A novel design of differential phase shifters and baluns with arbitrary bandwidth using Composite Right/Left-Handed Transmission Lines(CRLH-TL)

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Abstract

A principle and design procedure of differential phase shifters and baluns with a specified bandwidth is given. Phase shifters and baluns proposed here comprise of two transmission lines(TL), one is conventional while the other is CRLH-TL. The operating frequency is properly chosen as to obtain a maximum bandwidth. The bandwidth is related to number of unit cells comprising CRLH-TL.A Wilkinson balun with a $180^\circ \pm 10^\circ$ *bandwidth of 2.12GHz, centred at 1.5GHz is designed as an example.*

1. INTRODUCTION

Left-handed metamaterials(LHM) with simultaneously negative ε and μ is envisioned by Veselago[1], which exhibit many extraordinary characteristics such as negative refractive index. The first experimental realization of this kind of materials is made by Shelby et al[2] by arranging an array of split ring resonators and thin wires. Planar structure LHM is first designed by Eleftheriades et al[3] using series capacitors and shunt inductors. CRLH-TL is a general form of such planar structures and has been used to improve many conventional microwave components due to its extraordinary dispersion relations[4]. One of its applications is bandwidth enhancement in various components such as baluns and phase shifters.

Conventional differential phase shifters and baluns are narrow band due to the linear dispersive relation of the components used in constructing them. Recently, Antoniades et al[5] proposed a novel structure of broadband balun using two metamaterials transmission lines. However, even this structure exhibits only 2:1 bandwidth, thus is not much wide. This paper employs a conventional TL and a CRLH-TL[4] to develop a wideband balun, which has a 4.37:1 bandwidth, apparently greatly wider than theirs, thus ideal for feeding planar devices that require a broadband differential signal. Examples of such devices could include a printed bow-tie antenna or a series-fed dipole scanning array.

2. THEORY

CRLH-TL is implemented by cascading a number of unit cells, Fig. 1 shows the configuration of a unit cell.

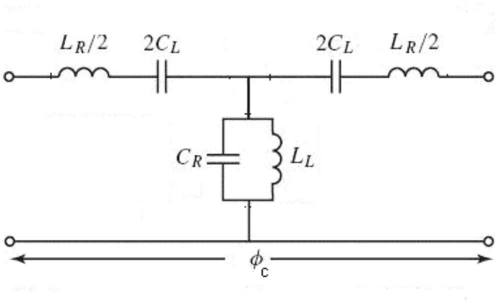

Fig.1: a unit cell of CRLH-TL

The phase shift of it is given approximately by $\phi_c=-\left(\frac{\omega}{\omega_R}-\frac{\omega_L}{\omega}\right)=-\left(\omega\sqrt{L_R C_R}-\frac{1}{\omega\sqrt{L_L C_L}}\right)$ subject to the impedance matching condition $Z_0=\sqrt{\frac{L_R}{C_R}}=\sqrt{\frac{L_L}{C_L}}$. At transition frequency $\omega_0=\sqrt{\omega_R \omega_L}$, $\phi_c=0$. Fig. 2 shows the phase response of a unit cell.

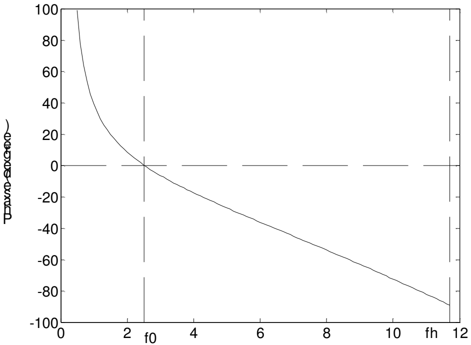

Fig. 2. phase response of a unit cell. (LR=1nH, CR=0.4pF, LL=10nH, CL=4pF)

It is apparent that at high frequency, well above $\omega_0 = 2\pi f_0$, it behaves like a straight line. A more accurate phase shift is derived by using ABCD theorem, as shown below:

$$\phi_C = -\arctan\left\{\frac{\frac{\omega_L}{\omega}[(\omega/\omega_0)^2-1]\left(2-\frac{\chi}{4}\right)}{2-\chi}\right\}$$

$$Z_0=\sqrt{\frac{L_R}{C_R}}=\sqrt{\frac{L_L}{C_L}}$$

$$\chi=\left(\frac{\omega}{\omega_R}-\frac{\omega_L}{\omega}\right)^2$$

$$\omega_0=\sqrt{\omega_R\omega_L}\ ,\omega_R=\frac{1}{\sqrt{L_RC_R}},\omega_L=\frac{1}{\sqrt{L_LC_L}}$$

we define a frequency $\omega_h = 2\pi f_h$ where $2-\chi=0$, thus

$\omega_h \approx \sqrt{2}\omega_R$

At this frequency, $\phi_C=\frac{\pi}{2}$. According to the homogeneous condition[7], $\phi_C\leq\frac{\pi}{2}$ Therefore, within a frequency band $[\omega_0,\omega_h]$, the phase shift can be considered as a linear function of frequency, but with a nonzero phase origin ω_0. Conventional differential phase shifters or baluns are inherently narrow band due to the linear frequency dependent phase shift and a zero phase origin of their components. They are composed of two conventional transmission lines, called Positive Right Handed Transmission Lines (PRH-TL). At the operating frequency ω_s, the differential phase shift is specified as $\frac{\pi}{2}$, for example . But the phase shifts can not be made parallel to each other, thus leading to a limited bandwidth. See Fig. 3(a) to get a clear picture.

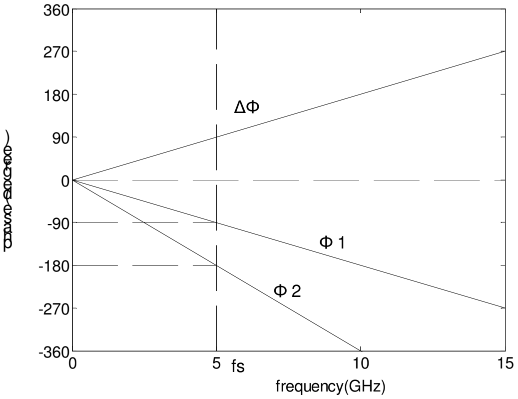

Fig.3(a). phase response of two PRH-TL in a conventional components with the operating frequency fs=5GHz and requiring a differential phase of 90° at fs

However, the mechanism proposed here for our new differential phase shifts or baluns are completely different. We deploy two transmission lines, one is CRLH-TL while the other is a PRH-TL. At the operating frequency ω_s, the differential phase shift is also specified, but unlike the conventional differential phase shifters or baluns, the CRLH-TL has a nonzero phase origin, thus the phase shift of PRH-TL can be made parallel to that of CRLH-TL, hence a wide bandwidth can be achieved. See Fig. 3(b) to get a clear picture.

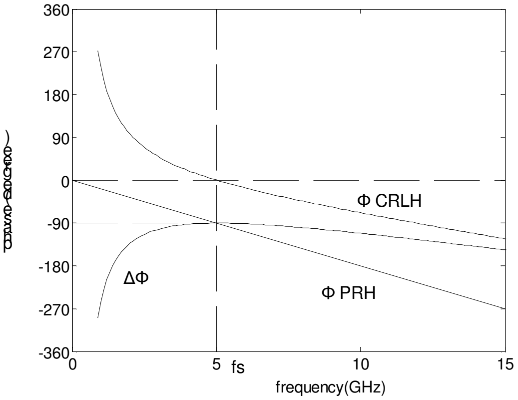

Fig.3(b). phase response of PRH-TL and CRLH-TL in the proposed components with the operating frequency fs=5GHz and requiring a differential phase of 90° at fs (LR=0.42nH, CR=0.17pF, LL=6.01nH, CL=2.43pF, N=3)

Another important point is where to locate ω_s. Itoh has arbitrarily designated ω_s near ω_0 or elsewhere, thus only achieved a fractional bandwidth of 21.7% or less[6]. In fact, ω_s should be $\frac{(\omega_0+\omega_h)}{2}$, only in this way, can we get a maximum bandwidth from ω_0 to ω_h for in this frequency band, ϕ_c is nearly linear dependent of ω. Because $\phi_c=0$ at ω_0, $\phi_c\approx\frac{\pi}{2}$ at ω_h, then at ω_s, $\phi_c\approx\frac{\pi}{4}$.

For CRLH-TL composed of N unit cells, $\phi_{CRLH}=N\phi_c=-N\left(\omega\sqrt{L_R C_R}-\frac{1}{\omega\sqrt{L_L C_L}}\right)$. For PRH-TL, $\phi_{PRH}=\frac{\omega}{\omega_S}\phi_{PRH,S}$ where $\phi_{PRH,S}$ is the phase shift of PRH-TL at ω_S.

Based on the above discussion, we can have the following design procedure to design any degree differential phase shifters or baluns with arbitrary bandwidth:

Step1: let $\Delta\phi$ be the differential phase of the phase shifters or baluns, that is, if we want to design a 90° degree phase shift, $\Delta\phi=-\frac{\pi}{2}$; if we want to design a balun, $\Delta\phi=-\pi$. Then,

$$\phi_{PRH,S}=\phi_{CRLH,S}+\Delta\phi=\frac{N\pi}{4}+\Delta\phi \qquad (1)$$

Step2: at ω_s, the slopes of phase shifts of the two transmission lines should be equal,

$$-N\left(\sqrt{L_R C_R}+\frac{1}{\omega^2{}_S\sqrt{L_L C_L}}\right)=\frac{\phi_{PRH,S}}{\omega_S} \qquad (2)$$

Step3: Let the characteristic impedance of the CRLH-TL be 50Ω

$$Z_0=\sqrt{\frac{L_R}{C_R}}=\sqrt{\frac{L_L}{C_L}}=50 \qquad (3)$$

from equations in (1)-(3) we get:

$$L_R=-Z_0\frac{\phi_{PRH,S}+\phi_{CRLH,S}}{2N\omega_S}$$

$$C_R=-\frac{\phi_{PRH,S}+\phi_{CRLH,S}}{2N\omega_S Z_0}$$

$$L_L=-\frac{2NZ_0}{(\phi_{PRH,S}-\phi_{CRLH,S})\omega_S}$$

$$C_L=-\frac{2N}{(\phi_{PRH,S}-\phi_{CRLH,S})\omega_S Z_0}$$

Because $\omega_0=\sqrt{\omega_R\omega_L}$, $\omega_h\square\sqrt{2}\omega_R$, $\omega_R=\frac{1}{\sqrt{L_R C_R}}$, $\omega_R=\frac{1}{\sqrt{L_L C_L}}$

then $\text{bandwidth}\square\frac{\omega_h}{\omega_0}=\sqrt{\frac{8N}{\Delta\phi\left(\frac{\pi}{2}+\frac{\Delta\phi}{N}\right)}}$.

It is clear that the more unit cells, the broader the bandwidth is

To design, we first choose appropriate number of cells N, calculate the bandwidth using the formula given above, then get initial values from (1)-(3), after tuning, the final values $L_R, C_R, L_L, C_L, \phi_{PRH,S}$ is obtained.

3. DESIGN AND SIMULATION

As an example, we design a Wilkinson balun based on the procedures above. It is composed of a Wilkinson power divider followed by two branches, one is CRLH-TL and the other is PRH-TL. Fig. 4 shows the proposed structure of the Wilkinson balun.

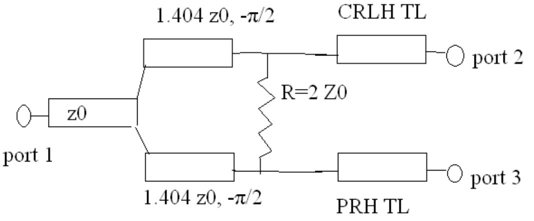

Fig.4. the block diagram of proposed Wilkinson balun using CRLH-TL.

Now, we will design the two branches. PRH-TL is a conventional microstrip transmission line while CRLH-TL is composed of a LC cascading network. Here, we choose N=10, then bandwidth=4, wide enough for our use. We let $\omega_S=2\pi*1.5GHz$

The initial values are:

$$L_R=5nH, C_R=2pF, L_L=34nH, C_L=14pF, \phi_{PRH,S}=10*\frac{\pi}{4}+\pi=\frac{7\pi}{2}$$

Next, we use Agilent Design System$^{@}$ to simulate and after tuning for optimization, the final results are:

$$L_R=4.56nH, C_R=1.82pF, L_L=54.49nH, C_L=21.80pF, \phi_{PRH,S}=3.51\pi$$

Fig. 5 shows the simulated phase responses of the two balun branches, as well as the differential output phase.

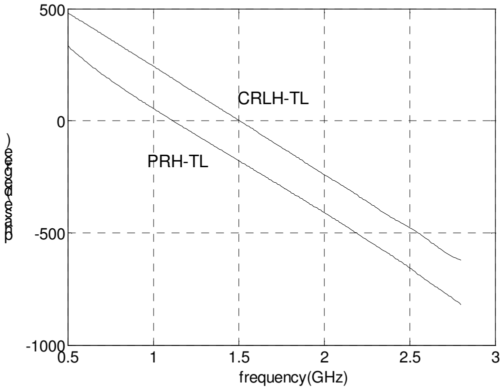

Fig.5. Phase response of S21(CRLH-TL), S31(PRH-TL)

It can be observed that phase characteristics of the two branches are parallel, leading to a relatively flat differential output phase. Fig.6 shows the comparison of bandwidth with [5].

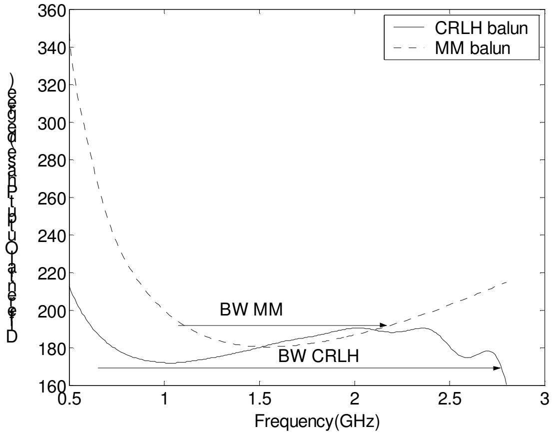

Fig.6. Differential output phase between CRLH-TL balun and MM balun[5]

The structure proposed here has a 180°±10° bandwidth of 2.12GHz, centered at 1.5GHz from 0.63GHz to 2.30GHz, or 4.37:1 bandwidth, approximately the same as calculated beforehand, while the structure proposed in [5] has only a bandwidth of 1.02 GHz centred at 1.5GHz, or 2:1 bandwidth. It is clear that the structure proposed here has much wider bandwidth. Fig. 7 shows excellent isolation for the device, as well as equal power split between the two output ports.

The return loss magnitude responses for all three ports are shown in Fig.8, indicating that the device is well matched within the bandwidth.

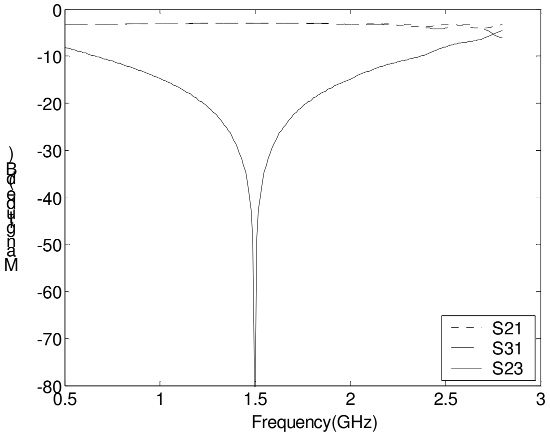

Fig.7. Isolation and through magnitudes for CRLH balun.

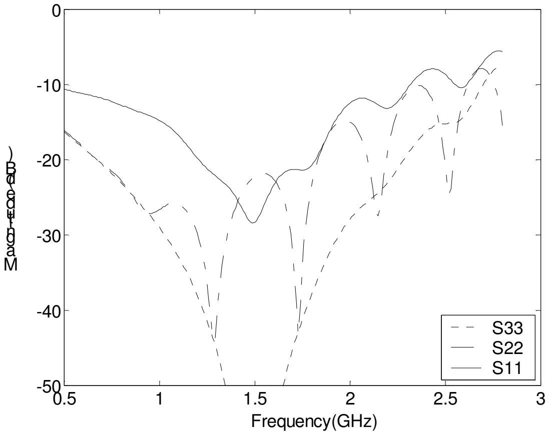

Fig.8. Return loss magnitude for all 3 ports for CRLH-TL balun

4. CONCLUSION

In this paper, a novel design of any degree differential phase shifters or baluns with arbitrary bandwidth has been discussed. An example of balun with 4.37:1 bandwidth has been given. The results correspond to the calculation very well, indicating the design procedure is quite effective. Compared to wideband Wilkinson balun designed in[5], the structure here has a much wider bandwidth.

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