A Parallel-Strip Ring Power Divider With High Isolation and Arbitrary Power-Dividing Ratio

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Abstract—In this paper, a new power divider concept, which provides high flexibility of transmission line characteristic impedance and port impedance, is proposed. This power divider is implemented on a parallel-strip line, which is a balanced transmission line. By implementing the advantages and uniqueness of the parallel-strip line, the divider outperforms the conventional divider in terms of isolation bandwidths. A swap structure of the two lines of the parallel-strip line is employed in this design, which is critical for the isolation enhancements. A lumped-circuit model of the parallel-strip swap including all parasitic effects has been analyzed. An equal power divider with center frequency of 2 GHz was designed to demonstrate the idea. The experimental results show that the equal power divider has 96.6% -10-dB impedance bandwidth with more than 25-dB isolation and less than 0.7-dB insertion loss. In order to generalize the concept with an arbitrary power ratio, we also realize unequal power dividers with the same isolation characteristics. The impedance bandwidth of the proposed power divider will increase with the dividing ratio, which is opposite to the conventional Wilkinson power divider. Unequal dividers with dividing ratios of 1 : 2 and 1 : 12 are designed and measured. Additionally, a frequency independent 180° power divider has been realized with less than 2° phase errors.

Index Terms—Arbitrary power-dividing ratio, parallel-strip line, ring structure, unequal power divider.

I. INTRODUCTION

THE WILKINSON power divider is one of the conventional and fundamental components in microwave engineering and exists in many microwave circuits. Both distributed and lumped Wilkinson power dividers have been applied in microwave integrated circuits and monolithic microwave integrated circuits [1]. Recently, extensive studies have been made to enhance the performances of the Wilkinson power divider, including size reductions by capacitive loading [2], folded circuitry [3] and resonating structure [4], [5], multiband operation [6], [7], unequal power dividing/combining [8], and active device [9] and waveguide implementations [10]. The power dividers discussed in this paper are focused on the isolation enhancement. The proposed divider is realized in the parallel-strip transmission line. Some parallel-strip circuits were reported with performance enhancement [11], [12]. The parallel-strip line provides more design flexibility than a microstrip line, especially in realization of a high-impedance line and transitions.

Many balanced circuits such as push–pull amplifiers, balanced mixers, frequency multipliers, and antenna arrays employ the Wilkinson power divider because of its simple design with high port-to-port isolation. Isolation is one of the important issues in the design of the power divider and directional coupler. High isolation implies the minimization of unwanted coupling between active devices, as well as the elimination of unexpected distortions and oscillations. It is because it may provide a positive feedback path for other frequencies, e.g., in Fig. 1, as unwanted oscillation at \( f_1 \) may be set up outside of the operation frequency \( f_0 \). Therefore, a wideband isolation operation is always preferred to suppress the coupling in other frequency bands.

The parallel-strip line belongs to a family of balanced transmission line. The conventional printed circuit board (PCB) fabrication technique is able to easily realize parallel-strip lines. It is a simple structure of a dielectric substrate sandwiched between two strip conductors. The signals flowing on the upper and lower strip conductors are always equal in magnitude and 180° out-of-phase. The quasi-TEM mode electric and magnetic fields distributions are close to the microstrip line. In this paper, a parallel-strip swap is employed to enhance isolation performance of the power divider. The swap is a passive microwave component. It forms a compact realization of 180° phase shift by interchanging the connection of two conductors in the balanced transmission line. Various swaps were proposed for performance enhancement in a 180° hybrid coupler [13]–[15].

Fig. 1. Balanced circuit at frequency \( f_0 \) and unwanted feedback at \( f_1 \).
A new equal power divider, which is realized on a parallel-strip line with a ring-like structure, was first demonstrated in [16]. The four arms and two shunt resistors in the divider provide a high degree of freedom for choosing the circuit parameters. In this paper, the proposed concept is generalized to arbitrary power dividing without an increase in design complexity. It shows a frequency-independent isolation characteristic, arbitrary power-dividing ratio without an external matching network, avoidance of a very thin strip line for achieving high characteristic impedance, and ease of realizing wideband 180° dividing. While the conventional Wilkinson power divider exhibits limited isolation bandwidth, unequal Wilkinson power dividing relies on an external quarter-wave transformer for realizing unequal power dividing for the same port impedances. High characteristics impedance transmission lines are required for the unequal power divider. The unequal divider has been used with strict restrictions in design and fabrication because it requires a transmission line with very high impedance [8]. On the other hand, the very thin transmission line limits the power handling of the devices. To overcome this limitation in realizing characteristic impedance, the upper and lower strip lines of the parallel-strip line are offset so that it will be easier to highly increase the characteristic impedance. Three power dividers with power-dividing ratios of 1:1, 1:2, and 1:12 were designed, fabricated, and tested.

II. THEORETICAL ANALYSIS

The structure of the proposed divider is illustrated in Fig. 2. In [13], the equal power divider has been analyzed using even- and odd-mode analysis because of symmetry of the divider. For the same reason, the circuit parameters, such as port impedance and line impedances, should be the same as their corresponding parameters \( Z_A = Z_C, Z_B = Z_D \), and \( Z_2 = Z_3 \). In this paper, we try to generalize the analysis to an unequal power divider with an arbitrary dividing ratio.

It consists of an 180° swap, four quarter-wave-long arms (with characteristic impedances \( Z_A, Z_B, Z_C, \) and \( Z_D \)) and two shunt resistors with resistance \( R \). These five parameters determine the input impedances, isolation, and dividing ratio of the divider. In order to determine the arm characteristic impedances and resistor values, several parameters should be known, including port impedances \( Z_1, Z_2, \) and \( Z_3 \) and power ratio \( k \).

Firstly, the impedance matching is considered. To achieve maximum power transfer, all the ports should be matched. The input impedance at port 1 is determined by \( Z_A \) and \( Z_C \) and port impedances \( Z_2 \) and \( Z_3 \). As illustrated in Fig. 3, it is assumed that a signal is injected to port 1 and will only pass through ports 2 and 3. There is no net current flowing from ports 2 to 3 due to port isolation between ports in the shaded region. Arms B and D with characteristic impedances \( Z_B \) and \( Z_D \), respectively, the two shunt resistors, and the swap can thus be replaced by an open circuit in analysis. The two arms are connected in shunt; the input impedance at port 1 can be expressed as

\[
Z_1 = \left( \frac{Z_2}{Z_A} + \frac{Z_3}{Z_C} \right)^{-1}. \tag{1}
\]

The signal injected to port 2 can be divided into two parts, one flowing to port 1 and the other being absorbed by shunt resistors as shown in Fig. 4. Obviously, there is no net current flowing from arm \( C \) to arm \( D \) and port 3 in the shaded region, which can be replaced by an open circuit in analysis. The input impedance at port 2 can be given as

\[
Z_2 = \left( \frac{Z_1}{Z_A} + \frac{R}{2Z_B} \right)^{-1}. \tag{2}
\]

Similarly, the input impedance at port 3 can be expressed as

\[
Z_3 = \left( \frac{Z_1}{Z_C} + \frac{R}{2Z_D} \right)^{-1}. \tag{3}
\]
For the unequal power dividing and assuming the power ratio of ports 2 and 3 to be \( k \), the power ratio can be determined by the ratio of input impedance of the arms \( A \) and \( C \), as shown in Fig. 3, as follows:

\[
k = \frac{Z_C^2}{Z_A^2} = \frac{Z_2^2 Z_3}{Z_A^2 Z_3^2}.
\] (4)

By solving (1), (2), and (4), \( Z_A \) and \( Z_C \) are determined and are expressed in (5) and (6), respectively.

Solving (4) and (1),

\[
Z_C = \sqrt{(1 + k) Z_1 Z_3}.
\] (5)

Solving (4) and (2),

\[
Z_A = \sqrt{\left(1 + \frac{1}{k}\right) Z_1 Z_2}.
\] (6)

Hence, the ratio of the square of \( Z_B \) and \( Z_D \) and shunt resistor \( R \) can be determined by solving (2), (3), (5), and (6).

Solving (5) and (2),

\[
\frac{Z_B}{R} = \frac{Z_3}{2} \left(1 + \frac{1}{k}\right).
\] (7)

Solving (6) and (3),

\[
\frac{Z_B}{R} = \frac{Z_2}{2} (1 + k).
\] (8)

There are four conditions, but five unknown parameters \( Z_A, Z_B, Z_C, Z_D \), and \( R \). Therefore, the solutions are singular, which implies there is no unique solution. The infinite number of solutions provide a high degree of freedom when the divider is designed. For example, the divider can not only be designed for any port impedance without external matching circuits, but also provides unequal power dividing with equal port impedance.

Isolation is a very important design issue. The symmetrical structure and the swap provide the possibility of frequency-independent isolation characteristics. Signals flowing through paths \( A-C \) and \( B-D \) should be equal in magnitude, but 180° out-of-phase. In order to provide frequency-independent isolation, the phase difference between paths \( A-C \) and \( B-D \) should be frequency independent at 180° out-of-phase and with equal amplitude, which is provided by the swap, and the characteristic impedance should be the same

\[
Z_A = Z_D \text{ and } Z_B = Z_C.
\] (9)

Equation (9) represents the fifth condition for designing a divider with frequency-independent isolation and arbitrary power ratio. After combining the previous conditions, the parameters \( Z_A, Z_B, Z_C, Z_D, \) and \( R \) become unique. The design formulas can be summarized as

\[
R = 2Z_1
\] (10a)

\[
Z_B = Z_C = \sqrt{(1 + k) Z_1 Z_3}.
\] (10b)

\[
Z_A = Z_D = \sqrt{\left(1 + \frac{1}{k}\right) Z_1 Z_2}.
\] (10c)

Extra insertion loss and phase delay are introduced by the vertical via, which can be analyzed by a lumped-circuit model. The lump-circuit model of the swap with two shunt resistors \( R_S \) is illustrated in Fig. 8. The parasitic capacitance \( C_S \) is used to model the edge couplings between strips with different layers. The parasitic capacitance \( C_C \) is used to model the total effect due to edge couplings between strips with the same layers and coupling between the vias. The parasitic inductance \( L_V \) and resistance \( R_V \) are introduced by vertical conductor in via-holes and soldering. The parasitic components can be extracted from full-wave simulations so that the lumped model of the swap was done.

The \( Z \)-parameter of the lumped equivalent model of the core in Fig. 8 is given by

\[
\begin{pmatrix}
Z_{11} & Z_{12} \\
Z_{21} & Z_{22}
\end{pmatrix} = \frac{1}{2} \begin{pmatrix}
Z_1 + Z_2 & Z_1 - Z_2 \\
Z_1 - Z_2 & Z_1 + Z_2
\end{pmatrix}
\] (11)
where \( Z_1 = R_V + j\omega L_V \) and \( Z_2 = (1/R_S + 1/j\omega C_C)^{-1} \). Hence, the \( S \)-parameter converted from \( Z \)-parameters of the core is determined as follows:

\[
S_{11} = S_{22} = \frac{Z_1 Z_2 + Z_0^2}{(Z_1 + Z_0)(Z_2 + Z_0)} \tag{12}
\]

\[
S_{12} = S_{21} = \frac{(Z_1 - Z_2) Z_0}{(Z_1 + Z_0)(Z_2 + Z_0)}. \tag{13}
\]

The structure shown in Fig. 7 is simulated by the full-wave electromagnetic (EM) simulator HFSS, determining the optimum design of the vias on the substrate dielectric constant of 2.65 and thickness of 1.5 mm where all the gapwidths are 0.2 mm and the radius of the metallic via is 0.55 mm. Deembedding of the parameters has been performed by utilizing the microwave circuit simulator, Agilent Technologies’s Advanced Design System (ADS). Both EM and circuit simulations of the parallel-strip swaps with 70.71-\( \Omega \) terminations are shown in Fig. 9. Good agreement of both the magnitudes and phases responses are achieved within the frequency band of interest. The values of parasitic elements are \( L_V = 2.181 \) nH, \( C_S = 0.2939 \) pF, \( C_C = 0.3878 \) pF, and \( R_V = 0.2624 \) \( \Omega \). The model circuit is analyzed and, hence, the scattering matrix representing the parallel-strip swap with shunt resistor \( R_S \) is, therefore, obtained, and the entire circuit can thus be easily modeled in the circuit simulation.

IV. RESULTS OF SIMULATION AND EXPERIMENT

A. Equal Power Divider

The power dividers are fabricated in a conventional printed circuit technique and the dividers designed for demonstration
are built on a substrate with a dielectric constant of 2.65 and a thickness of 1.5 mm, as shown in Fig. 10. The derivation in Section II is based on an ideal transmission line model. This analysis provides initial design parameters. Discontinuities or parasitic elements such as T-junctions and steps will be introduced. EM optimization is required to determine all circuit parameters with the best performance.

All the port impedances are designed at 50 \Omega, i.e., \( Z_1 = Z_2 = Z_3 = 50 \Omega \) The design parameters of an equal power divider are \( Z_A = Z_B = Z_C = Z_D = 70.71 \Omega \) and \( R = 100 \Omega \).

By removing portion of the ground of a microstrip line, the parabolic tapered transition between the parallel-strip line and microstrip line [11] was employed for connecting the coaxial connector for measurement purposes with less than 0.1-dB insertion loss within the entire tested frequency band. However, an approximate 0.5-dB extra insertion loss will be introduced if a subminiature A (SMA) connector is directly connected to the SMA connector. Fig. 11 shows both simulated and measured results of the equal power divider. The EM simulation tool is Ansoft’s HFSS. The measured insertion loss from ports 1 to 2 and 3 are less than 3.7 dB within the operation frequency band, as shown in Fig. 11(a). Some mismatches come from an inaccurate prediction of the vertical structure from the EM simulator and soldering. The mismatches in return losses shown in Fig. 11(b) are due to unexpected errors from soldering between the divider and SMA connectors. The ring-like structure implies similar input and output impedance characteristics, as shown in Fig. 10. The total usable impedance bandwidth is wider than that of the conventional Wilkinson power divider. Due to the imbalances of the two paths, e.g., electrical delay and insertion loss in the swap, the isolation has a finite value. Fortunately, the isolation can still provide great improvement over the conventional divider.

The impedance bandwidths of return loss lower than \(-10 \mathrm{dB}\) of the proposed divider is measured at 96.5%, as observed in Fig. 11(b). In Fig. 11(c), the proposed divider demonstrates more than 25 dB in the entire frequency band in the measurement, while a conventional Wilkinson power divider shows approximately 33% isolation bandwidth of more than 20-dB isolation. Good agreement between experimental and simulated results can be observed.

### B. Unequal Power Dividers

Apart from the equal power divider, two unequal power dividers with ratios of 1 : 2 and 1 : 12 are realized. The impedance bandwidth is usually reduced with the dividing ratio in the conventional Wilkinson power divider; however, the bandwidth of the proposed divider is increased with a power ratio of \( k \). The relation is shown in Fig. 12. Figs. 13 and 14 show the frequency responses of \( S \)-parameters and the dividing ratio of the 1 : 2 power divider. The design parameters are \( Z_A = Z_D = 61.24 \Omega \), \( Z_B = Z_C = 86.61 \Omega \), and \( R = 100 \Omega \). Measured results agree with EM simulation. Within the 125% operation bandwidth with
lower than —10-dB return loss, more than 26-dB port-to-port isolation is achieved and the average divider ratio is approximately 2.07.

A high dividing ratio implies the existence of some high characteristic impedance transmission lines. The implementation of high characteristic impedance remains challenge because of the technique of extremely thin microstrip line fabrication. The realization of the unequal power divider may be limited by fabrication of the thin strip line and low power-handling capacity of the divider.

In order to easily realize a high-impedance transmission line, a microstrip defected ground structure was proposed for the 1:4 unequal divider [8]. In [17], the characteristics impedance parallel-strip line was increased by offsetting the upper and lower strip lines in the finite ground microstrip line for stopband enhancement. Similarly, the characteristics impedance of a parallel-strip line can be increased by offsetting the strip lines, as shown in Fig. 15. Fig. 16 shows the relationship between characteristics impedances and normalized circuit parameters on the same substrate. It is obvious that the characteristics impedance (\(z\)) increases with offset distance (\(d\)) without use of very narrow strip lines. A high characteristic impedance parallel-strip line can be realized by offsetting the upper and lower strip lines and it does not need a very narrow line.

In the 1:12 power divider, two arms with high characteristic impedance are realized by offsetting the parallel-strip line. Figs. 17 and 18 show its S-parameters and the dividing ratio varied with frequency. The design parameters are \(Z_A = Z_D = 52.04\ \Omega\), \(Z_B = Z_D = 180.27\ \Omega\), and \(R = 100\ \Omega\). Good
agreement of both simulated and measured results are obtained. Within the 150% operation bandwidth with lower than 10-dB return loss, more than 24-dB port-to-port isolation is achieved and the average divider ratio is approximately 12.68.

C. Frequency-Independent 180° Power Divider

Conventionally, the symmetric power divider is used for in-phase power dividing/combining. A power divider with wideband 180° out-of-phase operation is needed for many balanced circuit such as a push–pull amplifier and balanced mixer. The 180° hybrid or the power divider with a 180° delay line is used for such purpose. A 180° divider can be easily realized by adding an extra section of delay line. However, a delay line limits the bandwidth of phase balances. The conventional 180° hybrid coupler or Wilkinson power divider with a delay line may not fulfill actual application demands and may degrade system performance. With a similar approach to [12], the frequency-independent 180° differential phase between ports 2 and 3 is realized by tapering the lower line in port 2 and the upper line in port 3, the parallel-strip line-to-microstrip line transition, which is used for measurement, is formed as shown in Fig. 19. All circuit parameters are the same as the equal power divider in Section IV. The magnitudes of simulated and measured S-parameters are close to that of the equal power divider, as shown in Fig. 11. A frequency-independent 180° phase difference is observed, as shown in Fig. 20. A small phase error within 2° is introduced due to the thickness of the substrate of the PCB, while it can be minimized by using a thinner substrate with a lower dielectric constant. Similarly, the 180° unequal power divider with an arbitrary dividing ratio can be realized via the same technique.

V. CONCLUSION

A novel power divider with better isolation than the conventional Wilkinson power divider has been presented. Design formulas for the proposed divider have been proven analytically. The ring-like structure provides design flexibility such as unequal power dividing without extra impedance matching networks. The equal and unequal power dividers were designed and tested with out-performed isolation characteristics. Additionally, a 180° equal power divider was realized by making use of the balanced structure of the parallel-strip line. Similarly, a 180° unequal power divider can be designed. The proposed design leads to realization of a new geometrical configuration for a high-performance power-divider concept.
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