



Design and Implementation of Slot-coupled Microstrip Components for Wideband Butler Matrix

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ABSTRACT

The design of a slot-coupled directional coupler and a slot-coupled crossover for use in a switched beamforming network operating over wideband has been presented and discussed. In order to achieve wideband characteristics, the coupler and the crossover use slot-coupled microstrip transmission line (MTL) technology. Since the slot-coupled components have a structure in which the two signal lines on the top and bottom side are coupled to each other through the rectangular slot on the common ground plane, the amount of the combined signal is determined by the width of the slot, the width of the line and the height of the substrate. The width of the slot should be set to be wider than the width of signal line to induce proper coupling, and the width of the slot should be about 1.5 times to the width of the signal line. It can be seen that the coupling coefficient increases as the ratio of the width of the line to the height of the substrate increases, which means that the amount of the signal coupled to the output port increases as the width of the line increases. The proposed coupler and the crossover have been obtained high performance of 3 ± 0.5 dB coupling, $90\pm 1^\circ$ phase difference, and 0.5 dB coupling and $45\pm 3.5^\circ$ phase shift in the operating frequency band, respectively. In addition, they have been implemented on the double-layered MTL in a small size and without intersecting lines on microstrip substrate.

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KEYWORDS: Slot-coupled directional coupler, Crossover, Switched beamforming network, Microstrip transmission line technology, Double-layered MTL, High performance

ARTICLE INFO: Received 24 July 2017, Revised 16 August 2017, Accepted 16 August 2017.

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1. Introduction

In recent years, there has been a demand for a high-speed wireless communication system capable of processing various multimedia services and big-capacity data services even in a high-speed mobile environment. Key technologies for solving such a problem include multiple input multiple output (MIMO) technology that can increase the channel capacity by reducing the influence of multipath fading, and smart antenna technology that can improve the utilization efficiency of frequency and reduce interference between multiple communication signals. Therefore, a number of researchers in 5G wireless communication fields are very concerned about a massive MIMO technology as it offers significant advantages reduced co-channel interferences and signal fading. Butler matrix is one of the most favorable approaches to realize the switched beam forming network for MIMO system in the wideband frequency range [1-2,8-13]. However, generally most of couplers and crossovers that realized in conventional planar technology such as microstrip, stripline and coplanar waveguide (CPW) transmission line have a narrow bandwidth [3,4].

In order to design the coupling components operating in wide frequency range, one of the most preferable techniques is to employ the slot-coupled technology using multilayer microstrip transmission lines (MTL) [5-6,14-15]. The slot-coupled directional coupler and the slot-coupled crossover can construct a compact geometry of Butler matrix that can be used in a

switched beamforming network for massive MIMO.

In this paper, to increase performance of the directional coupler and reduce the crossover size, we design the slot-coupled directional coupler and the slot-coupled crossover to obtain a 3dB coupling and 90° phase difference, and 0dB coupling and 45° phase shift, respectively. Considering easy configuration and wideband operation, and to avoid line-crossing of transmission lines, multilayer technology with slot coupling between two rectangular MTLs is proposed to design the hybrid directional coupler, crossover and phase shifter. The reason for using the slot-coupled microstrip components in the Butler matrix structure is to solve the structural problem caused by not using the crossover necessarily constituted in a general single layer substrate structure, to simplify the circuit structure and to reduce the overall size.

2. Slot-coupled Microstrip Components

2.1 Configurations of Slot-coupled Components

The configurations of the proposed slot-coupled components are shown in <Figure 1>. To obtain the wideband operation, the components consist of two rectangular MTLs facing each other at the top and bottom layer and a common ground. The coupling between these MTLs is achieved by cutting a rectangular slot in the ground plane

which is located at the middle layer. A common ground is in a position between the two dielectrics.

In <Figure 1(a)> configuration of slot-coupled directional coupler, Port 1 and Port 3 are on the top layer while Port 2 and Port 4 are on the bottom dielectric layer. The 3dB coupling and 90° phase difference of output signals is achieved by controlling the width of signal line and a rectangular slot on a common ground plane. By feeding at one of two input ports, the signal will appear with a half power at the two output ports of the coupler, which they have equal amplitude and 90° phase shift.

In configuration of slot-coupled crossover, the crossover is composed of two open-ended MTLs and a rectangular slot with a quarter-wavelength as shown in <Figure 1(b)>. It is only two-port network through the slot. This approach allows for simultaneous realization of a wideband MTL crossover and 45° phase shifter when used as a component of Butler matrix. Therefore, the proposed crossover can be obtained a high performance of around 0.5dB coupling and 45° phase shift without line crossing at the operating frequency band.

<Figure 2> shows the electric field distribution in the even-odd mode between the two signal lines when a rectangular slot is pierced through the common ground plane. <Figure 2(a)> shows the electric field distribution in the even mode. Since the voltage potential difference between the two signal lines is zero, there is no coupling between the two lines. On the contrary, <Figure 2(b)> shows the electric field distribution in the odd mode, which causes the maximum coupling

between the two signal lines due to the opposite voltage potential between the two lines. Therefore, this structure can be designed as a directional coupler and a crossover, and since two input ports can be positioned on the opposite sides, thereby solving the structural problem.

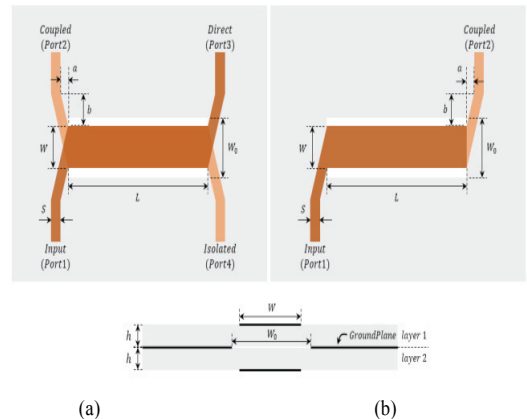


그림 1. 제안된 슬롯 결합 컴포넌트의 레이아웃 (a) 슬롯 결합 방향성 결합기, (b) 슬롯 결합 크로스 오버

Figure 1. Layout of the proposed slot-coupled components (a) slot-coupled direction coupler, (b) slot-coupled crossover

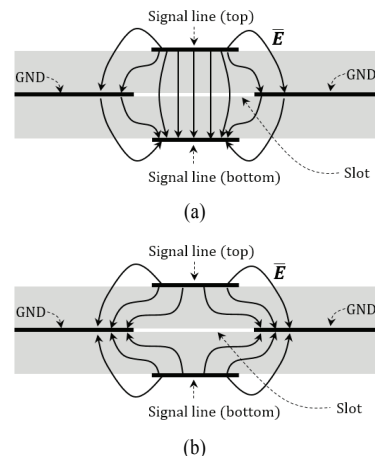


그림 2. 슬롯 결합 컴포넌트의 전기장 분포 (a) 짝수 모드, (b) 홀수 모드
Figure 2. The electric field distributions of a slot-coupled components (a) even mode, (b) odd mode

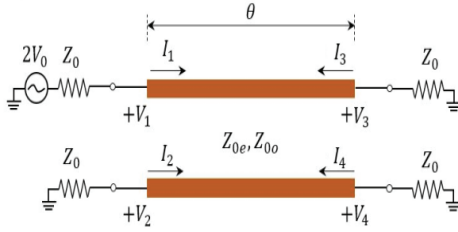


그림 3. 슬롯 결합 선로간의 등가회로
Figure 3. Equivalent circuit for the slot-coupled lines

<Figure 3> shows the equivalent circuit of a slot-coupled signal lines in terms of an electric circuit. The voltage coupling coefficients of the lines located on the top and bottom surfaces can be obtained by applying the even-odd mode analysis to the two lines. According to the principle of superposition, the feed of port 1 can be treated as the sum of feed in even mode and feed in odd mode applied by symmetry property. The input impedance at port 1 for the even mode is Z_{in}^e and the input impedance for odd mode is Z_{in}^o , since transmission line impedance for each mode can be regarded as having the characteristic even mode impedance Z_{0e} or odd mode impedance Z_{0o} , terminated in a load impedance Z_0 . Therefore, the input impedances should be written as follows.

$$Z_{in}^e = Z_{0e} \frac{\sqrt{Z_{0o}} + j\sqrt{Z_{0e}} \tan\theta}{\sqrt{Z_{0e}} + j\sqrt{Z_{0o}} \tan\theta} \quad (1)$$

$$Z_{in}^o = Z_{0o} \frac{\sqrt{Z_{0e}} + j\sqrt{Z_{0o}} \tan\theta}{\sqrt{Z_{0o}} + j\sqrt{Z_{0e}} \tan\theta} \quad (2)$$

The input impedance at port 1 of the coupler can be expressed as sum of the even and odd mode excitation.

$$Z_{in}^o = Z_0 + Z_{0o} \frac{2(Z_{in}^e Z_{in}^o - Z_0^2)}{Z_{in}^e + Z_{in}^o + 2Z_0} \quad (3)$$

By symmetry, as long as $Z_0 = \sqrt{Z_{0e} Z_{0o}}$ is satisfied, port 1 will be matched by the $Z_0 = \sqrt{Z_{in}^e Z_{in}^o}$.

For wideband design a slot-coupled components, it is important to decide the coupling coefficient C to be properly taken into the desired power and phase shift at the output ports. Coupling coefficient C is defined by even-odd mode analysis.

$$C = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \quad (4)$$

Characteristic impedance of the modes depends on the line width, slot width, dielectric constant of substrate, and substrate height[7].

By the law of voltage division, if matched port 1 ($S_{11} = 0$) and if isolated port 4 ($S_{41} = 0$) at the same time, the transmission coefficients at port 2 and port 3 are

$$S_{21} = \frac{jC \tan\theta}{\sqrt{1 - C^2} + j \tan\theta} \quad (5)$$

$$S_{31} = \frac{j\sqrt{1 - C^2}}{\sqrt{1 - C^2} \cos\theta + j \sin\theta} \quad (6)$$

Finally, if the characteristic impedance of and the voltage coupling coefficient of C are specified, then the following design equations for the required even and odd mode characteristic impedances can be easily derived from equation 4.

$$Z_{0e} = Z_0 \sqrt{\frac{1+C}{1-C}} \quad (7)$$

$$Z_{0e} = Z_0 \sqrt{\frac{1-C}{1+C}} \quad (8)$$

The characteristic impedance of the even-odd mode can be obtained by determining the characteristic impedance and coupling coefficient of the input and output stages composed of the coupled microstrip lines.

2.2 Slot-coupled directional coupler

In <Figure 1(a)> and in case of $\theta \ll \pi/2$ of equation 5 and 6, all power from port 1 is transmitted through port 3, with none being coupled to port 2. For $\theta = \pi/2$ in equation 5, the coupling C to port 2 is at its maximum. However, it shows that the voltage coupling coefficient C on the black-line of <Figure 4> is less than one at the design frequency. The coupler is a quarter wavelength. This type of coupler is best suited for weak couplings, as tight coupling requires lines that are too close together to be practical, or a combination of even and odd mode characteristic impedances that can be non-realizable.

2.3 Slot-coupled crossover

In <Figure 1(b)>, the crossover consists of two-port network with only port1 and port 2. In case of $\theta = \pi/2$ of equation 5, all power from port 1 is transmitted through port 2, and the coupling C on the red-line of <Figure 4> to port 2 is at its maximum at the design frequency. This type of crossover is a quarter wavelength, and is required for tight couplings between closely coupled microstrip lines.

3. Simulation and results

The slot-coupled components on <Table 1> are implemented on Taconic substrate (RF-35) with dielectric constant of 3.5 and thickness of 0.50mm, and are designed by using high frequency simulation software (HFSS). The performance of slot-coupled directional coupler and slot-coupled crossover depends critically on bandwidth and phase difference.

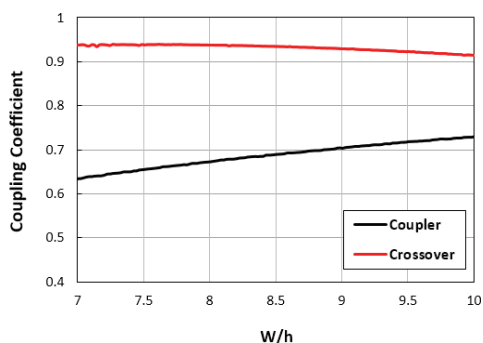


그림 4. W/h 에 따른 결합계수

Figure 4. Coupling coefficient vs. W/h

표 1. 결합기와 크로스오버의 설계 파라미터

Table 1. Design parameters of the coupler and crossover

Design parameters [mm]			
S	1.127	W_0	6.522
W	4.382	L	18.673
a	0.848	b	3.316

<Figure 4> shows the simulation value of voltage coupling coefficient versus $W/h=9.1$ are 0.707 and 0.94 for the slot-coupled coupler and the slot-coupled crossover, respectively. The performance has good quality for the coupler and the crossover design.

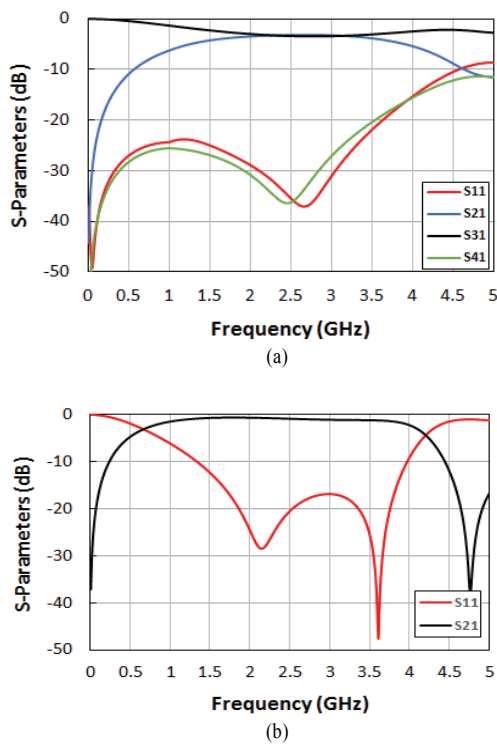


그림 5. 산란 파라미터의 크기 (a) 설계된 결합기, (b) 설계된 크로스오버

Figure 5. Magnitude of scattering parameters (a) the designed coupler, (b) the designed crossover

<Figure 5(a)> shows the scattering parameters of the designed slot-coupled directional coupler. When the flatness of insertion loss of S21 and S31 is within $6 \pm 0.5\text{dB}$, the 52% fractional bandwidth of the coupler is achieved in the operating frequency of 2.0 ~ 3.4GHz. Also, the return loss of S11 is less than 23.5dB and the isolation of S41 is greater than 21.6dB.

<Figure 5(b)> shows the scattering parameters of the designed slot-coupled crossover. When the deviation of insertion loss of S21 is less than 0.5dB, the 74% fractional bandwidth of the crossover is achieved in the operating frequency of 1.75 ~ 3.7GHz. Also, the return loss of S11 is greater than 16.7dB.

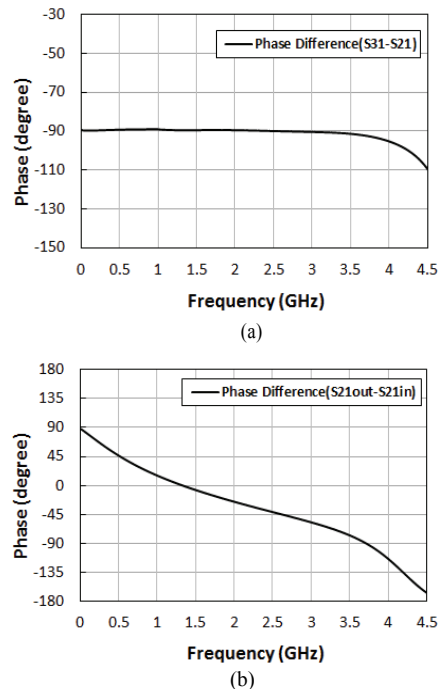


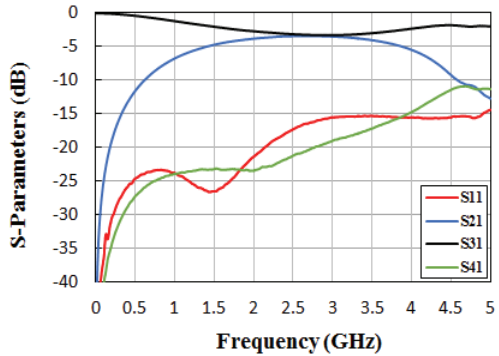
그림 6. 출력포트간의 위상차 (a) 설계된 결합기, (b) 설계된 크로스오버

Figure 6. Phase difference between output ports (a) the designed coupler, (b) the designed crossover

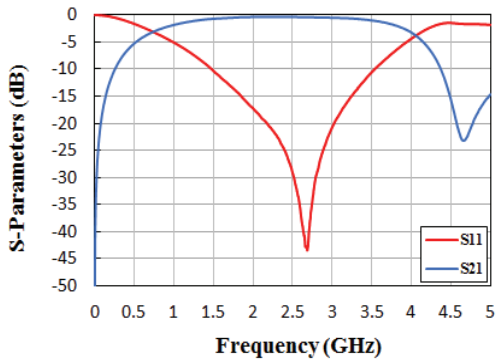
<Figure 6(a)> is a graph showing phase difference between output ports. The signal at port 3 must be delayed the phase of -90° when comparing with the signal at port 2. From the results, phase difference at the center frequency of 2.6GHz is -90.02° . The error of the phase difference is bigger when it is far from the center frequency. In addition, the phase differences at the edge frequency of 2.0GHz and of 3.4GHz within the desired frequency bandwidth are 89.47° and 91.01° , respectively. <Figure 6(b)> shows phase difference of the crossover between output port 2 and input port 1. The signal at port 2 is delayed the phase of -45° from port 1. The phase difference of the crossover is achieved less than 3.5° in the desired bandwidth of 2.5 ~ 2.7GHz.

<Figure 7(a)> shows measurement results of scattering parameters for the implemented slot-coupled directional coupler. When the flatness of insertion loss of S21 and S31 is within $6 \pm 0.5\text{dB}$, the 38.5% fractional bandwidth of the coupler is achieved in the operating frequency of 2.3 ~ 3.3GHz. Also, the return loss of S11 is greater than 15dB and the isolation of S41 is greater than 17dB.

<Figure 7(b)> shows measurement results of scattering parameters of the implemented slot-coupled crossover. When the insertion loss of S21 is less than 0.5dB, the 55.7% fractional bandwidth of the crossover is achieved in the operating frequency of 1.75 ~ 3.2GHz. Also, the return loss of S11 is greater than 15dB.



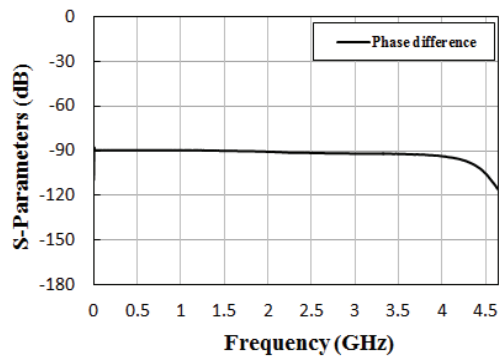
(a)



(b)

그림 7. 산란 파라미터의 측정 결과 (a) 구현된 결합기, (b) 구현된 크로스오버

Figure 7. Measurement results of scattering parameters (a) the implemented coupler, (b) the implemented crossover



(a)

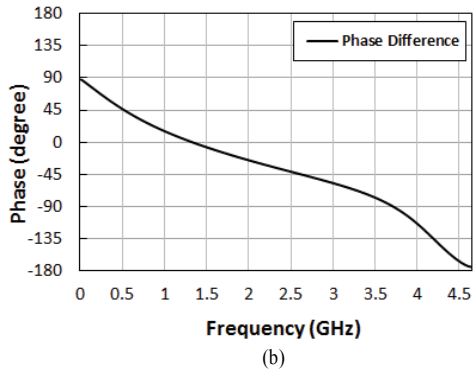


그림 8. 출력포트간의 위상차 측정 결과 a) 제작된 결합기, (b) 제작된 크로스오버

Figure 8. Measured results of phase difference between output ports (a) the fabricated coupler, (b) the fabricated crossover

<Figure 8(a)> is a graph that shows measurement result of phase difference between output port 3 and output port 2. From the measurement results, phase difference at the center frequency of 2.6GHz is -90.5° . The phase differences at the edge frequency of 2.0GHz and of 3.4GHz within the desired frequency bandwidth are 89.5° and 91.05° , respectively. <Figure 8(b)> shows measurement results of phase difference of the crossover between output port 2 and input port 1. The signal at the port 2 is delayed the phase of -45° from port 1. The phase difference of the crossover is achieved less than 3.57° in the desired bandwidth of 2.5 ~ 2.7 GHz.

From the above results, the measurement values are slightly smaller than the simulation ones because of dielectric loss and PCB manufacturing problems, and so on.

<Figure 9> shows photographs of the products of the slot-coupled coupler and the crossover

fabricated on the double-layer MTL for measurements.

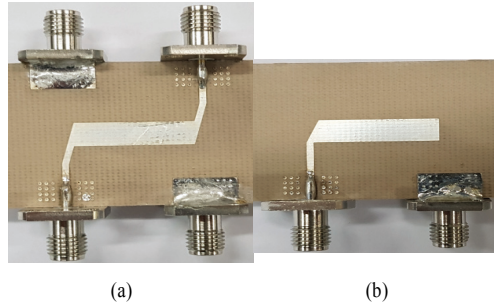


그림 9. 슬롯결합 컴포넌트의 제작품 (a) 커플러, (b) 크로스오버
Figure 9. Fabricated products of slot-coupled components (a) coupler, (b) crossover

4. Conclusions

The compact slot-coupled components for a switched beamforming network have been designed using microstrip multilayer technology. The slot-coupled directional coupler and the slot-coupled crossover operating over wide frequency band have been presented and simulated using by HFSS. Excellent coupling effect and phase difference have been achieved by controlling the width of signal line and rectangular slot on a common ground. The proposed coupler and the crossover have been obtained high performance of $3\pm 0.5\text{dB}$ coupling, $90\pm 1^\circ$ phase difference, and 0.5dB coupling and $45\pm 3.5^\circ$ phase shift in the operating frequency band, respectively. Its compact size and good performance makes it suitable for use in wideband switched beam forming network for angle diversity in multiple switched beams.

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광대역 버틀러 매트릭스용 슬롯 결합 마이크로스트립 컴포넌트의 설계 및 구현

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요 약

넓은 주파수 대역에서 동작하는 스위치형 빔성형 네트워크에 사용되는 슬롯결합 방향성 결합기와 크로스오버의 설계방법을 제시하고 논의하였다. 광대역 특성을 달성하기 위해 커플러와 크로스오버는 슬롯결합 마이크로스트립 전송선 기술을 사용한다. 슬롯결합 방향성 결합기는 윗면과 아랫면에 있는 두개의 신호선로가 공통 접지면의 직사각형 슬롯을 통하여 상호 결합되는 구조로 되어 있으며, 설계에 사용될 기판이 정해지면 선로의 폭과 선로의 길이, 슬롯의 폭에 따라 결합되는 신호의 양이 결정된다. 슬롯의 폭은 적절한 결합을 유도하기 위해 선로의 폭보다 넓게 설정해야 하며, 최적화 결과를 바탕으로 신호선 폭의 약 1.5배가 되도록 하였다. 결합계수는 기판의 높이에 대한 선로의 폭의 비가 증가할수록 커지는 것을 알 수 있으며, 이는 선로의 폭이 증가함에 따라 출력 포트에 결합되는 신호의 양이 커지는 것을 의미한다. 제안된 커플러와 크로스오버는 작동 주파수 대역에서 $3\pm 0.5\text{dB}$ 커플링, $90\pm 1^\circ$ 위상차, 그리고 0.5dB 커플링 및 $45\pm 3.5^\circ$ 위상 편이의 높은 성능을 각각 얻었으며, 크기가 작고 마이크로스트립 기판 상에 교차하는 선로 없이 구현하였다.



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