Design of Planar Wideband Balun Model

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Abstract. In order to meet the practical requirements of the balun structure while improving the output balance and isolation, an improved planar broadband balun model was designed based on Marchand balun. Aiming at the situation that the phase transition speed of the two output terminals is not synchronized due to the input transient transmission of the microstrip line, the method of compensating the microstrip line by loading the ground short-circuit ends of the two couplers is used to adjust the phase speed to synchronization and thereby improve the output balance. At the same time, a single-layer planar structure is used to reduce the volume of the balun structure, and isolation circuits are introduced at the input and output ends to optimize the isolation. Simulation verification based on the model showed that the minimum isolation at the working frequency of 2.969GHz -3.702GHz was reduced to -24.53dB, and the phase imbalance at the output fluctuated between+0.32 °and -0.99 °, and the amplitude unbalance degree does not exceed 0.08 db. The balance does not exceed -0.08dB. Both output balance and isolation have been significantly improved.

1. Introduction
Balun is a three-port network, which is mainly used to convert single-ended unbalanced signals into two balanced differential signals with equal amplitude and 180 ° phase difference [1]. It is widely used in radio frequency microwave circuits, antenna feeding systems, balanced mixers, push-pull amplifiers, filter circuits, and even radio frequency integrated circuits (RFICs) [2-3]. In recent years, scholars in the field of radio frequency and microwave science have done a lot of research work, dedicated to the optimization of performance parameters such as the expansion of the balun operating frequency band, the balance of the output signal, and the reduction of the layout size.

Marchand Balun has become a research hotspot due to its simple structure and good performance. Output balance and isolation are necessary guarantees for achieving good balun performance, and the size of the circuit structure is also an important factor in practical applications. In order to meet the requirements of practicability, in order to achieve a good balance of the isolation characteristics and transmission characteristics of the port at the same time, many scholars have designed the balun structure model. Antoniades, M.A. combined a composite left and right-handed transmission line to produce a new type of broadband planar balun, which maintains good phase characteristics within 77% of the working bandwidth [4]. Literature [5] uses a complementary transmission line to improve the iso-
lation of the balun structure circuit below -15dB, but the transition transmission line will cause the phase speed of the two output signals to be asynchronous, and reduce the balance of the output. Yu Zhongwu designed a broadband planar balun based on the Wilkinson power splitter and the broadband 180° phase shifter, which achieved a phase imbalance of less than 2.8° in the 2.16–6.04GHz frequency band. In the 1.13–6.01GHz frequency band, the amplitude imbalance is less than 0.6dB. However, a 3-section Wilkinson power splitter is used as the output port, which increases the size of the circuit [6].

This paper proposes an improved balun structure that refers to Marchand balun. According to the original layout requirements in the layout, a section of transmission line is loaded between the two input band lines of the coupler to ensure that the balun structure can work normally. In this structure, the original part of the aggregated parameters with phase speed compensation function that needs to be loaded is replaced by a microstrip transmission line, which is closer to the actual demand. At the same time, the structure is a single-layer planar type, which is easier to implement in full-wave simulation and even actual processing. This article establishes and analyzes the basic Marchand Barron's lumped parameter equivalent circuit model, determines the physical structure parameters of the coupling line, and designs and optimizes its compensation, isolation, and other structures [7].

2. Marchand Barron Basic Structure Analysis

The basic Marchand balun is shown in Figure 1. It consists of two sets of coupling strip lines with a length corresponding to the center frequency corresponding to the quarter wavelength (\(\lambda_c/4\)). The output strip line of each group is grounded at one end and connected to the load that needs to be fed. The characteristic impedance and coupling coefficient of the coupled microstrip line are \(Z_0\) and \(k\), port p1 is an unbalanced signal input terminal, and the input impedance is \(Z_s\); port p2 and port p3 are balanced signal output ports, and are connected to a load with impedance \(Z_L\) [8].

Using the scattering parameter matrix method to analyze the model, we can get the conditions that Balun needs to achieve the ideal function, namely: \(s_{11} = 0\) and \(s_{21} = -s_{31}\) [9]. It is known that when the electrical length \(\theta = \pi/2\), that is, \(l = \lambda_c/4\), the balun scattering parameter matrix with the same load at the input and output ends is shown in equation (1):

\[
\begin{bmatrix}
1 - 3k^2 & j2k\sqrt{1-k^2} & 1 + k^2 \\
1 + k^2 & 1 - k^2 & 2k^2 \\
j2k\sqrt{1-k^2} & 2k^2 & 1 + k^2 \\
1 + k^2 & 1 + k^2 & 1 + k^2
\end{bmatrix}
\]

(1)

When the load impedance \(Z_L\) and the input impedance \(Z_s\) in the model are not equal, the entire s-parameter matrix can be rewritten by Equation (2):

\[
[s]' = [A]^{-1}([s] - [\Gamma])([I] - [\Gamma][s])^{-1}[A]^*
\]

(2)

From the above, it can be obtained that when the input and output ends of the balun model are loaded with different loads, the balun s parameter matrix is as shown in equation (3):
According to \( s_{11} = 0 \), one of Balun's working conditions, the expression (4) of the coupling coefficient \( k \) can be derived:

\[
k = \frac{1}{\sqrt{\frac{2Z_l}{Z_s} + 1}}
\]

Reference [1] proposed a new design equation for the coupler based on the Y-parameter matrix analysis method. According to this equation, the even and odd mode impedances \( Z_{even} \) and \( Z_{odd} \) can be related to the input and load impedances. The new coupling line design equations are as follows (5a) and (5b):

\[
\begin{align*}
Z_{even} &= \frac{k}{1-k} \sqrt{2Z_lZ_s} \quad (5a) \\
Z_{odd} &= \frac{k}{1+k} \sqrt{2Z_lZ_s} \quad (5b)
\end{align*}
\]

When the coupling coefficient and the load impedance at the input and output satisfy Equation (4), this model can theoretically achieve functions such as power equalization and impedance transformation [10]. Using equations (4) and (5), the impedance and size parameters of the coupled microstrip line parity model in the model can be calculated from the input and output load.

3. Transition Transmission Line

3.1. Distributed parameter model of transmission line

Based on the above theoretical analysis, this paper constructs a Marchand Barron model structure. The structure model is intended to be etched on a 1.5 mm thick substrate with a dielectric constant \( \varepsilon_r = 4.4 \), and has the advantages of miniaturization in the plane, simple structure, good output balance, and operating frequency bandwidth. This structure sequentially introduces the input signal from the characteristic impedance \( \Omega = 50 \Omega \) signal source into two sets of coupling structures, and outputs it to a \( 150 \Omega \) load through impedance transformation, coupling, and phase shift.

Due to actual space constraints, a transition transmission line is generally required to be loaded between the input ends of the two sets of coupling lines. However, the electrical length \( x \) of the transition transmission line will cause a shift in the center frequency and a decrease in the balance of the output end. At the same time, its width \( w \) will also affect parameters such as return loss bandwidth and insertion loss. Therefore, the transition line parameters need to be reasonably selected [11]. Figure 2 shows the Marchand Balun structure loaded with the transition transmission line, and its distribution parameters have been marked in the figure.

![Figure 2 Distribution parameters of the balun with interim segment](image-url)
Where $l_c$ and $l_{\text{line}}$ are the length of the coupling line and the transition section, $Z_0$ is the characteristic impedance of the coupling line, $C_{11}, C_{22}, L_{11}$ and $L_{22}$ represent the distributed capacitance and distributed inductance of the unit length of the coupling line itself, and $C_m$ and $L_m$ are unit length coupling lines Mutual capacitance and mutual inductance, in the same way $C_T$ and $L_T$ are the distribution parameters of the unit length transition transmission line. The above parameters satisfy the following equations (6):

$$C_{11} = C_{22} = \frac{1}{\sqrt{v^2 Z_0^2 (1 - k^2)}} \quad (6a)$$

$$L_{11} = L_{22} = \frac{C_{11}}{(C_{11}^2 - C_m^2)v^2} \quad (6b)$$

$$C_m = kC_{11} \quad (6c)$$

$$L_m = kL_{11} \quad (6d)$$

$$C_T = \frac{1}{v Z_0} \quad (6e)$$

$$L_T = \frac{1}{v C_T} \quad (6f)$$

The transition transmission line is divided into two parts, which are equivalent to two sets of virtual coupling lines, as shown in Figure 3:

![Figure 3 Equivalent distribution parameters of the interim segment](image)

Where, $C_{11}^d = C_{22}^d = C_T$, $L_{11}^d = L_{22}^d = L_T$, $C_m^d = kC_T$, $L_m^d = kL_T$, and the coupling factor $k$ of the virtual coupling line generated by the equivalent is consistent with the $k$ value of the original coupling line. $C_{11}^d$ and $L_{11}^d$ represent the distributed capacitance and inductance of the transition transmission line itself. $C_{22}^d$, $L_{22}^d$, $C_m^d$ and $L_m^d$ are compensation parameters set for the equivalent virtual coupling line [12]. The length of the original coupler needs to be shortened to the expression (7) due to the incorporation of the virtual coupler:

$$l_c^d = l_c - \frac{l_c C_{11}^d}{2 C_{11}^d} \quad (7)$$

The distribution parameters corresponding to the unit length of the model obtained according to the above equation are shown in Table 1:

| Table 1. Unit Length Distribution Parameter Value |
|-----------------------------------------------|
| $C_{11} = C_{22}$ | $C_m$ | $C_T$ |
| 88.32 pF/m | 17.67 pF/m | 86.54 pF/m |
| $L_{11} = L_{22}$ | $L_m$ | $L_T$ |
| 131.1 nH/m | 26.22 nH/m | 128.4 nH/m |

According to the design equation (5) of the coupled microstrip line, the odd and even model impedances of the coupled line are calculated as $Z_{\text{even}} = 52.5 \Omega$ and $Z_{\text{odd}} = 28.26 \Omega$, and the characteristic impedance of the coupler is $Z_0 = 38.52 \Omega$. Then the width and length of the coupled parameter and the gap of the coupled line are obtained. The initial values are $w = 5.13$ mm, $l_c = 14.98$ mm, and $g = 0.13$ mm. Corresponding to the electrical length $\theta_T$ of the different transition transmission lines by bringing the above parameters into equation (7), the adjusted coupling microstrip line length (center frequency 3.5 GHz) can be adjusted as shown in Table 2:
3.2. Parameter optimization of transition transmission line

According to the analysis in Section 3.1, the schematic diagram is established in the ADS full-wave electromagnetic simulation software and the s-parameter scanning is performed. The results are shown in Figure 4 below:

Figure 4 Simulation results of $s_{11}$ and $s_{32}$ correspond to different $\theta_r$

It can be inferred from the graph that as the electrical length of the transition transmission line increases, the available bandwidth of the return loss increases first and then decreases, and the dive depth gradually decreases, with the maximum value appearing between $15^\circ$ and $30^\circ$; The magnitude of the amplitude does not change significantly, but like the return loss, the center frequency shifts toward high frequencies as the electrical length increases [13]. The trade-off of various parameters is to choose $\theta_r = 24.35^\circ$.

Another problem caused by the addition of the transition transmission line is the offset of the center frequency. Although the coupler length can be adjusted using equation (7), its effect is limited. The structure is also not conducive to the reasonable layout of devices and strip lines [14]. Therefore, as shown in Figure 5, a short-circuit strip line of length $\theta_a$ is connected in series at the two isolated ends of the coupler as compensation measures for the transition transmission line.

Figure 5 Structure with short-circuited compensation lines

The relationship between $\theta_a$ and the coupling line length $\theta_c$ and the transition transmission line length $\theta_r$ satisfies the following equation (8):

Table 2. The Length of the Original Coupling Line Corresponding to Different $\theta_r$ (mm)

| $\theta_r$ | 15°  | 30°  | 45°  |
|-----------|------|------|------|
| $l'_c$    | 13.78°| 12.59°| 11.39°|
\[
\cot \theta_a = \frac{\tan \theta}{\sqrt{1-k^2}} \quad (8a) \\
\theta_c = \sin^{-1} \sqrt{\frac{1-k^2}{2k^2}} \quad (8b) \\
\theta_i = 2\theta_a \quad (8c)
\]

It is calculated that when the length \( l_a \) of the compensation short-circuit line is about 1.69 mm, the center frequency of the balun structure returns to about 3.5 GHz as shown in Figure 5, and the length of the coupling line is 11.12 mm at this time.

4. Isolation Circuit

4.1. Input isolation resistance

Due to the unnecessary coupling between two parallel output and input ports, the isolation is reduced, and at the same time the available bandwidth of the return loss \( X \) is narrowed. Therefore, the introduction of isolated circuits (IC) or components (ICs) also needs to be considered in the design. In this paper, a Y-resistor is connected in parallel at the beginning and end of the signal input coupling strip line as an integral part of the isolation circuit. The effective working frequency band of \( Z \) has been effectively expanded, and the isolation \( W \) has also been optimized slightly. As shown in Figure 6:

![Figure 6 Comparison of shunted resistors and non-resistors](image)

4.2. Output isolation circuit

It is known from Figure 6 that although the effective bandwidth of the parameter has been greatly expanded after loading the resistor at the input, the isolation \( S_{32} \), which is the main optimization target, is still not ideal. Therefore, although it will slightly affect the overall \( S_{11}, S_{21} \) and other parameters, loading an isolation circuit between the two output terminals has a significant effect on improving the degree of isolation [15]. Based on the characteristics of Marchand Balun, the output signals of the two sets of couplers will have phase delays of -90° and 90°. In order not to impair other performance, this article chooses a strip line with an electrical length of 180° and a characteristic impedance of \( Z_i \). It is connected in series with two resistors \( R_i \) and is incorporated between the two output terminals of the structure, as shown in Figure 7:

![Figure 7 Structure of isolation circuit](image)

Among them, \( R_i \) is about twice of \( Z_i \). In this article, \( Z_i = 158 \Omega \) is selected, then \( R_i = 223 \Omega \).

The frequency response comparison of the isolation degree \( S_{32} \) with and without the isolation circuit is shown in Figure 8(a):
It is obvious from the above figure that after loading the isolation circuit, the $S_{32}$ parameters of the balun structure have been significantly optimized, from the original approach of -10dB to below -15dB, verifying the effectiveness of the structure.

In order to obtain a higher degree of isolation at the output, while ensuring the continuity between the isolation circuit and the output of the balun structure, this article divides the $\theta_i = 180^\circ$ transmission line in the IC structure into two $\theta_i = 90^\circ$ transmission lines, and the two resistors $R_i$ connected in series at both ends of the isolation circuit are merged into $R_{ic}$ and connected in parallel between the split transmission line and ground. $R_{ic} = Z_i^2 / R_i = 56\Omega$ after the structural adjustment. Simulation verification of the isolation degree $S_{32}$ of this improved IC structure is shown in Figure 8(b): the $S_{32}$ parameter is reduced from -16dB to about -22dB, and the isolation of the output of the balun structure is further improved.

5. Simulation of the Balun Model

Through the calculation and optimization of the above sections, the balun structure designed in this paper has begun to take shape. While combining and adjusting the above structural model, this article adds several transition and port lead-out structures on the basis of the schematic diagram, zigzags part of the structure and builds a 3D model in HFSS 15.0, as shown in Figure 9:

In the schematic diagram, p1 is an unbalanced input terminal, and p2 and p3 are balanced output terminals. Since the bending of the microstrip line and the change of the spatial position may affect the balun performance [16], based on the parameters obtained earlier, this section fine-tunes some of the structure and the original parameters, which are obtained in Ansys HFSS. The simulation results are shown in Figure 10:
As can be seen from the above figure, in the range of 2.969GHz-3.702GHz: the return loss \( s_{11} \leq -10\text{dB} \), the relative bandwidth is 21.98%, and the isolation \( s_{32} \leq -18.82\text{dB} \) is reduced to -24.53dB, which shows that the output isolation is good; The output phase imbalance fluctuates between \( +0.32^\circ \) and \(-0.99^\circ \), and the amplitude imbalance does not exceed -0.08dB.

6. Conclusion
In this paper, a wideband balun model based on Marchand balun is constructed by analyzing the parity parameter distribution model of the coupler and the Marchand balun scattering matrix and combining the balun working conditions. The model calculates the distribution parameters of the ground short-circuit compensation strip line at the output end for the unbalanced input end of the Marchand Balun structure connected to the transitional microstrip transmission line. Based on this parameter, the physical parameters of the compensation section are designed and simulated. The loss bandwidth has been significantly expanded and the isolation has also improved slightly. Based on operating conditions, the signals obtained by all balun structures at the output must have a high degree of phase and amplitude balance, that is, the phase difference is equal to 180°; in order to achieve this indicator, in addition to the load short circuit mentioned above In addition to the compensation section, this article also introduces an isolation structure at the input and output ends, respectively. The addition of the isolation resistance at the input end extends the bandwidth of the balun; and the isolation circuit at the output makes the isolation of the balun structure less than -10dB Increase to about -20dB. The model has the characteristics of operating frequency bandwidth, small size and easy construction, and high output signal balance.

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