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OPTIMIZED BROADBAND WILKINSON BALUN - DESIGN AND ANALYSIS USING METAMATERIAL

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Abstract— ***The design presented here mainly focuses on implementation of a broadband Wilkinson balun using composite right/left-handed (CRLH) transmission line. This has its components, namely Wilkinson power divider (WPD), microstrip phase shift line and CRLH unit cell along with interdigital capacitor, which forms base of the unit cell. The designing and implementation of WPD, CRLH unit cell and Interdigital Capacitor (IDC) has been done using HFSS 13.0. Results of proposed balun are discussed and compared with broadband Wilkinson balun using purely left handed transmission line (PLHTL).***

A balun is designed using the same. Compactness, losses and phase response are the key issues in microstrip balun design and are dealt with, for best output. The design idea for this balun was taken from [8] and in this paper the design is implemented with a new more compact unit cell and instead of using two quarter wave bridges at two output lines each, total of λ/8 lines are added in each branch this reduces the size to much extent. The final design has been optimized using HFSS 13.0 for best trade-off between losses and phase response. The presented balun has been optimized for best trade-off between losses and phase response, which is key part of a balun design. Bandwidth achieved is 2.75 GHz, with fractional bandwidth of 122%.

Keywords—***Bandwidth, Metamaterials, Phase Response, Wilkins-power Divider.***

1. INTRODUCTION

In recent years a new technology, named metamaterials has been the eye candy in microwave research. Metamaterials has helped in discovering new application along with improvement in current researches. The concept of metamaterials was first introduced with a research on split-ring resonators, which was accomplished by Vasalgo et.al [18], in 1968. In early 20's the metamaterials trend has increased, in microwave applications, both radiation and non-radiation. Many special properties of metamaterials lead its use in wide spread areas. The size restriction in conventional microstrip applications, are overcome due to the fact that a unit cell have size very much less than quarter of a wave, with same characteristics as conventional microstrip of that size. Metamaterials exhibit phase-advance property due to its inherent negative phase velocity whereas conventional microstrip exhibit phase-lag property [8], [21]. Due to this reason it can be used in Balun (Balanced to Unbalanced).

2. DESIGN

The PLH TL without a RH band is realized by a cross connection circuit using only distributed structures, such as a defected ground structure (DGS), a wire bonded interdigital capacitor (WBIDC) [10], and vias. The slope of the phase-response curve for the PLH TL can be flexibly controlled in the broad frequency range because the PLH TL has the capability of arbitrarily synthesizing the transmission phase response and can be realized as a phase-adjusting TL. The above properties of the PLH TL were applied to the implementation of a broadband balun. In the design process of a PLH TL balun, the balanced condition is not required because the PLH TLs have only LH transmission branch. In addition, a PLH TL with wide LH band can be easily designed by some transformations of the structure. Its LH bandwidth can also be controlled more easily than that of CRLH TL.

2.1 DESIGN EQUATIONS

First consider the thickness of the microstrip is zero (t=0). The design of a microstrip line is dependent on W/h ratio. In the quasi-TEM approximation, a homogeneous dielectric material with an effective dielectric permittivity is replaced with that of inhomogeneous dielectric–air media interface of microstrip. Transmission characteristics of microstrips are described by two parameters, namely, the effective dielectric constant ε_{re} and characteristic impedance Z_0, which may then be obtained by quasi-static analysis [23]. In quasi-static analysis, the fundamental mode of wave propagation in a microstrip is assumed to be pure TEM. The closed form equations for characteristic impedance (Z_0) and effective dielectric constant ($\mathrm{E_{RE}}$) are given as [23]

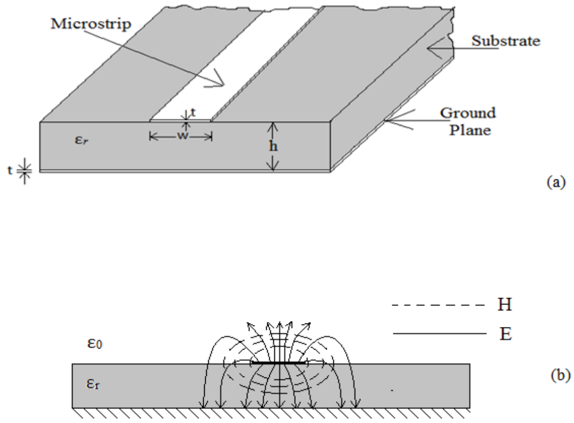

Figure1.1: Microstrip Line (a) Geometry and (b) Fields [23].

$$Z_0 = \begin{cases} \dfrac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left(\dfrac{8h}{W}+0.25\dfrac{W}{h}\right) & \text{for } W/h \le 1 \\ \dfrac{\eta}{\sqrt{\varepsilon_{re}}}\left\{\dfrac{W}{h}+1.393+0.667\ln\left(\dfrac{W}{h}+1.444\right)\right\}^{-1} & \text{for } W/h \ge 1 \end{cases}$$

Where η =120 π ohm, called Intrinsic Impedance and relative dielectric constant as follows:

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}F(W/H)$$

Where,

$$F(W/h) = \begin{cases} (1+12h/W)^{-1/2} + 0.041(1-W/h)^2 & \text{for } W/h \le 1 \\ (1+12Ah/W)^{-1/2} & \text{for } W/h \le 1 \end{cases}$$

The maximum relative error in $\mathrm{E_{RE}}$ and Z_0 is less than 1%. The expressions for W/h in terms of Z_0 and $\mathrm{E_{RE}}$ are as follows [23]:

For $Z_0\sqrt{\varepsilon_{re}} > 89.91$

$$\frac{W}{h} = \frac{8\exp(A)}{\exp(2A)-2}$$

For $Z_0\sqrt{\varepsilon_{re}} \le 89.91$

$$\frac{W}{h} = \frac{2}{\pi}\left\{B-1-\ln(2B-1)+\frac{\varepsilon_{re}-1}{2\varepsilon_{re}}\left[\ln(B-1)+0.39-\frac{0.61}{\varepsilon_{re}}\right]\right\}$$

Where

$$A = \frac{Z_0}{60}\left\{\frac{\varepsilon_{re}+1}{2}\right\}^{1/2} + \frac{\varepsilon_{re}-1}{\varepsilon_{re}+1}\left\{0.23+\frac{0.61}{\varepsilon_{re}}\right\}$$

$$B = \frac{60\Pi^2}{Z_0\sqrt{\varepsilon_{re}}}$$

(3.5 b)

These expressions also provide an accuracy of better than 1%. Values of the characteristic impedance and effective dielectric constant are a function of the W/h ratio. Now we consider effect of thickness (t) the design equations are reconsidered. Simple and accurate formulas for Z_0 and ε_{re} with finite strip thickness are as follows [23]:

$$Z_0 = \begin{cases} \dfrac{\eta}{2\pi\sqrt{\varepsilon_{re}}}\ln\left(\dfrac{8h}{W_e}+0.25\dfrac{W_e}{h}\right) & \text{for } W_e/h \le 1 \\ \dfrac{\eta}{\sqrt{\varepsilon_{re}}}\left\{\dfrac{W_e}{h}+1.393+0.667\ln\left(\dfrac{W_e}{h}+1.444\right)\right\}^{-1} & \text{for } W_e/h \ge 1 \end{cases}$$

Where

$$\frac{W_e}{h} = \begin{cases} \dfrac{W}{h}+\dfrac{1.25}{\pi}\dfrac{t}{h}\left(1+\ln\dfrac{4\pi W}{t}\right) & \text{for } W/h < {}^1\!/_2\,\pi \\ \dfrac{W}{h}+\dfrac{1.25}{\pi}\dfrac{t}{h}\left(1+\ln\dfrac{2h}{t}\right) & \text{for } W/h \ge {}^1\!/_2\,\pi \end{cases}$$

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}F(W/h) - \frac{\varepsilon_r-1}{4.6}\frac{t/h}{\sqrt{W/h}}$$

The effect of thickness on Z_0 and $\mathrm{E_{RE}}$ is insignificant for small values of t/h. However, the effect of strip thickness is significant on conductor loss in the microstrip line [23].Once the effective dielectric constant of a microstrip is determined; the guided wavelength for microstrip is given by [9]:

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{re}}} = \frac{300}{f(\mathrm{GHz})\sqrt{\varepsilon_{re}}}$$

(3.9)

Guided Wavelength, λ_g gives the effective wavelength, the wavelength in effect for the central frequency and the frequency band for which the microstrip RF components are designed.

$$\beta = \frac{2\pi}{\lambda_g}$$

Phase constant, β is a measure of the change undergone by the amplitude of the microwave at it propagates in a given direction. Quantity being measured is either electric field of flux density.

$$v_p = \frac{\omega}{\beta} = \frac{c}{\sqrt{\varepsilon_{re}}}$$

Phase velocity, v_p of a wave is rate at which the phase of the wave propagate in the space. It is given as the ratio of angular frequency and phase constant. Electrical length, is the length of transmission line given by

$$\theta = \beta l$$

3. PROPOSED DEIGN

The implementation of the proposed balun is done in a manner that each component of balun is implemented and simulated individually and then the design is implemented as a whole. First the implementation of the microstrip phase shift line and CRLH line using interdigital capacitor will be discussed and then final designed will be implemented. The substrate used here is Bakelite having dielectric constant value 4.8 and tangent loss 0.0035 and have a height of 0.983mm.

3.1. Microstrip Wilkinson Power Divider

Designed Wilkinson power divider is shown in figure 2.1. It is designed for matching to 50Ω lines, so Z_0=50Ω and bridge resistor to have a value equal to twice of the port resistance (Z_0=50Ω), i.e. 100Ω for isolation between two output branches. Using even- and odd-mode analysis [9] it can be shown that branches have length of quarter waves and are matched for Z_0=70.7Ω, in two branches to give half power output at desired frequency. A plane microstrip works as a high-pass filter with very large high-pass band thus if the network is perfectly matched then the network losses are very low. 50Ω and 70.7Ω lines are calculated to have a width of 1.74mm and 0.92mm, respectively. The lengths of the two branches of Wilkinson power divider are one fourth of the guided wavelength. The guided wavelength is calculated to have value 32.4mm, using equation [9,23]

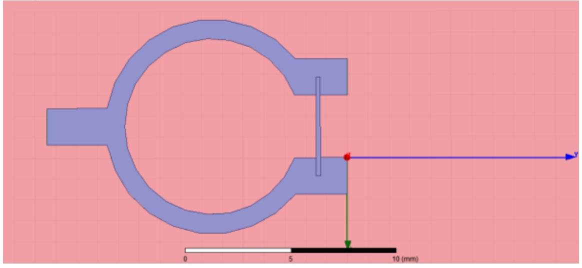

Figure 2.1: Microstrip Wilkinson Power Divider Geometry.

3.2. Microstrip Phase-Shift Line

Conventional microstrip line has positive phase response characteristics. That's why it can be used as a branch of balun for +90° phase shift [13, 18]. The microstrip line is designed to give that phase with a width, W and length, *l* given in terms of guided wavelength as, *l* =λ_g/4. Where guide wavelength, $\lambda_g = 300/f\sqrt{\varepsilon_{re}}$, f is measured in GHz. Conventional microstrip line can be used as a phase shift line. A line of length quarter wavelength gives a phase shift of 90°. Thus it is dependent on length of line. Chosen central frequency (f_0) is 3.6GHz, for a wideband device design. The microstrip phase-shift line has length of 17.74mm and the width of microstrip is calculated to be 1.74mm to match 50Ω port impedance.

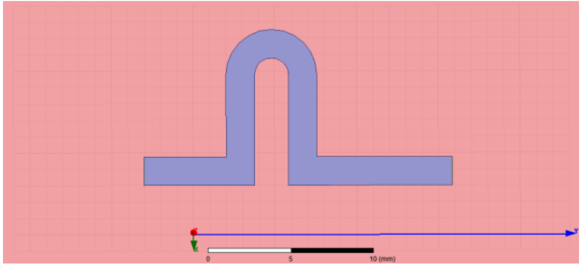

Figure 2.2: Microstrip Phase-Shift Preview Geometry

3.3. CRLH Unit Cell

The whole branch of balun is simulated separately, as MSL phase shifting line. The branch incorporates -80° at f_0, as a part of which microstrip line (having length equal to λ_g/8) shares 33° and unit cell imparts -113° of phase shift. Unit cell parameters are shown in table 1.1

C_L= Capacitance due to the digits (fingers) of IDC, given in equation [23]

C_R= Shunt capacitance of IDC, given by equation [23]

L_R= Inductance due to RH behavior of IDC, i.e. length of IDC, given by equation [23]

L_L= Inductance of first and last finger of IDC, which are shorted to ground, added to the inductance of vias (negligible).

Thus a CRLH unit cell acts as a band pass filter and is very small in size (approximately 3.5mm X 1.3mm which is around 10 times smaller, as compared to the conventional microstrip filters).

TABLE 1: PARAMETERS OF CRLH UNIT CELL

Parameter	IDC Parameters				Shorted Digit	fc1(lower cut-off)	fc2(upper cut-off)	Phase at f0
	CL	LR	CR	Z0	LL	1.84 GHz	5.91 GHz	Φ
Value	1.98pF	1.1 nH	0.72pF	47 Ω	2.54 nH			-113°

Using these values we can calculate the CRLH shunt and series frequencies as follows:

$$f_{se} = \frac{1}{2\pi\sqrt{L_R C_L}} = 3.41\text{GHz} \quad (4.1)$$

$$f_{sh} = \frac{1}{2\pi\sqrt{L_L C_R}} = 3.72\text{GHz}$$

As series frequency (f_{se}) and shunt frequency (f_{sh}) are a not equal but close values; thus the unit cell closely exhibits balanced nature and these values form an average of around 3.6GHz (f_0). The table 1 shows calculated parameters of the unit cell.

3.4. Implementation of the Balun

The last three sub-sections deal the implementation of three components of the proposed balun. These components are combined using 50Ω lines (1.74mm) and a 100Ω resistor is used for isolation between the two branches. The microstrip circuit thus formed is shown in the figure 2.3, shows the port 2 branch comprises of microstrip line phase shifter and other CRLH unit cell.

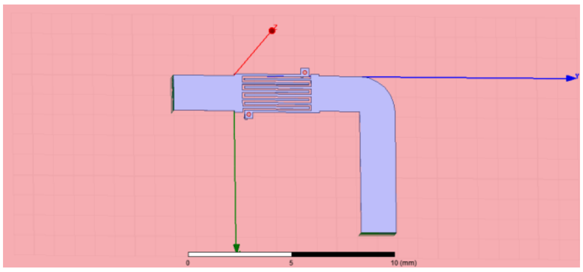

Figure 2.3: CRLH Unit Cell, width of fingers and all spacing's are 0.1mm, length of each finger is 3.3mm, via pads of size 0.4mm X 0.4mm and diameter of each via is 0.2mm and capacitor has 10 digits (fingers).

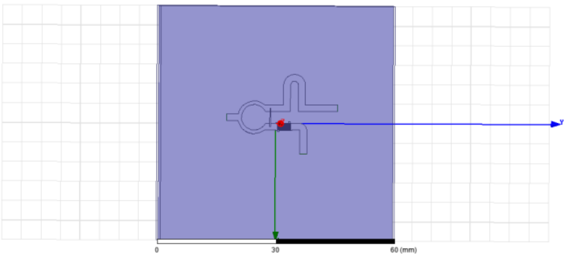

Figure 2.4: Proposed Balun Geometry

The circuital parameters are already shown in the previous sub-sections. The microstrip sections of port 2 and 3, except the unit cell and microstrip phase shift line have length equal to $\lambda_g/4$ (approximately 13 mm), each.

4. RESULTS AND DISCUSSION

In this chapter results of proposed balun design are discussed and a comparison is made with the broadband Wilkinson balun using PLH TL. This chapter gives final results of proposed balun that includes S-parameters, phase difference and Group Delay. Later a comparison of proposed balun is made with reference balun.

4.1. Broadband Wilkinson Balun using PLH TL

The balun [8] shown in figure 2.4 is simulated in HFSS 13.0 and this section deals with the simulation results of the balun. The figure 3.1 shows the simulated S-parameters of the balun. The band range from around 1.4GHz to 3.3GHz with power nearly equally split and the value of return loss at central frequency, 2.4 GHz is -18.98 dB. There is good isolation between the two ports, though the return loss is higher compared to the proposed balun. Though the design has been re-implemented using increased number PLH DGS unit cells, in same paper to reduce the losses and increase the band, but at cost of increased size.

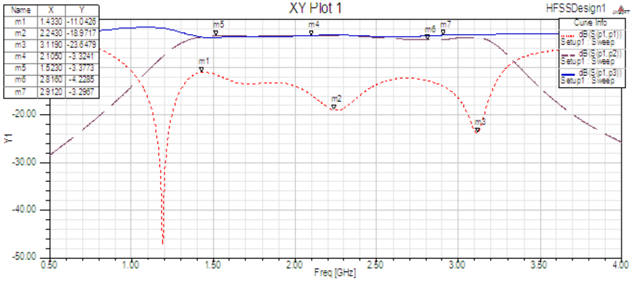

Figure 3.1: S-Parameters, S_{11}, S_{12} and S_{13} of Reference Balun [8]

The phase response for the simulated balun is quite good, 180°±10° and is consistent over frequency range of 1.45GHz to 3.55GHz, though losses restrict the range to 3.3GHz. The phase response is shown in figure 3.2, with phase difference at central frequency 2.4GHz equal to 181°.

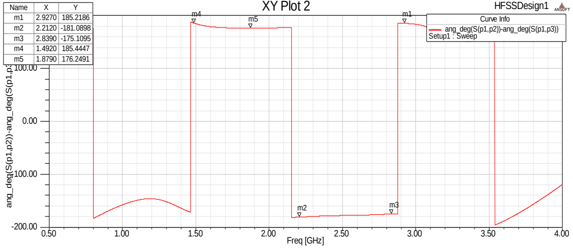

Figure 3.2: Phase-difference between Port2 and Port3, for Reference Balun [8]

The group delay is measured around 0.725 ns for range 1.6 GHz to 3.0 GHz, and it is more as compare, (which is < 0.3 ns) to proposed design due to its more compact size as shown in preceding section.

4.2. Proposed Balun Results

The phase response can be retained and low losses are achieved by replacing the PLH unit cell with a compact CRLH unit cell.

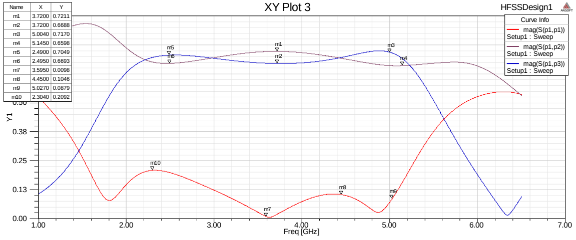

Figure 3.3: S-Parameters of Proposed Balun (dB)

Three sub units WPD, CRLH unit cell which works as metamaterials and MSL phase shift line. The figure 3.3 shows the simulated S-parameters of the balun. The band ranges from around 2.8 to 5.7 GHz, and in this range the phase difference between the two output ports is 180°±10°. The bandwidth thus is approximately 2.75 GHz and fractional bandwidth is calculated to be 122%.

TABLE 2: PARAMETERS OF COMPARISON

Sr. No.	Characteristics	Broadband Wilkinson Balun using PLH [8]	Proposed Balun
1.	S_{11}	-14.09dB to -21dB	-11dB to -14.87dB
2.	S_{12}, S_{13} (at central frequency)	3.3dB, 3.3dB	2.8dB, 3.4dB
3.	Phase-difference	180°±10°	180°±10°
4.	Group Delay	0.72 ns	0.3 ns
5.	Size	42.3mm X 43.4mm	28.52mm X 20.3mm
6.	Bandwidth (BW)	1.7 GHz	2.75GHz
7.	Fractional BW	71%	122%

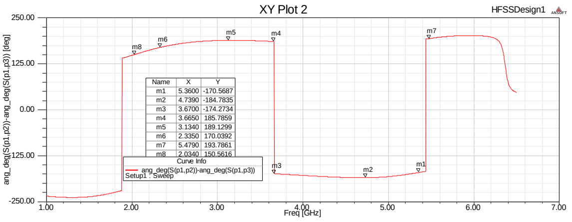

Figure 3.4: Phase Response of Port2 and Port3 of Proposed Balun

Figure 3.4 shows the phase response of port 2 and 3. The error of ±10° is bearable, though perfect 180° ensures the perfectly odd-mode in the unit cell's branch. There is always a trade-off between phase response and losses. The perfect 180 means perfect odd mode current in the branch, but due to imperfect nature there is always interference between input and odd mode branch. Figure group delay the group delay is less than 0.3 ns for port 1 -port 2 path and less than 0.4 ns for other path though in range 3.0 to 4.75 GHz it less than 0.3 ns. Comparing to the group delay in [8], which is nearly 0.72 ns in its band, for proposed design it is less.

5. CONCLUSION

The differences between the wideband Wilkinson balun [8] and proposed balun are shown in the table III; clearly the return losses are very low as compared to the balun [8].The phase response is very much bearable. Size of proposed balun is smaller around two times smaller area than that of [8]. Larger band, almost twice and fractional bandwidth is 122% and is larger than that of balun mentioned in [8]. Thus the new balun has been presented and compared.

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