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Modeling and design of millimeter-wave Marchand balun based on three-conductor coupled line

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Abstract: A novel broadband circuit model for millimeter-wave Marchand balun using three-conductor coupled line was proposed. Based on the c-mode and π-mode theory, the three-conductor coupled line was analyzed and modeled by the transmission line and several ideal transformers. The model parameters are extracted from the electromagnetic simulation and then the coupled line model is utilized to build the model of the Marchand balun. Using the proposed model, a millimeter-wave Marchand balun was designed and fabricated in GaAs process. The balun works at the frequency range from 15 GHz to 55 GHz, the measurement results show that the balun has good amplitude and phase imbalance performance and verify the model as well.

Key words: millimeter-wave, Marchand balun, model, three-conductor coupled line

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基于三导体耦合线的毫米波 Marchand balun 建模与设计

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摘要:提出了一种基于三导体耦合线结构的毫米波 Marchand 巴伦的新型宽带模型.基于 c 模和 π 模理论,对三导体耦合线进行了分析并采用传输线和理想变压器对其建立了模型.通过电磁场仿真提取了模型参数并使用该耦合线模型建立了 Marchand 巴伦的模型.基于该模型,使用 GaAs 工艺设计了一种毫米波 Marchand 巴伦并进行了流片制造,所设计的巴伦工作在 15 ~ 55 GHz 频率范围,测试结果表明该巴伦具有较好的幅值和相位平衡度,同时验证了模型的准确性.

关 键 词:毫米波;Marchand 巴伦;模型;三导体耦合线

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Introduction

As an imbalanced to balanced component, balun plays an important role in the balanced circuits to improve the performance of the wireless communication system. Transformer type balun and Marchand type balun are two most popular baluns which are always used in mixer, low noise amplifier, power amplifier and etc. While Marchand Balun is widely used in the microwave and millimeter-wave applications due to its good bandwidth performance and simple structure[1].

The insertion loss, amplitude balance and phase balance are main performances of the Marchand balun that we are concerned. Many researches have been done on Marchand balun. In millimeter-wave design, the amplitude and phase compensation methods were proposed for the Marchand balun which can improve the amplitude and phase balance effectively[2-4]. To reduce the loss, two low loss Marchand baluns that fabricated on the special substrate were proposed[5-6]. However, most of the Marchand baluns are based on the coupled lines with two conductors, only a few Marchand baluns with three-conductor coupled line have been studied in brief without modeling[7].

Compared with two conductors, the coupled line u-

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sing three conductors is more symmetric and has a tight coupling structure, which can reduce the loss and improve the balance for Marchand balun as well. In this paper, we proposed a scalable model for Marchand balun with three-conductor coupled line, then the model parameters were analyzed and extracted by electromagnetic tool. Using this model, a millimeter-wave Marchand balun with three-conductor coupled line was designed and fabricated in GaAs technology. The modeling and design process is described in detail in the following sections.

1 Balun modeling

The Marchand balun consists of two coupled lines and the structure is shown in Fig. 1. Each coupled line is the quarter-wave length of the signal. To build the model of the Marchand balun, the coupled line should be modeled in the first step.

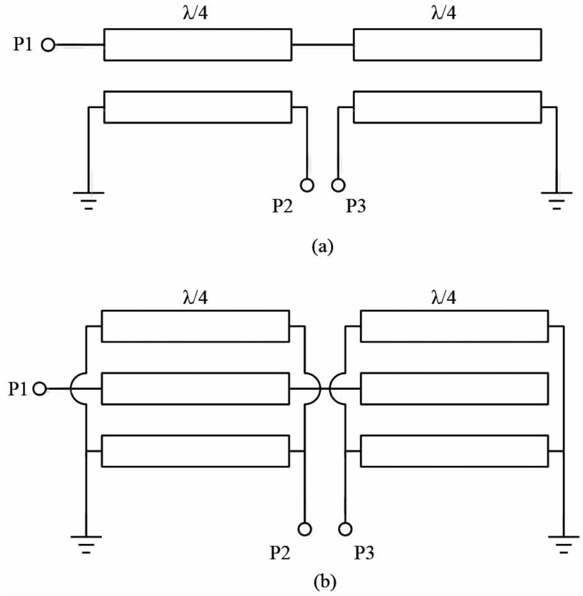

Fig. 1 The structure of the Marchand balun. (a) Marchand balun with two-conductor coupled line, (b) Marchand balun with three-conductor coupled line
图 1 Marchand 巴伦结构(a)二导体耦合线的 Marchand 巴伦,(b)三导体耦合线的 Marchand 巴伦

1.1 Three conductor coupled line modeling

For two-conductor coupled line shown in Fig. 1 (a), even and odd-mode analysis can be applied to extract the characteristic impedance and propagation constants if both conductors have identical width. However, this method can't be used here because three-conductor coupled line is not symmetric. Using GaAs process as an example, its layout is shown in Fig. 2.

The middle conductor is the primary side of the coupled line and two other conductors are connected by the air bridge at the end of the line to form the secondly side. To investigate this asymmetric three-conductor coupled line, the c and π-mode analyses are adopted to build the model.

In this model, the c-mode and π-mode have different propagation constants, γ_c, γ_π and characteristic impedances, Z_{c1}, Z_{c2}, $Z_{\pi1}$, $Z_{\pi2}$, as shown in Fig. 3(a).

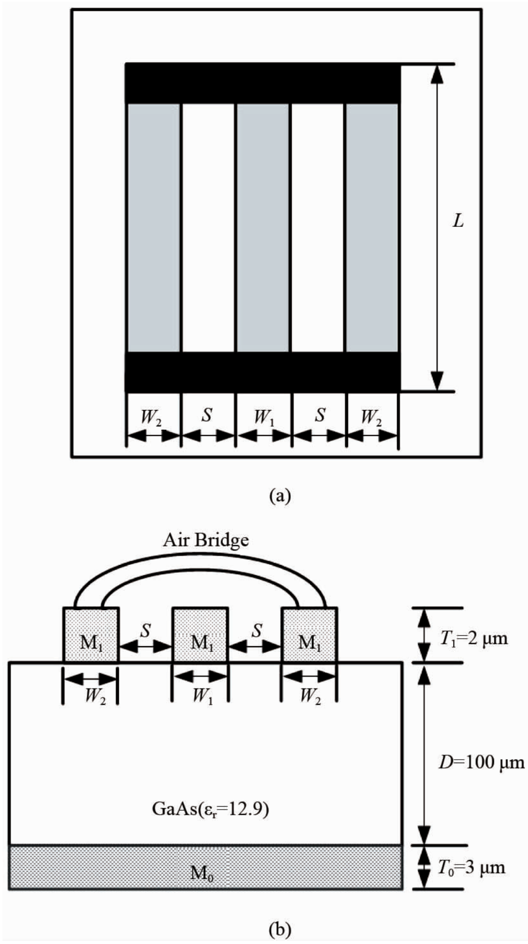

Fig. 2 Three-conductor coupled line. (a) Unit cell, (b) Cross-sectional view of the 0.15μm GaAs process
图 2 三导体耦合线结构(a)单元结构,(b)采用 0.15μm GaAs 工艺的剖面图

The model for the general asymmetric coupled line has been discussed in the literature[8-9]. The three-conductor coupled line can be equivalent to an asymmetric coupled line because the two outside conductors are connected together. Figure 3(b) shows the network model including the c-mode and π-mode for this coupled line. The transmission line sections of this model use the TLINP4 component in ADS[10]. Because its characteristic impedance is only available for real number, two additional transformers with transformer ratio of T_π(T_c) are serially connected to both sides of the transmission line in order to convert real impedance to complex value. The characteristic impedances for c-mode and π-mode are derived as

$$Z_\pi = \frac{Z_{\pi1}}{1-\dfrac{R_\pi}{R_c}} = Z_\pi^m \cdot T_\pi^2 \quad , \quad (1)$$

$$Z_c = \frac{Z_{c1}}{1-\dfrac{R_c}{R_\pi}} = Z_c^m \cdot T_c^2 \quad , \quad (2)$$

where Z_π and Z_c are real number, T_π and T_c are complex number.

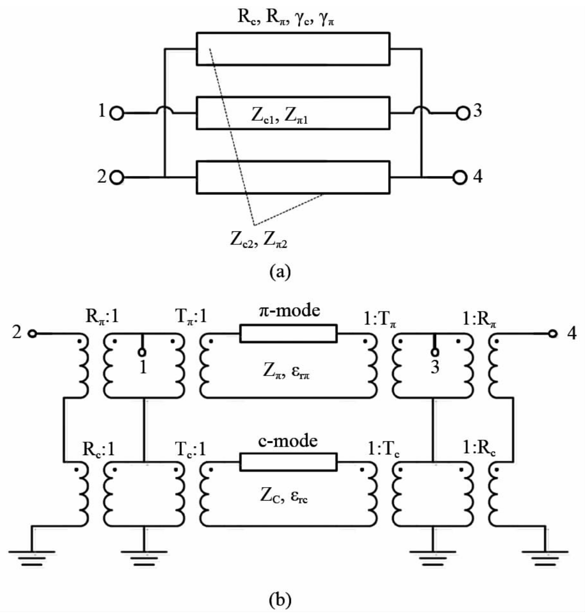

Fig. 3　The model of the three-conductor coupled line. (a) The schematic. (b) The network model
图 3　三导体耦合线模型(a)原理图,(b)网络模型

The π-mode and c-mode relative permittivity of the TLINP4 model are determined as

$$\varepsilon_{r\pi(c)} = \left(\frac{c}{2\pi f}\beta_{\pi(c)}\right)^2 \quad , \quad (3)$$

where β is the wave number with the relation of $\gamma = \alpha + j\beta$, and c is the light velocity in vacuum.

Based on the electromagnetic simulation for the coupled line, the four ports S-parameters can be calculated and used to extract the model parameters Z_c^m, Z_π^m, ε_{rc}, $\varepsilon_{r\pi}$, R_c, R_π, T_c, T_π, γ_π and γ_π. The detailed extracted method is described in Ref. 9. Table 1 shows the extracted model parameters of three-conductor coupled line in GaAs process.

Frequency: 30 GHz. Line dimension: $W_1 = 25$ μm, $W_2 = 25$ μm, $S = 15$μm, $L = 400$ μm.

表 1　三导体耦合线的提取参数
Table 1　Extracted parameters of three-conductor coupled line

Z_{c1}	$50.7+j1.03$	Z_c	$55.9+j0.68$	R_c	$0.173-j0.025$	ε_{rc}	7.7493
Z_{c2}	$-16.28-j5.04$	Z_π	$11.9-j3.75$	R_π	$1.874-j0.128$	$\varepsilon_{r\pi}$	9.9278
$Z_{\pi1}$	$-119.6+j26.1$	Z_c^m	55.9	T_c	$1+j0.0061$	γ_c	$15.5+j1748.2$
$Z_{\pi2}$	$40.15-j0.98$	Z_π^m	12.5	T_π	$0.988-j0.15$	γ_π	$10.8+j1978.7$

To find the frequency range for this model, the extracted model parameters with different frequency were simulated. From the results, we found that these parameters change a little when the frequency increases beyond 10 GHz, so this distributed model can be available in a large frequency range especially for millimeter-wave application. Figure 4 shows the c and π-mode impedance relative dielectric constant of the model with the frequency sweeping.

Using the extracted parameters, the S parameters of the coupled line were simulated by the circuit model and the results show good agreement with the EM simulation.

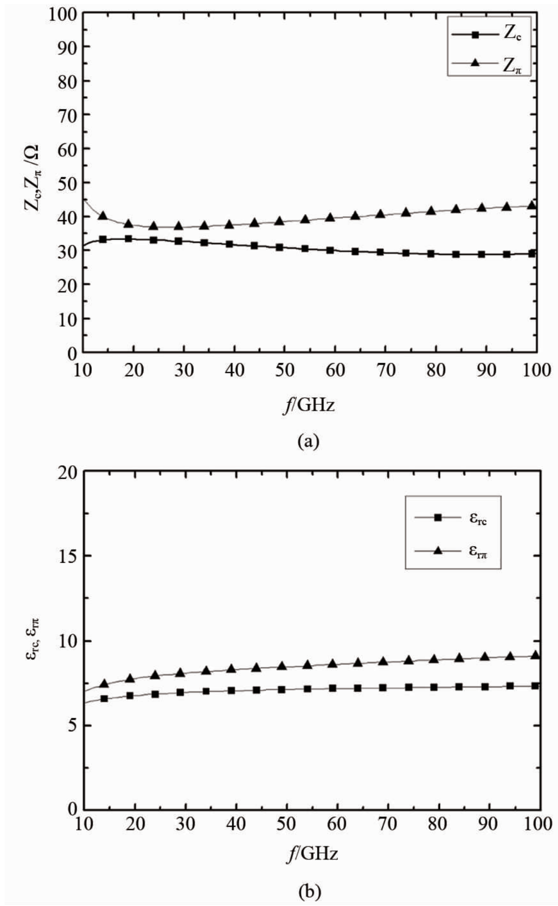

Fig. 4　the parameters of the model for the frequency sweeping ($W_1 = 25$ μm, $W_2 = 10$ μm, $S = 5$μm). (a) c and π-mode impedance vs. frequency, (b) c and π-mode relative dielectric constant vs. frequency
图 4　模型参数随频率变化关系($W_1 = 25$ μm, $W_2 = 10$ μm, $S = 5$μm) (a)c 和 π 模阻抗(b)c 和 π 模相对介电常数

Figure 5 shows the comparison of the S21 from the EM simulation and the circuit model.

1.2　Marchand balun modeling

Based on the circuit model of the coupled line, the Marchand balun can be modeled as shown in Fig. 6. Two quarter-wave coupled lines are connected together to form the Marchand balun. Each coupled line is replaced by the proposed model with one terminal shorting to the ground. The terminal 1 of the first coupled line is used as input port of the balun and the terminal 3 of both coupled lines are connected directly. The terminal 1 of the second coupled line is open-ended and the terminal 4 of both coupled lines are used as the output ports of the balun.

It is worth noting that the proposed model in Fig. 6 has the advantage of the scalability property. Through the simulation, we found that the model parameters of Z_c^m, Z_π^m, ε_{rc}, $\varepsilon_{r\pi}$, R_c, R_π, T_c, and T_π are only depend on the width(W_1, W_2) and space (s) of the coupled line rather than the length (L). Hence, the model of the Marchand balun is scalable to the length. The S21 of the Marchand balun with different length were simulated and shown in Fig. 7.

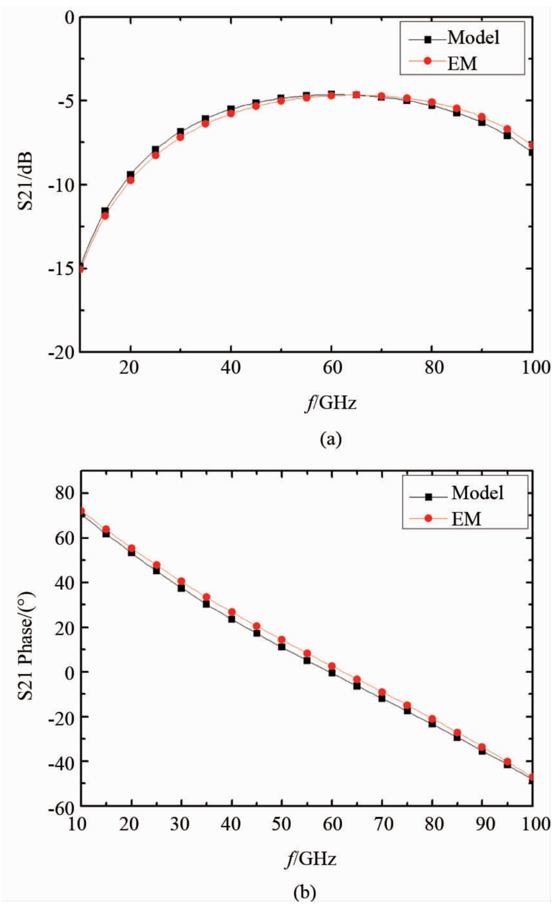

Fig. 5 Modeled and EM simulated S21 comparison of the coupled line(W_1 = 25 μm, W_2 = 10 μm, S = 5 μm). (a) magnitude, (b) phase

图 5 耦合线的 S21 模型与电磁场仿真对比(W_1 = 25 μm, W_2 = 10 μm, S = 5 μm) (a)幅值,(b)相位

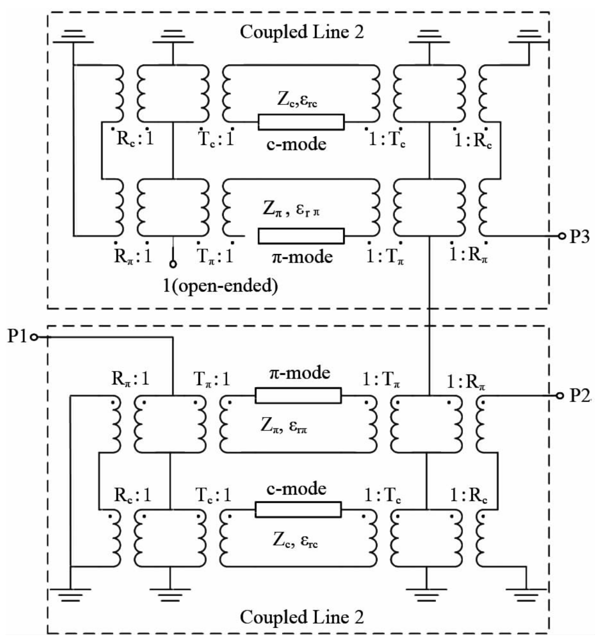

Fig. 6 Model of the Marchand balun

图 6 Marchand 巴伦模型

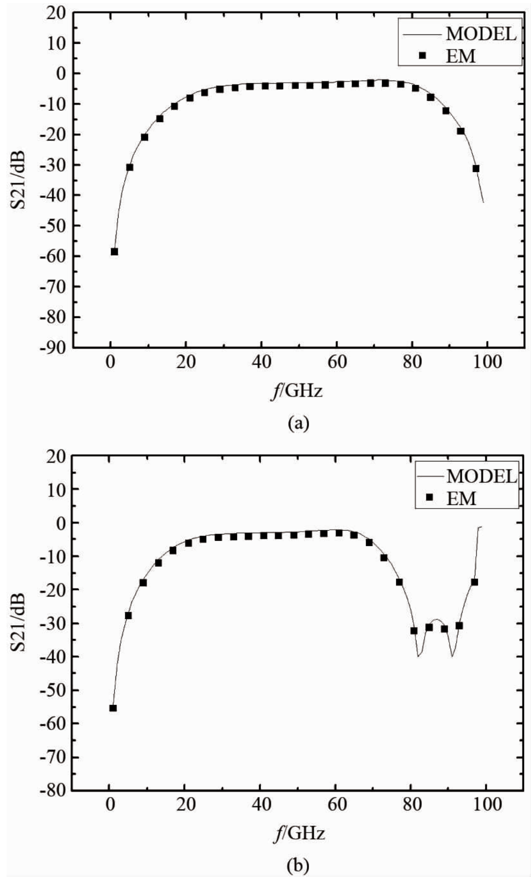

Fig. 7 Modeled and EM simulated S21 comparison of the Marchand balun(W_1 = 25 μm, W_2 = 15 μm, S = 20 μm). (a) L = 500 μm, (b) L = 600 μm

图 7 Marchand 巴伦的 S21 参数模型与电磁场仿真对比(W_1 = 25 μm, W_2 = 15 μm, S = 20 μm). (a) L = 500 μm, (b) L = 600 μm

2 Balun design

To verify the model, a Marchand balun with three-conductor coupled line was designed on 0.15 μm GaAs technology. It consists of two quarter-wavelength synthetic coupled lines which are implemented on top metal layer(M1) with the thickness of 2 μm, and the ground plane is realized by the backside metal(M0) on the back of the GaAs substrate. M1 and M0 are shown in Fig. 2 (b). In this design, the dimensional parameters of the coupled line are W_1 = 8 μm, W_2 = 8 μm, S = 10 μm, L = 700 μm. The balun is simulated based on the proposed model by ADS and the center frequency is 35 GHz. Two grounded terminals of the balun are connected to the backside ground plane by the back-via which goes through the GaAs substrate directly. The fabricated chip photo is shown in Fig. 8.

3 Measurement and analysis

The balun was measured on-wafer through Ground-Signal-Ground(GSG) RF probes with the pitch of 100 μm. The losses of the probes and cables were calibrated by the Agilent E8361A network analyzer in the frequency

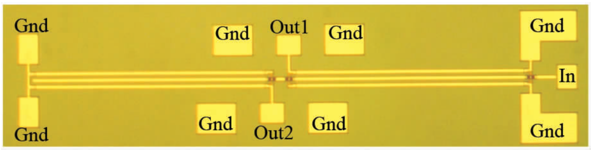

Fig. 8 Chip photo of the balun
图 8 巴伦芯片照片

range from DC to 67 GHz. To eliminate the effects of the pads, three identical pads (In, Out1, Out2) were fabricated and measured additionally for de-embedding. The measured and simulated S-parameters (S21, S31) are both provided in Fig. 9. This balun has a wide bandwidth and operates at the frequency from 15GHz to 55GHz. The S21 and S31 are 4.3dB and 5 dB at the center frequency of 35 GHz, respectively. Because the effects of the back-via is not included in the model which will lead to the additional loss for the balun, the measured S21 and S31 show a slight drop to the simulation. The measured imbalance of the balun is shown in Fig. 10. In the work bandwidth, the amplitude imbalance is less than 1dB and the phase imbalance is less than 2°, which shows a good balance performance in a broad bandwidth. Compared with our previous designed balun[11] with two-conductor coupled line, the proposed balun has better imbalance performance and wider bandwidth due to the three-conductor coupled structure which can provide tight coupling for the balun.

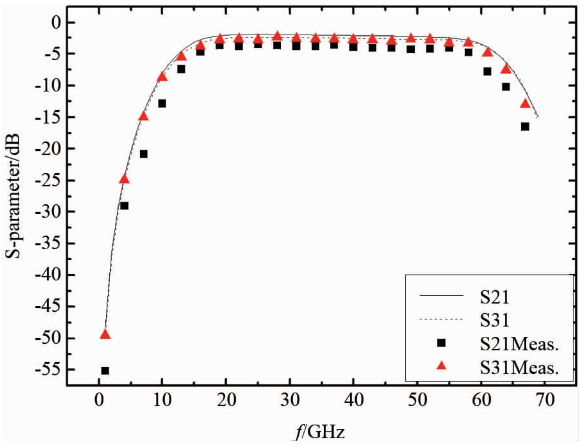

Fig. 9 Measured and simulated S-parameters
图 9 测试与仿真的 S 参数

4 Conclusions

In this paper, the millimeter-wave Marchand balun with three-conductor coupled line was studied. Based on the c-mode and π-mode theory, the three-conductor coupled line was analyzed in detail and an equivalent circuit model was built. A novel model for the Marchand balun was proposed. This model is scalable to the length of the balun and has a good resolution for millimeter-wave design. Using the model, a Marchand balun was designed and fabricated in GaAs process. The measurement results show the balun has better performance than the traditional Marchand balun using two-conductor coupled line.

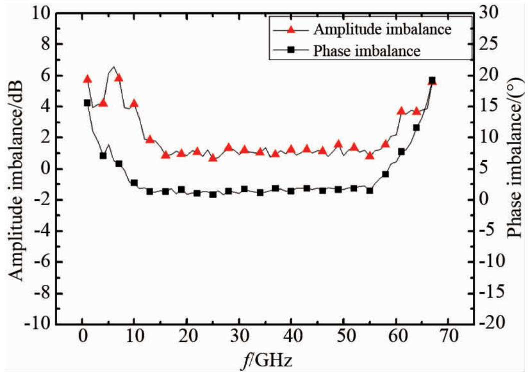

Fig. 10 Measured amplitude and phase imbalance of the balun
图 10 巴伦的幅值与相位不平衡度测试结果

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