Design of Millimeter-wave Transformer Balun with Isolation Circuit in Silicon Based Technology

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***Abstract*—In this paper a novel method to design a transformer based balun with isolation between output ports and matching characteristic at all ports is proposed. The main issue of transformer balun at millimeter-wave frequencies is that it has poor matching and isolation performance. In this work, an isolation circuit is introduced to place between output ports in the transformer balun design. As a validation, comparison has been made between the balun with and without isolation circuit, which has shown great performance improvement of proposed design. Moreover, design example is given for millimeter-wave on-chip implementation of this isolation circuit in standard silicon based technology with 6 metal layers.**

***Index Terms*—balun; isolation circuit; matching characteristic; millimeter-wave; silicon based technology; transformer**

I. Introduction

Baluns are used to convert between balanced signal and unbalanced signal. At low frequencies baluns are always implemented in a flux coupling transformer form, however at millimeter-wave frequencies it is not applicable due to large loss induced by the capacitive coupling between coils of the transformer. Recent progress in silicon based CMOS or BiCMOS process gives it not only competitive active devices but also high quality multi-layer metal connection for passive devices, which has made it good choice for millimeter-wave applications. Several designs of on-chip millimeter-wave balun using silicon based technology have been published based on silicon based process [1]–[7]. Continuous work has been done to investigate better performance [2], [3], tuning capacity [4], [5] and miniaturization [6], [7] of on-chip balun. However, no attention has been paid to the isolation between differential ports and matching characteristic of the transformer balun, which is of great importance for many applications. In [8], detailed analysis and design equations are given to realize simultaneously theoretically perfect isolation and perfect matching at all ports for different type of transmission line baluns. The analysis in [8] are focused on the microwave integrated circuit (MIC) or monolithic microwave integrated circuit (MMIC) implementation of the proposed balun, in which transformer type of balun has not been considered.

In this paper, for the first time, a method is proposed to add isolation circuit for the transformer balun. In this configuration as shown in Fig. 1, both isolation performance between output differential ports and matching characteristic at all ports of the balun can be achieved. Design example of the isolation circuit is given at millimeter-wave frequency using commercial 6 metal layer BiCMOS process .

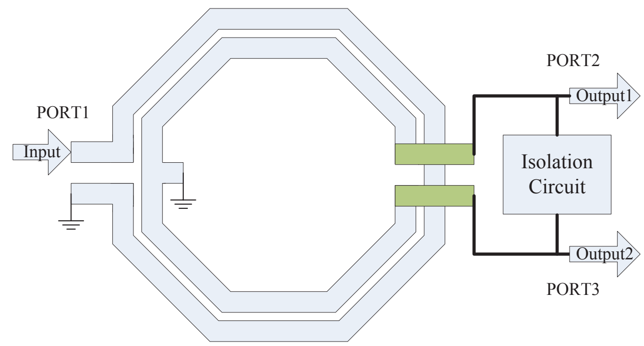

Fig. 1. Proposed transformer balun with isolation circuit.

II. Theory

As shown in Fig. 1, an on-chip transformer is used for implementation of proposed balun, both the primary and secondary coils are placed on the same metal layer. For ideal lossless three port balun, the theoretical scattering parameter matrix could be written in (1),

$$S_{balun\_lossless} = \begin{bmatrix} 0 & j/\sqrt{2} & -j/\sqrt{2} \\ j/\sqrt{2} & 1/2 & 1/2 \\ -j/\sqrt{2} & 1/2 & 1/2 \end{bmatrix} \quad (1)$$

Theoretical analysis has been performed which proves that all port matching is not possible for any lossless three port passive circuit. From (1), it can be observed that input port can be matched perfectly without any reflection signals, while reflection coefficient of output ports and isolation between output ports are all -6 dB ideally. To realize balun with isolation and all port matching characteristic which will change the balun's scattering parameter matrix into (2), an isolation circuit with loss is introduced as shown in Fig. 1,

$$S_{balun\_isolated} = \begin{bmatrix} 0 & j/\sqrt{2} & -j/\sqrt{2} \\ j/\sqrt{2} & 0 & 0 \\ -j/\sqrt{2} & 0 & 0 \end{bmatrix} \quad (2)$$

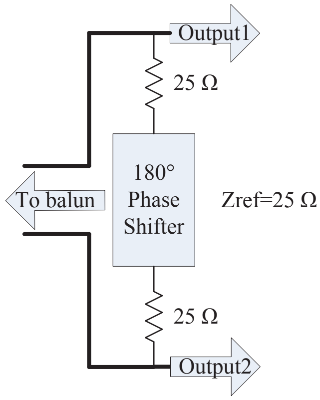

Fig. 2. Proposed isolation circuit.

TABLE I
BALUN PERFORMANCE COMPARISON AT REFERENCE FREQUENCY

	w/o isolation	w isolation
dB(S22)	-6.02	-218.1
dB(S33)	-6.02	-218.1
dB(S23)	-6.02	-330

As given in equation (2), unlike conventional lossless balun, matching and isolation can be realized when isolation circuit is introduced. Moreover, the loss circuit introduced will not deteriorate the transmission performance which means that S21 and S31 will remain the same, which could also be observed from scattering parameter in (2) . If we take an ideal transformer with turns ratio of 1:1 as shown in Fig. 1 into analysis, the input impedance is 50 Ω and two output impedances will be 25 Ω respectively for this transformer when its center tap is connected to ground as a balun. The scattering parameter of this transformer balun will be the same as in equation (1) if we take no parasitics into consideration. For isolation and matching performance of this transformer balun, we propose an isolation circuit to be implemented between differential ports which is shown in Fig. 2.

The proposed isolation circuit is composed by two 25 Ω resistors and a 180 degrees phase shifter in series connection. The phase shifter has a reference impedance of 25 Ω and 180 degrees phase shift can be perfectly achieved at reference frequency. Therefore the isolation and matching characteristic can be realized of the transformer balun with introduced isolation circuit. To verify the performance of this proposed isolation circuit, a commercial eda software is used to check the S22, S33 and S23 performance of the balun with and without isolation circuit at reference frequency, the result is shown in Table 1. From the comparison result in Table 1, the matching and isolation performance of the transformer balun has been tremendously improved with proposed isolation circuit.

III. DESIGN OF ISOLATION CIRCUIT

Due to the existence of 180 degrees phase shifter in proposed isolation circuit which will make the circuit bulky if transmission line is used, alternative measure must be taken. Slow wave structure [9] is a choice but still it will occupy large area. Hence in this design we use lumped elements to realize 180 degrees phase shift, in which inductors are put in parallel connection and capacitors are connected in series to provide more phase shift. Schematic using ideal components and design example are given at 60 GHz using standard 6 metal layer silicon based process as shown in Fig. 3.

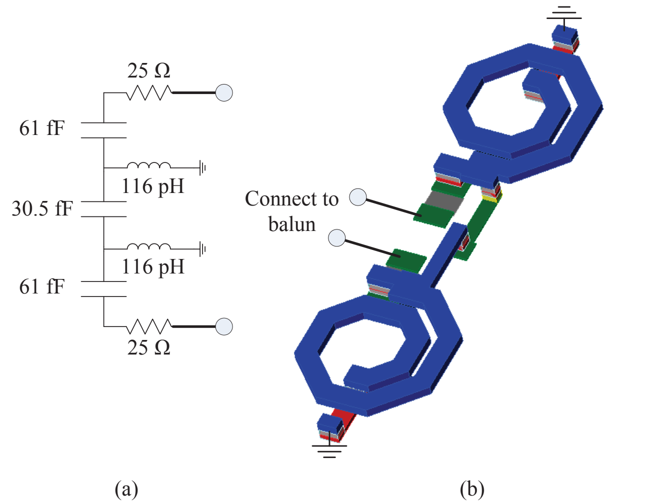

Fig. 3. Proposed isolation circuit using lumped elements. (a) Schematic using ideal components; (b) 3-dimensional structure implemented in silicon process with 6 metal layers.

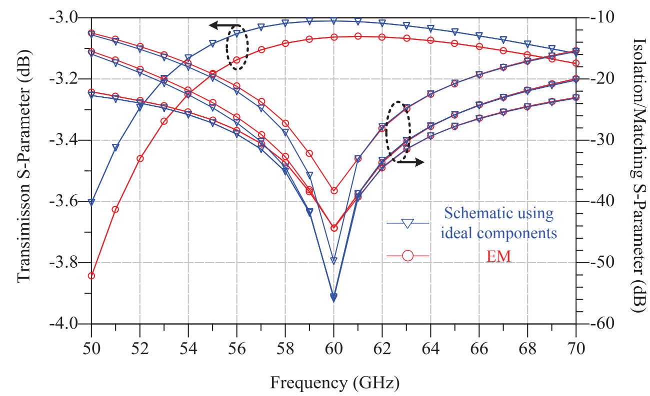

Fig. 4. Schematic simulation using ideal components and EM simulation result comparison of proposed isolation circuit.

As shown in schematic in Fig. 3(a), 180 degrees phase shifter is composed by 25 Ω resistors, 61 fF/30.5 fF capacitors and 116 pH inductors. To implement this isolation circuit in standard 6 metal layer silicon based technology, top metal layer with lowest loss is used for spiral inductor; capacitors are made by metal-insulator-metal (MIM) structure which is supported by the foundry; low value resistors in this design are thin film resistors. Three dimensional structure of proposed isolation circuit is shown in Fig. 3(b). Electromagnetic (EM) simulation has been performed for proposed isolation circuit, comparison of EM result with schematic simulation could be found in Fig. 4 for this isolation circuit when it is applied for ideal transformer balun with 1:1 turns ratio.

In Fig. 4, transmission scattering parameter refers to S21 and S31; isolation and matching scattering parameter is the result of S11, S22, S33 and S23, which should all be zero ideally in magnitude at design frequency. As illustrated in Fig. 4, result from EM simulation is very close to schematic simulation using ideal components, which means that it is applicable for this isolation circuit at 60 GHz in standard silicon process. At 60 GHz both reflection at each port and isolation are more than -30 dB from EM simulation result, which confirms that this proposed isolation circuit can be implemented to realize the isolation and matching performance at all ports for the transformer balun.

IV. Conclusion

In this paper, an isolation circuit is firstly proposed for transformer balun in silicon based technology. With proposed isolation circuit, theoretically perfect isolation and all ports matching characteristic can be achieved. Design example of the isolation circuit at 60 GHz using standard BiCMOS process with six metal layers is illustrated, final performance has been confirmed by electromagnetic simulations.

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