Progress In Electromagnetics Research Letters, Vol. 106, 75–80, 2022

Miniaturized Lumped-Element LTCC Quadrature Hybrid with LC Stacked Structure

Jixi Lu, Jiyi Bian, and Bo Zhou*

Abstract—A miniaturized lumped-element quadrature hybrid with a high density stacked structure is proposed in a 24-layer low temperature co-fired ceramic (LTCC) substrate. Stacking vertical-interdigital-capacitors (VICs) and vertically-spiral-inductors are for an entire size reduction. The transition between inductors realized in the inner space of the inductor further improves the utilization of three-dimensional space. The overall size of the quadrature hybrid is only $10.1 \times 3.8 \times 2.4$ mm, or equivalently $0.0040 \times 0.0015 \times 0.0009\lambda_g^3$, which achieves a size reduction of 30.2%. Meanwhile, the proposed hybrid operates at 60 MHz with a fractional bandwidth (FBW) of 33.3%. The measured S_{11}, S_{21}, S_{31}, and S_{41} are -14.5, -3.8, -3.7, and -14.2 dB within the operating frequency band, respectively, and both of the low phase imbalance and amplitude imbalance are achieved.

1. INTRODUCTION

The quadrature hybrid, also called as 90° hybrid, is extensively used in radio frequency (RF) circuits and systems, such as balanced mixers, image-rejection mixers, balance amplifiers, and phase shifters [1]. Most of these applications are space constrained, which indicates that size reduction and low-cost fabrication are demanded in modern wireless communication systems.

Over the years, several efficient approaches have been reported for miniaturizations [2–6]. In [2], a compact planar microstrip branch-line coupler using equal difference structures is proposed, which reduces the length of quarter-wavelength microstrip line and thus minimizes branch-line coupler dimension. A compact harmonic suppressed 3 dB coupler using H-shaped transmission line is proposed in [3] with a size reduction of 64%. Moreover, methods such as using anti-parallel lines with open stubs [4], meandered transmission line with broken symmetry between cross-coupling branches [5], and quarter-wavelength supershape transmission lines [6] have been implemented to reduce the size as well. Unfortunately, size reduction stays in conflict with desired electrical performance of microwave components, and it is difficult to optimize the parameters because of the complex geometry structures. Therefore, there is an increasing need for hybrids with uncomplicated structure and full use of the circuit space while ensuring the performance.

In this paper, an improved low temperature co-fired ceramic (LTCC) hybrid with inductor-capacitor (LC) stacked structure is proposed. Size reduction is achieved by stacking vertical-interdigital-capacitors (VICs) and vertically-spiral-inductors vertically. In addition, the connection between inductors is realized in the internal space, which makes full use of the three-dimensional space. The overall size of the quadrature hybrid is only $10.1\,\text{mm} \times 3.8\,\text{mm} \times 2.4\,\text{mm}$. The proposed hybrid has a good performance and can be widely applied into high integrated RF module in radar and communication systems.

Received 4 July 2022, Accepted 16 August 2022, Scheduled 1 September 2022

* Corresponding author: Bo Zhou (nick.zhou@njupt.edu.cn).
The authors are with the School of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210000, China.

2. CIRCUIT DESIGN

The quadrature hybrid in this work is required to work at the center frequency of 60 MHz with a bandwidth of 20 MHz. Since the size reduction is the main challenges of this work, the first step is to choose an appropriate circuit topology with a minimal number of L-C elements. Figure 1(a) shows the utilized circuit topology, which is originated from [7]. In the circuit topology, the three capacitors have the same capacitance $C_1 = C_2 = C_3$. The four inductors have the same inductance $L_1 = L_2$. Thus, the circuit topology can be easily optimized with only two parameters. The capacitances of C_1, C_2, and C_3 and inductances of L_1 and L_2 can be given by:

$$C_1 = C_2 = C_3 = \frac{1}{\omega Z_0} \tag{1}$$

$$L_1 = L_2 = \frac{Z_0}{\omega} \tag{2}$$

where Z_0 denotes the port impedance. The capacitance and inductance can be calculated by Equations (1)–(2).

Through circuit theory based simulation, the values of capacitors and inductors extracted from Microwave Office (MWO) [8] optimization are: $C_1 = C_2 = C_3 = 25\,\text{pF}$ and $L_1 = L_2 = 125\,\text{nH}$. Its simulated results are shown in Figure 1(b), which meet performance requirements of the hybrid.

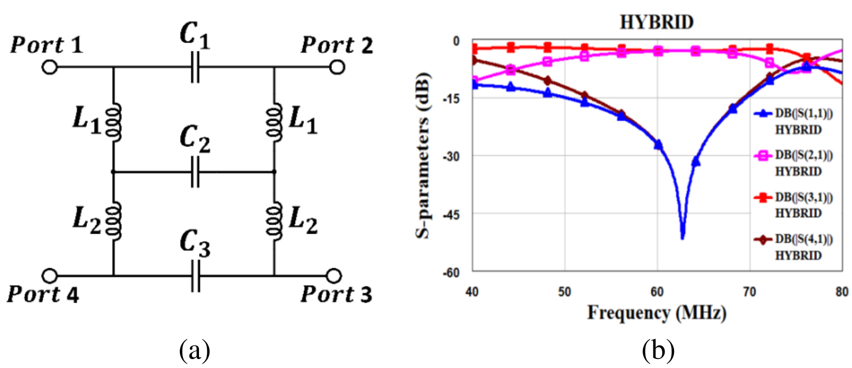


Figure 1. (a) Circuit topology and its (b) simulated S-parameters.

3. HYBRID IMPLEMENTATION

The proposed quadrature hybrid consists of 3 pieces of VICs and the 4 pieces of highly integrated spiral inductors. Meanwhile, stacking VICs and integrated spiral inductors are innovatively employed to further reduce the entire size of the hybrid. Incidentally, the stacked structure will change the boundary conditions of each component and generate the coupling effects between components, which require separate EM-optimization.

3.1. VICs Design

VICs with eight fingers are implemented in an LTCC substrate, which substantially reduces the size. Moreover, the square-finger design extensively reduces the number of parameters in the process of optimization, to an extreme of only W_{Cn} ($n = 1$, 2, and 3 for C_1, C_2, and C_3). The stacked structure requires the widths of the three capacitors in the proposed hybrid structure to be designed separately. Figure 2(a) shows the planar view and 3D structure of VICs.

3.2. Integrated Spiral Inductors Design

Vertical spiral inductors with 9.5-turns and a 0.2 mm line width, which own comparatively high Q-factor and reduced size, are proposed. Similarly, the widths (W_{Ln}, $n = 1$ and 2 for L_1 and L_2) of two inductors

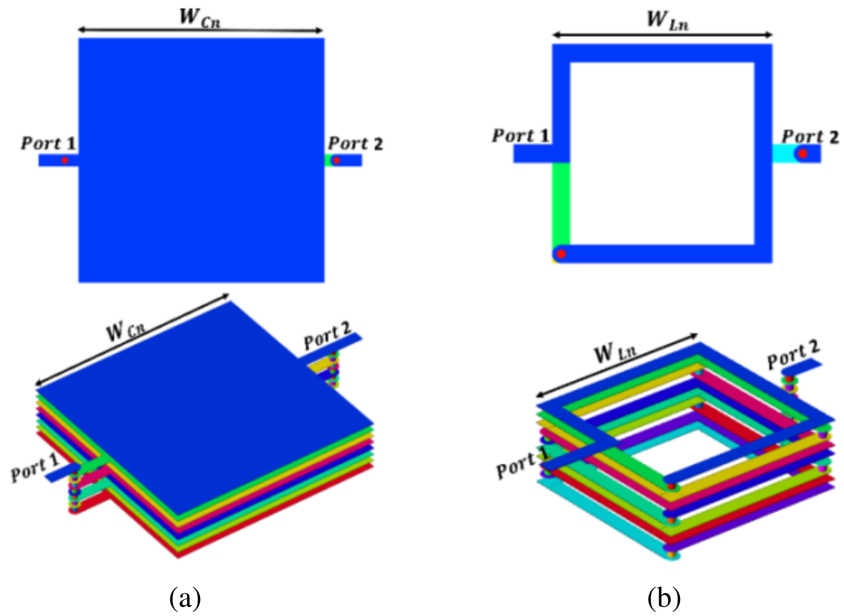


Figure 2. Planar view and 3D structure of (a) VICs and (b) integrated-spiral-inductors.

need to be optimized separately. The planar view and 3D structure of spiral inductors are shown in Figure 2(b).

3.3. Overall Design

On the basis of the 3D structure of the hybrid, whose size is 12 mm × 10 mm × 1 mm, reported in [7] in Figure 3(a), the stacked structure, which fully utilizes the stereo to further reduce the size, is proposed. Figure 3(b) shows the 3D view of the proposed hybrid, where three VICs are placed in the middle in a very compact structure and four spiral inductors fit well with the space left.

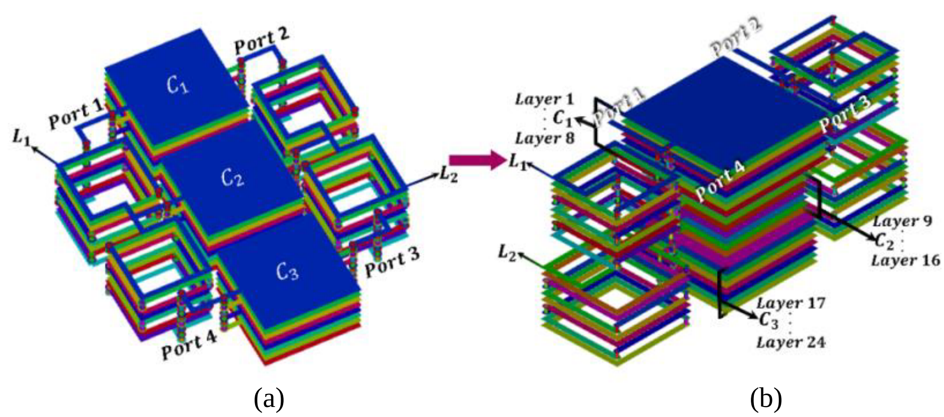
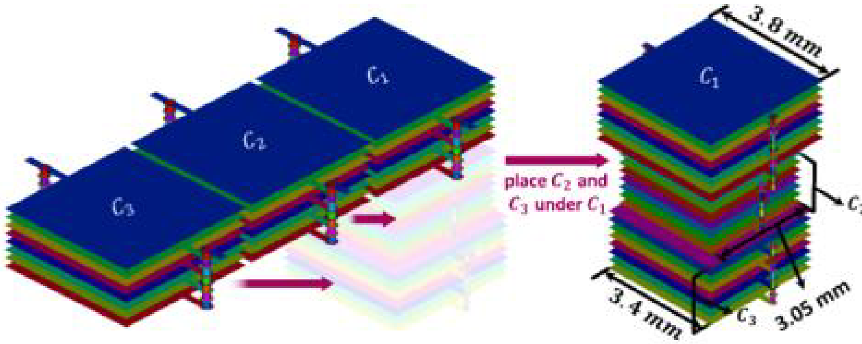
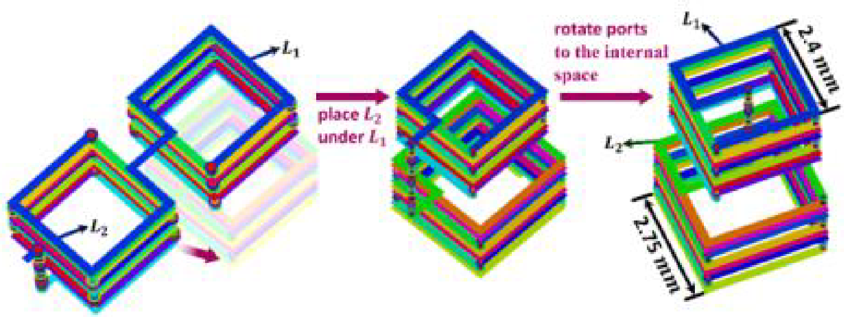


Figure 3. 3D view of (a) the hybrid in Ref. [7] and (b) the proposed hybrid.

For the stacked VICs, C_2 and C_3 are placed under C_1, from 9 to 16 layers and 17 to 24 layers, respectively. The stacked VICs result in the coupling between capacitors, which makes the capacitances of the three capacitors higher than the capacitance values they separated, thereby reducing the overall size, as shown in Figure 4(a). Through the optimization of the overall parameters, the capacitance values of the three capacitors are finally determined, and Figure 5(a) shows that capacitances of C_1,

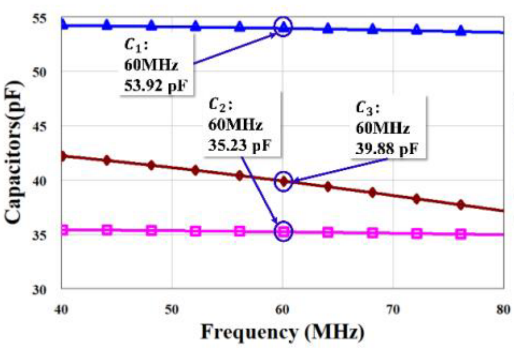


(a)

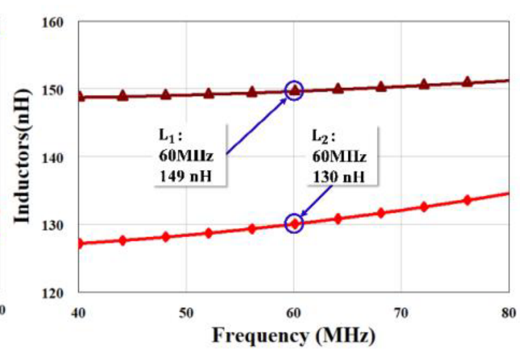


(b)

Figure 4. Implementation of stacked (a) capacitors and (b) inductors.



(a)



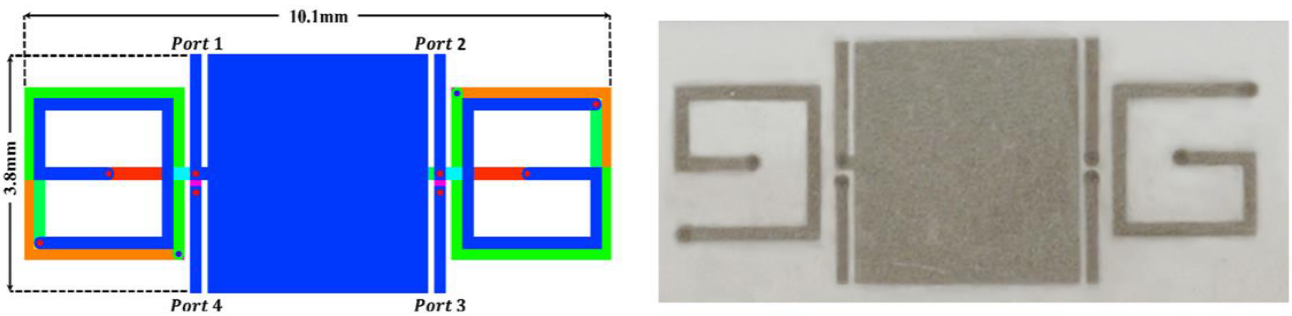
(b)

Figure 5. EM-simulated (a) capacitances of C_1, C_2 and C_3 and (b) inductances of L_1 and L_2.

C_2, and C_3 are equivalent to 53.92 pF, 35.23 pF, and 39.88 pF when $W_{C1} = 3.8$ mm, $W_{C2} = 3.05$ mm, and $W_{C3} = 3.4$ mm.

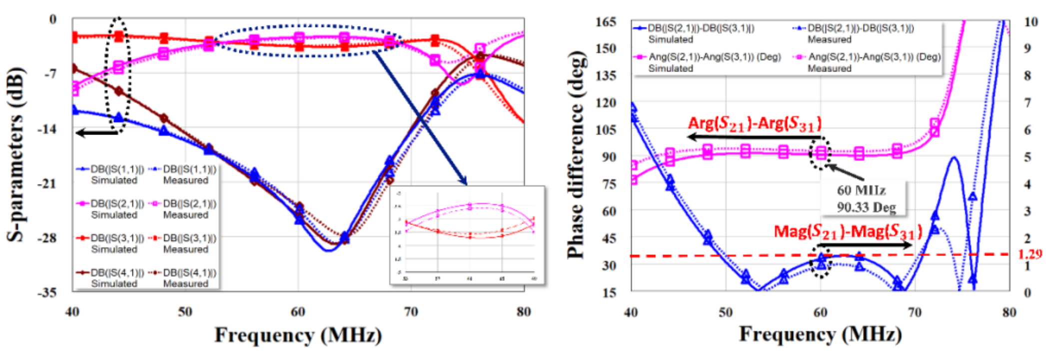
For the stacked design of inductors in Figure 4(b), L_2 is placed under L_1 from 15 to 24 layers, and the interval from 11 to 14 layers is used to interconnect signal to C_2. In consideration of the influence of excessively long transmission line, the connection distance between inductance and capacitance ports should be minimized as far as possible. The outward-facing ports of inductors are rotated to the internal space of inductors, allowing the two stacked inductors to better connect through vias. Consequently, the space inside the inductor is further utilized. Similarly, the inductance values are determined through the overall optimization, and the inductances of L_1 and L_2 are equivalent to 149 nH and 130 nH when $W_{L1} = 2.4$ mm and $W_{L2} = 2.75$ mm, as shown in Figure 5(b).

After the design and simulation of stacked capacitors and inductors, the details of the overall hybrid are eventually adjusted. In order to realize the high-density stacking of the hybrid and reduce the impact of attenuation, the unnecessary vertical vias are removed. The quadrature hybrid is assembled in a 24-layer LTCC substrate, and the post-fired thickness for each layer is only 0.096 mm with a dielectric constant of 5.9 and loss tangent of 0.002. Ports 1, 2, 3, and 4 are designed as input, direct, coupled, and isolated port, respectively. The top view and a photograph of the proposed hybrid are shown in Figures 6(a) and (b), respectively. The overall size of the hybrid is only 10.1 mm × 3.8 mm × 2.4 mm or equivalently $0.0040\lambda_g \times 0.0015\lambda_g \times 0.0009\lambda_g$, where λ_g is the guided wavelength on a 1 mm thickness ferro A6 substrate at 60 MHz, and the size reduction of 30.2% is obtained. Figure 7(a) shows that the measured S_{11}, S_{21}, S_{31}, and S_{41} are better than −14.5, −3.8, −3.7, and −14.2 dB from 50 to 70 MHz, respectively. Figure 7(b) shows that the phase differences and amplitude imbalances are within $180 \pm 2.36°$ in the working band.



(a) (b)

Figure 6. (a) Top view and (b) photograph of the proposed hybrid.



(a) (b)

Figure 7. Measured and EM-simulated results. (a) S-parameters. (b) Phase differences and amplitude imbalances.

4. COMPARISON AND DISCUSSION

Table 1 compares the measured results with implementations in [2–6]. Proposed work's return loss (RL), insertion loss (IL), phase imbalance, amplitude imbalance at the operation, fractional bandwidth (FBW), and size are compared with [2–6], respectively. The proposed hybrid has the widest FBW with an RL better than 14.2 dB. The proposed hybrid has smaller IL, phase imbalance, and amplitude imbalance than [2–6], which indicates its good performance. Furthermore, the stacked structure has a smaller size than [2–6] in Table 1.

Table 1. Performance and size comparisons.

Ref.	f_0 (MHz)	FBW (%)	RL (dB)	IL (dB)	Phase. Imb (Deg)	Amp. Imb (dB)	Size/λ_g^3
[2]	900	20.0	> 14.0	< 5.0	< 5.00	< 1.90	$0.1047 \times 0.1075 \times 0.0111$
[3]	900	15.5	> 14.0	< 4.0	< 4.82	< 2.30	$0.1151 \times 0.1951 \times 0.0044$
[4]	2500	26.4	> 14.0	< 5.0	< 2.40	< 1.35	$0.1908 \times 0.1908 \times 0.0066$
[5]	2500	16.0	> 14.0	< 3.9	< 9.10	< 1.45	$0.2500 \times 0.1900 \times 0.0111$
[6]	1250	32.2	> 14.0	< 3.9	< 11.66	< 1.80	$2.6250 \times 2.6250 \times 0.0056$
This work	60	33.3	> 14.2	< 3.8	< 2.36	< 1.29	$0.0040 \times 0.0014 \times 0.0009$

5. CONCLUSION

An improved lumped-element LTCC hybrid with stacked structure is proposed in a 24-layer LTCC substrate. The center frequency of the hybrid is extremely low at 60 MHz with a 33.3% FBW. The stacked structure, appropriate parameter adjustment, and configuration bring the significant size reduction. The transition between inductors realized in the inner space of the inductor further improves the utilization of three-dimensional space. The overall size of the quadrature hybrid is only $0.004\lambda_g \times 0.0015\lambda_g \times 0.0009\lambda_g$, and measured results demonstrate the hybrid's good performances. The hybrid with compact size, low-cost fabrication, and good performance can be widely applied into wireless communication systems.

REFERENCES

1. Velidi, V. K., A. V. G. Subramanyam, and V. V. Srinivasan, "Improved bandwidth via-free lumped-element quadrature hybrid couplers," *IEEE International Microwave and RF Conference (IMaRC)*, 229–232, 2014.
2. Chen, J.-H., S.-Y. Yuan, S.-R. Liou, and S.-S. Liao, "Compact planar microstrip branch-line coupler using equal difference," *Microwave and Optical Technology Letters*, Vol. 59, No. 13, 664–668, 2017.
3. Idury, S. K., R. K. Barik, S. S. Karthikeyan, and P. Kokil, "A miniaturized harmonic suppressed 3 dB branch line coupler using Hshapedmicrostrip line," *Microwave and Optical Technology Letters*, Vol. 59, No. 4, 913–918, 2017.
4. Wang, Y., X. Y. Zhang, F. X. Liu, C. H. Quan, and J. C. Lee, "A miniaturized rat-race coupler with ultra-wideband harmonic suppression," *Microwave and Optical Technology Letters*, Vol. 60, 1960–1963, 2018.
5. Bekasiewicz, A., "Miniaturized dual-band branch-line coupler with enhanced bandwidth," *Microwave and Optical Technology Letters*, Vol. 61, 1441–1444, 2019.
6. Tayebi, A. and D. Zarifi, "On the miniaturization of microstrip ring-hybrid couplers using Gielis supershapes," *IETE J. Res.*, 1–6, Dec. 2020.
7. Zhou, B., W. Sheng, and Y. Zheng, "Miniaturized and wideband lumped LTCC branch-line coupler for dozens of megahertz applications," *Microwave and Optical Technology Letters*, Vol. 56, No. 9, 2001–2005, 2014.
8. MWO, Microwave Office, Applied Wave Research Corporation, El Segundo, CA.