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Inductor-Less Broadband Energy-Efficient Active Balun up to 60GHz

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***Abstract*—The paper presents a non-inductive broadband energy-efficient active balun based on a differential pair, intended for use in the input block of a frequency divider for 22 nm technology. The developed device can operate in the frequency range from 2 GHz to 60 GHz with a supply voltage of 0.8 V and consume less than 3 mA. The special feature of the developed active balun is that it does not have inductive components, which reduces its size and signal loss. Amplitude of the output signal in working frequency range is from 450 mV to 200 mV. Signal gain in the range from 1-60 GHz varies from -10 dB up to 4 dB. The size of the circuit on the chip is 48x34 um. The device allows you to receive a stable signal at high data transfer rates and provides energy savings due to low current consumption.**

Keywords — analog integrated circuit; frequency divider; active balun; differential transformation; energy efficiency.

I. Introduction

A typical signal conversion task is converting a single-ended signal into a differential. Differential signals are insensitive to common-mode and paired noise distortions, provided that the conversion process from a single-ended signal to a differential one is performed with amplitude and phase balance. The differential signal has significant advantages from the point of view of linearity and reduced dependence on fixed grounding (virtual ground). Some components, such as balanced mixers and antennas, require a differential input signal for optimal performance. However, when the dimensions of the transmission lines begin to exceed several wavelengths, signals propagate as a single. Increased difficulty of keeping the exact balance amplitude and phase makes an application of coaxial cables or single-wire transfer lines more practical.

One-cycle differential converter (balun) is used to create an inverted and non-inverted in-phase differential signal. The classic solution is the implementation of a passive balun with two coupled inductors that form a passive transformer. Such designs have significant losses in the frequency range.

The alternative solution is to use an active balun, which combines the functions of the actual balun and the amplifier. Unlike their passive counterparts, these active baluns leverage transistors or operational amplifiers to provide gain, enabling enhanced performance characteristics across a broad frequency spectrum.

The emphasis on non-inductiveness in the design aims to mitigate losses associated with traditional inductive components, ensuring optimal signal integrity and efficiency and, providing good balance and low

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losses and not affecting the linearity of the circuit. In differential frequency dividers, where the input and output signals are inherently balanced, baluns are often used to interface with unbalanced components or transmission lines. This ensures seamless integration between different stages of the circuit as it is shown in Fig. 1.

Active baluns are reciprocal and can be used for the conversion of a single-ended signal for an input as well as for an output. Passive broadband baluns can be applied to signals of the central frequency band in amounts of several dozen MHz.

The development of a balun for gigahertz frequency bands is more complex. For this reason, a solution to several problems related to losses and amplitude and phase imbalance is required.

This work presents the development and research on the inductive balun based on differential pairs in the frequency range from 2 to 60 GHz with a supply voltage of 0.8 V and a consumption current of up to 3 mA. Energy efficiency is an essential goal of the active balun design. As the demand for portable and battery-powered communication devices grows, the need for signal-conditioning components with minimal power consumption becomes paramount.

In this context, the article explores strategies for energy-efficient biasing, dynamic power management, and low-power components, contributing to developing active baluns that align with the sustainability goals of modern electronic systems.

II. PROBLEM OF THE DIFFERENTIAL SIGNAL TRANSFORMATION

Differential signals are widely used in wireless communication systems, especially in circles with symmetrical links. For example, differential signals can enhance suppression of the sidebands in a balanced frequency doublers, the junction between ports in the mixer or bandwidth in a balanced amplifier.

Baluns are used in many devices of a microwave range, such as antennas, frequency dividers and doublers, balance mixers and push-pull power amplifiers.

According to the energy characteristics of the baluns, they can be divided into passive and active

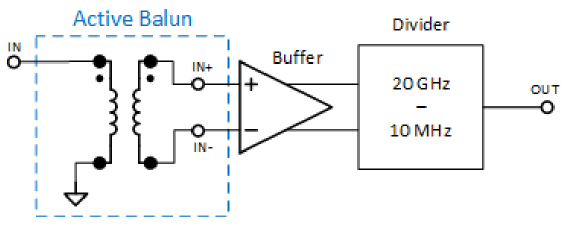

Fig. 1. Application of the active balun

types.

Passive baluns are usually more linear and have no energy consumption except for losses. One of the main disadvantages of passive baluns in comparison to active ones is their larger size. Passive baluns include Marchand baluns [1], baluns with concentrated components, transformer-type baluns, and Wilkinson baluns. They are intended for operation in broadband and narrowband applications [2]. Marchand baluns use connected transmission lines in their design, which usually results in broadbandness and leads to a large area of the crystal [3]. Baluns with concentrated components in the integral implementations are described in [4], [5]. Through the properties of concentrated circuits, baluns with concentrated components are more suitable for narrowband application.

However, at relatively low frequencies (below 10 GHz), transmission lines become too long for implementation on the crystal. Therefore, the bandwidth of a passive balun is limited from below. In addition, balun has excess introduced losses that reduce performance when converting a single signal to a differential. When implementing the CMOS process, balun losses further increase due to losses in the substrate. For example, Marchand balun undergoes insertion losses from 6 to 7 dB on broadband communication lines.

Another common type of balun is a transformer balun [6]. Dimensions of the transformer-type balun are relatively small since the circuit has few components. However, they may suffer from high losses in all ports. There are also baluns based on Wilkinson's power splitter [7].

Active baluns are usually monodirectional signal splitters. Their advantages are the circuit amplification index and the smaller area of a crystal. However, their main disadvantages are noise and energy consumption indicators.

Active baluns can have lower losses than passive ones. In conventional active balun designs, a common current source and field-effect transistor with a typical shutter are used to provide signal phase shift. There is a range of differential pair designs with a common current source designed to increase capacity and bandwidth while maintaining compact sizes. Thanks to the characteristics of differential amplifiers, they can work in the comparatively lower frequency range, even below 1 GHz. Development of active baluns in the millimetre range (30-300 GHz) faces numerous difficulties primarily due to the parasitic capacitances of the transistors.

Methods of improving the characteristics of active balun are the subject of numerous studies. Active balun

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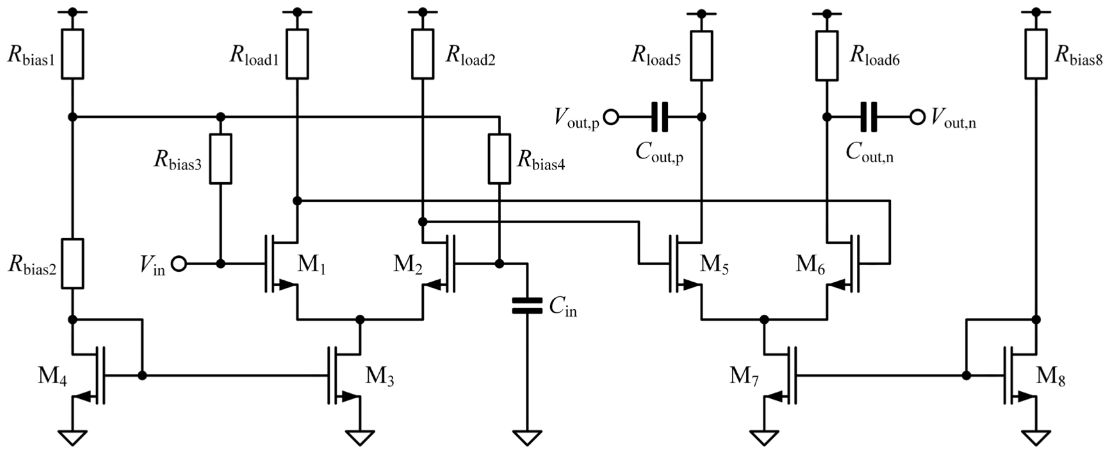

Fig. 2. Schematic diagram of the active inductor-less active balun .

with inductive elements, built on bipolar transistors, is used as a reference in this study [8].

In this work, an active balun design in 22 nm CMOS technology is proposed. Developed balun operates in the frequency range from 5 to 60 GHz. It is designed using two-stage differential pairs and reaches high productivity in the working range with gain compensation technology. Measurement results show that the gain of the signal on the 1-60 GHz band ranges from -10 to 4 dB. The size of the circuit on chips is 48 x 34 µm, and the phase difference differential of the signal over the entire working range is within the limits of 180°±5°.

III. CIRCUIT DESIGN

The balun's construction consists of two classic differential pairs with current mirrors and supporting protections.

Balun was built without inductive elements, significantly reducing the circuit size on chips and reducing current consumption.

The citcuit diagram of the developed active balun is presented in Fig. 2. The speed of the circuit depends on many factors, including the type of transistors. Field-effect transistors are used in the developed circuit instead of bipolar ones. One of the reasons for this is that the peak value of unity gain frequency of field-effect transistors is lower than that of bipolar ones, which ensures a higher speed of the circuit.

One of the critical links that provides the speed of the circuit is a differential pair of transistors M1 and M2, which implements the main balun functionality. The capacitance of the C, which equals 1.2 pF, provides shunting at high frequencies, ensuring more stable circuit operation.

However, despite all the advantages of the differential pair of transistors, there is an imbalance, which can reduce the performance of the circuit. The following cascade of the circuit partially corrects this imbalance. Fig. 3 demonstrates differential phases of signals after the first and the second cascade of the circuit.The graph shows that the phase imbalance between the circuit outputs may be minimized in the frequency range. Fig. 4 presents the amplitude imbalance between the outputs after two circuit cascades.

It can be observed that the phase difference after the second cascade significantly approaches 180°. The sizes of differential pairs decrease with each subsequent link because the second cascade performs

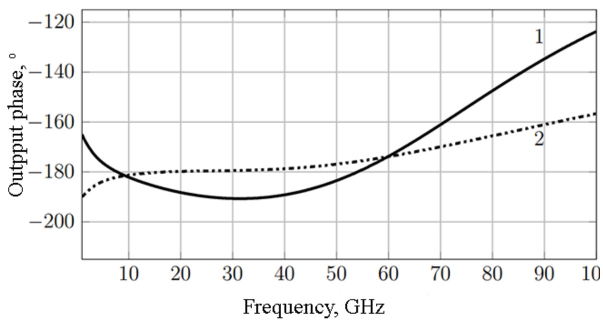

Fig. 3. Phase difference between the output signals after the first (1) and second (2) balun stages.

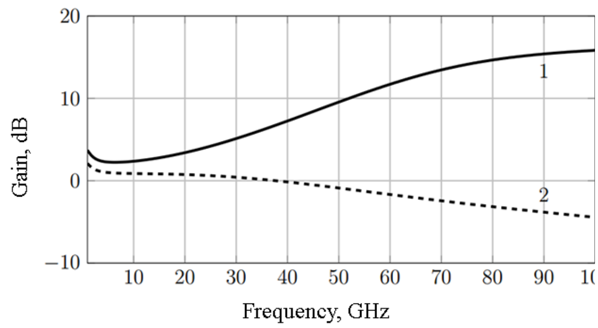

Fig. 4. Illustration of the difference in signal gain after the first (1) and second (2) balun stages.

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a corrective role, and the reduced size allows for decreased current consumption.

The sizes of the resistors were calculated according to the formula (1). They depend on the necessary amplitude of the output signal and current I, which passes through the differential pair.

$$V_{out} = V_{dd} - I \cdot R_{load} \quad (1)$$

It can be seen that after using the corrector, the cascade imbalance is more minor, and the output differential signal become more synchronous. Waiver to use inductive elements is due to the fact that their use requires increasing the area of the crystal several times. The advantage of the inductors is bandwidth broadening. Simulations were carried out both using inductive elements and without them. The results can be seen in Fig. 5.

Based on the analysis of the simulation results; it can be concluded that the use of inductors is inappropriate in this circuit due to the large sizes and insignificant influence on the parameters of the circuit. Fig. 6 illustrates the amplification difference between the two output signals. In the operating frequency range from 2 GHz to 60 GHz, the average difference reaches no more than 1 dB.

IV. TOPOLOGY

Analog circuits, inherently sensitive to process

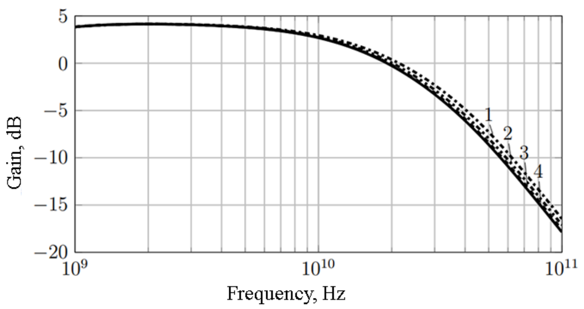

Fig. 5. Frequency dependence of signal gain at different inductance values. 1 - 350 pH, 2 - 200 pH, 3 - 50 pH, 4 - without inductance.

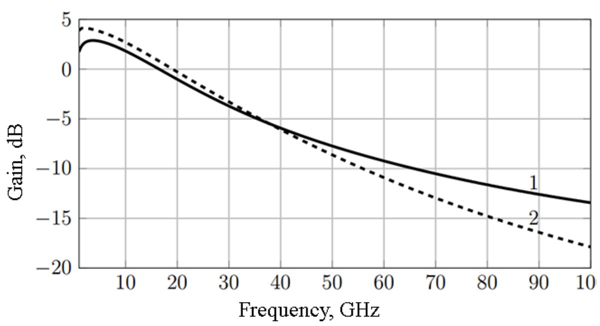

Fig. 6. Amplitude imbalance between balun output signals $V_{out.m}$ (1) and $V_{out.p}$ (2).

variations, face new hurdles in maintaining precision and reliability at the nano-scale. Issues such as increased parasitic capacitance, reduced signal-to-noise ratios, and heightened sensitivity to environmental factors necessitate innovative design approaches.

As digital systems increasingly incorporate analog functionalities, achieving a delicate balance between precision and power efficiency becomes a defining characteristic of success in VLSI design. The quest for low-power analog solutions at 22 nm opens avenues for novel circuit topologies, intelligent power management, and the integration of advanced materials to enhance performance while mitigating power consumption.

The active balun topology diagram is presented in Fig. 7. The active balun topology was development in the size of 48.1 µm by 34.2 µm, which is a high compactness indicator for these frequencies. Such an insignificant size is achieved due to the absence of inductive elements.

Differential pairs of transistors were placed as symmetrically as possible in order to increase circuit efficiency and decrease an imbalance of the output signals.

The metallization layers alternate in mutually perpendicular directions to avoid closely spaced parallel metallization of different types. The length and thickness of the lines were selected in such a way as to reduce the resistance of the conductors as much as possible and the distance between them — to reduce parasitic capacitances between two layers of metals. Also, not all accessible layers of metals were used to reduce the capacity; only every second one was used to increase the distance between the metals in the section.

The elements of the current mirror were placed in a symmetric checkerboard manner in order to preserve the identity of models and minimize distortion of signals due to the different lengths of the conductors. When constructing a topological drawing, a verification of parasitic phenomena, such as parasitic capacitors and supports, was performed, and the inspection for the depletion of conductors under the influence of current was carried out. For the developed topology, a multi-parametric optimization was performed, taking into account the requirements of the technological process. For this study, the Cadence Virtuoso software package was used.

The completed topological drawing allowed us to conduct simulations and analyze modes of the circuit operation in conditions close to real ones.

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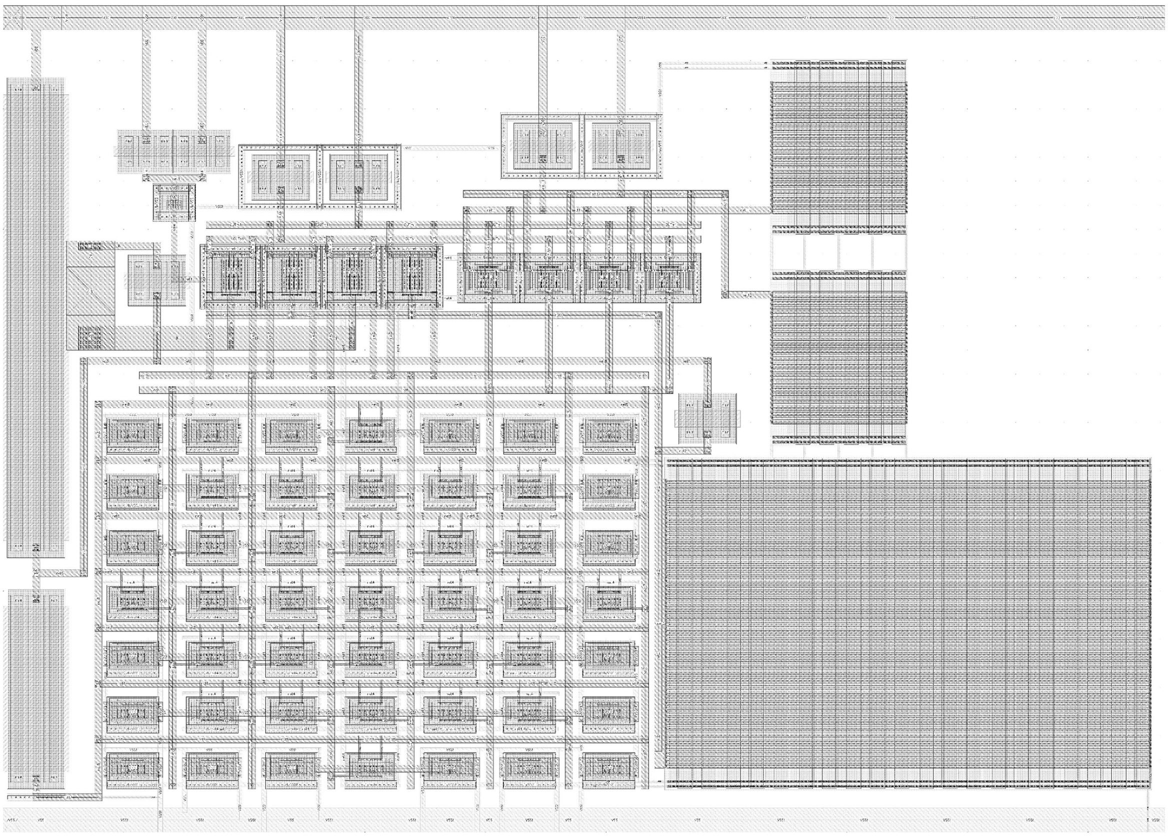

Fig. 7. Topological drawing of a broadband inductor-less active balun.

V. SIMULATION AND ANALYSIS

A plan for the machine experiment was created based on the developed topology using the Mentor Calibre software package for physical verification. This software allows layout verification, design rule checking, and electrical rule checking and proposes a flexibility tolerance control to provide the simulation accuracy according to the process design kit limitations. Simulations were carried out, considering the parasitic components, temperature and manufacturing errors.

Fig. 8 shows the amplification simulation results at the outputs of the active balun, considering parasitic phenomena. It can be seen that the result differs from the idealized one by at least 1 dB.

Given the parasitic components, the simulation of the phase shift between differential outputs shows that the additional phase shift is up to 2° from the ideal level as it sown in Fig. 9.

The corner analysis was implemented to verify the operation of the device with any variations in parameters related to the technology of production. This method allows the creation of an experiment plan to evaluate the significance of deviations of specific parameters and the sensitivity of operational characteristics to production parameters. Fig. 10 shows the study's results that focuses on the influence of

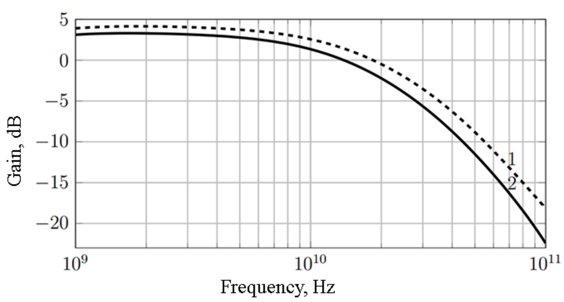

Fig. 8. Simulation of the balun gain with (2) and without (1) parasitic components.

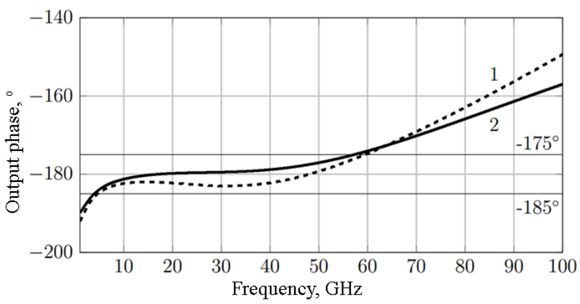

Fig. 9. Phase shift of the differential outputs with (1) and without (2) parasitic components.

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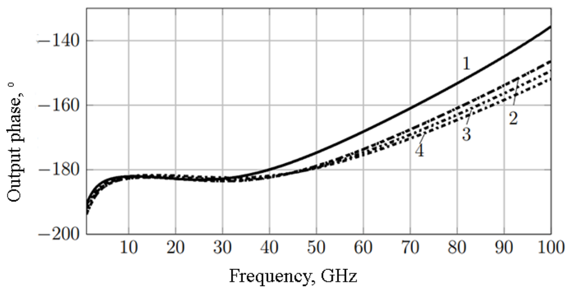

Fig. 10. Phase shift of differential outputs at different variations of transistor switching speed deviation: 1 - slow/slow; 2 - slow/fast; 3 - no variation; 4 - fast/fast.

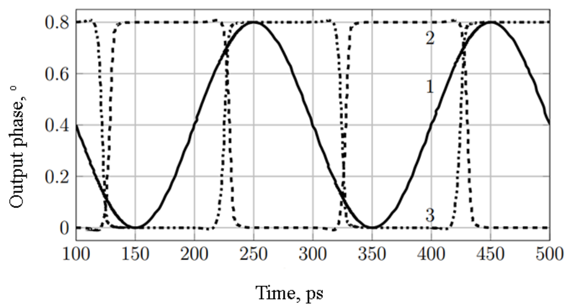

Fig. 11. Balun input signal and differential outputs at 5 GHz with an input signal amplitude of 400 mV: 1 - input, 2 - $V_{out.p}$, 2 - $V_{out.m}$

the deviation of the switching speed of transistors on the phase imbalance of the output signal. The results for slow and slow, slow and fast, and fast influence were given.

When developing the circuit, modern means of design and verification of the design of the circuit before production documentation were used. An active balun with a small size satisfies the conditions imposed by further links about the generated differential signal due to the absence of inductive elements.

Fig. 11 illustrates the correlation between the input signal of the active balun and the differential one, amplified by the original amplifier (buffer). For a comparative analysis of the characteristics of the developed active balun with similar developments, the following were selected:

- active balun designed for a range of up to 70 GHz on 130-nm SiGe technology [9];
- broadband phase-compensated balun up to 50 GHz on 90-nm CMOS technology [10];
- and a distributed active balun up to 70 GHz, produced using 65-nm CMOS technology [11].

A comparison of the leading models by operational characteristics is given in Table 1.

TABLE 1 COMPARISON OF THE ACTIVE BALUN IMPLEMENTATIONS

Implementation	proposed	[9]	[10]	[11]
Technology	CMOS	CMOS	CMOS	SiGe
Process, nm	22	90	65	130
Differential gain, dB	4,1	11,0	7,0	3,6
Bandwidth, GHz	60	50	>70	>70
Amplitude imbalance, dB	1,5	1,0	1,0	0,2
Phase imbalance, max, °	4	5	10	5
Power, mW	2,37	97	19	144
Square, mm^2	0,0016	0,46	0,64	0,42

It can be seen from the table that the developed balun, having competitive characteristics, is distinguished by significantly smaller dimensions and power with better phase balance.

CONCLUSIONS

In the dynamic landscape of modern communication systems, the demand for high-performance signal processing components continues to escalate. As wireless technologies, data transmission rates, and frequency bands evolve, an imperative arises to revisit and enhance the fundamental building blocks of signal conditioning circuits. The balun, a crucial component in transforming between balanced and unbalanced signals, plays a pivotal role in ensuring efficient and accurate data transfer.

The main goal of developing an inductor-less broadband energy-efficient active balun was to convert a unipolar input signal into a high-quality differential signal in a wide frequency range for further use in a frequency divider.

The developed device meets the stated requirements and can be used in larger projects.

One of the main advantages of the developed active balun is its size - only 48 µm by 34 µm, which allows it to be built into compact devices. In addition to the stated above, the device has high speed and low phase imbalance error, which is less than 2°.

Furthermore, the inductance of the active balun allows you to reduce signal loss and ensure the stability of the device, and a wide range of operating frequencies (from 2 GHz to 60 GHz) makes it a universal tool for use in various wireless communication systems.

As a disadvantage of the circuit, an amplitude imbalance can be mentioned, so after the active balun, it is necessary to use a buffer amplifier, although buffer amplifiers are still installed in most inter-cascade connections.

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The developed inductor-less broadband energy-efficient active balun is a very promising solution for use in many high-performance technologies where a high-quality differential signal is required in a wide frequency range.

References

[1] N. Marchand, "Transmission-Line Conversion Transformers," *Electronics, vol*. 17, pp. 142-145, 1944.

[2] H.-K. Chiou та J.-Y. Lin, «Symmetric offset stack balun in standard 0.13-μm CMOS technology for three broadband and low-loss balanced passive mixer designs.,» *IEEE Trans. Microw. Theory Techn. ,* vol. 59, pp. 1529–1538, 2011. **DOI:** 10.1109/TMTT.2011.2140123

[3] G. Yang, K. Tang та Z. Wang, «3.6–8.1 GHz CMOS balun with 1.8◦ in-band phase difference by using capacitive balance compensation technique.,» *Microw. Opt. Technol. Lett. ,* vol. 62, p. 1548–1551, 2020. **DOI:** 10.3390/electronics12020468

[4] H.-K. Chiou, H.-H. Lin та C.-Y. Chang, «Lumped-element compensated high/low-pass balun design for MMIC double-balanced mixer.,» *IEEE Microw. Wirel. Compon. Lett. ,* vol. 7, pp. 248–250, 1997. **DOI:** 10.1109/75.605493

[5] A. Kumar, F.-Y. Meng, C. Wang, K. Adhikari, T. Qiang, Q. Wu та Y. Wu, «Design analysis of integrated passive device-based balun devices with high selectivity for mobile application.,» *IEEE Access,* vol. 7, pp. 23169–23176, 2019. **DOI:** 10.1109/ACCESS.2019.2898513

[6] J. Cao, Z. Li, Q. Li та Z. Wang, «A wideband transformer balun with center open stub in CMOS process.,» *IEEE Microw. Wirel. Compon. Lett. ,* vol. 24, pp. 614–616, 2014. **DOI:** 10.1109/LMWC.2014.2328897

[7] U. Park, «A Wilkinson-type balun using a composite right/left-handed transmission line.,» *J.Inf. Commun. Converg. Eng. ,* vol. 11, pp. 147–152, 2013. **DOI:** 10.6109/jicce.2013.11.3.147

[8] V. Issakov, S. Trotta and H. Knapp, «Low-voltage flip-flop based frequency divider up to 92-GHz in 130-nm SiGe BiCMOS technology,» *2017 Integrated Nonlinear Microwave and Millimetre-wave Circuits Workshop (INMMiC),* pp. 1-3, 2017. **DOI:** 10.1109/INMMIC.2017.7927321

[9] P. Starke, V. Rieß, C. Carta, and F. Ellinger, «Active Single-Ended to Differential Converter (Balun) for DC up to 70 GHz in 130 nm SiGe,» *IEEE BiCMOS and Compound semiconductor Integrated Circuits and Technology Symposium (BCICTS),* pp. 1-4, 2019. **DOI:** 10.1109/BCICTS45179.2019.8972713

[10] Huang, Bo-Jiun Huang, Bo-Jr Lin, Kun-You Wang, Huei, «A 240 GHz active balun using 0.13 m CMOS process,» *Microwave and Wireless Components Letters,* no. 19, pp. 164-166, 2009. **DOI:** 10.1109/LMWC.2009.2013740

[11] B. Razavi, Design of analog CMOS integrated circuit, McGraw Hill, 2001. **ISBN:** 0-07-238032-2

[12] B. Razavi, RF Microelectronics (2nd Edition), Prentice Hall Press, 2011. **ISBN:** 0-13-887571-5

[13] W. M. C. Sansen, Analog Design Essentials (The International Series in Engineering and Computer Science), Berlin: Springer-Verlag, 2006. **DOI:** 10.1007/b135984

[14] K. Wu, K. Lai, R. Hu, and C. Chang, «DC-50GHz wideband phase- compensated 90nm-CMOS active balun design,» *Asia-Pacific Microwave Conference (APMC),* vol. 3, pp. 1-3, 2015. **DOI:** 10.1109/APMC.2015.7413445

[15] A. Jahanian and P. Heydari, «A CMOS Distributed Amplifier With Distributed Active Input Balun Using GBW and Linearity Enhancing Techniques,» *IEEE Transactions on Microwave Theory and Techniques,* vol. 60, no. 5, p. 1331–1341, 2015. **DOI:** 10.1109/RFIC.2011.5940664

[16] C. Huynh and C. Nguyen, «Ultra-Wideband Active Balun Topology and Its Implementation on SiGe BiCMOS Across DC 50 GHz,» *IEEE Microwave and Wireless Components Letters,* vol. 26, no. 9, p. 720–722, 2016. **DOI:** 10.1109/LMWC.2016.2597365

[17] J.-Y. Li, W.-J. Lin, M.-P. Houng, and L.-S. Chen, "A Low Power Consumption and Wide-Band Input Matching CMOS Active Balun for UWB System Applications", Journal of Electromagnetic Waves and Applications, vol. 24, no. 11-12, pp. 1449–1457, Jan. 2010. **DOI:** 10.1163/156939310792149641

[18] A. Niknejad, Electromagnetics for High-Speed Analog and Digital Communication Circuits, Cambridge University Press, 2007. **DOI:** 10.1017/CBO9780511805738.008

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Безіндуктивний широкополосний енергоефективний активний балун для частот до 60 ГГц

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***Анотація*—У статті представлено безіндуктивний широкосмуговий енергоефективний активний балун з використанням 22нм технології на основі диференціальної пари. Даний пристрій може працювати в діапазоні частот від 2 ГГц до 60 ГГц з напругою живлення 0,8 В і споживати до 3 мА струму. Особливістю цього активного балуна є те, що він не має індуктивних компонентів, що зменшує його розмір і втрати сигналу. Що стосується характеристик вихідного сигналу, то його амплітуда коливається від 450 мВ до 200 мВ в робочому діапазоні частот. Коефіцієнт посилення сигналу в діапазоні від 1 ГГц до 60 ГГц змінюється від -10 дБ до 4 дБ, розмір схеми на мікросхемі 48 мкм на 34 мкм. Крім того, прилад має високу швидкодію і малу похибку дисбалансу фаз, яка становить менше 2º.**

При розробці використовувалися сучасні методи дизайну та верифікації схеми перед виготовленням. Завдяки відсутності індуктивних елементів, активний балун, маючи невеликі розміри та знижене енергоспоживання, Відповідає необхідним умовам, щоб наступні блоки пристрою могли обробляти згенерований сигнал.

Під час побудови топології пристрою була проведена перевірка на наявність паразитних явищ, таких як паразитні ємності та опори, а також проведена перевірка на виснаження провідників під дією струму. Виконане топологічне креслення дозволило провести моделювання, яке наближає результати схеми до поведінки мікросхеми після виготовлення.

Загалом цей неіндуктивний широкосмуговий енергоефективний активний балун використовується як вхідний блок частотного поділу. Огляд актуальних конструкцій широкосмугового балуна, придатних для модуляції сигналів без нижчих частот зрізу, проведено дял порівняльної характеристики параметрів розробленого балуна.

Недоліком схеми можна назвати дисбаланс амплітуд, тому після активного балуна необхідно використовувати підсилювач, хоча найчастіше підсилювачі ставлять на вході будь-яких схем.

Запропонована схема демонструє найкращий розмірно-фазовий баланс у поєднанні з малою потужністю.

Він дозволяє отримувати стабільний сигнал на високій швидкості передачі даних і забезпечує енергозбереження за рахунок низького споживання струму.

Ключові слова — аналогова інтегральна схема; подільник частоти; активний балун; диференційне перетворення; енергоефективність.