A 180-370-GHz Wide-Bandwidth Marchand Balun with Lateral Ground Wall

- Realized in 40-nm CMOS Process -

Zhen YAN† Satoshi TANAKA† Takeshi YOSHIDA† and Minoru FUJISHIMA†

†Graduate School of Advance Sciences and Engineering, Hiroshima University 1-3-2 Kagamiyama, Higashi-Hiroshima City, Hiroshima, 739-8511 Japan

E-mail: †{m221831, tana, takeshi, fuji}@hiroshima-u.ac.jp

Abstract This paper presents the design and simulation analysis of a Marchand balun operating in the 300 GHz band (275 GHz center frequency) using 40 nm CMOS technology. The design has been data generated by electromagnetic field simulation. The results show that the factors affecting the performance come from the lateral and the bottom, respectively. The final design of the balun uses only the lateral ground wall and eliminates the bottom ground plate. This reduces transmission loss and ensures port reflection coefficients. The reduction of the layout area was achieved by folding the signal lines. The insertion loss at the operating frequency is only 0.76 dB. In addition, due to the good propagation characteristics of the signal line layer material of the process, the proposed balun has an extremely wide bandwidth of 180~370 GHz.

Keyword Marchand balun, 40 nm CMOS, 300 GHz-band, lateral ground wall

1. INTRODUCTION

With the ever-increasing demand for high frequency and high data rate communication systems, the development of integrated circuits operating in the millimeter-wave frequency range has become imperative. The 300 GHz-band, represents a crucial segment of the sub-terahertz spectrum for various emerging applications, including 6G. To harness the potential of this spectrum, the design and implementation of efficient components are essential. In this context, the Marchand balun stands as a fundamental building block, facilitating the transition between single-ended and differential signal domains.

In this paper, we present a Marchand balun designed using 40 nm CMOS technology that is customized to operate in the 300 GHz-band with a center frequency of 275 GHz. The layout is designed using a ground wall design. The design options for the grounding layout have been analyzed from two directions. The presence of lateral ground wall reduces the reflection coefficient of the ports, and the presence of a bottom ground plate increases the transmission loss. The final design utilizes a lateral ground only layout, i.e., a ground wall solution. This allows the performance of the balun to be optimized and improved.

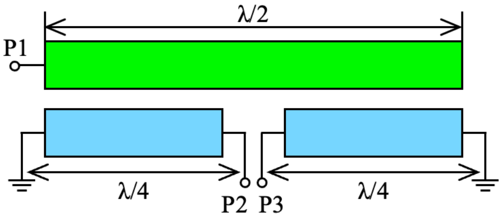


Fig.1. Schematic of Marchand Balun.

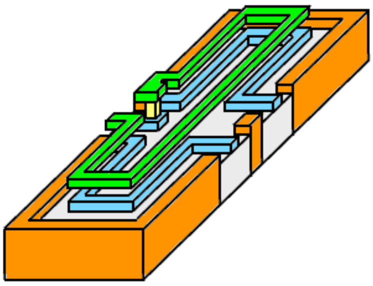


Fig.2. Overall layout of the Marchand balun with lateral ground wall.

2. DESIGN ANALYSIS AND LAYOUT OF MARCHAND BALUN

2.1. DIRECTIONS FOR OPTIMIZING LAYOUT

The main function of a Marchand balun is to convert a single-ended signal to a differential signal, or to synthesize a differential signal into a single-ended signal. This capability is critical to signaling in many high-frequency communication systems. Fig. 1 shows the schematic diagram of a Marchand balun. It consists of a λ/2 long signal line connected to a single-ended signal port and a pair of λ/4 long signal lines connected to a differential signal port. This structure is usually directly laid out as a coupled line in various designs [1] [2].

In [3], a coplanar waveguide type Marchand balun layout scheme is selected by analyzing the coupling coefficient k. The higher the coupling coefficient, the higher the signal transmission efficiency. The higher coupling coefficient of the stacked layout means that the loss of this layout is lower. Due to the design rules of the CMOS process and the characteristics of the metal layers in this paper, no ground wall can be added to the top layer, and it does not make a big difference whether it is added or not. This results in the structure shown in Fig.2.

This study aimed to improve performance by removing as much ground as possible. Signal line width is constant, the characteristic impedance will increase; to match a given reference impedance, as in the Marchand balun, the line width is increased and the characteristic impedance is decreased. This means that the signal line loss is reduced. If the bottom ground is removed, the silicon and the signal line will be coupled, and there is concern about the effect of the lossy silicon. However, in silicon substrates without channel doping, the loss is not so large and in many cases is not a concern. Also, having periphery ground wall only should concern about coupling between opposing coupled lines. But if the two are separated enough, the coupling will be negligibly small.

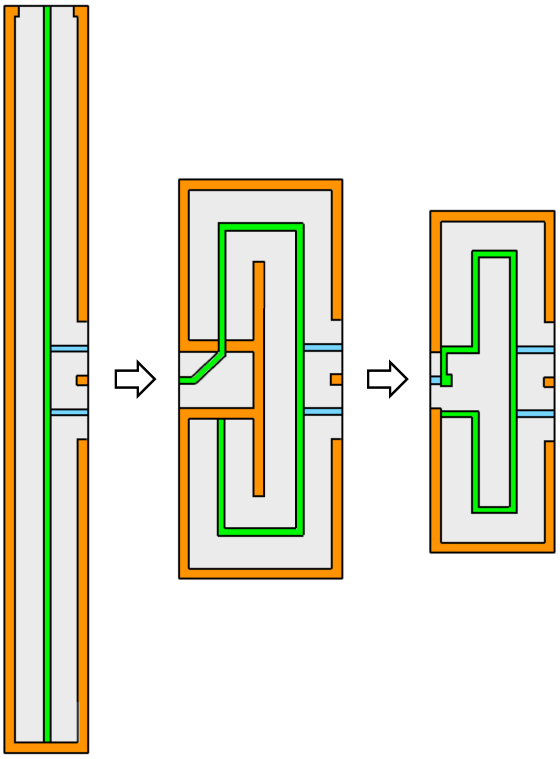
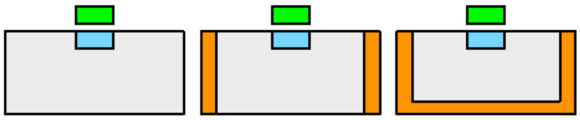


Fig.3. Area reduction from folding signal lines and optimizing grounding layout.



(a) (b) (c)

Fig.4. Cross-section of grounding layouts (a) without grounding layout (b) with ground wall (c) with ground wall and bottom ground plate.

As shown in Fig.3, by bending the Marchand balun, the narrow shape can be transformed into a rectangle with a smaller aspect ratio. Deleting the ground wall on the inside of the structure is not affected by the surrounding layout since the entire area is covered by the ground wall.

2.2. COMPARISON OF GROUNDING LAYOUTS

Fig.4 shows three balun layouts, where the main difference between (b) and (c) is whether or not to add a bottom ground plate. EM field simulations are performed for the 275 GHz center-frequency balun using Fig.4(a) and (b) grounding layouts, respectively. And connect the simulation circuit as shown in Fig.5 (De-embedding technique [4] has been applied.) to measure the S-parameters of Port 1 and Port 2. The results are shown in Fig.6. It can be clearly concluded that there is little difference in the effect of whether the lateral ground wall is laid out on the loss of transmission. The minimum value of reflection coefficient still > -20dB is not very good, and the placement of a ground wall can optimize this performance. The S11 and S22 will be about 5 dB lower when placing a ground wall.

Subsequently, the differences in S-parameters due to the grounding layout of Fig.4(b) and (c) are compared. To see the differences more clearly Fig.7 only shows the S21 parameters. The conclusion is that if the ground plate is laid out at the bottom layer it will increase the transmission loss of the balun. The lower the frequency the more significant the increase. At 275 GHz the increase is about 0.14 dB.

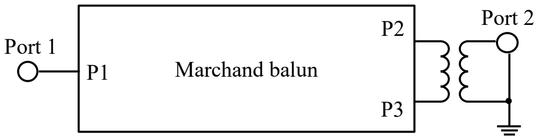


Fig.5. Schematic of simulation for balun.

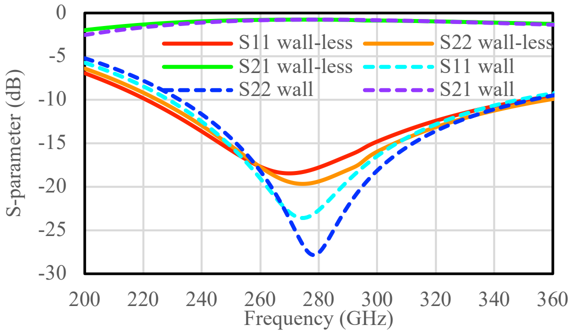


Fig.6. Comparison of S-parameter with ground wall (Fig.4(b)) and ground wall-less (Fig.4(a)) balun layout.

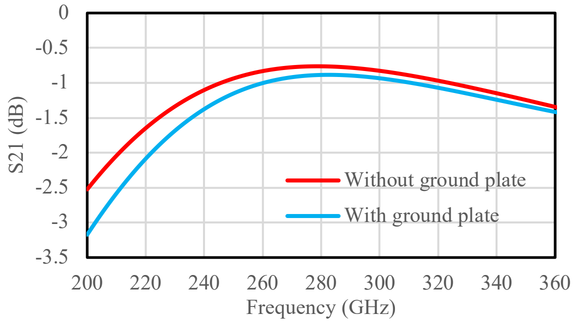


Fig.7. Comparison of baluns' S21 parameter with (Fig.4(c)) and without ground plate (Fig.4(b)).

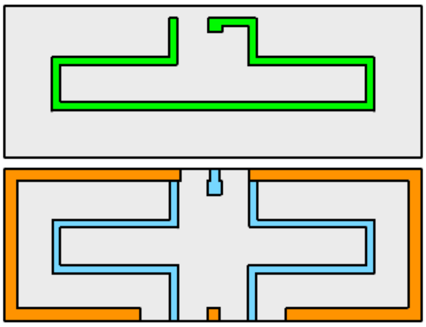


Fig.8. Top-down top layer layout and second layer layout.

3. LAYOUT AND SIMULATION

3.1. LAYOUT PARAMETERS FOR MARCHAND BALUN

The final layout adopts the new scheme of only laying out the lateral ground wall without placing the ground plate. The length is 111 µm, the width is 40 µm. The signal line width of the top and second layers is 2 µm (Using the same CMOS process as [3], this article demonstrates that this width provides the best performance for connecting a 50Ω CPW transmission line.). The ground wall is 3 µm wide and is laid out on the side from the second layer to the bottom layer. The specific layout of the first and second layers as viewed from above is shown in Fig.8, and the signal lines between the two layers are connected by the Via shown in the yellow part of Fig.2.

3.2. SIMULATION RESULTS

The results obtained from the EM field simulation of the design mentioned in the previous section are analyzed. Firstly, attention is paid to the differential signal ports P2, P3 mentioned in Fig.1.When it is input by P1, the phase output results of P2 and P3 are shown in Fig.9; the transmission coefficient output results are shown in Fig.10.

Calculate the phase imbalance [5] which is defined as

$$Phase\ Imbalance = abs(\angle P2 - \angle P3 - 180°). \qquad (1)$$

The calculation yields the phase imbalance < 4.68° up to 370 GHz. Where at 275 GHz the phase imbalance is 2.56°.

In addition, the amplitude imbalance is defined as

$$Amplitude\ Imbalance = abs(S21 - S31), \qquad (2)$$

where the $S21$ and $S31$ parameters are in dB. From the calculations, the amplitude imbalance is below 0.83 dB in the operating range. The imbalance value is 0.24 dB at 275 GHz.

Return to the analyzed circuit shown in Fig.5 to extract the results of the layout lateral ground wall in Fig.6 is shown in Fig.11. The reflection coefficients of the single-ended and differential ports at 275 GHz are -23.58 dB and -26.91 dB, respectively, and the insertion loss is -0.76 dB.

The proposed design is characterized by an extremely wide bandwidth. according to Fig.11, the 3dB compression point of this Marchand balun is at 180 GHz, and the higher frequency part has not yet reached the 3dB compression point in the simulation range of 500 GHz. However, based on the center frequency is 275 GHz, the 3dB bandwidth is taken to be 180~370 GHz, and the bandwidth is as wide as 190 GHz. Also concerned with the reflection coefficient of the port, the recommended operating frequency for this design is 230~350 GHz. the ports' reflection coefficients of proposed balun are less

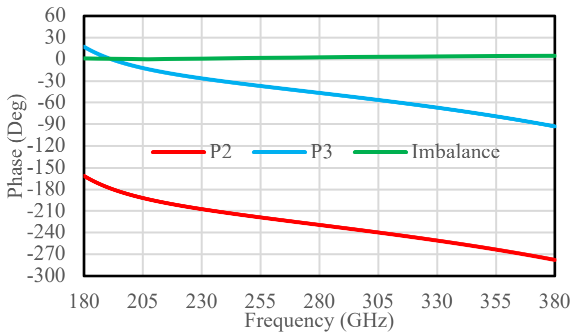


Fig.9. Simulated phase and phase imbalance results for the proposed balun.

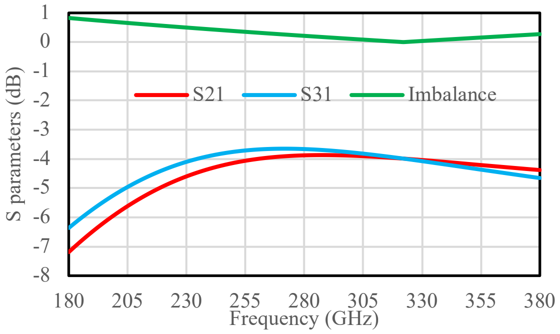


Fig.10. Simulated transmission coefficients and amplitude imbalance results for the proposed balun.

Table.1. Comparison of Balun Performance in Millimeter-Wave Band

Reference	Insertion loss (dB)$^{1)}$	Bandwidth (GHz)	Pha. /Amp. Imbalance (°/dB)	Area (mm^2)
[6]2019	1.75	110~170	< 7/ < 0.8	0.01
[3]2020	2.0	110~156	< 3/< 1.4	0.014
[7]2021	1.4	220~262 220~330(3dB)	< 5(220~262 GHz)/< 1.3 < 12(220~330 GHz)/< 1.3	0.008
This work	0.76	230~350 180~370(3dB)	< 4.36/< 0.50(230~350 GHz) < 4.68/< 0.83(180~370 GHz)	0.004

1) Excluding the ideal 3 dB insertion loss due to power division.

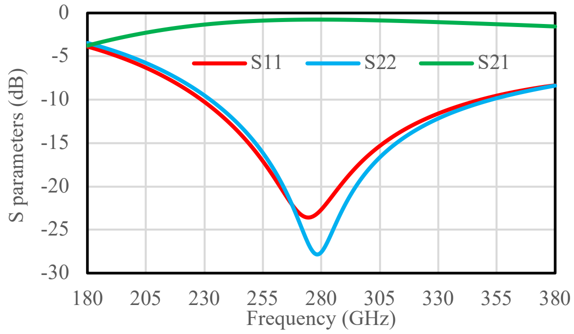


Fig.11. S-parameters of the proposed balun.

than -10 dB in this range.

Table.1 lists the performance parameters of some recent Marchand baluns above 100 GHz using high-precision processes. Because the metal layer of the signal line is thicker with this CMOS process, the loss in transmission is significantly reduced. Compared with other Marchand baluns of similar bands in the literature, the proposed Marchand balun achieves an unprecedented 3dB bandwidth while guaranteeing a low phase/amplitude imbalance, and the layout area is minimized.

4. CONCLUSION

In this paper, a small size Marchand balun using lateral ground wall is proposed by optimizing the grounding layout. It has low loss, low phase amplitude imbalance, and extremely wide bandwidth. The proposed Marchand balun has a 3dB bandwidth of 190 GHz (with a center frequency of 275 GHz), an insertion loss of 0.76 dB, phase imbalance of less than 4.68° and amplitude imbalance of less than 0.83 dB. The area of the layout is 0.004 mm^2. Comparison of the simulation results reveals that, under high-precision process conditions at frequencies higher than 100 GHz. It is concluded that the proposed balun employs a smaller area but has the widest 3dB bandwidth and the smallest insertion loss.

ACKNOWLEDGEMENT

This research work was financially supported by the Ministry of Internal Affairs and Communications of Japan with a scheme of “Research and Development for Expansion of Radio Wave Resources” (JPJ000254).

References

[1] L. Xu, Z. Wang and Q. Li, “A novel model for a planar wideband Marchand balun,” *Journal of Semiconductors*32.11: 115010, 2011.

[2] J. Li, K. Liu and T. Li, “A planar Marchand balun for wideband performance,” *Microwave and Optical Technology Letters*, Volume64, Issue1, pp. 42-46, Jan, 2022.

[3] H. Sakai, K. Takano and Y. Umeda, “A 135 GHz CMOS Marchand Balun with Ground Sheilds,” 2020 IEEE Asia-Pacific Microwave Conference (APMC), Hong Kong, pp. 531-533, Dec, 2020.

[4] K. Katayama, S. Amakawa, K. Takano and M. Fujishima, “300-GHz MOSFET model extracted by an accurate cold-bias de-embedding technique,” 2015 IEEE MTT-S International Microwave Symposium, Phoenix, AZ, USA, pp. 1-4, May, 2015.

[5] J. Yan, H. Liu, X. Zhu, K. Men and K. Yeo, “Ka-Band Marchand Balun with Edge- and Broadside-Coupled Hybrid Configuration,” *Electronics* 9, no. 7: 1116, 2020.

[6] A.-M. Schrotz, T. Maiwald, K. Kolb, S. Breun, M. Dietz, A. Hagelaueret al., “Design Methodology for Automatically Designed, Integrated Marchand Baluns with Low Insertion Loss at Lowest Phase Imbalance,” 2019 IEEE Asia-Pacific Microwave Conference (APMC), Singapore, pp. 771-773, Dec, 2019.

[7] H. Sakai, K. Takano, S. Hara, A. Kasamatsu and Y. Umeda, “A 220–330 GHz Wideband, Low-Loss and Small Marchand Balun with Ground Shields in SiGe BiCMOS Technology,” 2021 IEEE MTT-S International Microwave and RF Conference (IMARC), Kanpur, India, pp. 1-4, Dec, 2021.