Analysis and Design of a 3 dB Tunable Lumped-Element Directional Coupler

Jun Wu and Lu-Yu Wang

Abstract—An analysis of a 3 dB lumped-element directional coupler (LEDC) based on arbitrary terminal impedance is described numerically. To solve the conflicted requirement for broad bandwidth and small size in LEDC, a new structure of coupler is introduced, which can significantly improve bandwidth and whose size is only 3 cm×4 cm on the conditions of the frequency domain of 410 MHz to 490 MHz. The measure results are in good agreement with simulations despite the unexpected resistor loss.

Index Terms—Terminal impedance, bandwidth, lumped-element directional coupler (LEDC), varactor.

doi: 10.3969/j.issn.1674-862X.2010.02.013

1. Introduction

Conventional branch-line directional coupler (BLDC) is widely used as a power divider or power combiner in the circuit of balance mixer, image-rejection mixer, balance amplifier, sensor, etc[1]. The basic element of the BLDC is a quarter-wavelength transmission line that results in large area of the coupler, which limits the application of it, especially in system severely requiring for dimension. Therefore, size-reduction techniques are investigated in many studies. To conquer this shortcoming, the lumped-element design method incorporates in the BLDC[2][5] because fabrication techniques for lumped element have been substantially improved in recent years and the parasitic inductor and capacitance can be neglected, even in the ultra high frequency (UHF) band. Nevertheless, the bandwidth of the lumped-element hybrid is very narrow compared with a distributed constant network. Therefore, efforts to improve the bandwidth are undertaken, which are mainly through three aspects: embedding matching networks[6][7], adopting multistage networks[8][9], and the new structure[10][11].

In this paper, a simple design method that achieves a lumped-element directional coupler (LEDC) is proposed. The commercial microwave simulator is used to analyze the frequency properties of the designed coupler. The bandwidth of the LEDC, however, is only about 4% exhibited from simulation and measure results, which is very narrow compared to a distributed one. To overcome this shortcoming, a novel structure, broadband 3 dB tunable LEDC, is established. As an example, the coupler, on the conditions of the frequency domain of 410 MHz to 490 MHz, is measured and the whole size is only 3 cm×4 cm. It shows an input loss of 25 dB, an isolation of 20 dBc, and the phase difference exactly 90° in whole frequency range of design.

2. Analysis and Measure

2.1 Model of a 3 dB LEDC

The illustration of variable load impedance BLDC is shown in Fig. 1. The basic structure is composed of four quarter-wavelength transmission lines with different characteristic impedances. As well known, the λ/4 transmission line can be equivalent to a π circuit equivalent network. Applying the equivalent network of the transmission line section, the lumped-element equivalent circuit of the variable load impedance BLDC is obtained as shown in Fig. 2 (c).

By applying a matrix formulation, the ABCD-parameters of the λ/4 transmission line and the π circuit equivalent network can be deduced.

Manuscript received 8 September, 2009; revised 28 February, 2010.
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Fig. 2. Lumped-element equivalent circuit of the 3 dB BLDC: (a) λ/4 transmission line, (b) π equivalent circuit, and (c) LEDC.

$$A_L = \begin{bmatrix} 0 & jZ \\ \frac{1}{Z} & 0 \end{bmatrix}$$  \hspace{1cm} (1)

$$A_{LC} = \begin{bmatrix} 1 + \frac{L}{C} & j2\pi f_0 L \\ -j\frac{1}{2\pi f_0 C} \left(2 - \frac{L}{C}\right) & 1 + \frac{L}{C} \end{bmatrix}$$  \hspace{1cm} (2)

where $A_L$ and $A_{LC}$ are the ABCD-parameters of the λ/4 transmission line and the LC equivalent network respectively.

By comparing these two equations, the element values can be obtained as follows. Herein $L_1$, $L_2$ and $L_3$ indicate the series inductors of the main and the branch lines, $C_1$ and $C_2$ are the parallel capacitors of the main and the branch lines, respectively.

$$L_1 = \frac{Z_0}{2\pi f_0}$$  \hspace{1cm} (3)

$$L_2 = \frac{\sqrt{2}RZ_0}{4\pi f_0}$$  \hspace{1cm} (4)

$$L_3 = \frac{RZ_0}{2\pi f_0}$$  \hspace{1cm} (5)

$$C_1 = \frac{1}{2\pi f_0 Z_0} \left(1 + \frac{2}{\sqrt{R}}\right)$$  \hspace{1cm} (6)

$$C_2 = \frac{1}{2\pi f_0 Z_0} \left(\frac{1}{R} + \frac{2}{\sqrt{R}}\right)$$  \hspace{1cm} (7)

where 1, $\frac{R}{\sqrt{2}}$ and $R$ are the normalized characteristic impedances of the branch-lines, which are shown in Fig. 1.

From the analysis above, the model of the 3 dB LEDC is obtained. According to the load impedance $Z_L$, the values of the model are computed from (3) to (7).

The simulation and measure results of the 3 dB LEDC are shown in Fig. 3, which are in conditions of the center frequency $f_0=445$ MHz and the load impedance $Z_L=50 \Omega$. The bandwidth is only about 4%, while the isolation is better than 20 dBc and the phase imbalance is less than 2°. Meanwhile, a slightly amplitude imbalance exists between port2 and port3, which is caused by unexpected resistors.

The structure loading the capacitors is flexible, which is able to use the tunable characteristic to obtain a wide band. Meanwhile, to obtain a tunable inductor, the inductor can be replaced by two inductors and a capacitor, which is shown in Fig. 4 and the relationship between them is as follows:

$$\omega_0 L_0 = \omega_0 L_b - \frac{1}{\omega_0 C_b}$$  \hspace{1cm} (8)

where $\omega_0 = 2\pi f_0$.

Fig. 3. Simulation and measure results: (a) S parameter vs. frequency and (b) phase vs. frequency (measure).

Fig. 4. Equivalent model of the inductor.
2.1 Model of a 3 dB Tunable LEDC

Applying this equivalent section to the model of LEDC described before, a tunable structure is obtained as illustrated in Fig. 5. In this section, an assumption is made to simplify, \( L_A = L_B \), and therefore \( \beta \left( C_{L_1}, C_{L_2} \right. \) and \( \beta \left. \right) \) in Fig. 5) is obtained easily.

\[
C_{\beta} = \frac{1}{\omega^2 L_i}, \quad i = 1, 2, 3.
\] (9)

In the following simulations and measures are done. As an example, let \( f_0 \) equal 410 MHz to 490 MHz with step of 10 MHz, respectively, in conditions of \( Z_L = 50 \Omega \), and then the values of the model are computed by (3) to (7) and (9). Based on the computations, the optimization is done using CAD tools. Fig. 6 (a) shows frequency properties of the scattering parameter for this model. The model demonstrates a great bandwidth performance, in which the input return loss and the isolation are better than 25 dB and 20 dBc respectively in whole frequency range. Fig. 6 (b) shows corresponding phase of port2 and port3, which exhibits an excellent phase balance characteristic and has no phase imbalance that the relative phase difference is 90° exactly. Meanwhile, the whole size of this model is only 3 cm x 4 cm, which significantly reduces the occupation area comparing with the corresponding BLDC.

On the other hand, it is easy to note that the amplitude imbalance deteriorates and a maximum amplitude imbalance is 1.9 dB, which is mainly caused by the resistor loss. The losses come from two aspects. The first is the dc resistor brought from inductors, the same drawback as a model of LEDC mentioned before, which can be neglected. The second is the resistor of the varactors. Fig. 7 shows the equivalent circuit of the varactor, in which \( R_j(V) \) is the junction resistance that is large and negligible in reverse bias and \( R_s \) is the series resistance associated with the semiconductor. The simulated results in Fig. 8 prove that the serial resistors \( R_s \) lead to the losses and the amplitude imbalance obviously.

In this paper, the varactors are MV1164, of which the serial resistor is relatively large. So to improve the circuit performance, the smaller the serial resistor, the better it is.
3. Conclusions

This paper has proposed a numerical computation method for a 3 dB LEDC based on arbitrary terminal impedance. The simulation and measure have been done. To improve the bandwidth, a novel structure, broadband 3 dB tunable LEDC has been demonstrated, of which the center frequency can be adjusted in the whole frequency range and the dimension has been reduced either.

On the other hand, the varactors used in this paper have relatively large serial resistors that have caused loss, which lead to the amplitude imbalance. It is suggested that the smaller the serial resistor of the varactor adopted, the better it is.

Acknowledgment

The authors wish to acknowledge the assistance and support of the MSI (Micro System Integrate) Group of UESTC (University of Electronic Science and Technology of China). Meanwhile, they also thank Prof. Bo Zhang for encouragement. At last, acknowledge the EuMC Steering Committee for providing an opportunity for us to study and make progress.

References


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