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Miniaturized 60-GHz transformer-based balun splitter with isolation and matching performance in 0.18-μm SiGe BiCMOS

ZHANG Da-Wei[1,3*], XU Xin[1], LI Bin[1], XU Hui[1], YU Hong-Xi[1], LI Jun[1], MA Kai-Xue[2], THANGARASU Bharatha Kumar[3], YEO Kiat Seng[2,3]

(1. Dept. of Microwave Technology, China Academy of Space Technology (Xi'an), Xi'an 710049, China;
2. School of Microelectronics, Tianjin University, Tianjin 300072, China;
3. Singapore University of Technology and Design (SUTD), Singapore 487372)

Abstract: This paper presents the work of a miniaturized 60-GHz balun chip with isolation and matching performance fabricated in 0.18-μm SiGe BiCMOS process. The use of isolation circuit as key building blocks within a 60-GHz transformer balun leads to an improved isolation performance between output ports, while simultaneously achieving the matching performance of them. Moreover, compared to the conventional isolation circuit, the artificial left-handed transmission line is introduced to remove the bulky distributed elements, and the capacitive loading compensation technique is utilized for both matching and miniaturization. Both electromagnetic simulation and measurement results of the proposed 60-GHz transformer balun chip design with isolation and matching characteristics are given with good agreement. From measurement results, better than 25-dB isolation and 18-dB return loss of the output ports have been achieved at 60 GHz, with an occupied area of 0.022 mm^2.

Key words: transformer balun, isolation circuit, 60 GHz, left-handed transmission line (LHTL)

基于0.18-μm锗硅BiCMOS工艺的60 GHz匹配型高隔离小型化变压器巴伦

张大为[1,3*], 徐 鑫[1], 李 斌[1], 徐 辉[1], 于洪喜[1], 李 军[1], 马凯学[2],
THANGARASU Bharatha Kumar[3], YEO Kiat Seng[2,3]

(1. 中国空间技术研究院西安分院 微波技术研究所,中国 陕西 西安 710049;
2. 天津大学 微电子学院,中国 天津 300072;
3. 新加坡科技设计大学,新加坡 487372)

摘要:介绍了一种工作在60 GHz频率的具有输出端口间高隔离和全端口匹配特性的小型化变压器巴伦芯片,该芯片采用0.18-μm锗硅BiCMOS工艺设计并加工。通过在60 GHz变压器巴伦的输出端口之间引入隔离电路,提高巴伦的隔离度性能并改善输出端口匹配性能;在此基础上,提出了一种基于左手材料传输线的隔离电路,能大大改善传统隔离电路中分布式传输线尺寸大的问题;为了进一步实现巴伦的小型化,在设计中采用了负载电容补偿技术,同时能改善变压器巴伦输入端口的匹配性能。设计的巴伦芯片经过电磁场仿真,其结果与在片测试结果有较高的一致性,验证了提出的设计方法,设计的巴伦芯片具有全端口匹配和输出端口间高隔离度的特性。基于实测结果,在60 GHz频率处,设计的巴伦芯片实现了超过25 dB的输出端口隔离度和优于18 dB的输出端口回波损耗,且占用尺寸极小,仅为0.022 mm^2。

关 键 词:变压器巴伦;隔离电路;60 GHz;左手材料传输线

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Biography: ZHANG Da-Wei (1989-), male, Anhui China, Ph. D. Research area involves Spaceborne Microwave&Millimeter-wave MMIC and RFIC design. E-mail: qbgu@163.com.

* **Corresponding author**: E-mail: qbgu@163.com

Introduction

Baluns, which convert between unbalanced signal and balanced signal, are crucial components for various modern radio-frequency systems [1-6]. At low frequencies, baluns are commonly implemented in a flux coupling transformer form, which are known as the transformer-based balun. As frequency increases, transformer balun can be created by utilizing high-quality multilayer metal connections provided by nowadays advanced silicon-based semiconductor technology. A transformer-based balun splitter is a three-port circuit component providing power division with out-of-phase outputs, which occupies less circuit area as compared to the widely used Wilkinson divider, making it more suitable for radio frequency integrated circuit (RFIC) design. The isolation and matching performances of balun splitter are critical, because the least interaction between the two channels before combination is expected. However, for ideal lossless balun splitters, the isolation and return loss of output ports is only 6 dB [6],[7]. This 'ideal' lossless isolation performance commonly exists in a conventional Marchand balun splitter; however, due to the existence of intrinsic inductance of the transformer windings, the matching performance of transformer-based balun splitter can be even worse.

To address the above issues, firstly capacitive loading compensation technique is utilized for both 'ideal' lossless performance and size reduction. Then, to further improve the isolation and matching performance, a distributed isolation circuit (IC) must be introduced to the transformer balun, as discussed in Ref. [7]. Circuit examples of several isolated Marchand baluns and branch-line baluns have been proposed [8],[9]. In Ref. [10], a lumped-element isolation circuit is introduced for size reduction of a balun band-pass filter. However, none of these research studies the improvement on isolation and matching performance of the transformer-based balun splitter. Therefore, in this work, we introduce the isolation circuit to a 60-GHz transformer-based balun splitter. To reduce the size caused by conventional distributed isolation circuit, a lumped isolation circuit based on artificial left-handed transmission lines (LHTLs) [11] is utilized. Moreover, design equation of the LHTL-based lumped isolation circuit is further deduced. The transformer-based balun splitter design is implemented in a commercial 0.18-μm SiGe BiCMOS process with six metal layers, the core part occupying only 0.022-mm^2 area. For a 50-Ω system, measurement results show that, at 60 GHz, better than 25-dB isolation between output ports has been achieved, and the return loss is better than 18 dB.

1 Analysis and design of proposed transformer-based balun splitter

The proposed 60-GHz transformer-based balun splitter is designed and fabricated in 0.18-μm SiGe BiCMOS process. Fig. 1 shows the block diagram of the proposed transformer-based balun splitter, which is composed by a conventional transformer balun with capacitive loading compensation (CLC) technique [6] for size reduction, and an LHTL-based lumped isolation circuit placed between the two output ports to improve the isolation and matching performance.

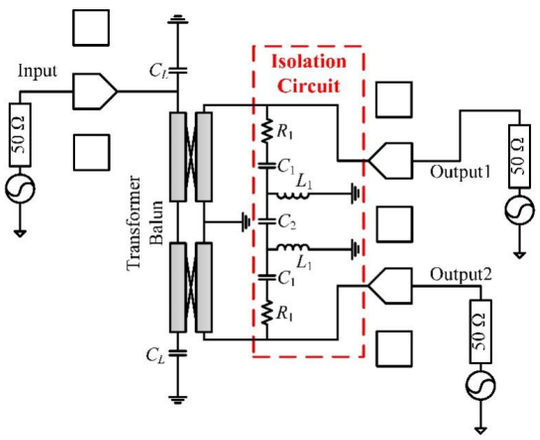


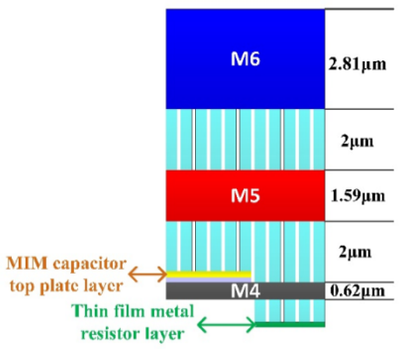
Fig. 1 Block diagram of proposed transformer-based balun splitter with isolation and matching characteristic.
图1 本文提出的匹配型高隔离变压器巴伦的原理图

1.1 Capacitive loading compensation technique

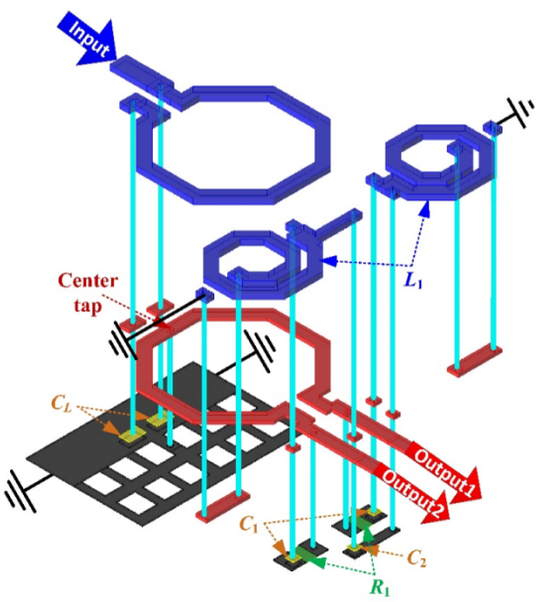
The proposed transformer-based balun splitter adopts two broadside-coupled couplers, as depicted in Fig. 2, where the primary and secondary vertically stacked octagonal coils are shown. There are 6 metal layers in the implemented BiCMOS process, the thickness of top metal (M6) is 2.81 μm, while it is 1.59 μm and 0.62 μm for the two metal layers (M5 and M4) below M6, as shown in Fig. 2(a). M6 and M5 are adopted to build the primary windings and secondary windings respectively, while M4 is utilized as the common ground layer. The vertical metal-insulator-metal (MIM) capacitor is realized using M4 as the bottom plate and additional top plate layer, with an area capacitance of 2 fF/μm^2. The thin film metal resistor is formed below M4 with sheet resistance of 24.5 Ω/sq.

For the proposed transformer-based balun splitter, as depicted in Fig. 2(b), the width and diameter of primary coil at top metal M6 is 6 μm and 68 μm respectively, while M5 is adopted to form the secondary coil with the same width and diameter. The center tap of the secondary coil is connected directly to the common ground at M4. The spacing between primary and secondary coils is 2 μm according to the dielectric thickness of the process.

The loading capacitor C_L, as shown in Fig. 1, if being controlled properly, the length of the coupled lines of transformer balun can be reduced effectively [6]. As discussed in Ref. [6], under lossless condition, there is perfect match at the input port of the ideal three-port balun splitter. However, due to the existence of intrinsic inductance of the transformer windings, the matching performance of transformer-based balun splitter can be even worse. By introducing the CLC technique, it avoids the need to increase the transformer winding size to realize input matching performance. Therefore, CLC technique



(a)



(b)

Fig. 2 Physical composition of proposed transformer-based balun splitter, (a) cross-sectional view of implemented BiCMOS back-end process, (b) three-dimensional layout representation of the proposed balun.
图2 提出的变压器巴伦的物理结构,(a) 采用的锗硅 BiCMOS 工艺的剖视图,(b) 提出的巴伦的三维结构示意图

is utilized for both input matching performance and size reduction. C_L is implemented in MIM capacitor form, with top plate connected to the primary coil ends and bottom plate connected to the common ground at M4, as illustrated in Fig. 2(b). The value of C_L is chosen to be 103 fF with the size of 5.6 μm×9.2 μm. In this configuration, the size of the capacitive loaded 60-GHz transformer balun structure is only about 90 μm×80 μm. The capacitive loaded transformer balun is three-dimensionally modeled and simulated using Keysight's Momentum simulator, of which the results are shown in Fig. 3.

As depicted in the electromagnetic (EM) simulation results in Fig. 3, more than 15-dB input return loss has been realized at 60 GHz of the capacitive loaded transformer balun, while the isolation and return loss of the output ports is around 6.5 dB, with the size of only 90 μm×80 μm. Hence, by utilizing the CLC technique, both input matching performance and size reduction of

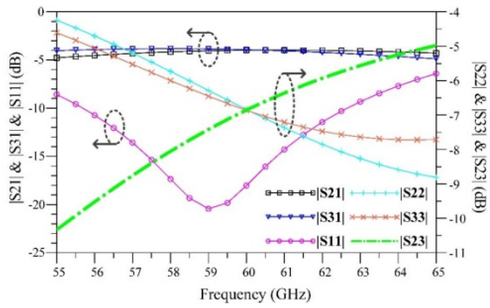


Fig. 3 Electro-magnetic simulation result of capacitive loaded transformer balun.
图3 电容负载补偿变压器巴伦的电磁场仿真结果

the transformer-based balun splitter can be achieved.

1.2 LHTL-based isolation circuit

Under lossless condition, the optimum scattering parameter matrix of an 'ideal balun splitter' can be written as [6],

$$S_{ideal\ balun} \cong \begin{bmatrix} 0 & \frac{j}{\sqrt{2}} & \frac{-j}{\sqrt{2}} \\ \frac{j}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{-j}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} . \quad (1)$$

Eq. (1) reveals that the isolation and return loss performance of the output ports of an ideal balun splitter is 6 dB. To further improve the isolation and matching performance of a balun splitter, a resistive isolation circuit must be introduced. As discussed in Ref. [7], the resistive isolation circuit should be placed between the two output ports to improve the isolation and matching performance, while it is composed by a 180° transmission-line section and two sets of series' connection of R_i and C_i, as shown in Fig. 4(a).

In this case of the capacitive loaded transformer-based balun splitter, since its size is only 90 μm × 80 μm, the large size of the bulky distributed 180° transmission line is not acceptable. To make the balun more compact and feasible in layout routing, the bulky distributed 180° transmission line should be removed. In this work, a lumped LHTL-based isolation circuit is proposed for the capacitive loaded transformer-based balun splitter, of which the schematic is shown in Fig. 4.

Compared to right-handed 180° transmission lines, LHTLs can achieve more time delay, more phase shift and more compact design because of the larger phase constant [11]. Fig. 4(b) shows the adopted LHTL unit-cell with series' capacitance and parallel inductance connection; by cascading these LHTL cells together, certain value of phase shift can be achieved. In this design, we adopt 2 identical LHTL cells; by absorbing the series connected capacitors together as shown in Fig. 4(b), the schematic of proposed lumped isolation circuit can be further obtained as illustrated in Fig. 4(c). Based on the dispersion relation analysis of each LHTL cell in Ref. [12], the phase shift Φ of each LHTL cell can be further

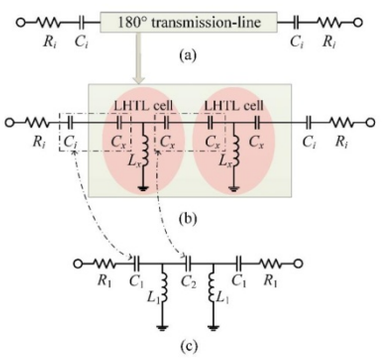


Fig. 4 Schematic of isolation circuit for baluns, (a) conventional isolation circuit, (b) cascaded LHTL-cells replacing 180° transmission line, (c) proposed lumped isolation circuit
图4 巴伦的隔离电路原理图,(a) 传统隔离电路原理图,(b) 级联左手材料传输线替换180°传输线,(c)提出的集总隔离电路原理图

derived as,

$$\cos \Phi \cong 1 + ZY \quad , \quad (2)$$

where, Z and Y correspond to the series' impedance and parallel admittance of the periodic LHTL cell structure, which can be written as,

$$Z = \frac{1}{j\omega C_x} \quad , \quad (3)$$

$$Y = \frac{1}{j\omega L_x} \quad , \quad (4)$$

where ω is the angular frequency.

By substituting Eq. (3) and Eq. (4) into Eq. (2), the phase shift of each LHTL cell can be further calculated as

$$\Phi = -\arccos\left(1 - \frac{1}{\omega^2 L_x C_x}\right) \quad . \quad (5)$$

To realize the 180° phase shift at 60 GHz, as well considering the implemented process, L_x and C_x are chosen to be $116pH$ and $61fF$, respectively. From Eq. (5), the phase shift of each cell can be obtained as 89.7°; by cascading two of the identical LHTL cells as shown in Fig. 4(b), about 180° phase shift can be realized. The phase shift and insertion loss performance of the 2 cascaded LHTL-cells are simulated under 50-Ω termination, and comparison is made with the simulated performance of a thin-film micro strip 180° transmission line using the same process, as shown in Fig. 5.

The thin film micro strip 180° transmission line is created by utilizing M4 as ground layer and M6 as signal layer. In this configuration, the line width of the 180° transmission line can be calculated as $6\mu m$ and the line length is 1450 μm; as a comparison, it has a much more compact size of the 2 cascaded LHTL-cells, which is only 160 μm × 50 μm. As revealed from Fig. 5, close to 180° phase shift and 0 dB insertion loss performance can be achieved of both cascaded LHTL-cells and 180° transmission line at 60 GHz, which means that the cascaded LTHL-cells can be well-implemented for the isolation circuit. Therefore, with the proposed cascaded LHTL-cells for the isolation circuit design, miniaturization of transformer-based balun splitter with isolation and matching performance can be enabled.

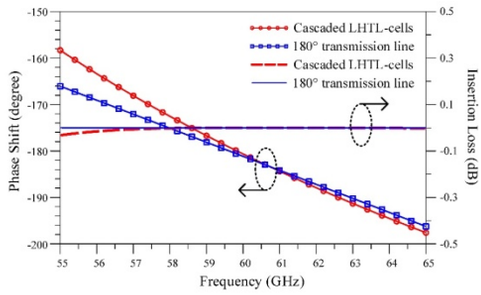


Fig. 5 Performance comparison between cascaded LHTL-cells and 180° transmission line
图5 级联左手材料单元和180°传输线性能对比

Based on the analysis above, the value of each circuit component can be calculated as, $L_1 = L_x = 116$ pH, $C_2 = C_x/2 = 30.5$ fF, $C_1 = C_x \cdot C_i/(C_x + C_i)$, $R_1 = R_i$. By taking the lumped components into co-simulation with the capacitive loaded transformer balun, the value of R_1 and C_1 can be further determined as, $R_1 = 17\ \Omega$, $C_1 = 35$ fF. Then, the lumped LHTL-based isolation circuit is connected to the two output ports of capacitive loaded transformer balun as shown in Fig. 1, and the three-dimensional structure of the designed transformer-based balun splitter is illustrated in Fig. 2(b).

2 Experimental results

The proposed transformer-based balun splitter has been designed and checked by performing EM simulations using Keysight Momentum simulator, before fabrication in a commercial 0.18-μm BiCMOS technology. The measurement setup and die photograph of the designed transformer-based balun splitter are shown in Fig. 6. The core part of the proposed balun splitter occupies only 160 μm × 140 μm. The fabricated transformer balun die is measured by using a Keysight N5247A 4-port vector network analyzer (VNA), together with Cascade probe station and RF probes. The additional on-chip 4th port is only for measurement use and directly connected to the on-chip ground. The 3-port S-parameter data of the fabricated balun can be further obtained from the VNA's 4-port measurement result. The designed transformer-based balun splitter is measured under a 50-Ω system, of which the comparison result between measurement and simulation is shown in Fig. 7.

At 60 GHz, the measured isolation performance between output ports is more than 25 dB, and the return loss of the output ports is better than 18 dB. From 55 GHz to 65 GHz, the isolation and return loss of the output ports are better than 15 dB and 10 dB, respectively. Fig. 7(b) displays the measured insertion loss, amplitude and phase imbalance versus frequency. The amplitude and phase imbalance performance is expressed in terms of the amplitude difference between S21 and S31, and phase difference with reference to 180° of S21 and

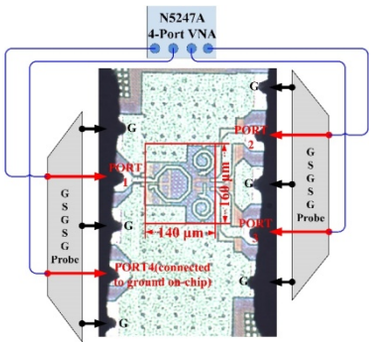


Fig. 6 Measurement setup and die photograph of designed balun splitter.
图6 在片测试设置和设计的巴伦芯片照片

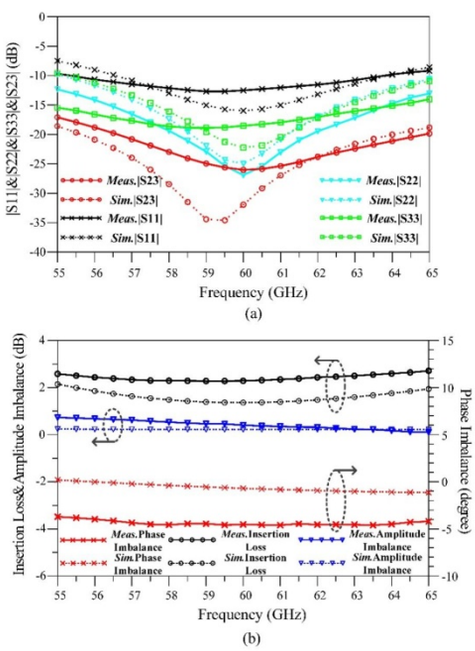


Fig. 7 Measurement results comparison of the fabricated balun splitter chip (a) isolation and return loss result from measurement and simulation, (b) insertion loss and imbalance result from measurement and simulation
图7 设计的巴伦芯片的实测数据对比(a)仿真和在片实测的隔离度和回波损耗结果对比,(b)仿真和在片实测的插入损耗和不平衡度特性结果对比

S31 as proposed in Ref. [6]. The insertion loss is the average loss value of S21 and S31 excluding the 3-dB theoretical loss. The measured insertion loss is better than 2.7 dB, while the amplitude and phase imbalance are better than 0.8 dB and 5° respectively, within the frequency range of 55 GHz to 65 GHz. As compared with the state-of-the-art designs summarized in Table I, more than 25-dB isolation of the transformer balun is firstly achieved at 60 GHz, with only 0.022-mm^2 compact size.

3 Conclusions

This paper presents a miniaturized 60-GHz transformer-based balun splitter chip with isolation and matching characteristic. With the proposed LHTL-based isolation circuit, isolation and matching performance can be achieved of the transformer balun, compact size can be maintained as well. The fabricated balun splitter achieves a compact chip area of 0.022 mm^2 and more than 25-dB isolation at 60 GHz. Good agreement on simulation and measurement indicates positive research value in realizing compact balun splitter chip, and to be applied in future millimeter-wave highly integrated systems.

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Table 1 Performance summary of reported 60-GHz on-chip balun splitter
表1 已发表的60-GHz在片巴伦性能总结对比

Reference	Topology	Band (GHz)	Isolation (dB)	Output return loss (dB)	Insertion loss (dB)	Phase error (°)	Amplitude error (dB)	Size (mm^2)
[1]	Transformer	30-60	N. A.	N. A.	<3	<±1	<0.2	0.029
[2]	Marchand	20.8-51	N. A.	N. A.	<2	<±2	<0.3	0.042
[6]	Transformer+CLC	40-60	N. A.	N. A.	2~2.4	<2.7	<0.2	0.036
[8]	Marchand+IC	25-65	N. A.	>13@60 GHz	<7	<±10	<2	0.55
This work	Transformer+CLC+IC	55-65	>25@60 GHz	>18@60 GHz	2.3~2.7	4.4~4.8	<0.8	0.022

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