A Wideband Transformer Balun With Center Open Stub in CMOS Process

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***Abstract*—This letter presents a wideband transformer balun with a center open stub. Since the interconnected line between two coupled-lines greatly deteriorates the performance of balun in millimeter-wave designs, the proposed center open stub provides a good solution to further optimize the balance of balun. The proposed transformer balun with center open stub has been fabricated in 90 nm CMOS technology, with a compact chip area of 0.012 mm^2. The balun achieves an amplitude imbalance of less than 1 dB for a frequency band ranging from 1 to 48 GHz along with a phase imbalance of less than 5 degrees for the frequency band ranging from 2 to 47 GHz.**

***Index Terms*—CMOS, open stub, transformer balun.**

I. Introduction

VARIOUS Balun configurations have been reported to be used in ultra-wide band (UWB) and microwave monolithic integrated circuits (MMICs) [1]–[4]. The planar version of the Marchand balun [4] is perhaps one of the most attractive configurations due to its excellent robustness to process and wide-band performance. However, the unbalanced port of Marchand balun cannot be absorbed in dc current path of some practical designs. Actually, compared to Marchand balun, transformer balun has two advantages: i) Compact chip area at the same operating frequency. The length of each coupled-line can be significantly reduced $(< \lambda/4)$ [5]. ii) The unbalanced port can be absorbed in dc current path and functions as inductive load without dc voltage drop [6].

There are some reasons which restrain transformer balun from being used in MMICs. The magnetic flux leakage and capacitance between every two windings degrades the transformer performance, especially at higher frequency band [7]. The reported characteristics of transformer baluns display large output phase and amplitude imbalance [8]. This letter presents a spiral transformer balun with a center open stub fabricated on silicon substrate. The design aspects in terms of insertion loss and output balance have been addressed in this work. The balanced output characteristics range from 2 to 47 GHz.

II. Analysis and Design of Proposed Wideband Transformer Balun

Fig. 1(a) shows the block diagram of conventional transformer balun, which consists of two identical coupled-line sections with electrical length of θ. In order to investigate the characteristic, we can derive the expression of S_{21} and S_{31} by using the voltage wave's relationships [9]:

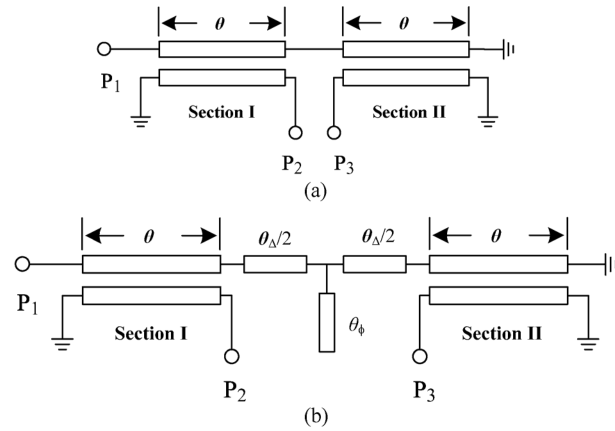

Fig. 1. (a) Block diagram of conventional transformer balun. (b) Block diagram of proposed transformer balun with a center open stub.

$$S_{21} = -S_{31} = -\frac{xy}{z^2}\left(1+\frac{x^2}{z^2-y^2}\right) \quad (1)$$

Where $x = \sqrt{1-k^2}$, $y = \mathrm{j}k\sin\theta$ and $z = \sqrt{1-k^2}\cos\theta + \mathrm{j}\sin\theta$, k is the coupling factor.

Since the balun is ideal and symmetrical, it is apparent that S_{21} and S_{31} can completely satisfy the amplitude and phase imbalance. Fig. 1(b) shows the block diagram of proposed transformer balun, which consists of two identical coupled-line sections, an interconnected line and a center open stub with electrical length of θ, θ_Δ and θ_φ. Since the interconnected line between the two coupled-lines greatly deteriorates the performance of balun in millimeter- wave designs, the proposed center open stub provides a good solution to further optimize the imbalance of balun. The expression of S_{21} and S_{31} can be derived as:

$$s_{21} = -\frac{xy}{z^2}\left[1+\frac{x^2 e^{-\mathrm{j}\theta_\Delta}(1+3e^{-\mathrm{j}2\theta_\varphi})-(z^2-y^2)(1-e^{-\mathrm{j}2\theta_\varphi})}{(z^2-y^2)(e^{-\mathrm{j}2\theta_\varphi}+3)e^{\mathrm{j}\theta_\Delta}+x^2(1-e^{-\mathrm{j}2\theta_\varphi})}\right] \quad (2)$$

$$s_{31} = \frac{xy}{z^2}\left(1+\frac{x^2}{z^2-y^2}\right) \times \frac{2(z^2-y^2)(e^{-\mathrm{j}2\theta_\varphi}+1)}{(z^2-y^2)(e^{-\mathrm{j}2\theta_\varphi}+3)e^{\mathrm{j}\theta_\Delta}+x^2(1-e^{-\mathrm{j}2\theta_\varphi})} \quad (3)$$

The balance of balun is sensitive to the input impedance of the second coupler according to [9]. In order to keep this imbalance as small as possible, the proposed open stub is parallel with the second coupler. As a result, the input impedance of the

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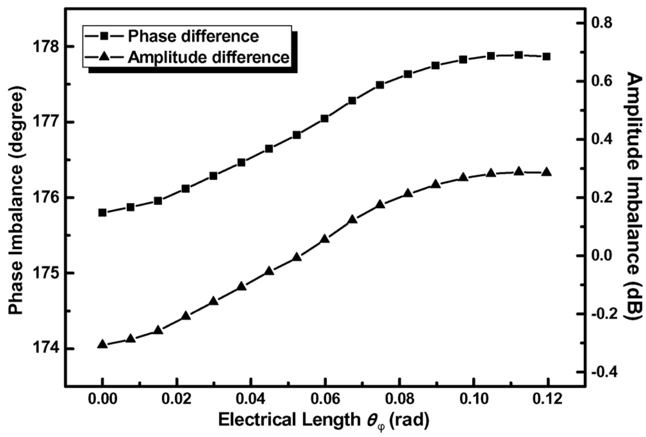

Fig. 2. Calculated phase and amplitude imbalance versus the electrical length θ_φ at $\theta = 0.8$ rad.

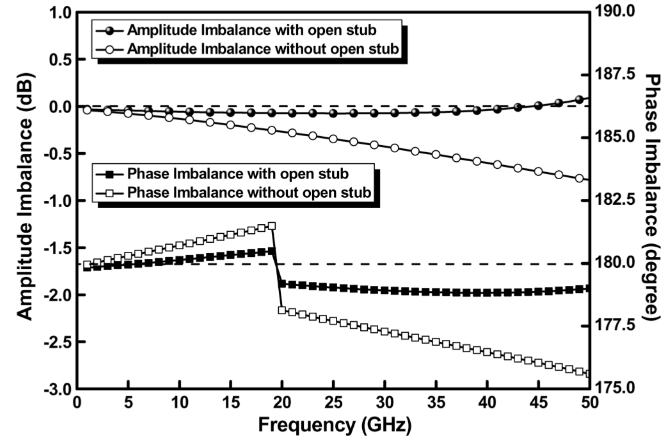

Fig. 4. Simulated amplitude and phase imbalance both with and without a center open stub.

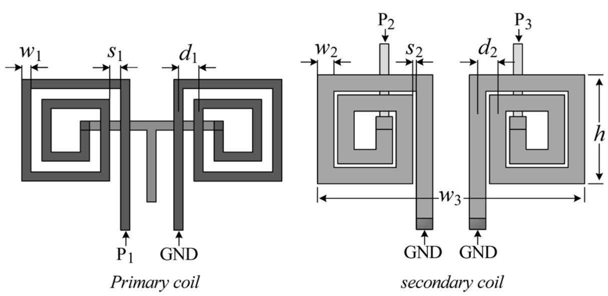

Fig. 3. Implemented primary coil and secondary coil.

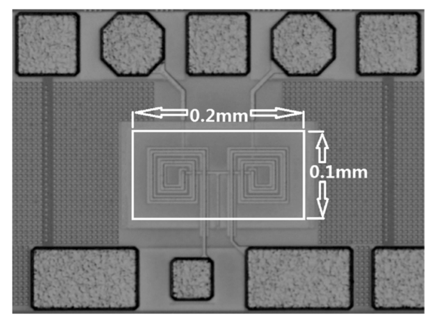

Fig. 5. Chip photograph of proposed transformer balun.

TABLE I
DESIGN PARAMETERS (UNITS: μm)

w_1	s_1	d_1	w_2	s_2	d_2	w_3	h
3	9.5	12.5	11	1.5	12.5	170	70

second coupler can be adjusted by the electrical length of the open stub. Both phase and amplitude of the second coupler will increase with the increasing length. Fig. 2 shows the calculated phase and amplitude imbalance versus the electrical length θ_φ at $\theta = 0.8$ rad. Both phase and amplitude imbalances increase with respect to the electrical length of center open stub. However, the minimum values of phase and amplitude imbalances are different, which implies that there will be some compromises in practical designs.

To reduce the chip area, the proposed transformer balun adopts two spiral broadside-coupled couplers, as can be seen from Fig. 3, where the implemented primary and secondary coils are shown. The size of the coils is shown in Table I. The balun is designed as a vertically stacked 1:1 structure. The open stub is located at the center of the proposed transformer balun, therefore no additional chip area is consumed. The coupling factor of the coupler is chosen to be around 0.7 and the single coupler's length is about 478 μm. Since the spacing between every two metal layers and the material of the substrate are fixed, the coupler's coupling factor k can only be adjusted by changing the conductor width and choosing reasonable metal layers. There are 9 metal layers in 90 nm CMOS technology. The top metal with thickness of 3.4 μm is adopted as primary coil and the width of primary coil w_1 is selected to be 3 μm to obtain a large self-inductance and reduce the chip area. The space s_1 is not chosen to be the minimum space defined by the process, rather an optimum value of 9.5 μm is used. The length of interconnected line is about 80 μm, which properly keeps the two couplers away from each other. The secondary coil employs metal 6 with width w_2 of 11 μm and space s_2 of 1.5 μm. The spacing between primary and the secondary coils is about 2.9 μm according to the process.

A center open stub with an electrical length of $\theta_\varphi = 0.08$, the corresponding length of 60 μm and the width of 3 μm has been employed. Fig. 4 shows the simulated phase and amplitude imbalance both with and without an open stub. The center open stub significantly improves the phase and amplitude imbalance of transformer balun, whereas it shows little effect on the return and insertion loss. The insertion loss only increases by 0.2 dB at 35 GHz and 0.5 dB at 50 GHz.

III. EXPERIMENTAL RESULTS

The proposed transformer balun has been designed and fabricated in TSMC 90 nm CMOS technology. The die photo of the proposed transformer balun is depicted in Fig. 5. The balun core is only 0.1 mm × 0.2 mm (without contact pads). To reach the required density, there are floating metal blocks filled in the layout. The transformer balun is measured by using an Agilent N5245A performance network analyzer (PNA) which can directly obtain the final three-port S-parameter data. To compare with the designs in the reported papers, this transformer balun

TABLE II
PERFORMANCE SUMMARY OF TRANSFORMER BALUNS

Ref.	Configuration	Amplitude Imbalance	Phase Imbalance	1dB BW (GHz)	RBW (100%)	S_{21} (dB)	Area (mm^2)
This work	Stacked	1dB @1-48GHz	5° @2-47GHz	17-47	93.8	-8.1	0.02
[8]	Planar	1dB @4-19GHz	5° @1-25GHz	10-19	62	-8	0.05
[10]	3D	0.6dB @1-10 GHz	7° @1-10GHz	5-10	66.7	-4.4	0.01

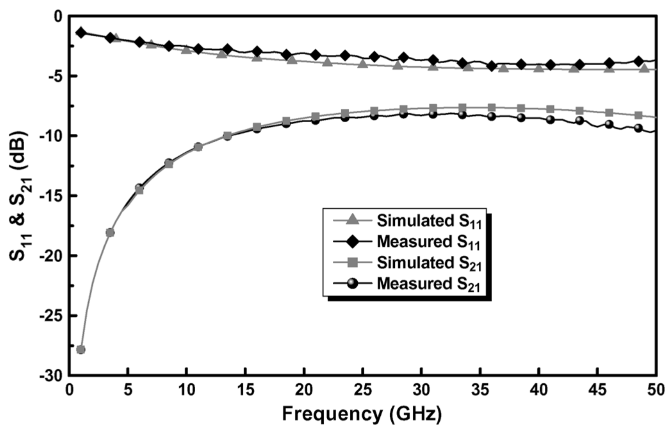

Fig. 6. S_{11} and S_{21} versus frequency.

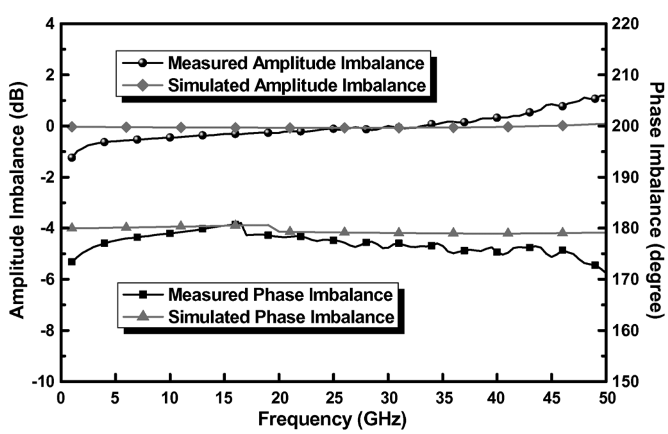

Fig. 7. Phase and amplitude imbalance versus frequency.

is measured with three terminations of 50 Ω. Fig. 6 shows the measured S_{11} and S_{21} versus frequency.

The 1 dB bandwidth ranges from 17 to 47 GHz, which means the relative bandwidth (RBW) is 93.8%. S_{21} is lower than -8 dB which is caused by the poor matching to 50 Ω. Here we focus on the amplitude and phase balance, which can be improved by the proposed center open stub. The input/output matching network can be employed when balun operates with an active device [5], [6]. Fig. 7 displays the measured phase and amplitude imbalance versus frequency. The frequency band with amplitude imbalance less than 1 dB ranges from 1 to 48 GHz, and the frequency band with phase imbalance less than 5 degrees ranges from 2 to 47 GHz. Table II summarizes the comparison of the proposed balun with other reported transformer baluns and it can be seen that the proposed transformer balun shows an excellent performance [10].

IV. CONCLUSION

This letter has presented a spiral transformer balun with a center open stub. The proposed center open stub effectively improves the phase and amplitude balance of the transformer balun, which is fabricated in 90 nm CMOS technology. The balun achieves a compact chip area of 0.02 mm^2 and balanced output characteristics from 2 to 47 GHz.

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