Progress In Electromagnetics Research Letters, Vol. 88, 1–8, 2020

A Wide-Band Compact Quadrature Coupler on Multi-Layer Package Substrate

Umar Dilshad*, Chen Chen, Amjad Altaf, Anyong Hu, and Jungang Miao

Abstract—This paper presents the design of a 3.8 $\sim$ 8.0 GHz wide-band quadrature coupler on a multi-layer package substrate. The asymmetric coupled-line 3-dB quadrature coupler has been designed on a four-layer microwave substrate, with a 10-mil thick top layer of Roger's RO4350B substrate press-joined to a 20-mil thick bottom layer of RO4350B, through 4-mil thick bond-ply material RO4450B. In the proposed design, the second and third metal layers are used as coupling layers, while the fourth (bottom) layer provides four signal pads and one large ground pad for connection with the test circuit. The mutual coupling is achieved through the overlay of coupled lines. Four VIA holes are used for signal transition from coupling layers to the bottom-layer pads. The SMD package quadrature coupler provides the ease of integration with other microwave circuits. The quadrature coupler chip size is 4.0 mm $\times$ 8.0 mm $\times$ 0.9 mm. The measurement results show a close resemblance to the EM-simulation results. The measured results depict reasonably flat 3-dB coupling and quadrature phase difference. The amplitude imbalance remains within 1.0 dB, while the phase imbalance always remains much less than 3.0 degrees. The return loss and isolation are better than 13 dB, throughout the whole frequency band. The proposed design is quick and simple. The manufacturing process is also cost-effective. To the best of the author's knowledge, these measured performance parameters in 71% fractional bandwidth associated with the compact size of the self-packaged device are better than those of the earlier published 4-layer design schemes of wideband quadrature couplers.

1. INTRODUCTION

Quadrature couplers are often required in wide-band communication systems for quadrature division and combining of signals. The traditional branch-line coupler [1] is narrowband, having around 20% fractional bandwidth. For its bandwidth broadening, multiple cascaded stages can be employed [2, 3]. Some researchers also proposed additional matching stubs, compensation circuits, or additional broadband phase shifters for this purpose [4–6]. However, the disadvantage in the above-mentioned cases is the increased layout area. Micro-strip Lange couplers [7] are relatively broadband, but they are often difficult to realize using conventional manufacturing techniques, and they also require bond wire connections. So, the design of a compact and wide-band directional coupler with efficient and flat 3-dB quadrature coupling is quite challenging, using two-layer microstrip structures. In recent years, some design topologies of multi-layer compact wide-band directional couplers have been proposed. Slot coupled hybrids, employing efficient broadband tight coupling through the ground aperture [8–14], require bottom layer ground clearance. So, they are not suitable for integration in compact systems. Multilayer quadrature couplers based on substrate integrated suspended line (SISL) technology [15–17] utilize small circuit areas and exhibit good performance in wideband but at low center frequencies. However, their design is complex as it involves a lot of design parameters, and the manufacturing cost is also relatively high due to a large number of layers. Due to the usage of a large number of thick

Received 5 September 2019, Accepted 30 October 2019, Scheduled 8 November 2019
* Corresponding author: Umar Dilshad (umar_dilshad@buaa.edu.cn).
The authors are with the School of Electronic and Information Engineering, Beihang University, Beijing, China.

substrates layers, the device height is also large, which is not suitable for compact systems with low cover heights. Similarly, a modified tandem coupler based on stripline configuration developed on a 4-layer Roger's RO4356B substrate [18] exhibited only 45.5% measured fractional bandwidth. The circuit area is also relatively large, and it is not a self-packaged coupler.

Another available option is multi-layer coupled-line couplers based on Low-Temperature Co-Fired Ceramic (LTCC) substrates, which utilize the coupling based on the overlaying transmission line sections on adjacent substrate layers [19, 20]. However, the limitation is that multi-layer manufacturing on LTCC substrates is relatively difficult, and the cost is also relatively high. The main advantage of the multi-layer substrate is System-on-Package (SoP). We can combine various active chips fabricated from different technologies using interconnections, and additionally passive components can be designed and embedded inside the same multi-layer substrate, in a cost-effective manner. These limitations drive the motivation for the design of a compact surface-mount device (SMD) package multi-layer wide-band quadrature hybrid, using the commonly used microwave substrate and employing some relatively easy manufacturing techniques. In this paper, we propose the design of a $3.8 \sim 8.0$ GHz wide-band compact quadrature coupler on a 4-layer Roger's package substrate. The proposed design exhibits good measured results of amplitude and phase imbalance, matching, and isolation, in wide bandwidth and an extremely compact size.

2. PROPOSED COUPLER DESIGN AND ANALYSIS

In this paper, we propose the design of a $3.8 \sim 8.0$ GHz wide-band quadrature coupler on a multi-layer package substrate. The asymmetric coupled-line 3-dB quadrature coupler is designed on a four-layer Roger's RO4350B microwave substrate. Fig. 1 shows the layer stack-up structure of the substrate employed in this design. The multi-layer substrate consists of a 10-mil thick top layer of Roger's RO4350B substrate press-joined to a 20-mil thick bottom layer of RO4350B, through 4-mil thick bond-ply material RO4450B. The dielectric constants of RO4350B and RO4450B, considered for the design, are 3.66 and 3.54, respectively. The loss tangent for both materials is 0.004.

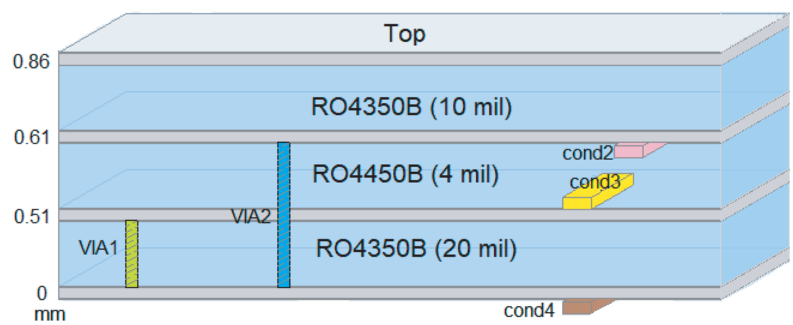
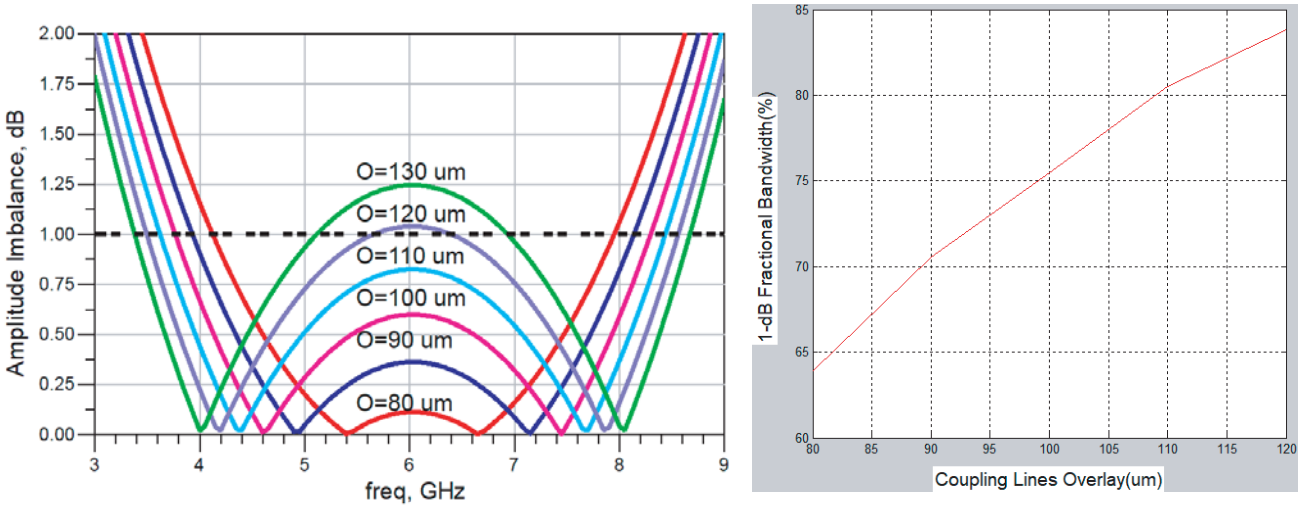


Figure 1. Cross-sectional view of the multi-layer package substrate.

In the proposed design, the second and third metal layers are utilized as coupling layers, while the fourth (bottom) layer provides four signal connection pads and one large ground polygon for connection with the test circuit. 17 µm thick copper material is used in metal layers (2, 3, and 4). The mutual coupling is achieved through overlaying coupled lines. The strength of the coupling amplitude mainly depends upon the width of the coupling lines, their overlay, and the vertical gap between these coupling lines. The vertical spacing between the coupling lines depends upon the thickness of the pre-peg/bond-ply material used. In our case, we utilize 4-mil/100 µm thick RO4450B material for this purpose. However, the actual vertical gap between the coupling lines is much less than 100 µm, because 17 µm thick tracks are somewhat intruded into the pre-peg substrate, depending upon the percentage of copper used in the coupling layers. For the simulation model, a 70 µm vertical gap is assumed. For quadrature phase difference between the through and coupled ports, the electrical lengths of the coupling lines are equal to quarter wavelength ($\lambda/4$) at the center frequency around 6 GHz.



(a) (b)

Figure 2. (a) Simulated amplitude imbalance for different values of coupling offset. (b) Calculated fractional bandwidth versus the coupling offset.

The coupling overlay has been carefully chosen after performing the fractional bandwidth analysis. Actually, we use 1-dB amplitude imbalance criterion for the usable fractional bandwidth of the coupler. In order to obtain maximum possible fractional bandwidth from this 4-layer substrate structure (with the fixed pre-peg thickness), we sweep the overlay between the coupling layers to change the coupling level and plot the amplitude imbalance versus the frequency band. Fig. 2(a) shows the amplitude imbalance plots for the different values of coupling overlay 'O'. Then, we apply the 1-dB criterion to calculate the usable bandwidth for each overlay between the coupling layers. Fig. 2(b) shows the plot of fractional bandwidth versus the coupling overlay. It is evident from both the plots that the fractional bandwidth is maximum at an optimum value of overlay, and it decreases when the overlay decreases from that value, because the amplitude imbalance starts to increase at the edges, and hence the 1-dB fractional bandwidth shrinks. When the overlay increases from that optimum value, the coupling at the center frequency increases, and the amplitude imbalance increases beyond 1-dB. So, after this analysis, we finally choose 120 µm overlay as the optimum value for our proposed design on this substrate structure to obtain a maximum fractional bandwidth. This analysis shows that the proposed design has the capability of achieving more than 80% fractional bandwidth on the chosen substrate structure. Table 1 shows the finalized physical design parameters of the coupler (including the widths and lengths of the coupling lines, and their overlay), calculated using the conventional circuit simulation tool, and then slightly optimized in Electromagnetic Momentum simulator.

Table 1. Quadrature coupler design parameters.

Sr.	Parameter	Layer-2	Layer-3	Layer-4	Units
1	Impedance	64.0	56.0	50.0	Ω
2	Width	0.31 & 0.90		0.42	mm
3	Overlay	0.12		N/A	mm
4	Length	7.10 ($\lambda/4$ at f_c)		0.50	mm

Figure 3 depicts different views of the overall design structure of the coupler chip. The track width of the $\lambda/4$ long coupling lines is 0.31 mm, while the overlay between the lines is 0.12 mm. There is no metal on the top layer. Four VIA holes of 0.20 mm diameter are used for signal transition from coupling layers to the bottom layer signal pads. The bottom signals tracks/PADs have been designed

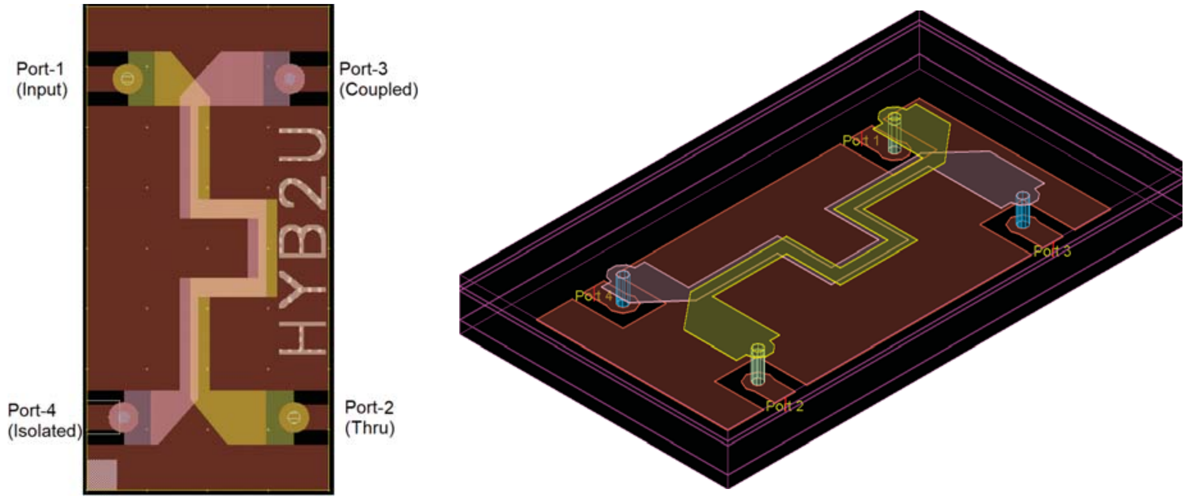


Figure 3. Layout of the proposed quadrature coupler chip (different views).

for 50 Ω, and their width is 0.42 mm. The distance between the signal pad(s) and ground on the bottom layer is optimized to be 0.25 mm, in order to adjust the parasitic capacitance and obtain good input matching. For achieving size compactness, the coupling lines are mitered. The final design is simulated and optimized in the EM simulator. The overall size of the coupler chip is 4.0 mm × 8.0 mm × 0.9 mm.

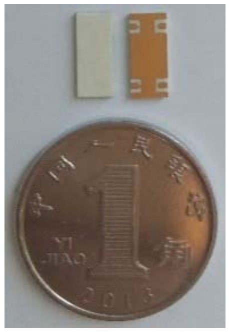
In order to emphasize the size compactness of the proposed coupler, we normalize the physical dimensions of the quadrature coupler with the guided wavelength (λ_g) at the center frequency to calculate the electrical size, which makes it independent of the frequency and the dielectric material used. The electrical size of the coupler comes out to be $0.13\lambda_g \times 0.26\lambda_g$, which is smaller than that of the earlier published design schemes on a similar 4-layer microwave substrate. The SMD package quadrature coupler provides the ease of integration with other microwave circuits. The proposed design also provides the ease of manufacturing in addition to the improvement in performance parameters and size compactness.

3. RESULTS AND DISCUSSION

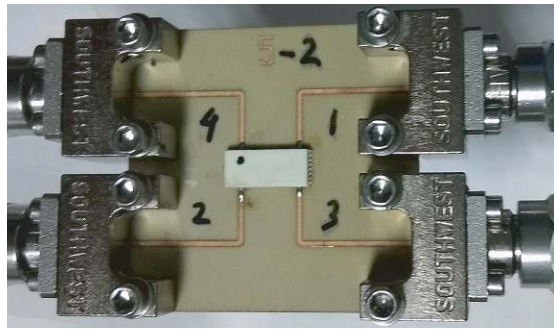
In order to verify the performance of the proposed quadrature coupler design, the coupler chip is mounted on a Rogers RO4350B (10-mil) test circuit board, in the EM-simulation model. The test circuit contains the bottom footprint of the coupler chip and interconnecting micro-strip transmission lines for the four signal connections. A two-dimensional array of 0.3 mm size VIA holes is used on the ground polygon of the test circuit. The EM-simulation results show satisfactory performance in the frequency range of 3.6 ∼ 8.4 GHz. Then the coupler chip is manufactured, and the measurements are performed for performance verification.

Figure 4(a) shows the top and bottom views of the manufactured quadrature coupler chip placed near a ¥0.1 coin (for size estimate), while Fig. 4(b) shows the quadrature coupler chip assembled on the aforementioned test board. The assembly is performed manually using the conventional reflow soldering process. Very sophisticated 2.92 mm Jack (female) end launch connectors from Southwest Microwave are used for measurements. The 4-port S-parameters measurement of the assembled quadrature hybrid (shown in Fig. 4(b)) is performed using Agilent's PNA network analyzer (Model: E5225). The measurement results generally show a close resemblance to the EM-simulation trends. The measured results depict reasonably flat 3-dB coupling and quadrature phase difference between the through and coupled ports. The measured and simulated amplitude responses (S_{21}, S_{31}) of the quadrature hybrid in 3.0 ∼ 9.0 GHz frequency range are shown in Fig. 5.

It is evident that the measured amplitude response is reasonably good in 3.8 ∼ 8.0 GHz band, and the amplitude imbalance between the through and coupled ports mostly remains less than 1.0 dB. Although the EM-simulated amplitude imbalance is better than 1 dB in the whole frequency range of



(a)



(b)

Figure 4. (a) Top and bottom views of fabricated quadrature coupler chip. (b) Quadrature coupler chip assembled on test board for measurements.

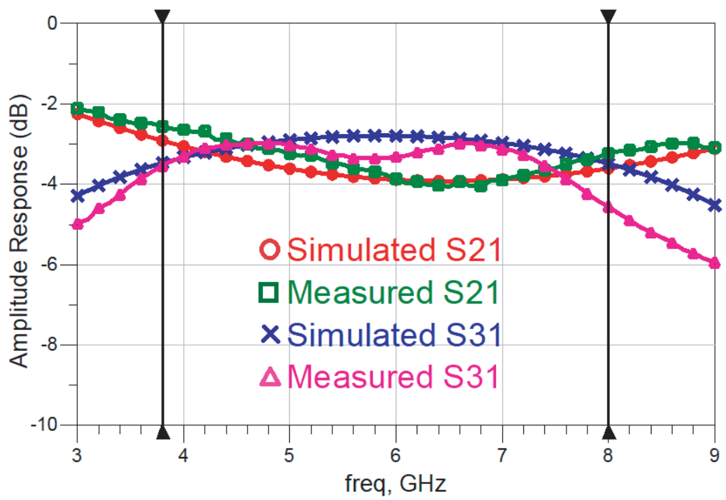


Figure 5. Quadrature coupler amplitude response (S_{21}, S_{31}).

$3.6 \sim 8.4$ GHz, in the actual measurements, the quadrature coupler showed slight loose coupling (S_{31}), which degrades the amplitude imbalance, especially at frequencies higher than 8.0 GHz.

The main reason for this variation in the measured coupling level is tolerances of the manufacturing process. In order to deeply investigate this slight deviation, the internal microscopic inspection of the quadrature coupler chip is performed. The coupler chip is cut into two pieces along the x-dimension (4.0 mm), and the physical measurements are performed by vertically placing each piece under an electron microscope. It is observed that the actual vertical gap between the coupling lines is around 75 μm, instead of the 70 μm value assumed in the simulation model. This 5 μm increase in the vertical gap causes a slight decrease in the coupling amplitude. The same is reverified by using the actual gap value in the simulation. So, the control of pre-peg thickness is very crucial for the proposed design, as it affects the actual vertical gap between the coupling lines. However, after one process iteration, the EM-model can be made very accurately. In that case, the proposed design has the capability to achieve a less amplitude imbalance in a wider bandwidth, than the measured performance depicted in Fig. 5. It is also pertinent to mention here that the loss of the long interconnecting transmission lines is de-embedded from the measured amplitude response depicted in Fig. 5.

Figure 6 shows the measured and simulated phase differences between the through and coupled ports. The measured phase response shows a reasonably flat quadrature response in the frequency range of $3.0 \sim 8.0$ GHz. In this frequency band, the phase difference varies from 87.5 deg to 93.0 deg, which corresponds to phase imbalance much less than 3 deg. Fig. 7 presents the measured and simulated return losses at all four ports (S_{11}, S_{22}, S_{33}, and S_{44}). The measured return loss is always better than 12.5 dB

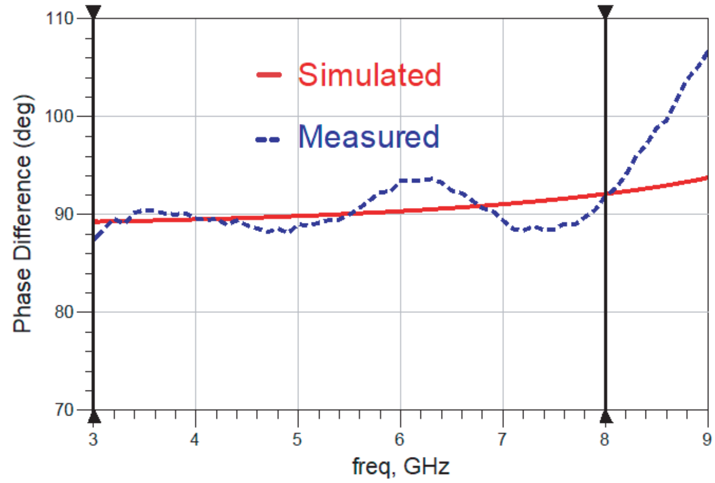


Figure 6. Quadrature coupler phase response (S_{21}–S_{31}).

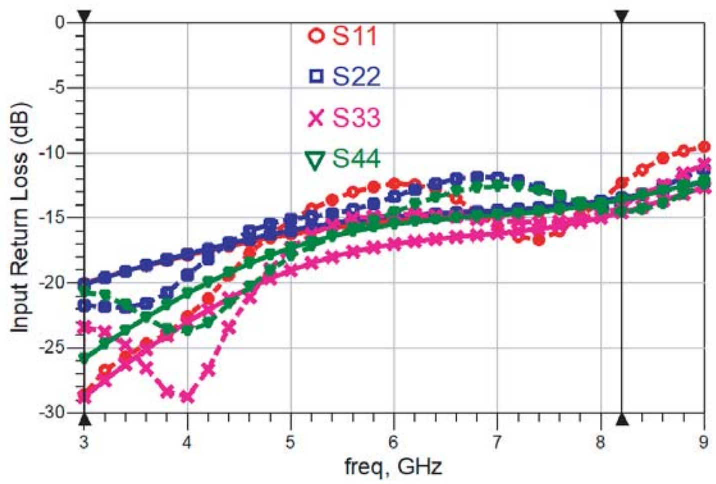


Figure 7. Quadrature coupler input return loss response, simulated (shown in solid lines) and measured (shown in dotted lines).

Table 2. Comparison of multilayer wideband quadrature couplers.

Parameter	[9] in 2012	[10] in 2017	[18] in 2018	This Work
Fractional Bandwidth	66%	62.5%	45.5%	71%
Amplitude Imbalance	2.0 dB	1.0 dB	1.5 dB	1.0 dB
Phase Imbalance	7.0 deg	5.0 deg	1.0 deg (simulated)	3.0 deg
Electrical Size	$0.48\lambda_g \times 0.58\lambda_g$	$0.18\lambda_g \times 0.51\lambda_g$	$0.24\lambda_g \times 0.36\lambda_g$	$0.13\lambda_g \times 0.26\lambda_g$
Number of Layers	4	4	4	4
Total Height	1.0 mm	1.0 mm	3.8 mm	0.9 mm
Self-Packaged	No	No	No	Yes

in the frequency band from 3.0 $\sim$ 8.2 GHz for all four ports. The measurement trends are reasonably close to the simulation responses. Similarly, Fig. 8 shows the measured and simulated isolations (S_{41}). The measured isolation is also better than 13 dB in the desired band of 3.0 $\sim$ 8.0 GHz and closely follows the simulation behavior.

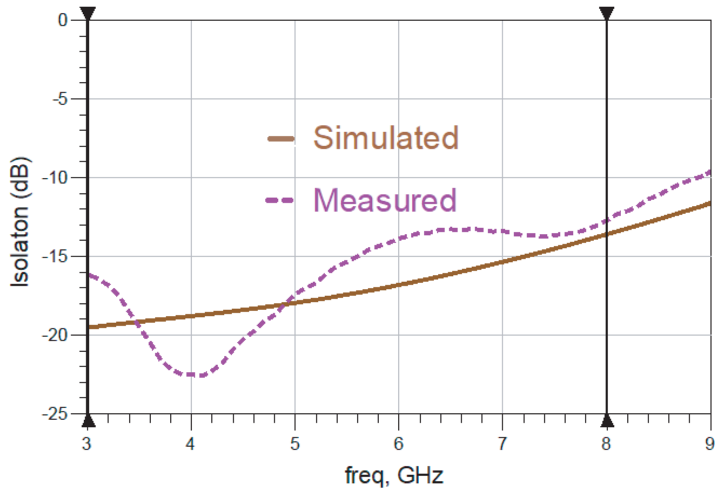


Figure 8. Quadrature coupler isolation response (S_{41}).

4. CONCLUSION

The design of compact broadband quadrature coupler, based on a 4-layer Roger's RO4350B package substrate, is proposed. The measurement results of the manufactured coupler show good amplitude imbalance within 1.0 dB and low phase imbalance less than 3 degrees in the frequency range of $3.8 \sim 8.0$ GHz. The measured return loss and isolation are mostly better than 13 dB, in the whole frequency band. The fabricated quadrature coupler chip size is $4.0\,\text{mm} \times 8.0\,\text{mm} \times 0.9\,\text{mm}$, which is reasonably compact for wide-band quadrature hybrids in this frequency band. However, it can be made further compact if the design is realized on any material with a higher dielectric constant as compared to that of RO4350B. According to the best of the authors' knowledge, these performance parameters and size are among the best reported in this wide fractional bandwidth of 71%, using the microwave package substrate. The same is also evident from the comparative analysis of the recently published design schemes of 4-layer wideband quadrature couplers presented in Table 2. It is pertinent to mention here that some of the parameters written in the table for [9, 10, 18] are not explicitly provided in the papers, so they are interpreted/calculated from the given measurement results. The SMD package of the proposed coupler makes the assembly convenient with the main microwave circuit board, using the traditional reflow soldering process. The proposed coupler design is suitable for incorporation into SoP applications and can be used as an SMD component in various transmitting and receiving systems.

ACKNOWLEDGMENT

This work is sponsored by the National Natural Science Foundation of China (Grant No. 61731001) and the Ministry of Science and Technology of the People's Republic of China (Contract No. 2016YFC0800401); for the development of passive millimeter-wave imager being developed in Beihang University, Beijing, China.

REFERENCES

1. Pozar, D. M., *Microwave Engineering*, 3rd Edition, Wiley, New York, 2005.
2. Dilshad, U., C. Chen, X. Chen, and J. Miao, "Broadband quadrature hybrid for image rejection in millimeter-wave receivers," *IEEE 2019 16th International Bhurban Conference on Applied Sciences (IBCAST)*, 975–978, Islamabad, Jan. 2019.
3. Kim, H. J., S. J. Wang, W. Jung, and J. Kim, "Wideband 3 dB quadrature microstrip line coupler with unequally reduced wave impedances and asymmetrical configuration in parallel lines," *2015*

IEEE 16th Annual Wireless and Microwave Technology Conference (WAMICON), 1–4, Cocoa Beach, FL, 2015.

4. Wang, L., G. Wang, and J. Sidén, "High-performance tight coupling microstrip directional coupler with fragment-type compensated structure," *IET Microwaves, Antennas & Propagation*, Vol. 11, No. 7, 1057–1063, 2017.
5. Han, R., R. Sun, and S. Shi, "A wideband planar hybrid coupler using coupled-line power divider and broadband phase shifter," *2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP)*, 1–3, Xi'an, 2017.
6. Bonney, J. and J. Schoebel, "Synthesis of extremely flat broadband multi-section quadrature coupler," *German Microwave Conference (GeMIC)*, 1–4, Hamburg-Harburg, Germany, Mar. 2008.
7. Xu, Q. and Y. Ethan Wang, "Design and realization of compact folded Lange coupler," *IEEE MTT-S International Microwave Symposium Digest*, 1–3, Montreal, QC, Jun. 2012.
8. Stec, B. and M. Czyzewski, "Quadrature hybrid coupler with two broadside coupled microstrip-slot lines," *2018 22nd International Microwave and Radar Conference (MIKON)*, 282–285, Poznan, 2018.
9. Ahmed, O. M. H., A.-R. Sebak, and T. A. Denidni, "A novel butterfly-shaped multilayer backward microstrip hybrid coupler for ultrawideband applications," *IEEE Microwave and Optical Technology Letters*, Vol. 54, No. 10, 2231–2237, Oct. 2012.
10. Chen, Y., J. Zhou, Z. Yu, Y. Yin, and G. Peng, "Design of an ultra-wideband compact 90-degree 3 dB coupler for image-rejection up-converter," *2017 Sixth Asia-Pacific Conference on Antennas and Propagation (APCAP)*, 1–3, Xi'an, 2017.
11. Abdelghani, L., T. A. Denidni, and M. Nedil, "Design of a broadband multilayer coupler for UWB beamforming applications," *2011 IEEE 41st European Microwave Conference*, 810–813, Manchester, Oct. 2011.
12. Binti Muklas, N. S., S. K. A. Rahim, and N. Seman, "Ultra wideband coupler design for Butler Matrix application," *IEEE 17th Asia Pacific Conference on Communications*, 506–511, Sabah, Oct. 2011.
13. Moscoso-Martir, A., J. G. Wanguemert-Perez, I. Molina-Fernandez, and E. Marquez-Segura, "Slot-coupled multisection quadrature hybrid for UWB applications," *IEEE Microwave and Wireless Components Letters*, Vol. 19, No. 3, 143–145, Mar. 2009.
14. Abbosh, A. M. and M. E. Bialkowski, "Design of compact directional couplers for UWB applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 46, No. 2, 189–194, Feb. 2007.
15. Wang, Y., K. Ma, and S. Mou, "A transformer-based 3-dB differential coupler," *IEEE Transactions on Circuits and Systems I: Regular Papers*, Vol. 65, No. 7, 2151–2160, July 2018.
16. Wang, Y., K. Ma, and S. Mou, "A low loss and self-packaged patch coupler based on SISL platform," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, 192–195, Honololu, HI, 2017.
17. Wang, Y., K. Ma, and S. Mou, "A high performance tandem coupler using substrate integrated suspended line technology," *IEEE Microwave and Wireless Components Letters*, Vol. 26, No. 5, 328–330, May 2016.
18. Zhu, H. and Y. J. Guo, "Modified wideband tandem couplers with arbitrary coupling coefficient and its implementation in beam-forming networks," *2018 Asia-Pacific Microwave Conference (APMC)*, 542–544, Kyoto, 2018.
19. Dai, Y.-S., Y.-L. Lu, Q.-S. Luo, B.-Z. Zhan, X. Wang, and Y.-B. Jiang, "A microminiature 3 dB multilayer double-octave hybrid coupler using LTCC," *IEEE Asia-Pacific Microwave Conference Proceedings*, Suzhou, Dec. 2005.
20. Al-Taei, S., P. Lane, and G. Passiopoulos, "Design of high directivity directional couplers in multilayer ceramic technologies," *2001 IEEE MTT-S International Microwave Symposium Digest (Cat. No. 01CH37157)*, Vol. 1, 51–54, Phoenix, AZ, May 2001.