; almost identical four beams are switched to cover a 115-degree sector with equal angular spacing.

References


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