Journal of Knowledge Information Technology and Systems

ISSN 1975-7700

http://www.kkits.or.kr

Implementation of Slot-Coupled Broadband Butler Matrix Based on Multiple Layered Microstrip Transmission line

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A B S T R A C T

Switched beamforming network required for multiple input multiple output (MIMO) technology and smart antenna technology can adaptively adjust the beam direction of the array antenna according to the moving direction of the mobile station. Therefore, the proposed beamforming network called Butler matrix is a power feeding system capable of forming beams in various directions by adjusting the magnitude and phase of the feed signals applied to the array antenna. In this paper, a combination of microstrip slot-coupled directional couplers and slot-coupled crossovers including 45° phase shifter has been employed to expand the bandwidth of the 4x4 Butler matrix and reducing the number of conventional crossovers. The proposed slot-coupled components consist of two rectangular microstrip transmission lines (RMTLs) facing each other at the top and bottom layer and a common ground. The coupling between these RMTLs 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. From the simulation and measurement results, the proposed Butler matrix has a good performance of broad fractional bandwidth of 43%, return loss of 15.5dB, insertion loss of 6.5±0.4dB and progressive phase shift of -45, 135, -135, 45 ±5° in 2.5~2.7GHz operating frequency band.

K E Y W O R D S : Switched beamforming network, MIMO, Smart antenna, Butler matrix, Feeding System, Array antenna, Microstrip slot-coupled directional coupler, Crossover, Broad bandwidth, Progressive phase shift

A R T I C L E I N F O : Received 25 July 2017, Revised 16 August 2017, Accepted 16 August 2017.

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1. Introduction

Multiple input and multiple output (MIMO) system is introduced to make better the performance of wireless communication systems and make their capacity bigger by spatial signal processing and filtering. Because MIMO system can separate spatially and spectrally the mixed signals from multiple subscribers. For the purpose, a wideband wireless communication technology is strategic to have wide bandwidth and spatial filtering, which has been getting more popular for high speed connectivity and enlargement of mobile subscribers.

Switched beam forming network in MIMO systems is used to track and locate the antenna beam on the mobile target. One of the most well-known of switched beam networks is Butler matrix [1-3]. However, conventional Butler matrices composed of hybrid branch-line directional couplers and crossovers have a narrow limited bandwidth and demands for relatively large space [4-5].

For wideband applications, many configurations of Butler matrices have been described in [6-9]. In [6-12], microstrip applications on Butler matrix using wideband crossover have been proposed. This matrix has still broadband because of the limited band of the hybrid couplers and crossovers used in these structures. In [13], a multilayer matrix using low temperature cofired ceremic (LTCC) technology has been presented. The suspended strip lines with via connections of multilayer structures have been studied in [14], but the bandwidth was limited due to the phase differences of broadband phase shifters and of via connections. In [15,16], 3-dB coplanar waveguide (CPW) directional slot-coupled couplers and 3dB CPW branch line couplers have been applied to eliminate crossovers. Using this approach, a 4x4 Butler matrix operating at 5.8GHz with more than 6% bandwidth has been accomplished. In this case, small size and wideband characteristics have been achieved, but the bandwidth of the matrix is limited by differential phase characteristics.

In this paper, the design of broadband multilayer beam-forming network using slot-coupled microstrip technology is presented. This 4×4 Butler matrix is based on slot-coupled directional couplers, slot-coupled crossovers and phase shifters. This structure allows offering a wide bandwidth and reducing the use of number of crossovers. In order to achieve the operation over the complete long term evolution (LTE) frequency band at 2.5~2.7GHz, slot-coupled directional couplers, slot- coupled crossovers and phase shifters, being the combination of two microstrip transmission lines (MTLs), have been studied. And also, the simulation results including insertion loss, return loss, and phase difference are presented and discussed.

2. Configuration of 4×4 Butler matrix for beam forming network

The most attractive technique for designing and manufacturing microwave circuits, such as Butler matrices using for switched beam forming network of antenna array system, is a MTL technique. Because it uses a single laminate substrate and permits for easy packaging of surface mount device components.

The broadband 4×4 Butler matrix configured in two TMLs are obtained that broad bandwidth and small phase differences are achieved by combining four slot-coupled directional couplers with two the slot-coupled crossovers and 45° phase shifters [17,18]. The use of slot-coupled technique using two MTLs eliminates branch-line hybrid directional couplers and branch-line crossovers that are present in a conventional planar matrix design.

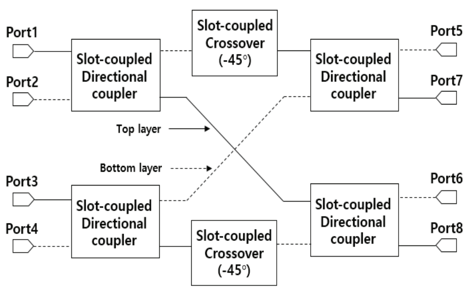


그림 1. 4×4 버틀러 매트릭스의 도식적 다이어그램
Figure 1. Schematic diagram of a 4×4 Butler matrix

<Figure 1> shows a schematic diagram of a 4×4 Butler matrix. It consists of four slot-coupled directional couplers, two slot-coupled crossover including 45° phase shifters.

The slot-coupled directional coupler is constructed on three conductor layers interleaved by two dielectric layers. A common ground is in position between the two dielectrics. 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 ground slot.

The slot-coupled crossover has been composed of two open-ended MTLs with a quarter-wavelength and ground slot. It is only two-port circuit. This approach allows for simultaneous realization of a MTL crossover and broadband 45° phase shifters. Therefore, the proposed crossover has a high performance of around 0.5dB coupling and phase shift of 45±3.5° at the desired frequency band.

3. Simulation results

3.1 Slot-coupled directional coupler

In order to determine the matrix dimensions, two rectangular MTLs and slot dimensions of slot-coupled directional coupler are optimized using high frequency simulation software (HFSS) tool. The intention is to have the transmitting signal at input port divided equally to two output ports, minimize power reflected back to input port and isolation port. The final dimensions of rectangular MTLs and slots are found to be rectangular MTL width of W=4.382mm, slot width of W0=6.522mm, and the rectangular MTL and slot length of L=18.673mm. The simulated results for return loss, coupling, and isolation of the designed coupler are shown in <Figure 2>.

The coupling is 3±0.5dB, and the isolation and return loss are better than 21.6dB over the simulated frequency band of 2.0 to 3.4GHz, as shown in <Figure 2>. The coupler provides phase difference of 90±1.0° between its two output ports in the same band.

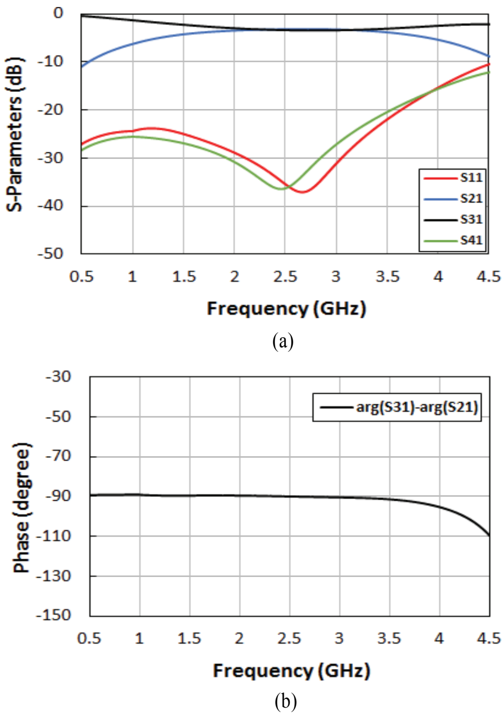


그림 2. 설계된 커플러의 시뮬레이션 결과 (a) 산란계수의 크기, (b) 위상차

Figure 2. Simulation results for the designed coupler (a) amplitude of scattering parameter, (b) phase difference

3.2 Slot-coupled crossover

The slot-coupled crossover including 45° phase shifter consists of two rectangular MTLs opened its end, which are connected to the input and output port at top and bottom layer, respectively. Its design is similar to the slot-coupled directional coupler. The coupling between the open-ended rectangular MTLs is achieved via a rectangular slot in the common ground plane, located at middle layer. The capability of phase shift is obtained by controlling the length of open-ended rectangular MTLs and rectangular slot.

By using HFSS optimization tool, the dimensions of open-ended rectangular MTLs and slot for phase shift of 45° are found to be W=4.382mm, W0=6.522mm and L=18.673mm. Input and output port of slot-coupled crossover is terminated to MTL with 50Ω impedance.

The simulated performance of the slot-coupled crossover is shown in <Figure 3>. The return loss of the crossover is better than 19.5dB and the insertion loss is about 0.5dB in the 1.95 ~ 2.94GHz. The differential phase shift of approximately 45° is within 2.5 to 2.7GHz, as presented in <Figure 3>. Otherwise, there is phase deviation of approximately ±3.5° in the same frequency band.

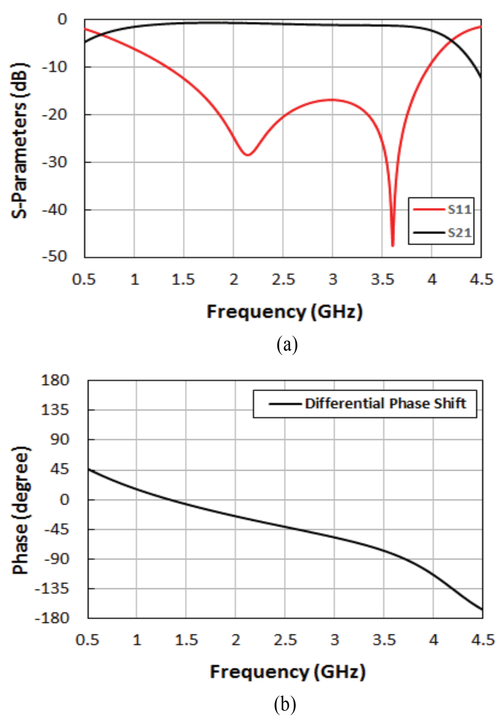


그림 3. 설계된 크로스오버의 시뮬레이션 결과 (a) 산란계수의 크기, (b) 위상차

Figure 3. Simulation results for the designed crossover (a) amplitude of scattering parameter, (b) phase difference

3.3 4×4 Butler matrix

All of the components of Butler matrix are implemented on Taconic substrate (RF-35) with dielectric constant of 3.5 and thickness of 0.5mm, and are designed using HFSS. As the performance of the Butler matrix depends critically on the bandwidth and the phase shift of slot-coupled coupler and slot-coupled crossover, they are analyzed inclusively using HFSS simulation tool.

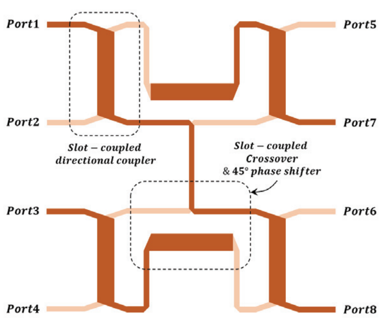
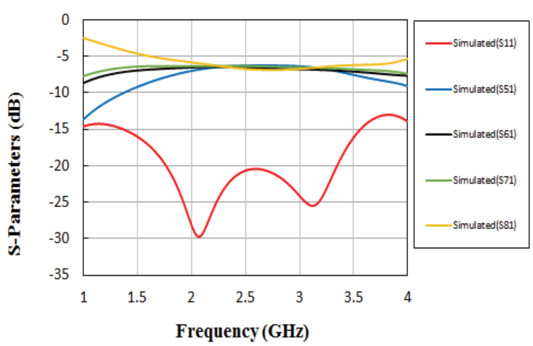


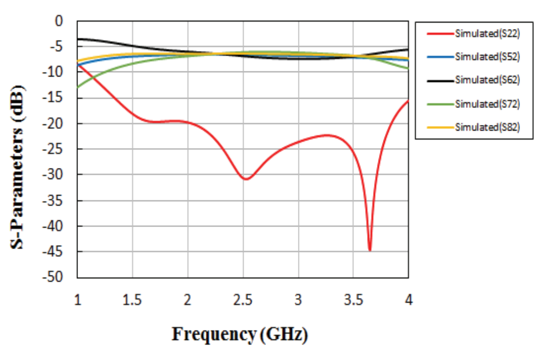
그림 4. 4×4 버틀러 매트릭스 구조의 단면도

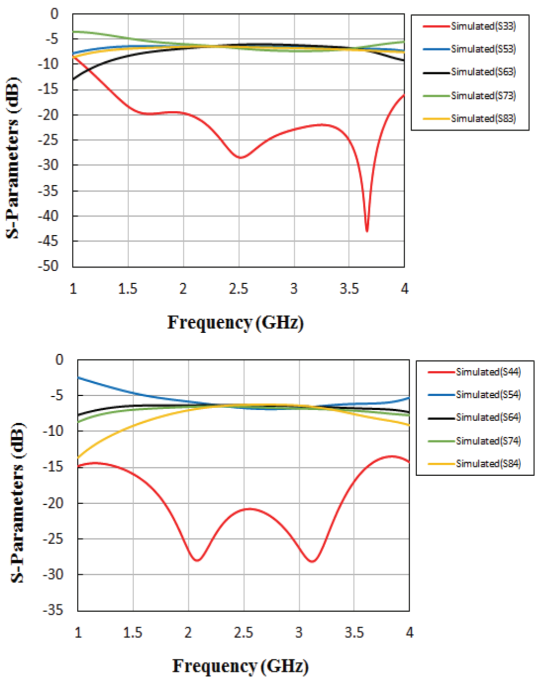
Figure 4. a cross-sectional view of 4×4 Butler matrix structure

<Figure 4> shows a cross-sectional view of 4×4 Butler matrix structure combined four slot-coupled directional couplers with two slot-coupled crossovers. Simulation and measurement results are shown in <Figure 5> and <Figure 6>. It can be seen that the obtained results of <Figure 5> are in almost agreement with the measurement ones of <Figure 6> regarding the imbalance of amplitude characteristics and small phase deviations. The insertion losses in <Figure 5(a)> and <Figure 6(a)> show the simulations and measurements delivered to output ports 5 through 8 when signals are sequentially fed to input ports 1 through 4 of the Butler matrix. And also, The phase differences in <Figure 5(b)> and <Figure 6(b)> show the simulations and measurements delivered in the Butler matrix.

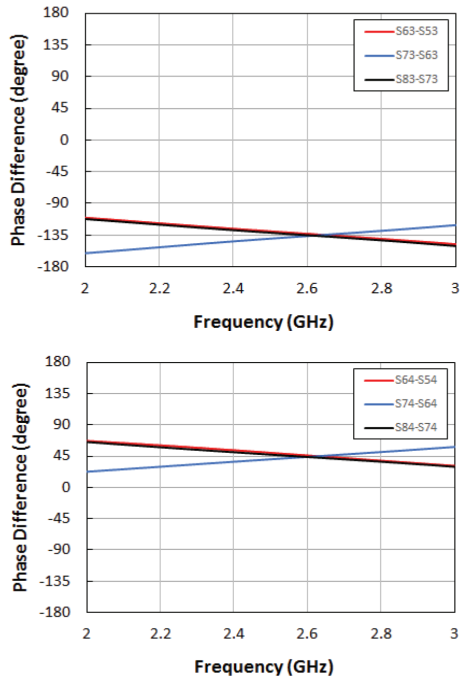
The proposed matrix has a broad bandwidth in terms of insertion loss of 6.5±0.5dB and progressive phase shift of -45°, 135°, -135°, and 45° in the center frequency of 2.6GHz. There are maximally phase deviation less than 5° in the operating frequency band from 2.5GHz to 2.7GHz. Moreover, the matrix has excellent return loss and isolation characteristics better than 15.5dB for all input ports.







(a)



(b)

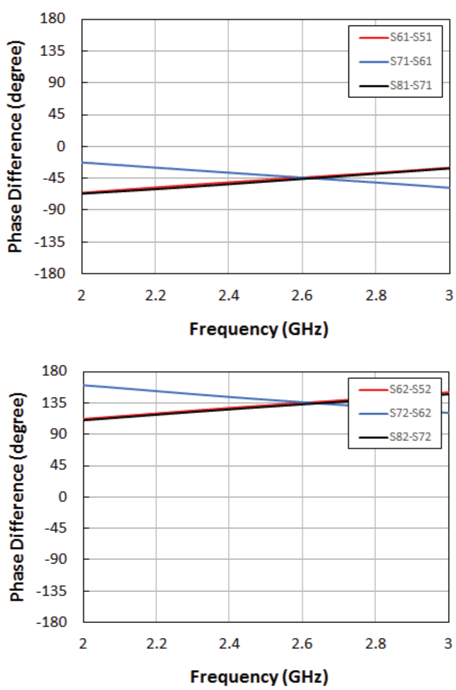
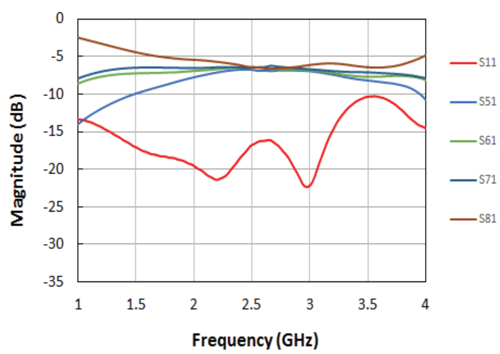
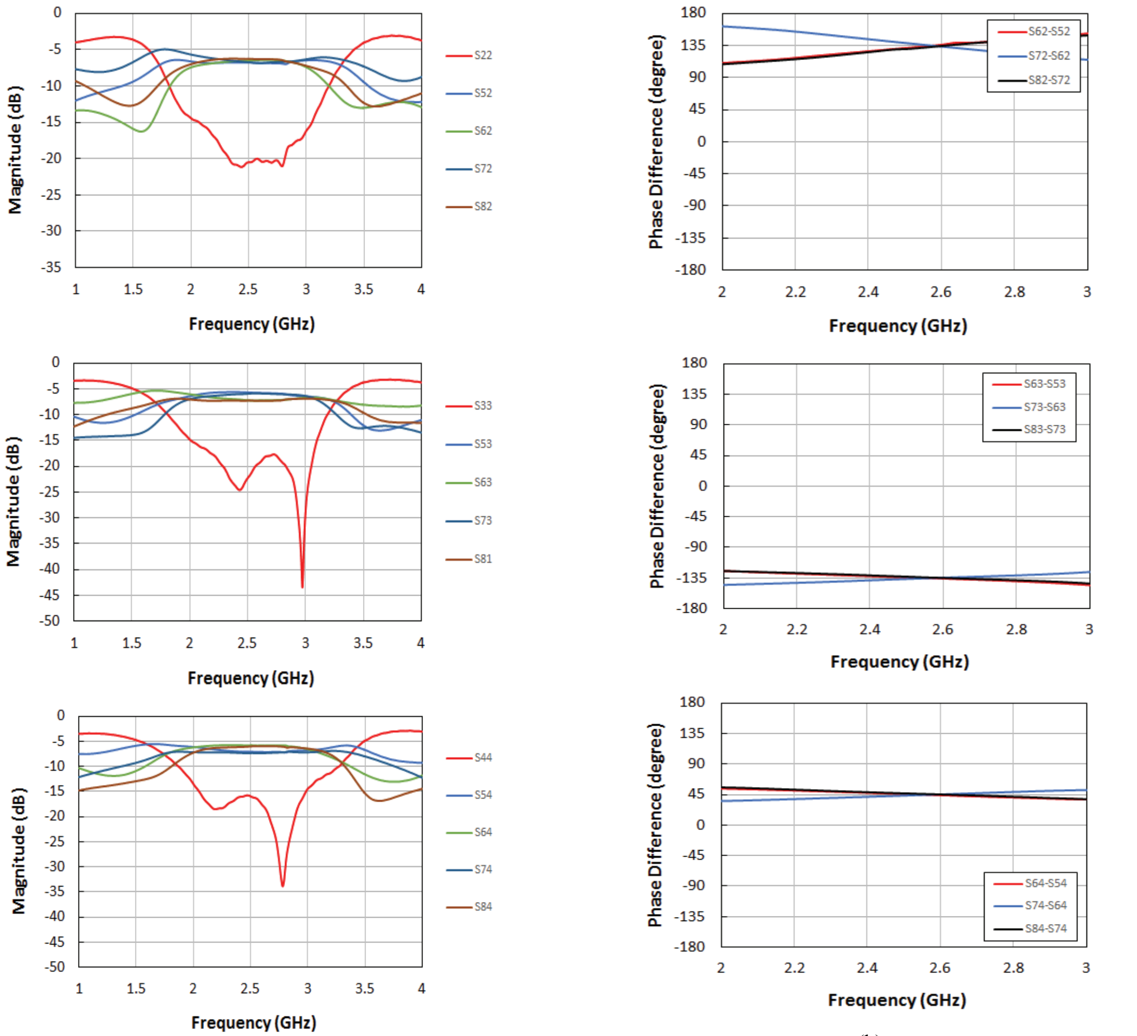


그림 5. 4×4 버틀러 매트릭스의 시뮬레이션 결과 (a) 산란계수의 크기, (b) 위상차

Figure 5. Simulation results of 4×4 Butler matrix (a) scattering parameter, (b) phase difference





(a) (b)

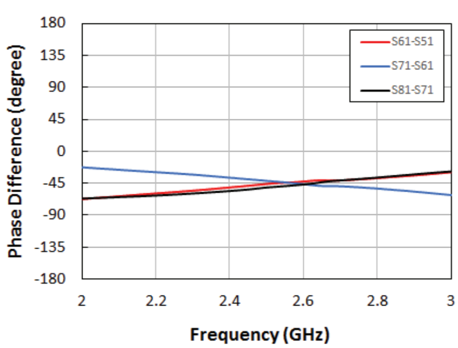
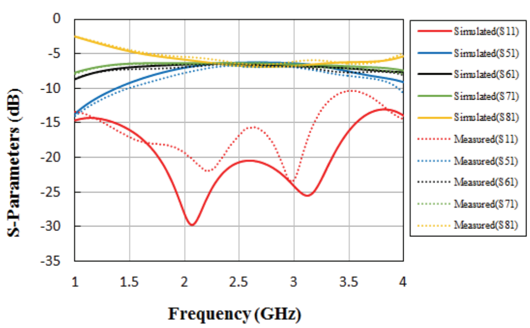


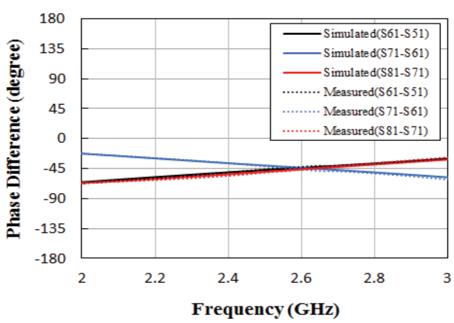
그림 6. 4×4 버틀러 매트릭스의 측정 결과 (a) 산란계수의 크기, (b) 위상차

Figure 6. measurement results of 4×4 Butler matrix (a) scattering parameter, (b) phase difference

The comparison between simulation and measurement results of output port 5 to 8 when input signal is fed to port 1 shows on one graph of <Figure 7>. The results for amplitude and phase difference are similar to each other in the full scale frequency band. However, the measurement values of return loss is 5dB smaller than simulation results in the operating frequency band from 2.5GHz to 2.7GHz. The proposed matrix has the insertion loss of 6.5±0.4dB and phase shift of -45° at 2.6GHz center frequency. This matrix has excellent return loss and isolation characteristics. In addition, the photograph of fabrication product for the proposed Butler matrix shows in <Figure 8>.



(a)



(b)

그림 7. 포트 1 급전 버틀러 매트릭스의 비교 결과 (a) 산란계수의 크기, (b) 위상차

Figure 7. Comparison results of Butler matrix feeding in port 1 (a) scattering parameter, (b) phase difference

4. Conclusions

A compact broadband 4×4 Butler matrix has been designed using slot-coupled microstrip multilayer technology including in switched beam forming network.

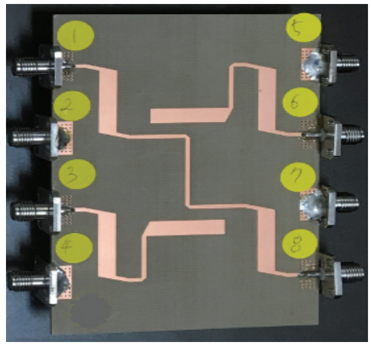


그림 8. 버틀러 매트릭스의 제작품 사진

Figure 8. Photograph of fabrication product for the Butler matrix

In the proposed design, a combination of a microstrip slot-coupled directional coupler and slot-coupled crossover including 45° phase shifter were employed to expand the bandwidth of the Butler matrix and reducing the number of conventional crossovers. Measurement results show that a relative bandwidth of 43% at the center frequency of 2.6GHz has been achieved. From the simulation and measurement results, the proposed matrix has a broad bandwidth in terms of return loss of 15.5dB, insertion loss of 6.5±0.4dB and progressive phase shift of -45°, 135°, -135°, and 45° in the center frequency of 2.6GHz. And phase deviation is less than 5° in operating frequency band from 2.5GHz to 2.7GHz. Its compact size and good performance makes it suitable for use in broadband switched beam forming network for angle diversity in four switched beams in the LTE wireless applications of 2.6GHz.

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다층 마이크로스트립 전송선 기반 슬롯 결합 광대역 버틀러 매트릭스 구현

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요 약

다중 입출력 (MIMO) 기술과 스마트 안테나 기술에 요구되는 제안한 스위치형 빔 포밍 네트워크는 이동국의 이동 방향에 따라 어레이 안테나의 빔 방향을 적절하게 조정할 수 있다. 따라서 버틀러 매트릭스(Butler matrix)라 불리는 제안된 빔 성형 네트워크는 배열 안테나에 인가되는 급전 신호들의 크기와 위상을 조정하여 다양한 방향으로 빔을 형성할 수 있는 급전 시스템이다. 이 논문에서는 마이크로 스트립 슬롯결합 방향성 결합기와 45° 위상 천이기를 포함한 슬롯결합 크로스오버를 조합 구성하여 4x4 버틀러 매트릭스의 대역폭을 확장하고 기존 매트릭스 구성에서 요구되는 크로스오버의 수를 줄였다. 제안된 슬롯결합 부품은 상부와 하부 층에서 서로 마주하는 2개의 직사각형 마이크로스트립 전송선(RMTL)과 공통 접지면으로 구성된다. 이러한 RMTL 간의 커플링은 2개의 유전체 사이의 중간층에 위치한 접지면에 직사각형 슬롯을 냄으로써 이루어진다. 시뮬레이션 및 실험 결과로부터 제안된 버틀러 매트릭스는 2.5 ~ 2.7GHz 동작주파수 대역에서 43%의 넓은 주파수 대역폭, 15.5dB의 반사손실, 6.5±0.4dB의 삽입손실 및 -45, 135, -135, 45 ±5° 순차적 위상 천이의 양호한 성능을 나타내었다.

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