Wide Band Nonuniform Substrate Integrated Waveguide (NSIW) Wilkinson Power Divider

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***Abstract*—** A new wideband Wilkinson Power Divider which use the nonuniform substrate integrated waveguide (NSIW) method is presented in this paper. This structure utilizes NSIWs instead of the uniform quarter wavelength SIWs in conventional Wilkinson power divider. The proposed structure is analyzed by odd and even mode analysis. The proper NSIW section widths can be extracted by using even mode while the divider resistances are achieved by odd mode analysis. Moreover using of half mode structure in the NSIW and two output ports reduces the overall size of the proposed divider. Finally a wideband Wilkinson power divider is designed and simulated to verify the proposed design method. A good return loss (S_{11}, S_{22}) and insertion loss (S_{21}) across a very wideband width from 10 GHz to 20 GHz is achieved. Also, the isolation (S_{23}) is better than -10 dB from 9.5 GHz to 21.5 GHz for the designed NSIW divider.

***Index Terms*—** SIW, Wilkinson power divider, nonuniform line.

I. INTRODUCTION

The power dividers are passive devices that allow a microwave signal to be split equally or non-equally between two or more branches, depending on the design requirement. The T-junction H-plane waveguide power divider is a lossless three ports device which has two problems: being not matched at all ports and low isolation between the output ports [1]. To solve these problems, Wilkinson power divider (WPD) can be used [2]. The Wilkinson power divider is a lossy network that uses a resistance branch in order to increase the output ports isolation.

On the other hand, substrate integrated waveguide (SIW) is a kind of waveguide which has a structure between rectangular waveguides and microstrip transmission lines [4]. The low cost, low profile, and compactness in size in addition to the easy integration with planar circuits are some advantages of this transmission line [5, 6]. Nowadays, the applications of SIW devices are extensively developed in the RF circuits which increase the needs for the design improvement of them [7, 8]. In this way, some SIW power dividers have been introduced in [9-11]. Although these SIW dividers have a wideband behavior, but their bandwidth can be improved by the proposed idea in this paper.

Here, a new method is used to design a wide band SIW Wilkinson power divider. In this proposed method, nonuniform SIWs (NSIWs) are used instead of the quarter wavelength uniform SIWs in the

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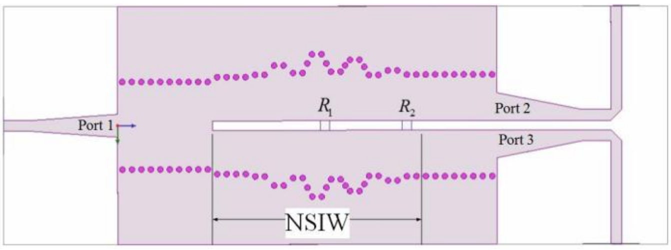

Fig. 1. The proposed wideband NSIW Wilkinson power divider

conventional Wilkinson power divider structures. . The non uniform microstrip transmission line has been used previously in the Wilkinson power diver structure for miniaturization or bandwidth enhancement such as [12-14]. Here, we use the non uniform SIW transmission line to design a wideband Wilkinson power divider. To analysis the structure, NSIW are divided into K sections with equal length and different widths. Then the odd- even mode method is used to analysis the NSIW power divider. The NSIW section widths are extracted by even mode while the divider resistances are calculated by odd mode. Finally, a 10 GHz- 20 GHz NSIW Wilkinson power divider is designed and simulated to show the ability of the proposed method. Moreover, comparison of the proposed NSIW divider with the literatures verifies the capability of the idea.

II. WIDE BAND NSIW WILKINSON POWER DIVIDER

The proposed wideband NSIW Wilkinson power divider is shown in Fig. 1. In this proposed structure after the microstrip to SIW transition, there is a uniform SIW with Z_0 characteristic impedance. Then, the NSIWs are used instead of the quarter wavelength uniform SIWs in the conventional Wilkinson power divider structure. Finally, the output signals are delivered in the two separate ports by microstrip-SIW transition. Also, two isolation resistors are mounted between two nonuniform sections to maintain an acceptable isolation in the output ports.

A schematic diagram of the proposed wide band NSIW Wilkinson power divider is shown in Fig. 2 where each conventional uniform SIW section is replaced with a NSIW. It has been mentioned in [11] that a SIW with width of w can be considered as a ordinary rectangular waveguide by a very good approximate with width of w_{eff} as

$$w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \qquad (1)$$

where d is the via diameter and s is the center to center distance between two adjacent vias. Therefore, we consider the analysis for the equivalent non uniform rectangular waveguide instead of the NSIW

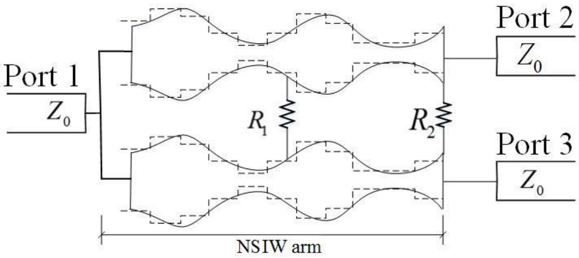

Fig. 2. The schematic diagram of the proposed wide band NSIW Wilkinson power divider

which depicted also in Fig. 2. To analysis the circuit, the NSIW with length of L is divided into K uniform waveguide sections with length of Δz where

$$K = \frac{L}{\Delta z} \tag{2}$$

The ABCD matrix of these rectangular waveguide sections can be found easily by

$$T_i = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = \begin{bmatrix} \cos\beta(w_i)\Delta z & jZ(w_i)\sin\beta(w_i)\Delta z \\ \frac{j}{Z(w_i)}\sin\beta(w_i)\Delta z & \cos\beta(w_i)\Delta z \end{bmatrix} \tag{3}$$

where $\beta(w_i)$ is the propagation constant and $Z(w_i)$ is the waveguide characteristic impedance. Notice that both of these parameters are function of the section width, w_i, as

$$\beta(w_i) = \sqrt{\omega^2\mu\varepsilon - (\frac{\pi}{w_i})^2} \tag{4}$$

$$Z(w_i) = \frac{\omega\mu}{\beta(w_i)} \tag{5}$$

Now, even and odd analyses are used to find the proper widths of the NSIW sections as well as the isolation resistors.

A. Even Mode Analysis

The equivalent circuit of the even mode of the divider is shown in Fig. 3. As it can be seen, the sources are in phase in this mode and the current is zero in the middle of main circuit, consequently. Therefore, the two resistance branches can be considered as open. In other words, their values cannot be achieved by this mode analysis. In fact, this nonuniform transmission line with length d matches a source with impedance $Z_S = 2Z_O$ into a load with impedance $Z_l = Z_O$.

The transmission matrix of the nonuniform waveguides with length of d can be found by multiplexing the ABCD matrixes of the K uniform waveguide sections as

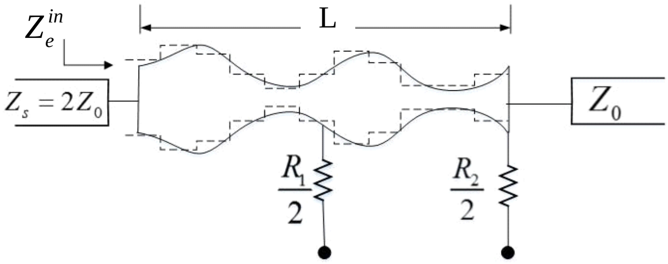

Fig. 3. The even mode schematic of the proposed NSIW Wilkinson power divider

$$\begin{bmatrix} A_{NWG}^e & B_{NWG}^e \\ C_{NWG}^e & D_{NWG}^e \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \times \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \times \dots \times \begin{bmatrix} A_K & B_K \\ C_K & D_K \end{bmatrix} \qquad (6)$$

where the NWG is stand for the *nonuniform waveguide*. Now, the goal is to find the waveguide section widths in such a way that the reflection coefficient between the source and load would be minimum in the operation bandwidth. For this purpose, the reflection coefficients are determined in *n* frequency points, f_i in the operation bandwidth and error function is defined as below

$$error_e = \max\{|\Gamma_e(f_1)|^2, \dots, |\Gamma_e(f_i)|^2, \dots, |\Gamma_e(f_n)|^2\} \qquad (7)$$

where

$$\Gamma_e(f_i) = \frac{Z_e^{in}(f_i) - Z_s}{Z_e^{in}(f_i) + Z_s} \qquad (8)$$

and $Z_e^{in}(f_i)$ can be written in terms of ABCD matrix of the NWG as below

$$Z_e^{in}(f_i) = \frac{A_{NWG}^e(f_i)\, Z_l + B_{NWG}^e}{C_{NWG}^e(f_i)\, Z_l + D_{NWG}^e} \qquad (9)$$

Notice that Z_l is the load impedance. To extract the waveguide section widths, the error function in (7) should be minimized. Notice that the minimization of the maximum value of the $\Gamma_e(f_i)$ in *n* frequency points forces the minimization of all Γ_e.

B. Odd Mode Analysis

The equivalent circuit of the odd mode is shown in Fig. 4. In this mode, the sources have 180 degree phase difference and the middle of main circuit is grounded. In order to increase the isolation between the output ports, NWG is partitioned in two separate parts and at the end of each part an isolation resistance is placed .Thus the transmission matrix of this non uniform line can be written as

$$\begin{bmatrix} A_{NWG}^o & B_{NWG}^o \\ C_{NWG}^o & D_{NWG}^o \end{bmatrix} = T_{segment1} \times T_{\frac{R_1}{2}} \times T_{segment2} \times T_{\frac{R_2}{2}} \qquad (10)$$

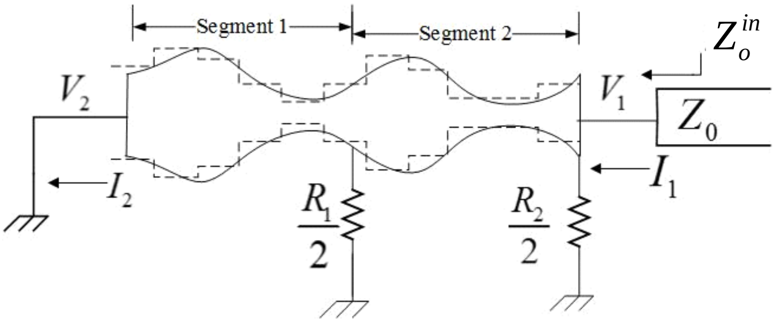

Fig. 4. The odd mode schematic of the proposed NSIW Wilkinson power divider

Here, similar to the even mode, reflection coefficient is determined in *n* points in the operation bandwidth and the error function is defined as below

$$error_o = \max\{\left|\Gamma_o\left(f_1\right)\right|^2,\ldots,\left|\Gamma_o\left(f_i\right)\right|^2,\ldots,\left|\Gamma_o\left(f_n\right)\right|^2\} \tag{11}$$

where

$$\Gamma_o\left(f_i\right) = \frac{Z_o^{in}(f_i) - \mathrm{Z}_o}{Z_o^{in}(f_i) + \mathrm{Z}_o} \tag{12}$$

According the odd mode schematic presented in Fig. 4, we have the below relation to find the Z_o^{in} as

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_{NWG}^o & B_{NWG}^o \\ C_{NWG}^o & D_{NWG}^o \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{13}$$

Now by placing $V_1 = 0$, the input impedance of odd mode can be found as

$$Z_o^{in} = \frac{V_1}{I_1} = \frac{B_{NWG}^o}{D_{NWG}^o} \tag{14}$$

Notice that the section widths, w_i found in the even mode are used here and the isolation resistance , R_1 and R_2, are determined in this mode to minimize the error function in (11). In other words, the waveguide section widths are extracted from the even mode analysis, while the resistances are calculated from the odd mode analysis.

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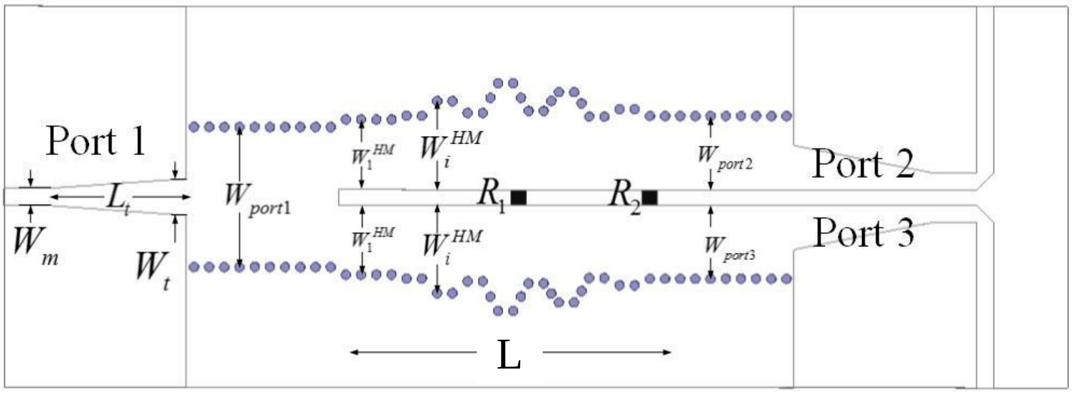


Fig. 5. The wideband NSIW Wilkinson power divider

TABLE I. NONUNIFORM LINE SECTION WIDTHS

section No.	section widths in rectangular wave guide, w_{eff}, *mm*	section widths in SIW, w_{i} , *mm*
1	8.5	9.18
2	8.5	9.18
3	9.00	9.69
4	10.91	11.60
5	9.36	10.04
6	13.26	13.95
7	9.63	10.31
8	12.11	12.80
9	8.98	9.67
10	9.88	10.56

III. DESIGN, SIMULATION AND COMPARISON

Here, we design and simulate a wide band NSIW Wilkinson power divider as an example of the proposed method. The length of each NSIW in the Wilkinson power divider is selected as 20 *mm* and they are partitioned in two 10 *mm* parts where the isolation resistances are placed at the end of parts.

The desired bandwidth is considered 10 GHz to 20 GHz. The NSIW are divided into K=10 sections with 2 mm length. Two metallic vias compose each uniform section with s=1 *mm* and d=0.6 *mm* diameter. Also, the bandwidth are divided into n=20 points. To extract the section widths, the error function presented in (7) is minimized by using *fmincon* function in MATLAB. This minimization problem should be restricted by $|S_{ii}| \leq -10dB$ and $|S_{23}| \leq -10dB$ conditions over the bandwidth. For this purpose, theses condition are converted to the ABCD parameters by the well known relation presented in [1], and then applied into the fmincon as constrains. These conditions mean that the reflection loss in ports and the isolation between ports 2 and 3 should be low enough, respectively. As mentioned previously, these section widths are in rectangular form and they should be converted into the equivalent SIW width by using (1). The resulted section widths are tabulated in Table. I in both SIW and waveguide.

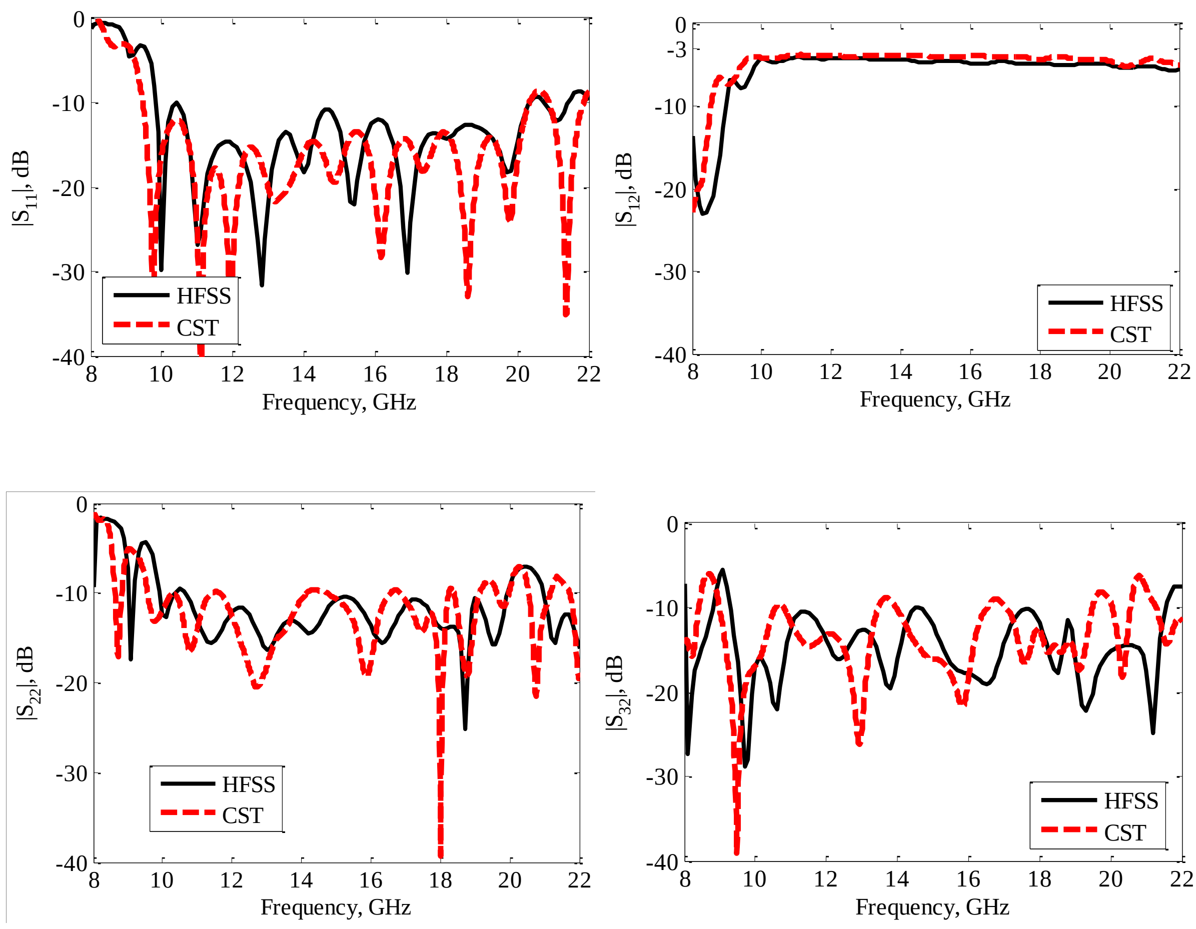
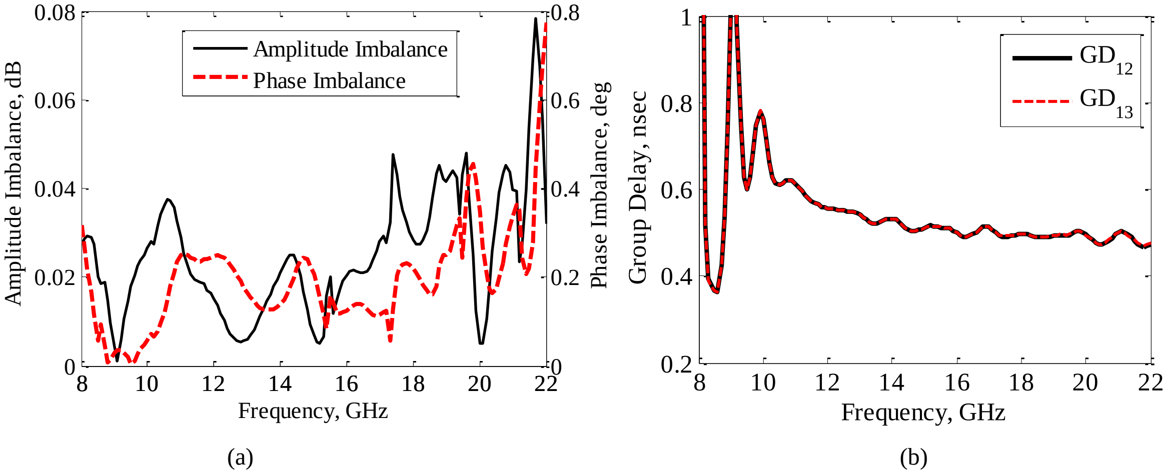


Fig. 6. Simulated S-parameters of the proposed wideband NSIW Wilkinson power divider.

Now, by the odd mode analysis and the error function minimization based on (11), the isolation resistances are found as $R_1 = R_2 \approx 50\Omega$.

The uniform parts width in input port is 9 mm which connected to the output ports (2 and 3) with two NSIWs. The maximum calculated section width in the NSIW is about 14 mm in section 6 which means that we need at least 28 mm circuit width in the implementation. In other words, the whole circuit dimensions are not small enough. To compact the structure, we use half mode SIW [12] in two NSIWs as well as the output ports. Also, SIW to microstrip transition is used in all three ports with $W_t = 2.4mm$, $W_m = 1.14mm$ and $L_t = 9.02mm$. The final design layout of the NSIW Wilkinson power divider presented in Fig. 5 is simulated on Rogers 4003 substrate with 20 mil thickness and relative dielectric constant of 3.55.

The Simulation results are shown in Fig. 6 performed by High Frequency Structure Simulator (HFSS) and CST Microwave Studio full simulation softwares. The good agreement between these two simulation software results can validate the design process.



(a) (b)

Fig.7. a) Phase and amplitude imbalance of between the divider output ports b) group delays (GD) of the divider outputS

TABLE II. THE PROPOSED DIVIDER COMPARISON WITH THE LITERATURES

Reference	**Frequency Range**	**Band Width**	**Loss**
[8]	13 GHz – 17 GHz	26%	1-3 dB
[9]	8.4 GHz – 12.6 GHz	40%	1-3 dB
[10]	8.8 GHz-11.2 GHz	24%	0.25-0.75
NSIW	10 GHz – 20 GHz	66%	1-2 dB

It can be seen that the reflection losses, $|S_{ii}|$ is less than -10dB in the whole of the designed bandwidth and the insertion loss, $|S_{21}|$ is about -4dB. Also, the isolation between the output ports, $|S_{23}|$ is less than -10dB in the bandwidth. The proposed divider bandwidth is 66% from 10 GHz to 20 GHz. Moreover, the phase and amplitude imbalance between the output ports of the divider are depicted in Fig.7 which show a good balnce in the whole of bandwidth. Also, the group delay of the divider outputs are plotted in Fig. 7 (b) which have a very small value and flat attribute versus the frequency. Comparison between the proposed nonuniform SIW and other WPD reported in [8-10] is tabulated in Table II. As it considered in these references, the bandwidth is defined when |S11|, |S32|, |S22|, and |S33| are less than −10 dB. It is clear that our proposed NSIW Wilkinson divider has a significant enhancement in the bandwidth. The SIW divider in [10] presents a lower insertion loss compared with our design, but it needs two bi-layered technology for fabrication which causes some practical problems. These comparisons show the ability and power of the proposed design.

IV. CONCLUSION

A new method to design a wide band NSIW Wilkinson power divider was proposed. The uniform quarter wavelength SIW between input and output ports were replaced with NSIW. By appropriate selection of the NSIW sections and odd- even mode analysis, the wide band operation of the divider has been obtained. The NSIW section widths have been found by even mode analysis, where two isolation resistors have been calculated through the odd mode circuit analysis. Finally, a wide band NSIW Wilkinson power divider was designed and simulated to operate from 10 GHz to 20 GHz to show the ability of the proposed method. Moreover, the comparison of the designed NSIW divider with the literatures verified the capability of the idea.

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