Journal of KIIT. Vol. 20, No. 7, pp. 77-85, Jul. 31, 2022. pISSN 1598-8619, eISSN 2093-7571 77
http://dx.doi.org/10.14801/jkiit.2022.20.7.77

Design of a Three-Branch Line Quadrature Hybrid Coupler with Reduced Size

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This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the National Program for Excellence in SW (2019-0-01183) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation)

Abstract

This paper presents a design of a three-branch line quadrature hybrid coupler with reduced size implemented in the microstrip line. The designed coupler is to be used in the feeding of a crossed-dipole circularly polarized antenna for receiving GNSS signals at 1.16-1.61 GHz. The performances of the two- and three-branch line couplers are investigated first. Characteristic impedances of the three branch lines are adjusted for a better balance in coupling coefficients. To reduce the size of the three-branch line coupler, the main lines are meandered inward and outward using the optimized coupler. Meandering reduces the size of the quadrature hybrid coupler by 35.2% in one direction. The outward-meandered coupler shows slightly larger bandwidth than the inward-meandered design. The outward-meandered coupler shows magnitude and phase imbalances of 0.36 dB/0.7° at 1.16 GHz, and 0.43 dB/0.8° at 1.61 GHz.

요 약

본 논문은 마이크로스트립 선로로 구현된 크기가 감소된 3개 가지선로 90° 하이브리드 커플러의 설계를 제안한다. 설계된 커플러는 1.16-1.61 GHz에서 위성항법 신호를 수신하기 위한 교차 다이폴 원편파 안테나의 급전에 사용하기 위한 것이다. 2개 및 3개 가지선로 커플러의 성능을 우선 확인하였다. 결합계수의 향상된 대칭을 위해 가지선로의 특성 임피던스를 조정하였다. 3개 가지선로의 크기를 줄이기 최적화된 커플러를 사용하여 주선로를 안쪽 및 바깥 방향으로 구부렸다. 미앤더링에 의해 한 방향으로 90° 하이브리드 커플러의 치수가 35.2% 감소하였다. 바깥쪽 미앤더 커플러가 안쪽 미앤더 커플러보다 약간 더 넓은 대역폭을 보인다. 바깥쪽 미앤더 커플러와 바깥쪽 미앤더 커플러가 비슷한 특성을 보였다. 안쪽 미앤더 커플러는 1.16 GHz에서 0.36 dB/0.7°, 1.61 GHz에서 0.43 dB/0.8°의 크기와 위상 비대칭 특성을 보인다.

Keywords
branch line coupler, hybrid coupler, size reduction, antenna feed network

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· Received: Jul. 04, 2022, Revised: Jul. 25, 2022, Accepted: Jul. 28, 2022
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I. Introduction

The branch-line hybrid coupler is a passive component for combining or dividing two signals with high isolation [1]. It is used in antenna feed networks [2][3], analog signal processing[4], and power combining in high power amplifiers[5]. Pertinent characteristics required of a quadrature hybrid include good amplitude and phase balances, high isolation, low loss, and good input and output matching.

The size of a quadrature hybrid coupler is approximately 0.25 λ × 0.25 λ, where λ is the wavelength of the transmission line used to implement the hybrid, which is often too large in many applications. There have been numerous research efforts to reduce the size of the quadrature hybrid coupler[6]-[8]. Line-meandering and stub-loading methods are among most popular methods for the miniaturization of the quadrature hybrid coupler. The degree of miniaturization is proportional to the degree of meandering and sub-loading, where inferior performance is expected with a higher degree of miniaturization.

The basic two-branch line hybrid coupler is not broadband enough(about 15-20%) so that multi-section branch-line couplers are often used for wider bandwidth(30-50% with three or four branch lines) [9]-[11]. A review of branch-line hybrid couplers has recently been published[12], where research works on wideband and miniature designs of the quadrature hybrid couplers in various transmission lines are summarized.

In this paper, we present a design of a three-branch line microstrip quadrature hybrid coupler whose size is reduced by meandering the main lines. The coupler is to be used in a feed network of a crossed-dipole antenna operating at 1.16-1.61 GHz for the reception of multi-GNSS signals(GPS, Galileo, GLONASS, and BeiDou).

First, a two-branch line coupler is investigated to check whether its bandwidth is large enough for the multi-GNSS signal reception. Next, a three-branch line coupler is designed and used for miniaturization. Then two geometries of the reduced-size coupler are designed where the branch lines are meandered outward and inward. The design has been carried out using the CST Studio Suite 2021.

II. Coupler Design

Fig. 1 shows a three-branch line quadrature hybrid coupler for feeding a circularly-polarized antenna employing crossed dipoles. The antenna is to operate at 1.16-1.61 GHz(center frequency 1.39 GHz, bandwidth 32.5%) for the reception of multiples GNSS signals such as GPS, GLONASS, BeiDou and Galileo. The ground plane dimension is optimized for the best axial ratio performance. The size of the quadrature hybrid coupler is reduced so that the coupler is implemented within the boundary of the ground plane of the crossed dipole antenna.

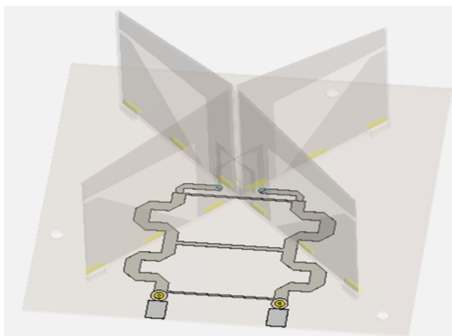


Fig. 1. Three-branch line quadrature hybrid coupler feeding a circularly polarized crossed-dipole antenna

As the first step in the design of the reduced-size coupler, a standard two-branch line quadrature hybrid coupler shown in Fig. 2, where the dimensional parameters of the coupler are denoted. The characteristic impedances of the transmission lines are given by

$$Z_0 = 50\ \Omega \tag{1}$$

$$Z_1 = Z_0 = 50\ \Omega,\ Z_2 = Z_0/\sqrt{2} = 35.4\ \Omega \tag{2}$$

The widely-used FR-4 substrate with ε_r = 4.3, tanδ = 0.02, and 1-mm thickness is used to realize the coupler. The dimensions(in millimeter) of the designed two-branch line coupler is as follows: L_1 = 30.40, L_2 = 29.80, W_1 = 1.94, and W_2 = 3.30. The following shows the line design at 1.39 GHz.

Line 1: ε_{re1} = 3.26, Z_1 = 50.3 Ω, L_1 = 0.255 λ
Line 2: ε_{re2} = 3.41, Z_2 = 35.5 Ω, L_2 = 0.255 λ

Since the lengths of input and output lines are arbitrary, they are excluded when we mention the size of a coupler. The width and height of the two-branch line coupler in Fig. 2 are L_2+W_1(31.74 mm) and L_1+W_2(33.70 mm).

The frequency response of the coupler is plotted in Figs. 3 to 5. Fig. 3 shows the magnitude of the reflection and transmission coefficients of the coupler. The coupling or transmission coefficients are good only at 1.30-1.60 GHz.

The reflection coefficient at the input port(S_{11}) is less than -15 dB at 1.28-1.54 GHz, while the transmission coefficient between ports 1 and 4(S_{41}) or the negative of the isolation is less then -15 dB at 1.25-1.57 GHz.

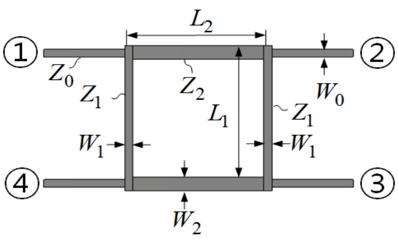


Fig. 2. Structure of two-branch line quadrature hybrid coupler

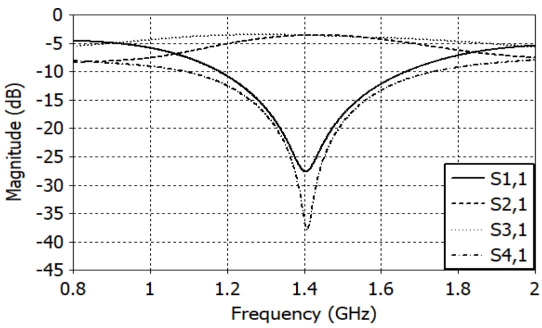


Fig. 3. Reflection and transmission coefficients of the two-branch line quadrature hybrid coupler

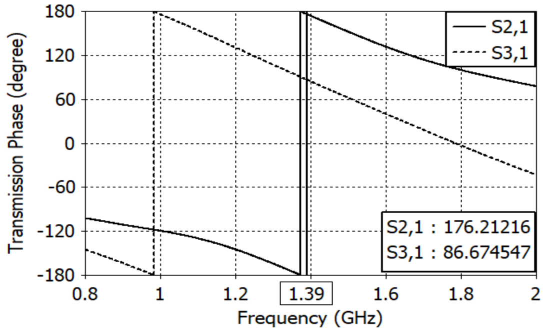


Fig. 4. Transmission phase of the two-branch line quadrature hybrid coupler

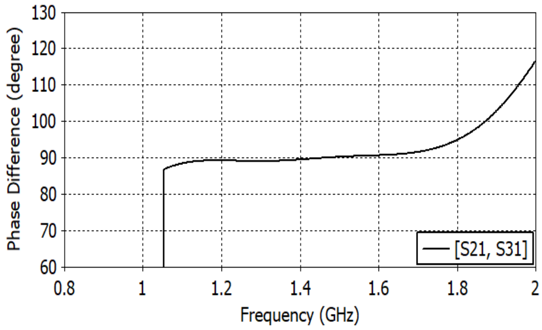


Fig. 5. Transmission phase difference of the two-branch line quadrature hybrid coupler

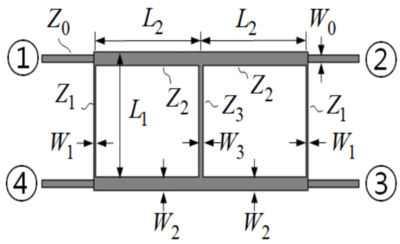


Fig. 6. Structure of a three-branch line quadrature hybrid coupler

Fig. 4 shows the transmission phase of the coupler, while Fig. 5 shows the difference in the transmission phase. At 1.16-1.61 GHz, the transmissionㄴ phase difference ranges from 81.6° to 92.0°. The two-branch line coupler shows amplitude balance of less than 0.28 dB, phase difference of 89.5° to 90.4°, and reflection coefficient of less than –15 dB at 1.28-1.53 GHz(17.8% bandwidth)

The performance of the two-branch line coupler is rather poor due to inherent narrow bandwidth property of the structure and due to the capacitive discontinuities in the microstrip line junctions.

Next a three-branch line quadrature hybrid coupler of the Butterworth response is designed whose structure is shown in Fig. 6, where the dimensional parameters(in mm) of the coupler are denoted. Dimensions(mm) of the coupler are as follows: L_1 = 31.72, L_2 = 30.93, W_1 = 0.26, W_2 = 3.10, W_3 = 3.07. Theoretical values of the line impedances[9] are

$$Z_1 = Z_0 \ / \ 0.4149 = 120.5 \ \Omega \tag{3}$$

$$Z_2 = Z_0 \ / \ 1.3432 = 37.2 \ \Omega \tag{4}$$

$$Z_3 = Z_0 \ / \ 1.3774 = 36.3 \ \Omega \tag{5}$$

The following is the information on the lines used in the coupler.

Line 1: ε_{re1} = 2.92, Z_1 = 121.0 Ω, L_1 = 0.249 λ
Line 2: ε_{re2} = 3.39, Z_2 = 37.2 Ω, L_2 = 0.264 λ
Line 3: ε_{re3} = 3.39, Z_3 = 37.4 Ω, L_3 = 0.270 λ

The width and height of the unreduced three-branch line coupler are $2L_2+W_1$(62.12 mm) and L_1+W_2(34.82 mm).

Figs. 7-11 show the performance of the three-branch line quadrature hybrid coupler with Butterworth response. In Fig. 7, we note that the reflection coefficient $|S_{11}|$(dB) is less than -15 dB at 1.10-1.65 GHz. The negative of the isolation $|S_{41}|$(dB) is of the same level as $|S_{11}|$(dB).

Fig. 8(a) shows an expanded view of the coupling with the substrate loss included. At 1.61 GHz, $|S_{31}|$ is -2.41 dB while $|S_{21}|$ is -5.72 dB(3.31 dB imbalance). At 1.61 GHz, $|S_{31}|$ is -2.98 dB while $|S_{21}|$ is -5.35 dB (2.37 dB imbalance). Fig. 8(b) shows the coupling without the substrate loss. At 1.61 GHz, $|S_{31}|$ is -1.73 dB while $|S_{21}|$ is -5.49 dB(3.76 dB imbalance). At 1.61 GHz, $|S_{31}|$ is -2.12 dB while $|S_{21}|$ is -4.46 dB (2.34 dB imbalance). The dielectric loss is about 0.5 dB at 1.16 GHz and 0.9 dB at 1.61 GHz.

Fig. 9 shows the transmission phase of the three-branch line coupler, while Fig. 10 shows the difference in the transmission phase. The phase difference is 87.1° at 1.16 GHz and 93.2° at 1.61 GHz.

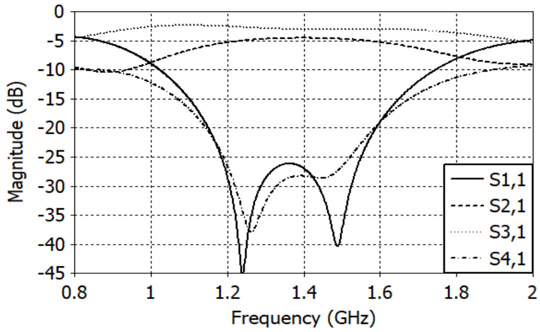
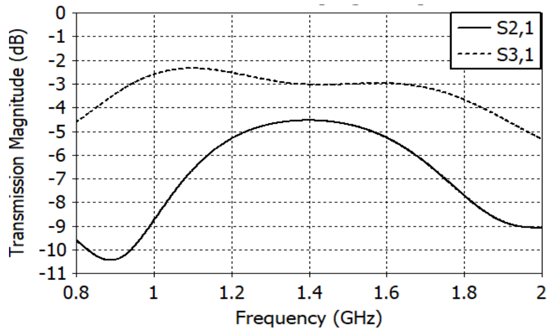
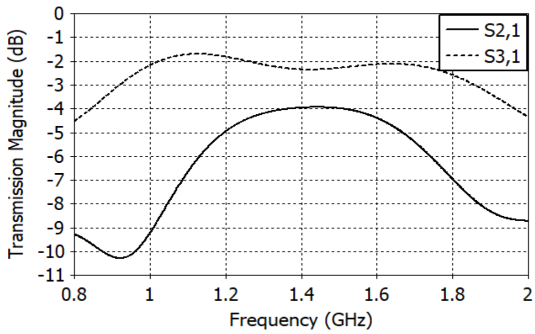


Fig. 7. Reflection and transmission coefficients of the three-branch line quadrature hybrid coupler with Butterworth response



(a) With substrate loss



(b) Without substrate loss

Fig. 8. Coupling values of the three-branch line quadrature hybrid coupler with Butterworth response

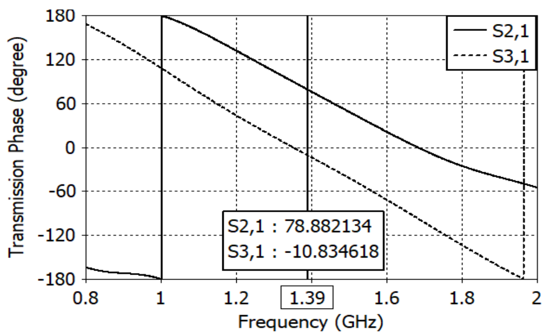


Fig. 9. Transmission phase of the three-branch line quadrature hybrid coupler with Butterworth response

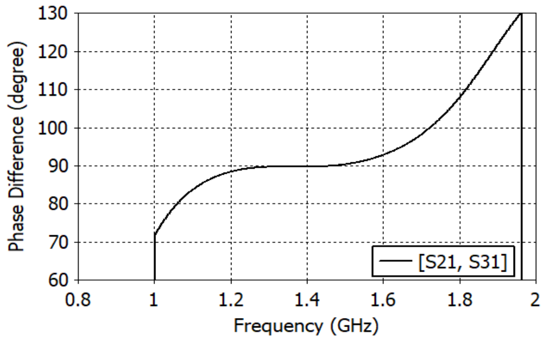


Fig. 10. Transmission phase difference of the three-branch line quadrature hybrid coupler with Butterworth response

As seen in Fig. 7, the amplitude-balance performance of the theoretical three-branch line coupler is very poor(2.38 dB at 1.61 GHz, 2.38 dB at 1.61 GHz) and needs to be improved.

The poor performance of the theoretical design is mostly due to microstrip junction discontinuities, which are pronounced at the junction of narrow lines(first and third branches) and the wide main lines.

To improve the performance, the characteristic impedance of the branch lines has been adjusted since the compensation of the junction effects is not simple. Optimized dimensions in mm are: W_1 = 0.46, W_2 = 3.10, W_3 = 1.34. The parameters of the lines in the coupler are given below.

Line 1: ε_{re1} = 2.98, Z_1 = 99.7 Ω, L_1 = 0.253 λ
Line 2: ε_{re2} = 3.39, Z_2 = 37.16 Ω, L_2 = 0.265 λ
Line 3: ε_{re3} = 3.17, Z_3 = 61.95 Ω, L_3 = 0.261 λ

Figs. 11-13 show the performance of the improved three-branch line coupler. The reflection coefficient is -19.5 dB and -26.3 dB at 1.16 GHz and 1.61 GHz respectively. $|S_{21}|$ and $|S_{31}|$ are -3.84 dB and -3.51 dB at 1.16 GHz(0.33 dB imbalance), -3.60 dB and -3.98 dB at 1.61 GHz(0.38 dB imbalance). In Fig. 13, we note the transmission phase difference is 88.9° and 90.5° at 1.16 GHz and 1.61 GHz(±0.5° imbalance).

By comparing Fig. 11 with Fig. 7, one can see that the balance of the coupling coefficients has been significantly improved. Modification of branch-line characteristic impedances has an effect of compensating the junction effects.

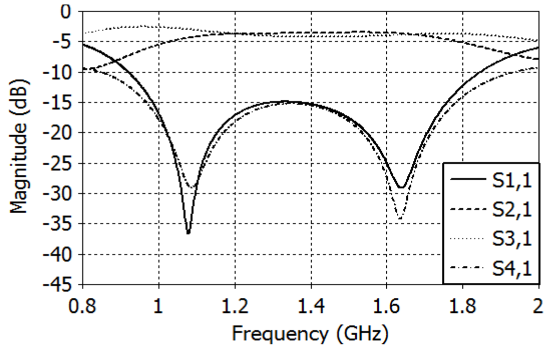


Fig. 11. Reflection and transmission coefficients of the improved three-branch line quadrature hybrid coupler with Butterworth response

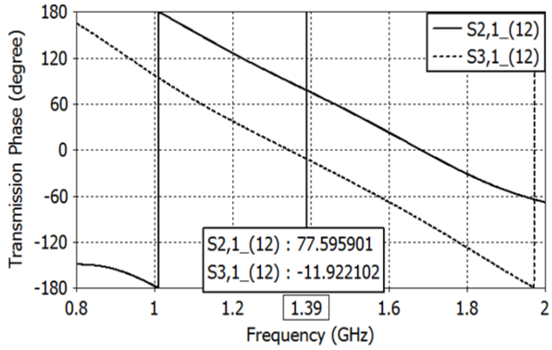


Fig. 12. Transmission phase of the improved three-branch line quadrature hybrid coupler with Butterworth response

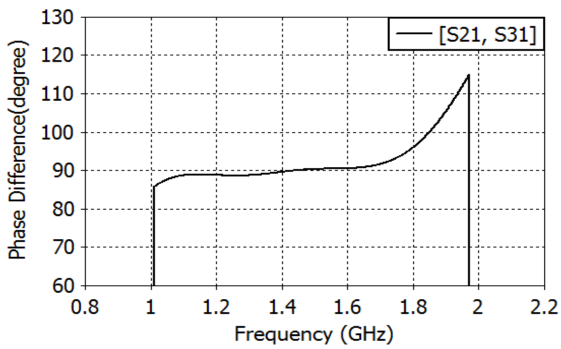


Fig. 13. Phase difference between two output ports of the improved three-branch line quadrature hybrid coupler with Butterwork response

The non-meandered three-branch line coupler shows amplitude balance of less than 0.65 dB, phase difference of 89.0° to 92.3°, and reflection coefficient of less than -14.9 dB at 1.16-1.72 GHz(38.9% bandwidth)

Based on the improved design, the size of the three-branch line coupler is reduced by meandering the main lines as shown in Fig. 14(inward meandering) and Fig. 18(outward meandering). It is speculated that the inward meandering of Fig. 14 gives inferior performance due to close proximity of the main line to the branch line. Therefore we have investigated both types of meandering.

Branch line widths are optimized from the non-meandered design of Fig. 6 for improved performance. This is necessary because the meandering of the main lines introduces additional discontinuity effects at microstrip bends.

The dimensional parameters are shown in Fig. 14 whose values in mm are: L_4 = 11.2, L_5 = 4.35, L_6 = 4.80. The length of the main line along its center is 30.72 mm. The width of W_1 is optimized to 0.45 mm, while that of W_3 is adjusted to 1.94 mm.

The width and height of the unreduced three-branch line coupler in Fig. 14 are $2L_4+4L_5$(40.28 mm) and L_1+W_2(34.82 mm).

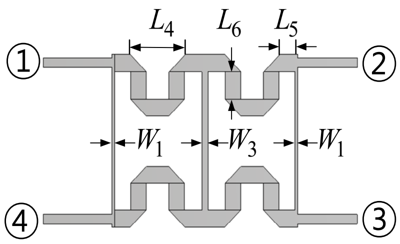


Fig. 14. Structure of an inward-meandered three-branch line coupler

Figs. 15-17 show the performance of the coupler with the main lines meandered inward. The reflection coefficient is -29.2 dB and -25.5 dB at 1.16 GHz and 1.61 GHz respectively. $|S_{21}|$ and $|S_{31}|$ are -3.76 dB and -3.47 dB at 1.16 GHz(0.29 dB imbalance), -3.74 dB and -3.79 dB at 1.61 GHz(0.05 dB imbalance). The transmission phase difference is 89.4° and 91.1° at 1.16 GHz and 1.61 GHz(-0.6°/1.1° imbalance). The inward-meandered coupler shows amplitude balance of better than 0.65 dB, phase difference of 89.4° to 91.9°, and reflection coefficient of less than -17.2 dB at 1.16-1.68 GHz(36.6% bandwidth).

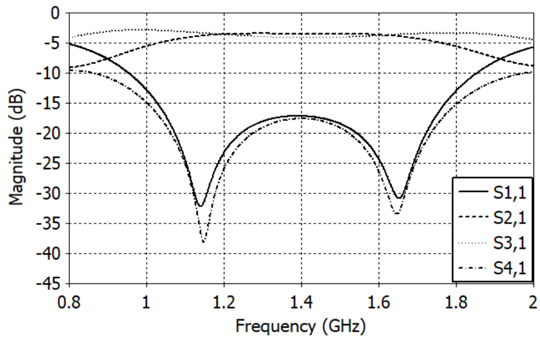


Fig. 15. Reflection and transmission coefficients of the inward-meandered three-branch line coupler

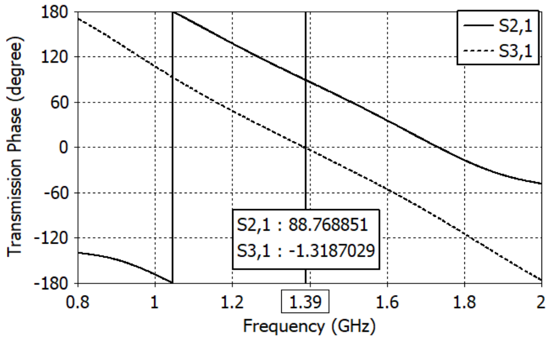


Fig. 16. Transmission phase of the inward-meandered three-branch line coupler

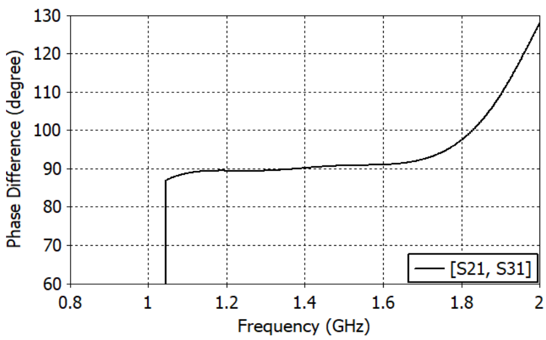


Fig. 17. Transmission phase difference of the inward-meandered three-branch line coupler

The coupler's size is reduced by meandering the main lines outward as shown in Fig. 18. Branch line widths are optimized for improved performance. The dimensional parameters are shown in Fig. 18 whose values in mm are: L_7 = 11.2, L_8 = 4.35, L_9 = 4.80. The length of the main line along its center is 30.72 mm. The adjusted values of W_1 and W_3 are 0.36 mm and 1.94 mm respectively.

Figs. 19-21 show the performance of the coupler with the main lines meandered outward.

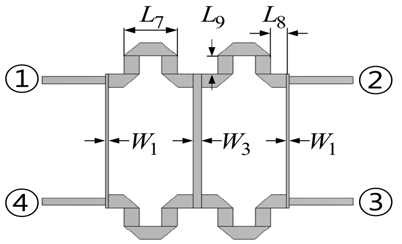


Fig. 18. Structure of an outward-meandered three-branch line coupler

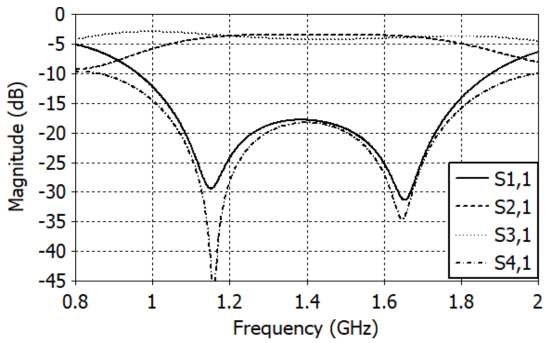


Fig. 19. Reflection and transmission coefficients of the outward-meandered three-branch line coupler

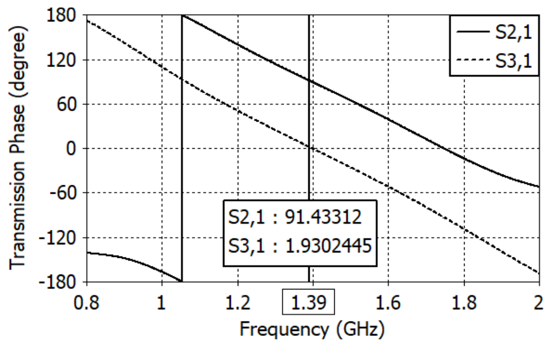


Fig. 20. Transmission phase of the outward-meandered three-branch line coupler

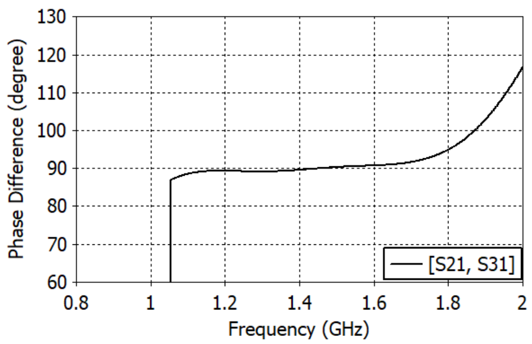


Fig. 21. Phase difference between two output ports of the outward-meandered three-branch line coupler

The reflection coefficient is -28.9 dB and -26.2 dB at 1.16 GHz and 1.61 GHz respectively. $|S_{21}|$ and $|S_{31}|$ are -3.80 dB and -3.44 dB at 1.16 GHz(0.36 dB imbalance), -3.54 dB and -3.97 dB at 1.61 GHz(0.43 dB imbalance). The transmission phase difference is 89.3° and 90.8° at 1.16 GHz and 1.61 GHz(±0.8° imbalance). The outward-meandered coupler shows amplitude balance of better than 0.77 dB, phase difference of 89.2° to 92.3°, and reflection coefficients of less than -17.8 dB at 1.15-1.73 GHz(40.3% bandwidth). The bandwidth is slightly larger than that of the inward-meander case, and slightly smaller than the non-meander case.

Table 1 compares the size of the branch line couplers investigated in this paper. Three-branch line coupler in Muraguchi's work shows a bandwidth of 29-39%[10]. Gosh and coworkers designed a four-branch microstrip line coupler with inward meandering. Their coupler operates at 0.775-1.125 GHz(36.8% bandwidth)[11]. It appears that it is not practical to implement four-branch line microstrip quadrature hybrid coupler due to the high impedance ratio and the resulting junction effects.

Table 1. Size comparison of the branch line couplers

Coupler	Width (mm)	Height (mm)	Width ratio (%)	Bandwidth (%)
2-branch	31.74	33.70	51.1	17.8
3-branch (No meander)	62.12	33.70	100.0	38.9
3-branch (In-meander)	40.28	33.70	64.8	36.6
3-branch (Out-meander)	40.28	42.72	64.8	40.3

III. Conclusion

In this paper, we presented a design of a three-branch line microstrip quadrature hybrid coupler with reduced size. The size reduction has been realized by meandering the main lines. Based on the theoretical design, a unreduced three-branch line coupler has been optimized for better magnitude and phase balance. From the optimized coupler, a size reduction has been obtained by meandering the main lines. The designed outward-meandered coupler offers 35.2% size reduction in the longitudinal direction and shows magnitude and phase imbalances of 0.36 dB/0.7° at 1.16 GHz, and 0.43 dB/0.8° at 1.61 GHz. The coupler design presented in this paper may find applications in wideband feed networks for circularly polarized antennas.

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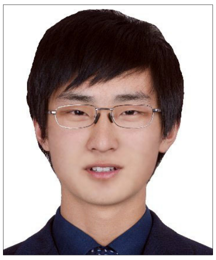

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