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An Efficient and Comapct Design of Coupled-Line Unequal Wilkinson Power Divider

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Abstract

In this paper, 3:1 and 10:1 unequal Wilkinson power dividers are designed and investigated. Unequal power dividers are an integral part of the feeding network for antenna array where their performance affects a group of elements rather than an individual element. Thus, there is a need for an accurate design for such dividers. A coupled-line section with two grounding via has been used to attain the high characteristic impedance line. This is done in order to outplay the microstrip fabrication constraints of printing very thin/fine conductor lines. Further to reduce the size of the structure, meandering of the transmission line has been done which procreates three designs, namely: 0^0 Serpentine Flexure, 180^0 Serpentine Flexure and Compact Meandered Flexure. Verification of the design methodology has been done by creating a 10:1 Unequal WPD. The structures are implemented on a high-resistive silicon substrate (HRS) for a centre frequency of 1.575 GHz. Further, their EM analysis is done in terms of S-parameters such as return loss and insertion loss using commercially available FEM solver. Satisfactory RF performance, with return loss better than -10 dB and required power split for all the structures, has been achieved.

Index Terms: Wilkinson power divider; Coupled line section; Meanders; High resistive silicon; microstrip.

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1. Introduction

Power dividers are widely used power division components in various microwave communication systems such as antenna arrays; power amplifiers etc. and are also an integral part of these systems [1-2]. Traditionally, there are three available power divider types, namely: T-junctions, resistive and Wilkinson power dividers. Wilkinson Power Dividers (WPDs) are usually preferred over T-junctions and resistive type dividers because they are lossless, matched and their designing is quite effortless [3].WPDs are mainly of two types: equal division and unequal division type [4]. Unlike equal power dividers, which are simple to design, unequal power dividers are designed with strict fabrication limitation. This is because they usually require a high characteristic

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impedance transmission line i.e. a very thin conductor width which is quite difficult to realize using a conventional microstrip structure. To overcome this fabrication constraint, there are many methods reported in literature [5-15].

2. Related Work

Achieving high-characteristic impedance line for unequal WPD using DGS contributes a supplementary inductive component to the transmission line which makes it to be realizable with characteristic impedance above 150 Ω. Thus, relaxing the fabrication constraints but it has a disadvantage of incompetency when the power splitting ratio is greater than 4:1 [5-6]. With double-sided parallel striplines (DSPSL), it is difficult to maintain a proper distance between the two parallel striplines during their fabrication and thus, formulating these unequal power divider structures using microstrip technology is quite an onerous job [7]. For realizing the power divider with high dividing ratio, grooved substrate has been proposed [8]. But fabrication of this substrate is difficult in comparison to conventional microstrip lines. In the conventional power divider, replacing the very low-impedance line with dual transmission lines procreates a new class of unequal power dividers [9]. However, such a method results into increased divider size. In place of dual transmission lines, application of T-shaped transmission lines has also been proposed [10]. But this solution reduces the operational bandwidth of the power divider.

In [11], addition of extra transmission line between the output ports and in series with the isolation resistor results into creation of a new class of unequal power dividers. In this, the output ports can directly connect to the power divider without using impedance transformers. However, the power divider bandwidth is reduced a bit. In another approach, two shunt stubs have been incorporated in the designing of conventional Wilkinson power divider [12]. The power division ratio has been controlled by the lengths of the employed stubs. But the design has a disadvantage of reduced bandwidth in comparison to the conventional WPD. In [13], unequal power divider with high dividing ratio has been achieved with the application of loaded transmission line. Optimizing the dimensions of these transmission lines loaded with open or short-circuited stub has lead to easy implementation of power divider with high-dividing ratio but with increased cover-area. In [14], a compact unequal WPD with arbitrary power division has been proposed. It is constructed by incorporating power divider cells, recombinant structure, low power branch and transformers for matching the circuit. Inculcation of these extra structures results into increased divider size.

In [15], coupled-line structure has been mainly proposed to realize the high-impedance transmission line for unequal WPD. Coupled-line section with two shorts is usually preferred because, unlike all the above stated structures, it can be easily designed based on its even- and odd-mode analysis and is compatible with microstrip circuits through single layer fabrication technique. Application of these coupled-line structures provides a power divider with high dividing ratio and operational bandwidth.

In this paper, a 3:1 unequal Wilkinson power divider is designed and analyzed using a coupled-line section. Also, for size reduction, meandering technique is incorporated in the design of power divider which further procreates its three models, namely: Serpentine 0^0, 180^0 and Compact meandered flexure. To verify this technique and the design methodology, a 10:1 unequal power divider is also presented. All the structures are simulated on a high resistive silicon substrate (ρ>8KΩ-Cm, h=675μm and ε_r= 11.8) for the targeted L-Band with 1.575 GHz as the resonating frequency.

The design methodology of proposed unequal WPDs is detailed in the section 3. Results pertaining to RF-performance of the designed dividers have been discussed in section 4 before the paper is finally concluded in section 5.

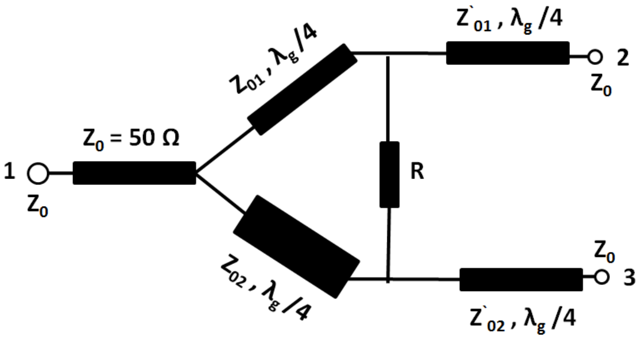

Fig.1. Conventional circuit of Unequal Wilkinson Power Divider

3. Design Methodology

The conventional circuit of unequal Wilkinson Power Divider is shown in fig. 1. Calculations for the characteristic impedances of transmission lines and isolation resistor are carried out from the following mathematical relations:

$$Z_{01} = Z_0\sqrt{k(1+k^2)} \tag{1}$$

$$Z_{02} = Z_0\sqrt{(1+k^2)/k^3} \tag{2}$$

$$Z'_{01} = Z_0\sqrt{k} \tag{3}$$

$$Z'_{02} = Z_0/\sqrt{k} \tag{4}$$

$$R = Z_0\left(\frac{k+1}{k}\right) \tag{5}$$

where, Z_0 is the characteristic impedance of input and output ports and k^2 is the power dividing ratio.

In our structure, for k^2=3, the calculated characteristic impedances using eqn. (1)-(5) are: Z_{01}=131.605 Ω, Z_{02}=43.86Ω, Z'_{01}=65.802Ω, Z'_{02}=37.992 Ω and R= 78.868 Ω. Now, the obtained high impedance, Z_{01}, has a line-length of 46.8 mm and width of 0.015mm which is practically not realizable using the conventional microstrip structure due to fabrication limitations. To overcome this limitation, a coupled-line section is employed to attain the required high characteristic impedance line and thus, achieving the desired 3:1 power dividing ratio. Coupled-line section allows the high impedance to be realized in terms of its even and odd-mode impedances, Z_{0e} and Z_{0o}, which are calculated after performing its even- and odd-mode analysis using following relations, eqn. (6)-(7):

$$Z_{0e} = Z_{01}\left(\frac{C}{1-C}\right) \tag{6}$$

$$Z_{0O} = Z_{01}\left(\frac{C}{1+C}\right) \tag{7}$$

Where C= coupling coefficient whose value can be in the range of 0.2-0.4. In this paper, 'C' is taken as 0.3 as it maintains the perfect balance between the fabrication difficulty and operating bandwidth of the device. Once the values of Z_{0e} and Z_{0o} are known, the line-length, width and separation between the coupled-lines can be easily calculated. Thus, the calculated value for line-length, width and separation, at the centre-frequency of 1.575 GHz, is 17.5 mm, 0.461 mm and 0.224 mm respectively. This enlarged conductor width and reduced length has a great advantage in design and realization of such a high impedance line and smaller circuit.

Using the aforesaid procedure, three models of the 3:1 unequal Wilkinson power divider are presented: 0 ° Serpentine Flexure, 180 ° Serpentine Flexure and Compact Meandered Flexure. In 0 ° Serpentine Flexure, the output ports of the divider are in the same axis whereas in 180 ° Serpentine Flexure, they are at right angles to the input port and the compact meandered flexure represents the design having the smallest divider size among all the three designs.

3.1 0 °Serpentine Flexure:

This model consists of two meandered impedance lines ($Z_{01}$and Z_{02}) connected with stepped impedance lines ($Z'_{01}$and Z'_{02}) through an isolation resistor to provide proper matching and isolation between the output ports. In order to reduce the separation between the output ports, 12.676 mm length of impedance Z_{01} and 10.903 mm of Z_{02} is bent and meandered to decrease their overall line-length. Also, $Z'_{01}$and Z'_{02} impedances are moulded in such a way that these transmission lines have their output ports along the same axial plane or 0^0 apart from one another as shown in fig. 2. The minimum distance in the entire structure is 4.3mm. The distance between the two output ports is 27.5mm. Thus, a miniaturized serpentine look-alike flexure is obtained having total cross-sectional area of “28.7×21.5” mm^2.

3.2 180 °Serpentine Flexure:

This design also incorporates meandering technique, as used in 0^0 Serpentine Flexure, in order to reduce the divider size. Impedances $Z_{01}$and Z_{02} are bent at right angles using microwave bends and then miniaturization of their line-length is done by meandering them while maintaining a required separation of 0.224 mm between the coupled-lines (Z_{01}). Thus, a total of 13 mm and 11.4 mm of Z_{01} and Z_{02}, respectively, is meandered in order to provide a serpentine structure. Similarly, Z'_{01} and Z'_{02} are also meandered (11.95mm and 12.25mm, respectively) using bends from two positions to have output ports at right angle to the input port as shown in fig. 3. The output ports in this divider are 32.7 mm apart and the total cover area of this model of 3:1 Unequal WPD is “32.7×20.7” mm^2.

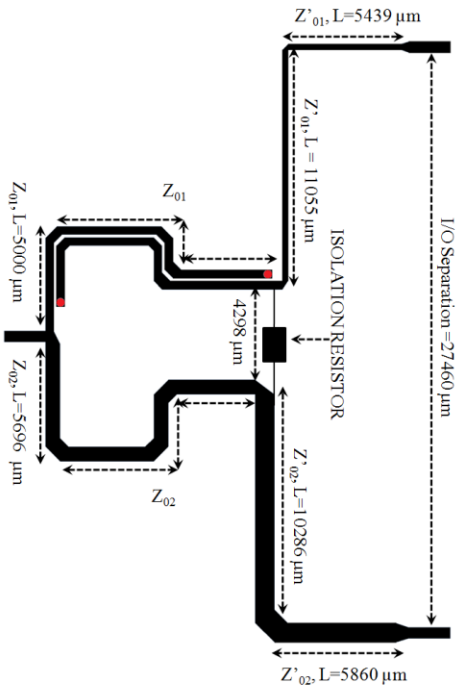

Fig.2. 3:1 Unequal 0^0 Serpentine flexure

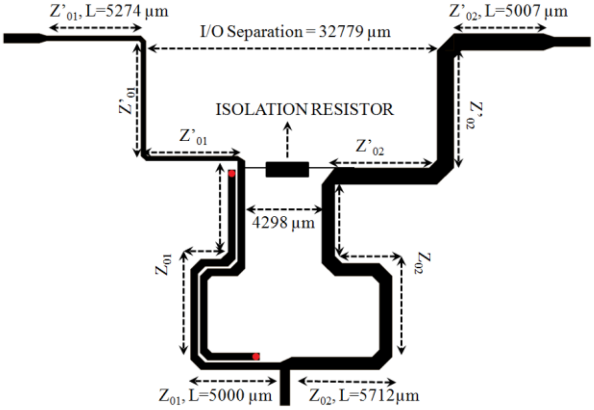

Fig.3. 3:1 Unequal 180^0 Serpentine flexure

3.3 Compact Meandered Flexure

This model is designed to meet the size constraints of the system employing unequal power dividers. In this, meandering technique is applied for all the impedance lines in order to miniaturize the divider. The total length of the impedances that is meandered in order to provide a compact flexure is: Z_{01}= 12.67 mm, Z_{02}= 10.90 mm, Z'_{01} = 13.58 mm and Z'_{02}= 10.914mm. The overall covered area of this divider is “25×11” mm^2 which is 342.05 mm^2 and 401.89 mm^2 smaller than serpentine 0^0 and 180^0 flexure respectively.

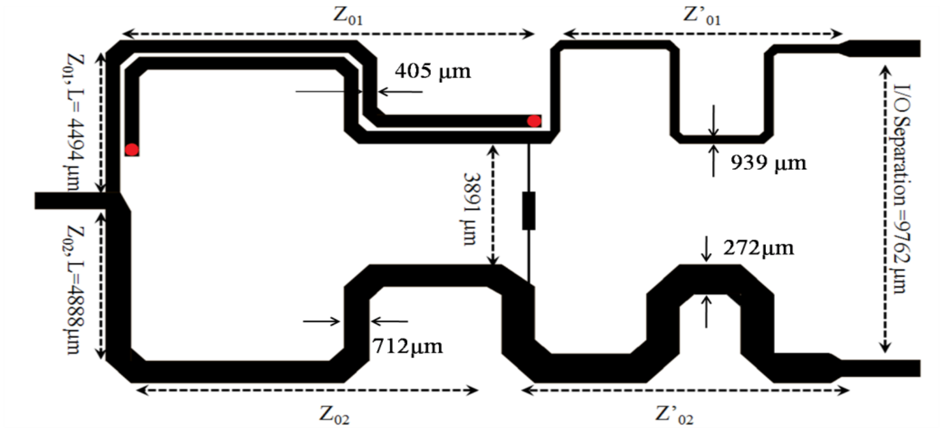

Fig.4. 3:1 unequal Compact meandered flexure

In order to verify the design methodology adopted for 3:1 unequal Wilkinson Power Divider, a 10:1 Unequal WPD is also designed using the same substrate and coupled-line technique. For k^2=10, the calculated values for various impedances are: Z_{01}=294.9Ω, Z_{02}=29.5Ω, Z'_{01}=88.9Ω, Z'_{02} =28.1Ω and the value for isolation resistor comes out to be, R=65.81 Ω. For coupling coefficient C=0.30, the even and odd-mode impedances of coupled-line section are calculated as 126.28 Ω and 68.05 Ω, respectively. Thus, the obtained coupled-line width, length and separation are 0.470 mm, 17.454 mm and 0.272 mm respectively. The compact meandered structure of 10:1 unequal WPD is shown in fig. 5 with total cover area of "23.6×37.2" mm^2.

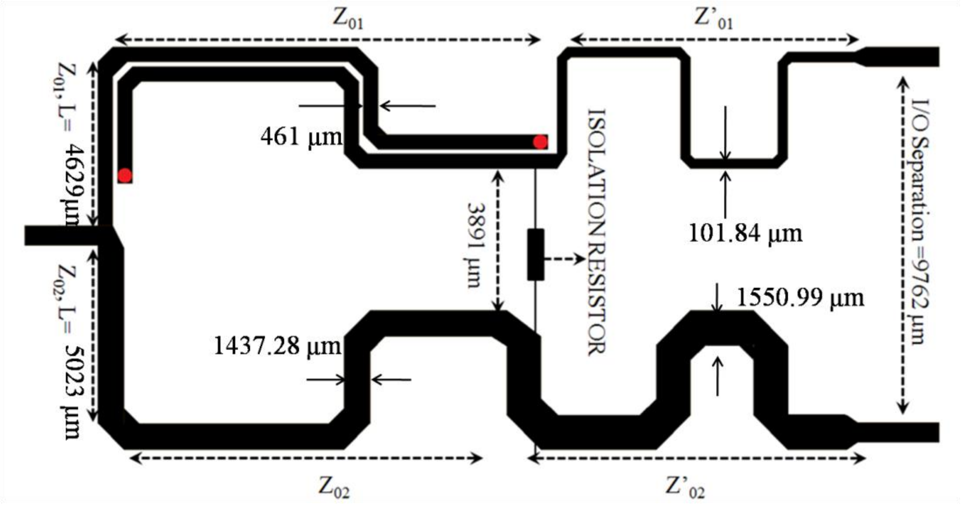

Fig.5. 10:1 Unequal Compact Meandered Flexure

4. Results and Discussion

Both 3:1 and 10:1 unequal WPDs are analyzed in commercially available FEM solver [16] that provides with the more refined results due to the entire 3D structure under consideration. These analysis are better than 2D or surface analysis because classic calculations involves 2D simulation and do not provide sufficient accuracy whereas FEM solver efficiently optimize the design using tetrahedral meshing and solved by an iterative, direct or pardasio solver. The above mentioned structures are simulated on a high-resistive silicon substrate ($\rho>8K\Omega$-Cm, h=675μm and ε_r= 11.8) for a centre frequency of 1.575 GHz. Thin substrates with high dielectric constant are very effective in minimizing undesired radiations which also considerably reduce the size of the structure. Thereby, making silicon a highly proficient choice for the designed unequal WPDs. RF performance of 3:1 and 10:1 unequal WPDs is shown in fig. 6 and with their comparative study summarization in table 1.

From the graphs, depicting the RF-Performance of the designed dividers, it is clear that all the three designed 3:1 unequal WPDs provide the required power dividing ratio at the output ports with satisfactory value of return and insertion loss. All the dividers have return loss better than the targeted value of -10 dB and an insertion loss of -6 dB and -1 dB at the output ports which signify that the required power dividing ratio is achieved. Return loss of 0^0 serpentine flexure is -45.237 dB at the resonating frequency of 1.575 GHz whereas for 180^0 serpentine flexure and compact meandered flexure its value is -40.046 dB and -30.016 dB respectively. Thus, in terms of RF-performance, 0^0 serpentine flexure is the best designed power divider out of all the proposed 3:1 unequal WPDs. However, if total cover area is considered then compact meandered, having the smallest cover area is the ideal choice for 3:1 unequal power division. All the proposed 3:1 unequal WPDs provide a sufficient bandwidth of around 1 GHz for their smooth functioning. The design methodology adopted for 3:1 unequal WPD is verified successfully with the satisfactory RF-performance of designed compact meandered type 10:1 unequal WPD. It provides a return loss of -45.968 dB and an insertion loss value of -10.316 dB and -0.454 dB for both the output ports i.e. satisfy the required power split ratio. Also, the bandwidth provided by this design is around 2.5 GHz which is larger than that of 3:1 unequal WPD by 1.5 GHz. Thus, the proposed unequal WPDs designed using coupled-line sections have satisfactory RF-performance with required power split ratio and operational bandwidth.

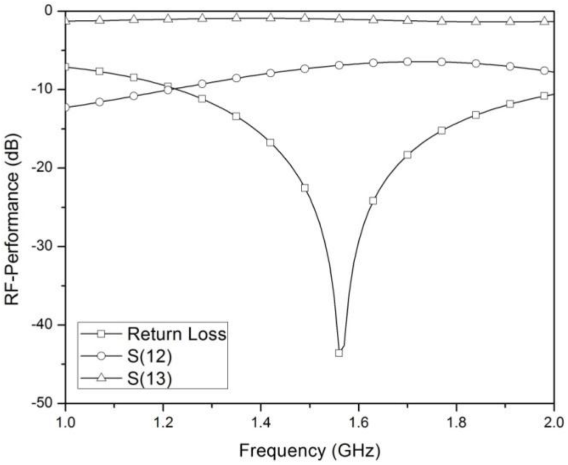

Fig.6. (a): RF Performance of 0^0 Serpentine Flexure of 3:1 unequal WPD

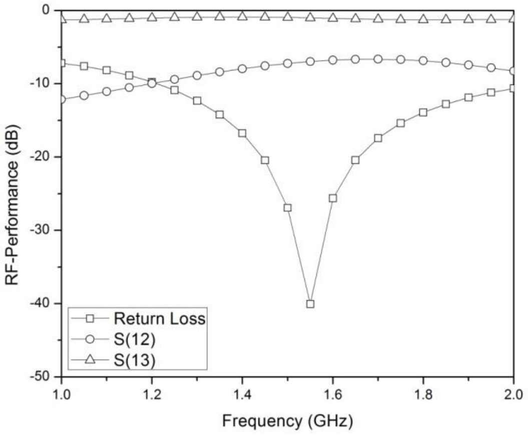

Fig.6. (b): RF Performance of 180^0 Serpentine Flexure of 3:1 unequal WPD

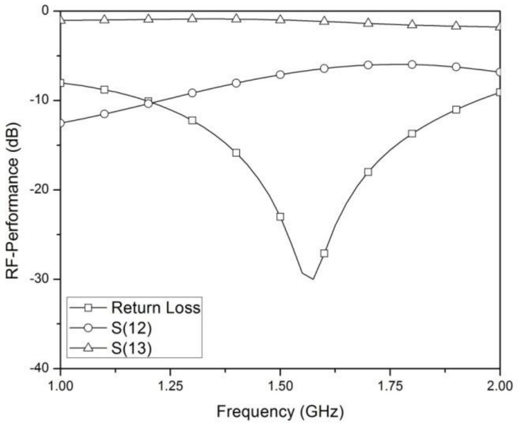

Fig.6. (c): RF Performance of Compact Meandered Flexure of 3:1 unequal WPD

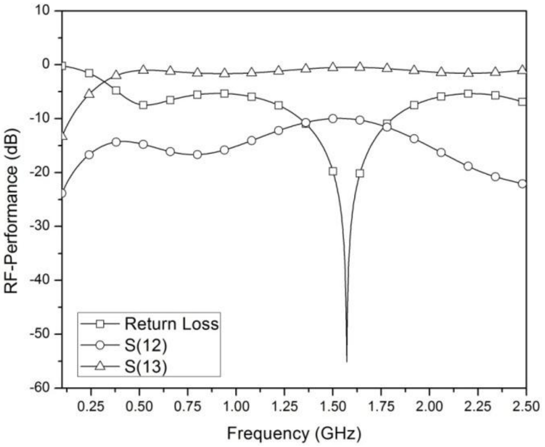

Fig.6. (d): RF Performance of basic structure of 10:1 unequal WPD

Table 1. Performance Comparison of Designed Unequal WPDs

Parameters (at f=1.575 GHz)		*3:1 Unequal WPD*			*10:1 Unequal WPD*
		0^0 Serpentine Flexure	*180^0 Serpentine Flexure*	*Compact Meandered Flexure*	
Return Loss (S_{11} ; dB)		*-45.237*	*-40.046*	*-30.016*	*-45.968*
Insertion loss (dB)	*S_{12}*	*-6.963*	*-6.777*	*-6.569*	*-10.316*
	S_{13}	*-1.006*	*-1.054*	*-1.117*	*-0.454*
Size (mm^2)		*28.7×21.5*	*32.7×20.7*	*25×11*	*23.6×37.2*

5. Conclusions

Both the unequal Wilkinson Power Dividers (3:1 and 10:1) have been analyzed and simulated. All the models of 3:1 unequal power divider have return loss better than -10 dB and also satisfy the required power dividing ratio. However, among these models, 0^0 serpentine flexure has the highest return loss value i.e. -5 dB and -15 dB more than serpentine 180^0 and compact meandered flexure whereas in terms of the divider size, compact meandered flexure has the smallest size among all the three flexure designs. Thus, if output ports are required to be in same axial plane with high return loss value than 0^0 serpentine flexure can be preferred whereas, in applications, if size is a constraint then compact meandered flexure can be employed. However, if output ports are required to be at right angles to the input port with moderate divider size and return loss value then 180^0 serpentine flexure will be the best choice. The return loss of 10:1 unequal WPD is above -40 dB and also satisfies the required power dividing ratio. Thus, the coupled-line section adopted in designing the unequal power dividers along with meandering technique fulfils its purpose satisfactorily which is supported well by the excellent RF performances of both the dividers (3:1 and 10:1) at the required centre frequency.

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