Abstract—This paper presents an unequal Wilkinson power divider operating at arbitrary dual band without reactive components (such as inductors and capacitors). To satisfy the unequal characteristic, a novel structure is proposed with two groups of transmission lines and two parallel stubs. Closed-form equations containing all parameters of this structure are derived based on circuit theory and transmission line theory. For verification, two groups of simulation results of different stub shapes for the same schematic design has been done. It can be found that all the analytical features of this unequal power divider can be fulfilled at arbitrary dual band simultaneously.

I. INTRODUCTION

POWER dividers and combiners are key components in microwave and millimeter-wave systems. With the proliferation of dual band requirement in wireless communication systems, although many advances have been made on the design of dual band power dividers, they do not involve the issue of unequal power dividing ratio, which has been proposed in [1]–[5] for single-band operations.

In this paper, a new structure of dual band unequal Wilkinson power divider is proposed. Its isolation structure only contains a resistor and the impedance characteristics are asymmetric. General, this structure has two main features, which are: 1) a distributed structure is adopted without reactive components, which means that the power divider can be fabricated easily and characteristic distortion of reactive components can be avoided at high frequency and 2) two structures, i.e., an open stub and a short stub, can be chosen to satisfy the application flexibility. Since power dividing ratio is unequal in this structure, the traditional even-mode and odd-mode analysis is not available in this case. Analytical solutions are therefore inferred from circuit theory and conventional transmission line theory.

II. THEORY AND DESIGN EQUATIONS

The proposed structure for the power divider is shown in the Fig.1. The isolation resistor $R$ is provided.

A. Characteristic Impedance Design

The Design is divided into two parts: First part is to calculate all the circuit parameters in block $T$, and the other is to design the rest of the components. If the power division ratio is $k^2(P_3/P_2 = k^2)$

$$R_2 = k^2 R_3, \frac{Z_{in\_2}}{Z_{in\_3}} = k^2.$$

Circuit of power divider with voltage source at port 2

To match port 1 $Z_0$ must be equal to the parallel combination of $Z_{in\_2}$ and $Z_{in\_3}$.

$$Z_0 = \frac{Z_{in\_2}Z_{in\_3}}{Z_{in\_2} + Z_{in\_3}} = \frac{k^2}{1 + k^2} Z_{in\_3}.$$

From the above equations we can get $Z_{in\_2}$ and $Z_{in\_3}$ in terms of $Z_0$.

$$Z_{in\_2} = (1 + k^2)Z_0, \quad Z_{in\_3} = \frac{1 + k^2}{k^2} Z_0.$$

Based on Monzon's theory to match all the output ports at both frequencies $f_1$ and $f_2 = mf_1$, where is the frequency ratio, the corresponding characteristic impedances of port 2 and
port3 must satisfy:

\[
\begin{aligned}
Z_3 &= Z_0 \sqrt{\frac{k}{2p^2}}(1 - k) + \sqrt{\left(\frac{k}{2p^2} (1 - k)\right)^2 + k^3} \\
Z_4 &= \frac{kZ_2}{Z_3} \\
Z_5 &= \frac{Z_4}{k} \\
Z_6 &= \frac{Z_3}{k}
\end{aligned}
\]

where

\[p = \cot(\theta).\]

And

\[\theta = \frac{n\pi}{1 + m}, \quad n \in \mathbb{N}^+; \quad m > 1\]

\[n\] is chosen as 1 for compact power divider. Next step is to ascertain parameters in \(T\), i.e. \(R_1, Z_1, Z_2\) and two stubs for which we make use of combinational circuit theory and transmission line theory. All ports are matched exactly. Ports 1 and 3 are grounded, while a voltage source is connected to port 2.

Applying Kirchoff’s law:

\[
\begin{aligned}
U_1 &= I_1Z_0, I_{2i} = I_1 + I_{3i}, I_{2o} = I_2 + I_R \\
I_R &= \frac{U_2 - U_3}{R}, I_{3o} = I_3 + I_R, I_{3o} = \frac{U_3}{R_3} \\
U_2 &= A_{T1}U_1 + B_{T1}I_{2i} \\
I_2 &= C_{T1}U_1 + D_{T1}I_{2i} \\
U_1 &= A_{T2}U_3 + B_{T2}I_3 \\
I_3 &= C_{T2}U_3 + D_{T2}I_3.
\end{aligned}
\]

For perfect isolation we also infer that:

\[U_3 = 0.\]

The equivalent transmission matrices of each arm can be written as a transmission line followed by a stub and then a transmission line who’s equation will reduce to the following form:

\[
T_i = \begin{bmatrix} A_{T1} & B_{T1} \\ C_{T1} & D_{T1} \end{bmatrix} =
\begin{bmatrix}
\cos^2 \theta - Y_{S1}Z_1 \sin \theta \cos \theta - \sin^2 \theta \\
j \cos \theta (2 \sin \theta / Z_1 + Y_{S1} \cos \theta) \\
\end{bmatrix}
\begin{bmatrix}
j Z_1 \sin \theta (2 \cos \theta - Y_{S1}Z_1) \\
\cos^2 \theta - Y_{S2}Z_1 \sin \theta \cos \theta
\end{bmatrix}
\]

Similarly for second arm, equivalent T matrix is:

\[
T_2 = \begin{bmatrix} A_{T2} & B_{T2} \\ C_{T2} & D_{T2} \end{bmatrix} =
\begin{bmatrix}
\cos^2 \theta - Y_{S2}Z_2 \sin \theta \cos \theta - \sin^2 \theta \\
j \cos \theta (2 \sin \theta / Z_2 + Y_{S2} \cos \theta) \\
\end{bmatrix}
\begin{bmatrix}
j Z_2 \sin \theta (2 \cos \theta - Y_{S2}Z_2) \\
\cos^2 \theta - Y_{S2}Z_2 \sin \theta \cos \theta - \sin^2 \theta
\end{bmatrix}
\]

After some manipulation we get the resistor value \(R\)

\[
R = \frac{U_2}{I_R} = -\left( \frac{A_{T1}B_{T2} + B_{T1}D_{T2}}{Z_0} \right)
\]

We know that if the characteristic impedances of the two arms are \(R_3\) and \(R_5\), then, we can express the input impedances of the ports in terms of the T matrix parameters and the characteristic impedance as follows:

\[
\begin{aligned}
Z_{in1} &= \frac{A_{T1}R_2 + B_{T1}}{C_{T1}R_2 + D_{T1}} \\
Z_{in3} &= \frac{A_{T2}R_3 + B_{T2}}{C_{T2}R_3 + D_{T2}}
\end{aligned}
\]

From the first relation between \(Z_0\) and \(Z_{in2}, Z_{in3}\) and the T matrix equivalent and the above relation, we can get:

\[
\begin{aligned}
(1 + k^2)kZ_0^2 &= Z_0^2 \tan^2 \theta \\
1 + k^2 &= Z_0^2 \tan^2 \theta \\
1 - Y_{S1}Z_1 \tan \theta - \tan^2 \theta &= 0 \\
1 - Y_{S2}Z_2 \tan \theta - \tan^2 \theta &= 0.
\end{aligned}
\]

From the above relation, we can find the values of \(Z_1\) and \(Z_2\) and the stub admittances in terms of \(\theta\) and \(Z_0\):
B. Analysis of the Impedance Values

Here, the relationships between the available impedance values and the corresponding scope of the frequency ratio \( m \) are presented. The power dividing ratio is set to \( k = \sqrt{2} \) as the analysis on the equal power dividing case where \( k = 1 \) shows that impedances of lines and stubs vary with the frequency ratio \( m \). Assuming that the available impedance values are in the range \((7,150)\) the maximum frequency ratio range is \((1.79,2.51)\) for the short stubs case and \((1.59,2.12)\) for the open stubs case. Like the unequal single band power divider, the difference between impedance values at the two branches will become greater as the power dividing ratio \( k \) increases. Therefore, the maximum frequency ratio range decreases as \( k \) increases. For the proposed dual band unequal power divider, it is necessary to employ special techniques to implement high impedance transmission lines when \( k \) is large.

III. SIMULATION AND MEASUREMENT

In this section, two dual band unequal power dividers have been fabricated on an F04 substrate with 0.8-mm thickness and 4.4 relative permittivity to verify the proposed design method. The simulation is based on ideal lossless transmission line model (in closed-form equations) and circuit model. The simulation is done for two different stub shapes and their effects on the s-parameters is studied.

A. Schematic simulation

The above shown s-parameter graphs are schematic simulated graphs. The first graph shows the reflection coefficients of each port without the isolation resistor \( R = 106.066017 \). The second graph is the same s-parameters, but with isolation.
resistor. The last graphs show how much power is given to each port. The power ratio at the specified $f_1$ and $f_2$ are almost the same. $|S_{21}|$ and $|S_{31}|$ are around -2dB and -5dB respectively which satisfies the condition.

B. Momentum simulation

Here the power divider layout is created and the simulation is performed with respect to additional layout constraints. Two layouts having a stub structure difference have been simulated and the results are as below. The first layout has a bend in the stub and the second layout has a straight stub.

The layout1 results in a small shift from the desired frequency due to the length and bend constraints. The related plots of the s-parameters of each port is given below

![Layout1](image1)

When the layout is simulated we first notice that there is a small shift in frequency from the schematic as the present results depend upon the geometry of the transmission line structures. The results of the $S_{11}$ show that the $f_1 = 1.26$ and $f_2 = 2.29$ GHz respectively. The power division has also become asymmetric in both bands. The first band power ratios of port 2 and 3 are around 2dB is to 5dB, while in the f2 band, it is 2dB is to around 6dB.

The last plot is similar to the schematic simulation without isolation resistor result where the $|S_{22}|$ is not high enough. This matches with the fact that no isolation resistor has been included in the layout simulation.

![Layout2](image2)
Now it is very evident from the second layout that the performance has increased. The rejection $|S_{11}|$ has increased significantly by around 5dB. In addition the frequencies $f_1$ and $f_2$ are very close to the actual frequency for which the power divider was designed for. Adding an isolation resistor after fabrication is supposed to enhance rejection of reflections in the port two and three.

C. Experimental Results

The layout of the power divider is shown below. We can see that the $S_{11}$ is having high attenuation very near to 1.2GHz and 2.2GHz of around -35dB.
The values of S21 and S31 are found to be close to the simulation results. The values ranging close to 5dB and 4dB respectively. The soldering points and finite length of isolation resistor and resistance due to the solder etc cause the values to deviate from the ideal values which was obtained from simulation results.

CONCLUSION

In this paper, Dual Band Wilkinson Power divider without Reactive Components was designed, simulated and implemented. The two stubs in each arm are designed in two different ways in layout and simulated out of which the better one is implemented in hardware. In the frequency bands selected, we see high reflection coefficients in each port. The power is divided in the ratio 2:1. The measured and simulated results show good similarity in characteristics, which shows that the power divider can be of application in microwave circuits.

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