Characterization and Analysis of Patterned Shields for Millimeter-Wave Broadside-Coupled Balun in CMOS Technology

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***Abstract*- Extensive studies on the performance of on-chip millimeter-wave broadside-coupled baluns with different patterned shields are carried out in this paper. Based on the advantage of multi-layer metals in the standard 0.18-μm RF CMOS process, the proposed Marchand balun takes the form of the broadside-coupled lines to enhance the coupling effect. In addition, to save the precious chip area, the proposed balun has been folded in the shape of a square geometry. The loss mechanism of the balun is analyzed and the losses of the balun in the conductive silicon substrate can be displayed with the aid of EM simulations. Different patterned shields are proposed and their influences on the balun device in terms of insertion loss, magnitude and phase balances are evaluated through EM simulations. According to the best of the authors' knowledge, the patterned floating shield (PFS) is introduced for the first time to reduce the losses of the broadside-coupling Marchand balun in the CMOS technology. The results show that the PFS has the better effect than the patterned ground shield (PGS) for the proposed balun, the performance of the balun can be improved obviously with PFS in the operating frequency range. Besides, the influences of different PFS types, widths and spacing on the performance of balun have been compared and discussed.**

I. INTRODUCTION

In recent years, Millimeter-Wave circuits have been extensively implemented in advanced CMOS processes, their superior RF performance depend largely on the quality of silicon-based passive components. Among the passive components, baluns play an important role in RFIC design for impedance transformers and single to differential conversion of RF signals[1]. The insertion loss, magnitude and phase balances are the most important concerns in millimeter-wave silicon-based balun design. However, due to the conductive substrate, the time-varying magnetic and electric fields cause serious power losses at high frequency[2], the performance of baluns are strongly influenced by substrate losses.

To reduce the substrate losses, one practical way is to employ an appropriate patterned ground shield (PGS), which provide a short terminal to prevent the electromagnetic field penetration into the conductive substrate. Previous studies of PGS for inductors, transformers and transmission lines have been reported[2-7], it was demonstrated that PGS can reduce the losses effectively. However, the large parasitic capacitance between PGS and the metal lines may deteriorate the high frequency performance for passive components. Recently, patterned floating shields have been proposed to improve the performance of passive devices[8-10]. Most of the literatures have made their efforts to investigate the improvements of inductors and transformers, to the best of the authors' knowledge, only a few literatures analyze the impact of the patterned shield on monolithic baluns[1, 11].

In this paper, a broadside-coupled balun in millimeter-wave band is proposed. The characteristics of different patterned shields are analyzed. To the authors' knowledge, this is the first time broadside-coupled balun with patterned floating shields are studied. Based on the EM simulations, the loss mechanisms of the balun are exposed, the principles and topologies of the patterned shields are detailed. The influences of different PFS types, width and spacing on the performance of balun are compared and discussed, and finally, an optimized PFS structure is obtained.

II. BALUN DESIGN

As shown in Fig.1, the balun uses Marchand type structure and consists of two symmetrical quarter-wave coupled lines. To yield a tight coupling and improve performance, broadside structure is adopted for coupled lines rather than edge coupling.

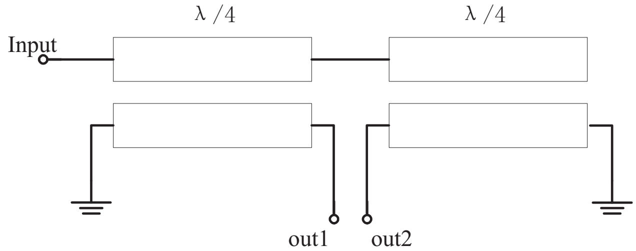

Fig. 1 Schematic diagram of Marchand balun

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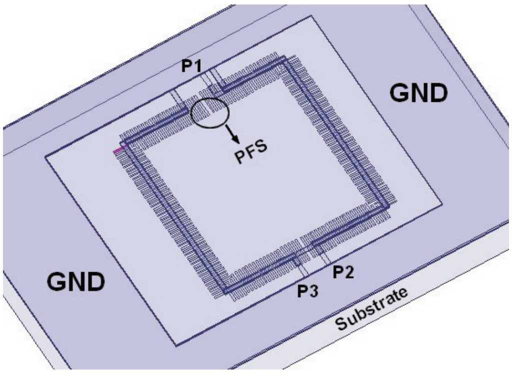


Fig. 2 Balun structure with PFS in 3D view

The balun with patterned shield is designed in a 65-nm 1P6M CMOS process. The resistivity of the substrate is 10 Ω·cm. The top metal layer (M6) is of 2 μm-thick metal and is used to implement the output line, the fourth metal layer (M4) is of 1 μm-thick metal and is used to implement the input line. The patterned shield is implemented by the bottom metal layer (M1). To reduce the size, the balun is folded in the shape of a square geometry. Fig. 2 shows the balun structure with PFS.

The relative permittivity of substrate ε_r=12, s1=1μm, s2=2μm. There are three main parameters to characterize the performance of balun, they are amplitude imbalance, phase imbalance and insertion loss.

Because the layout is not absolute symmetry in real design, the signals will show some slight imbalance at two output ports. According to the S-parameters of the balun, the amplitude imbalance ζ and phase imbalance θ are defined as:

$$\zeta = -20\lg\left|\frac{S_{21}}{S_{31}}\right| \quad (1)$$

$$\theta = 180 - \left|\arctan\left(\frac{\mathrm{Im}(S_{21})}{\mathrm{Re}(S_{21})}\right) - \arctan\left(\frac{\mathrm{Im}(S_{31})}{\mathrm{Re}(S_{1})}\right)\right| \quad (2)$$

The insertion loss *IL* is mainly caused by conductor and substrate losses when signal passes through the balun.

$$IL = -10\lg(|S_{21}|^2 + |S_{31}|^2) \quad (3)$$

III. CHARACTERIZATION OF PATTERNED SHIELDS

Integrated baluns are suffered from conductor and substrate losses at the high frequency. Conductor losses are mainly determined by metal conductivity, proximity effect and skin effect. Substrate losses are related to electric and magnetic fields, magnetic field produces eddy currents circulating on the substrate underneath the conductors, while electric field causes displacement currents flowing perpendicularly to the conductors and capacitive coupling. In order to reduce substrate losses, patterned shields are used to limit the penetration of the electric and magnetic fields.

A. Patterned Ground Shield

PGS is a kind of particular shaped metal which is connected to ground and designed between the device and substrate, providing a short terminal to the electric field leaking into the substrate. However, the large parasitic capacitance between PGS and the conductors leads to a much lower resonant frequency, the high frequency characteristic of the balun will deteriorate. Meanwhile, an on-chip true ground reference is hardly to gain and the energy will lose to the conductive substrate as the voltage varies.

B. Patterned Floating Shield

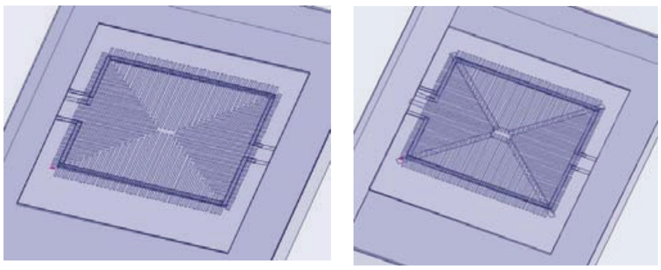
Unlike PGS, PFS does not have the ground reference and can be implemented conveniently.PFS can also reduce the substrate current by preventing the electric field of the conductors from reaching the substrate. Moreover, by using PFS, the isolation of the devices and the high frequency performance will be improved for its none grounded connection. The dummies which are required for the strict metal density can be replaced by PFS with the improvement on the quality factors.

IV. INFLUENCE OF DIFFERENT SHIELDS ON BALUN PERFORMANCE

To explore how patterned shield impacts the performance of Marchand balun in broadside coupled structure, different configurations of patterned shields are discussed in type, width and spacing, respectively. The baluns with PGS and PFS are simulated by HFSS, the relationship between shield parameters and Balun performance can be shown in charts clearly.

A. Shield Type

Two types of patterned shield are designed for comparison. The layout of the PGS and PFS are shown in Fig. 3. The bar width and the spacing of bars are both 5μm, the simulated insertion loss is shown in Fig. 4.



(a) PFS (b) PGS

Fig. 3 layout of balun with PFS and PGS

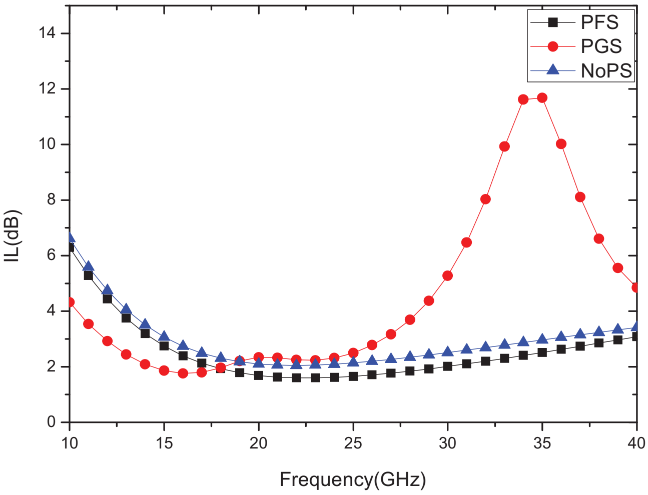


Fig. 4 Insertion losses of balun with PGS and PFS

The insertion loss of balun with PFS is 2 to 3 dB in the frequency range from 20GHz to 40GHz, it is better than that of balun without PS. Compared two insertion losses of PGS and PFS in Fig. 4, it is obviously that PGS has the worse effects than PFS. The balun with PGS has less bandwidth and its insertion loss drops quickly when the frequency increases beyond 25GHz. In addition, the curve of PGS has a turning point and the insertion loss reaches the minimum value of 12dB at 35GHz. This is caused by the increasing of the capacitance between the bottom metal line of the balun and GND.

Due to the better performance of PFS, we concentrated our research on PFS, so the following simulations are based on PFS, its structure is shown in Fig.2.

B. *Shield Type*

To find the rules between balun performance and bar width of PFS, the shield bar width is set to 2, 4, and 6μm with fixed bar spacing of 2μm. The simulated results are shown in Fig. 5 and Fig. 6.

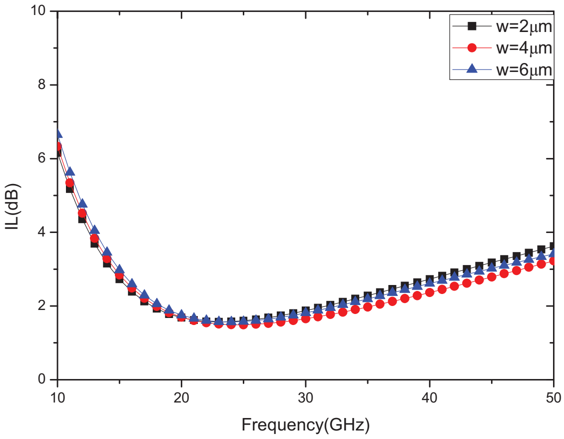


Fig. 5 Insertion loss with different bar width

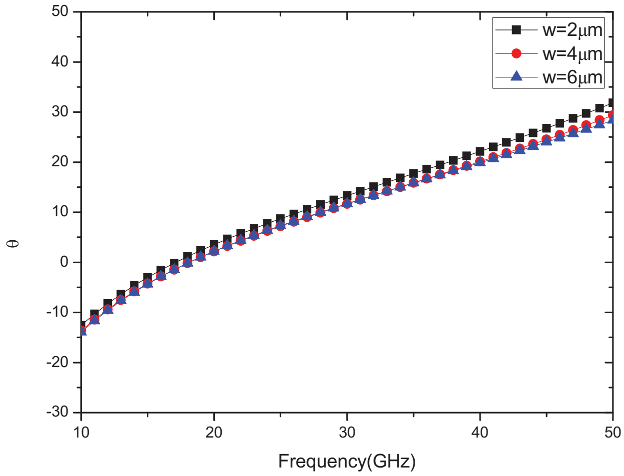


Fig. 6 Phase imbalance with different bar width

It is obviously that the insertion loss is not proportion to the bar width of PFS. Among three selected bar width, the best insertion loss is achieved in bar width of 4μm, which implies that there should have an optimal bar width to get the best insertion loss. In addition, the insertion losses of different bar width have little varies when the frequency is low, however, their difference become more apparently as the frequency goes up. The phase imbalance with bar width of 2μm is a little worse than that of the other two bar width.

C. *Shield Bar Spacing*

The shield bar spacing is set to 2, 4, and 6μm with fixed bar width of 4μm. The simulated results are shown in Fig. 7 and Fig. 8.

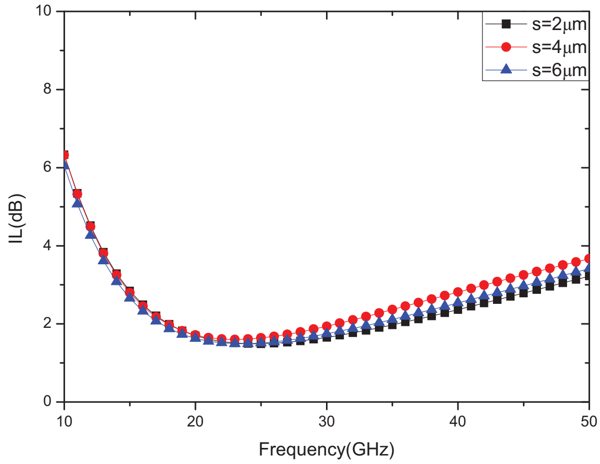


Fig. 7 Insertion loss with different bar spacing

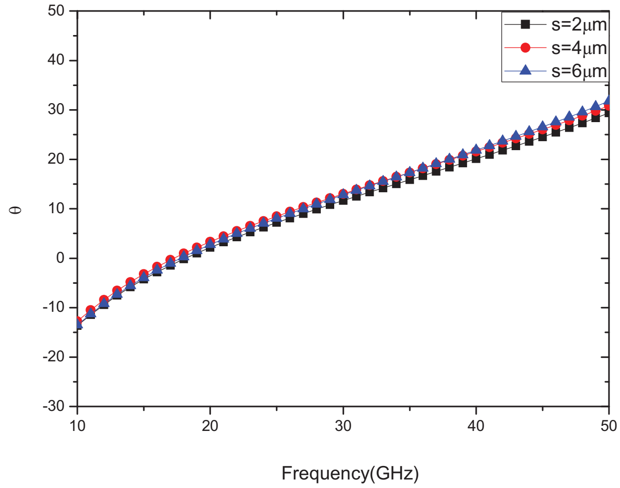


Fig. 8 Phase imbalance with different bar spacing

Compared the balun performance based on three different bar spacing of PFS, the PFS with the least spacing of 2μm has the best insertion loss. This result also agree with the theory analysis, when the bar spacing decreases, the more electromagnetic wave will be prevented from penetrating into the substrate. Since the wave length has inverse ratio to the frequency, the effects of spacing will become more obviously as the frequency goes up. The phase imbalance is influenced a little by different bar spacing, the balun with bar spacing of 2μm has better phase imbalance than others.

V. CONCLUSION

The performance of broadside coupled balun in square structure can be improved by patterned shields. By using EM simulation tool(HFSS), the results show that the PFS has much better effect than that of PGS. The bar width of PFS has an optimized medium value for the best balun performance, and the performance will be improved as the bar spacing reduces.

ACKNOWLEDGMENT

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