Rigorous Analysis and Investigation of the Bandwidth Broadening Mechanism in a Compact Power Divider With Physical Port Isolation

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\textbf{ABSTRACT} This paper proposes a compact power divider with simultaneous physical port isolation and wideband operation based on the simple Wilkinson power divider (WPD) configuration. Rigorous analysis based on the even- and odd-mode bisected networks has been performed to investigate the relationship between the design parameters and the overall performance. Theoretical analysis revealed that the impedance and isolation bandwidth are directly related to the reflection coefficients of the even- ($\Gamma_e$) and odd-mode ($\Gamma_o$) bisected networks. Simultaneous broadening of the impedance and isolation bandwidth is possible through the optimum choice of design parameters which confines the trajectories of the $\Gamma_e$ and $\Gamma_o$ in the low constant-Q region on the Smith Chart. Experimental verification by the prototype designed at 1 GHz exhibited the widest overall system bandwidth (43.2\%) and the lowest total electrical length (140.8\degree) as compared to the previous state-of-the-art WPD’s with physical port isolation.

\textbf{INDEX TERMS} Bandwidth, even-mode, isolation network, odd-mode, physical port isolation, Wilkinson power divider.

\section{I. INTRODUCTION}

The Wilkinson Power Divider (WPD) [1], [2], [3] is one of the most popular passive components for system implementation. Practically, the key performance indices of a power divider are return loss, isolation, and insertion loss with corresponding S-parameters being $S_{11}/S_{22}/S_{33}$, $S_{23}$, and $S_{21}/S_{31}$ given that port 1 is the common port. The narrowest bandwidth among the parameters determines the applicable system bandwidth.

In the conventional design approach, the even- and odd-mode analysis are applied with a purely resistive load of 100 \,$\Omega$ as the isolation termination. The impedance matching condition for the even-mode bisected network imposes the adoption of the quarter-wave impedance transformer between the common and split ports. Such arrangement has the advantage of the ease of design but generally occupies a large area. Various size reduction techniques have thus been proposed to implement the 90-degree electrical length with a shorter physical one. Among them, reactive loading technique was proposed [4], [5], [6] in which the isolation termination remained purely resistive. Further size reduction was made possible by introducing complex isolation networks (INWs) containing reactive components in addition to the resistive one [7], [8], [9], [10], [11], [12]. In [7], both the capacitive loading and the complex INW were applied and the overall size was reduced to $\lambda/30$ ($\lambda$ is the wavelength at the center frequency of operation). Despite the very compact size achieved, the main issue was the very limited space between the split ports. Such space limitation would induce unwanted
couplings between the split ports which is undesired for specific scenarios such as large-scale antenna arrays. Over the past, additional transmission line sections were adopted to provide necessary isolation between the split ports.

The idea of the port-extended power dividers was proposed in [13] and [14] that provided physical isolation between the split ports. The physical port isolation was achieved by moving the complex INW toward the common port by an electrical length of $90^\circ - \theta$ as shown in Fig. 1(a). Such configuration provided additional degree of freedom in terms of the design and synthesis for the odd-mode bisected network. Thus, quite a lot of research efforts have been dedicated to the performance improvement of power dividers using complex INWs [15], [16], [17], [18], [19], [20].

Recently with the advent of the 5G technology at millimeter-wave frequency bands, the need and development for wideband phased array antenna systems has spurred [21]. In such systems, the carrier aggregation technique together with wideband antennas are essential to acquire enough bandwidth for the boost of data transmission rates. Thus, emerging demand in the development of wideband power dividers is expected. Since very large scale antenna arrays for beamforming purposes are desired with ultra-high integration levels, compact power divider technology is necessary. In addition to the compactness in size, such power divider must possess port isolation characteristic to suppress the unwanted couplings due to the very tight spacing between antenna elements. Recently, implementation of such power divider at millimeter-wave frequencies has started to attract research attention [22]. In this work, implementation of the conventional complex INW using parallel-RC configuration over the patterned ground plane in 0.18m-CMOS technology has been firstly demonstrated at 33 GHz.

Although WPD-related fields seemed to be relatively mature, it is still very challenging to achieve both the impedance and isolation bandwidth simultaneously while maintaining the physical port isolation as concluded from the previous publications. In most cases, the limitation in bandwidth was associated with the impedance matching condition at the common port under even-mode operation. It is thus the main target of this work to achieve simultaneous impedance and isolation bandwidth with physical port isolation based on the simple conventional WPD topology.

In this paper, we performed rigorous analysis to investigate the relations between the design parameters and the bandwidth performance. The derivations revealed that the reflection coefficient of the odd-mode bisected network ($\Gamma_o$) critically determines the system bandwidth. Simultaneous broadening of impedance and isolation bandwidth could be possible by proper selection of the design parameters so that the trajectories of $\Gamma_e$ and $\Gamma_o$ with respect to frequency were confined in the low-Q portion on the Smith Chart. Moreover, optimum combination of the design parameters minimizes the difference between $\Gamma_e$ and $\Gamma_o$ which maximizes the system bandwidth. The proposed technique has been validated experimentally by the prototype designed at 1 GHz. The measurement results exhibited the widest overall system bandwidth (43.2%) and the lowest total electrical length (140.8°) as compared to the previous state-of-the-art WPD's with physical port isolation.

II. ANALYSIS

Fig. 1(a) shows the proposed configuration based on the conventional WPD configuration. Different from the conventional WPD case where the resistive isolation is connected at the split ports, a complex isolation network is moved toward the common port by an electrical length of $90^\circ - \theta$ from the split ports. Such shift corresponds to the physical isolation that can be pre-determined based on the specific application scenarios.

A. EVEN- AND ODD-MODE ANALYSIS

The even-mode bisected equivalent circuit is shown in Fig. 1(b). With the pre-determined electrical length of
The total size reduction as functions of the levels of physical port isolation in electrical length. In this plot, different transmission line impedance sections have been adopted showing the tradeoff between size reduction and physical port isolation.

Once the location of the INW from the split ports (90° – θ) is determined, the length of the transmission line sections between the common port and the INW can be synthesized by the above equations.

$$Z_o = \sqrt{2Z_LZ_m}$$

$$\theta_m = \sin^{-1}\left(\frac{Z_o}{Z_m}\sin \theta\right)$$

$$BZ_o = \left(\cos \theta_m - \cos \theta\right) \csc \theta$$

FIGURE 3. The total size reduction as functions of the levels of physical port isolation in electrical length. In this plot, different transmission line impedance sections have been adopted showing the tradeoff between size reduction and physical port isolation.

FIGURE 4. The synthesized (a) capacitance and (b) resistance of the isolation network with different Z_m at 1 GHz.

The impedance matching condition at the split ports then governs the equality between Z_o, and Z_L which in turn determines the impedance of the complex INW, Z_{iso}, as

$$Z_{iso} = Z_L \sin^2 \theta - jZ_0 \sin \theta \cos \theta$$

With θ less than 90°, (8) represents a series combination of a resistor and capacitor. The corresponding values of the components can be derived as

$$R_{iso} = Z_L \sin^2 \theta$$

$$C_{iso} = \left(\pi fZ_0 \sin 2\theta\right)^{-1}$$

where f is the center frequency. Fig. 4 shows the synthesized capacitance and resistance with different choices of Z_m at 1 GHz. As observed, the synthesized values are independent of Z_m.

The S-parameters of the power divider can then be derived from the reflection coefficients of the even- and odd-mode subnetworks as [23]

$$S_{11} = \Gamma_e$$

$$2S_{22} = (\Gamma_e + \Gamma_o)$$

$$2S_{23} = (\Gamma_e - \Gamma_o)$$

B. BANDWIDTH ANALYSIS

It is observed that the size reduction becomes less significant as the level of port isolation increases beyond 45° in electrical length. In general, the choice of high Z_m values tends to help size reduction as depicted in Fig. 3. However, high impedance lines may induce higher transmission loss. The corresponding admittance level acting as capacitive loading could then be uniquely synthesized by (3) once θ and Z_m are determined.

Referring to Fig. 1(b), the impedance at the split port and the reflection coefficient of the even-mode bisected network can be derived as (4a), shown at the bottom of the next page.

$$\alpha = 2BZ_m + \tan \theta_m$$

$$\beta = B + Z_m \tan \theta_m$$

$$\Gamma_e = (Z_{e,in} - Z_L) (Z_{e,in} + Z_L)^{-1}$$

Similarly, the corresponding impedance and reflection coefficient for the odd-mode sub-network shown in Fig. 1(c) can be derived as

$$Z_{o, in} = Z_{iso} \csc^2 \theta + jZ_0 \cot \theta$$

$$\Gamma_o = (Z_{o, in} - Z_L) (Z_{o, in} + Z_L)^{-1}$$

The S-parameters of the power divider are directly related to the reflection coefficients of the even- and odd-mode sub-networks. Thus, the investigations of the relation between S-parameters and the overall system bandwidth are performed.

Note that the size reduction is defined as the reduction in electrical length compared to that of the conventional WPD which is 90° at the center frequency.
Starting from the output terminations of the split ports in the even-mode sub-network, the trajectories of the transmission-line segments are plotted in the Smith Chart as shown in Fig. 5. Two different levels of $Z_m$, namely, 90 $\Omega$ (Fig. 5(a)) and 150 $\Omega$ (Fig. 5(b)), are selected for the illustration purposes. For each $Z_m$, different locations of the complex INW expressed in terms of $\theta$ are analyzed. Referring to Fig. 1(b), the selection of larger $\theta$ means that the INW is located closer to the split ports. It is observed in Fig. 5 that under the same impedance matching condition for the even-mode bisected network, when the INW is positioned close to the split ports, the impedance transformation trajectories surpassed the high constant-Q region leading to narrower bandwidth. Similar behavior has been observed for higher $Z_m$ level. In both cases, the longer trajectories are related to high $B$ values as is governed by (3).

Fig. 6 shows the plots of $\Gamma_e$ with different values of $\theta$ ($45^\circ$, $65^\circ$, and $85^\circ$) swept from 0.8 - 1.2 GHz on the Smith Chart with different $Z_m$ levels. The boundaries of the constant Q regions are also included. As observed, the trajectories associated with higher $Z_m$ levels exhibited longer paths spanning over higher Q areas. This is in accordance with the analysis results shown in Fig. 5. Evidently, there is a trade-off between the operational bandwidth and the extent of size reduction.

The selection of a higher $Z_m$ level synthesizes a shorter physical length of a transmission line according to (2), yet the corresponding compensating reactance increases according to (3). Overall, such an increase in reactance may lead to bandwidth narrowing.

Fig. 7 illustrates the corresponding plots for the odd-mode sub-network illustrated in Fig. 1 (c). In contrast to the trend of the even-mode case, the trajectories surpassed the high constant-Q region for the case when the location of the INW was close to the common port. Based on the trend, the ratio of $Z_L/R_{iso}$ and $C_{iso}$, are the factors affecting the matching trajectories. Fig. 8 shows the similar contour of $\Gamma_o$ on the Smith Chart with different $\theta$ for various $Z_m$ levels. Unlike the case in the even-mode analysis where the input return loss is solely dependent on $\Gamma_e$, the overall bandwidth of the isolation ($S_{23}$) and the return loss at the split ports ($S_{22}$, $S_{33}$) is dependent on the summation or subtraction of the even- and odd-mode reflection coefficients as derived.

Fig. 9 shows the calculated bandwidth as functions of the location of the complex INW based on the previous analysis

$$
\frac{Z_{in,e}}{Z_o} = \frac{Z_m - \alpha Z_o \cot \theta + j2Z_S [\beta Z_m + Z_o \cot \theta (Z_m (1 - 2B\beta)) - B \tan \theta_m]}{2Z_S [Z_o (Z_m (1 - 2B\beta) - B \tan \theta_m) - \beta \cot \theta] + j(Z_m \cot \theta + \alpha Z_o)}
$$

(4a)
The calculated (a) impedance bandwidth at the common port ($S_{11}$), (b) impedance bandwidth at the split ports ($S_{22}/S_{33}$), (c) isolation ($S_{23}$) bandwidth, and (d) bandwidth of the extra insertion loss ($S_{21}/S_{31}$) in the excess of $-3$ dB power split as functions of the synthesis parameters. The center frequency of calculation was set to be 1 GHz.

On the contrary, the impedance bandwidth at the split ports and the isolation bandwidth, are sensitive to the variation of the location of the complex INW as shown in Fig. 9(b) and (c). Both of them exhibited a monotonic increasing trend for a certain range of $\theta$ and started to decrease drastically. Such observation agreed with that in [17] where physical isolation was achieved by moving the complex isolation network closer to the common port at the expense of the reduction in bandwidth. Finally, the insertion loss bandwidth in Fig. 9(d) almost followed the same trend as the impedance bandwidth at the common port. Practically, the applicable operation bandwidth of the system should be defined as the narrowest one among those depicted in Fig. 9 which is shown in Fig. 10. As shown, the choice of the location of the complex INW ($\theta$) at 65$^\circ$ exhibits the best system bandwidth performance. This is mainly because that the difference between $\Gamma_o$ and $\Gamma_e$ is the smallest as is evidenced from Figs. 5 and 7. Indeed, the reflection coefficient of the odd-mode bisected network ($\Gamma_o$) plays a critical role in determining the overall bandwidth based on the above analysis.

The design procedure of the above analysis can be summarized as follows:

**Step 1:** Based on specific application scenarios, the design starts with the determination of the physical isolation ($90^\circ - \theta$).

**Step 2:** Once $\theta$ is fixed, the design curves as shown in Figs. 2 and 3 can be applied for the selection of $Z_m$ and $\theta_m$. The tradeoff between the impedance level and the overall transmission line length between P1 and point A(A’) should be made.
Step 3: The rest of the key parameters can be synthesized using equations (1)-(3) after the determination of $Z_m$.

Step 4: Finally, the component values of the complex isolation network can be determined using even- and odd-mode analysis with the desired impedance and isolation bandwidth.

### III. EXPERIMENTAL VERIFICATION

To validate the theoretical analysis of the proposed configuration, a prototype centered at 1 GHz was designed, fabricated, and characterized. The prototype was built on a RO4003 substrate with a thickness of 0.508 mm, a dielectric constant of 3.38, and a loss tangent of 0.0027. The layout as well as the fabricated prototype are shown in Fig. 11, with detailed dimensions listed in Table 1. Based on the previous analysis, the location of the INW has been selected at $\theta = 65^\circ$ for optimum applicable bandwidth. Further reduction in size while maintaining physical isolation was achieved by the selection of $Z_m = 90 \, \Omega$, leading to the synthesized reactance of 4.36 mS at 1 GHz.

The S-parameters of the fabricated prototype was characterized using an Anritsu MS46522A analyzer. Fig. 12 shows the measured and simulated responses. The simulation was performed using CST Studio Suite [24]. Fig. 12(a) shows the insertion loss and the return loss at the common port. The measured results exhibit an extra insertion loss of 0.08 dB (in the excess of the $-3\text{dB}$ power split) at the center frequency. As for the impedance bandwidth, a 487 MHz bandwidth at the common port was achieved with $S_{11} < -20 \, \text{dB}$. Very good impedance bandwidth at the split ports was also observed. Fig.13 shows the simulated and measured amplitude and phase imbalance characteristics of the fabricated prototype.

Table 2 lists the comparisons of the proposed power divider with the previously published works. For fair comparison purposes, we have just included the ones with physical port isolation. As discussed in the previous sections, inclusion of the complex INW increases the degree of freedom leading to possible bandwidth broadening. This is evidenced...
TABLE 2. Performance comparison with previous publications.

| Ref. | $f_c$ (GHz) | Tech./INW | $^\text{a}E_{\text{tot}}$ (degree) | Physical Port Isolation | $S_{11}$ (%) | $S_{22}$ (%) | $S_{23}$ (%) | System BW (%) |
|------|-------------|-----------|----------------------------------|-------------------------|-------------|-------------|-------------|---------------|
| 13$^a$ | 1.5 | Extra QIT/parallel RCINW | 198.24 | Yes | 37.5 | 8.3 | 5 | 5 |
| 16$^b$ | 2 | Series RC | 180 | Yes | 25 | 16.21 | 20 | 16.21 |
| 17 | 1 | Coupled Line Section/parallel RCINW | 180 | Yes | 31.9 | 8.3 | 8.3 | 8.3 |
| 18$^c$ | 1.5 | Extra QIT/parallel RCINW | 198.5 | Yes | 30.2 | 11.7 | 4.8 | 4.8 |
| 19 | 1 | Series RC | 146.88 | Yes | 35.64 | 13.83 | 28.49 | 13.83 |
| 20 | 2 | Bandpass filter & multiple resistors/RTINW | 630 | Yes | 38.7 | 16 | >100 | 16 |
| This Work | 1 | High Impedance Line/series RCINW | 140.8 | Yes | 43.2 | 45.9 | 48.1 | 43.2 |

$^\text{a}E_{\text{tot}}$: Total electrical length, $^b$: Type I, $^c$: 3-way power divider, $^d$: Unequal power divider

FIGURE 14. The trajectories of (a) $\Gamma_e$ and (b) $\Gamma_o$ for the proposed configuration and other previously published works.

in [13], [17], and [18] in which substantial broadening in the impedance bandwidth (up to 37.5% in [13]) compared to the conventional WPD has been successfully demonstrated. However, the overall system bandwidth is very limited and the total electrical length remains almost the same as the conventional WPD for these cases. In [16], the location of the complex INW was optimized to obtain wider bandwidth for $S_{22}$ and $S_{23}$, achieving an overall system bandwidth of 16.21%.

Among all the works, it is obvious that the proposed configuration provides a very competitive solution in terms of the widest system bandwidth as well as the compactness in size. To highlight the main reason leading to the superior performance, the trajectories of $\Gamma_e$ and $\Gamma_o$ are plotted in Fig. 14 for comparison. Clearly, with the optimum selection of the INW location and the impedance level of $Z_m$ for size reduction, the proposed configuration exhibited the confinement of the trajectories in the low constant-Q region on the Smith Chart. Furthermore, for the proposed configuration, it is obvious that the difference between $\Gamma_e$ and $\Gamma_o$ is the smallest contributing to the best impedance bandwidth at the split ports as well as the isolation bandwidth. Overall, the proposed power divider has the shortest electrical length (140.8°) leading to a compact structure. The power divider also displayed the highest -20 dB system bandwidth of 43.2% by effectively achieving almost similar isolation and impedance bandwidth when compared to the other state-of-the-art power dividers.

IV. CONCLUSION

In this paper, a method for miniaturization and system bandwidth improvement based on a modified Wilkinson power divider with physical port isolation using high-impedance transmission lines and a complex isolation network is proposed. A rigorous analysis of the relationship between the applicable system bandwidth and the reflection coefficients of the even- and odd-mode sub-networks has been performed which determined the optimum combination of the isolation network location and the level of transmission line impedance for size reduction. Validated by the experimental work, the fabricated prototype exhibited a practical operation bandwidth of 43.2% with low loss, while maintaining physical isolation and compactness.

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