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EuMC07 : Passive Power Dividers 1

Chair: Anne-Laure Franc, LAPLACE
Co-Chair: Nikolina Jankovic, University of Novi Sad
Venue: Room 252B, Time 13:50 – 15:30, Tuesday 8th September 2015

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A Design of Unequal Power Divider With Positive and Negative Group Delays

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***Abstract*—This paper presents group delay investigation and implementation of unequal power divider with very high power division ratio. The proposed structure consists of Wilkinson power divider and branch-line where direct and coupled ports are terminated with resistors. By analytically study, the group delay associated with transmission paths between 3 and 1 is negative whereas the group delay associated between transmission path 2 and 1 is positive. Moreover, the negative group delay (NGD) characteristics are purely controlled by resistor connected in branch-line. For experimental validation, the power divider with power division ratio of 21.39 dB and NGD of -0.529 ns was designed, fabricated and measured at center frequency of 2.14 GHz.**

Keywords— Branch-line, high power division ratio, negative group delay, transmission line, unequal power divider,

I. INTRODUCTION

Power dividers are essential blocks in microwave and millimeter systems and have been applied for power combining and splitting in various applications such as antenna feeding networks, high power amplifiers (PAs), linearization of PAs, mixers, and measurement circuits [1]-[3]. These applications require power dividers with high power division ratios, which require transmission line sections with high characteristics impedance typically higher than 150 Ω [4]. The characteristic impedances higher than 150 Ω are not easy to implement with microstrip format, and therefore the restriction on fabrication [5] with such high power division ratios may be inevitable. However, the conventional power dividers provide the positive group delay (PGD). Moreover, the group delay (GD) matching between different paths is essential in various circuits and systems such as dynamic power supply or envelope tracking of PA [6]. For these circuits and systems, the power divider with negative group delay (NGD) characteristics will be beneficial in order to compensate the time mismatch between the dynamic power supply and the signal envelope [6].

In addition, there has been an increasing amount of research on NGD circuits at microwave frequencies. In region of anomalous dispersion, which is inside of absorption band, the group velocity and consequently, the GD can become negative [7]. Typically, the NGD phenomenon in RF circuits can be observed within a limited frequency band through the signal attenuation condition. Therefore, various approaches have been applied to designing two-port active/passive microwave NGD circuits using *RLC* resonators [8]-[10]. To overcome the limited availability problem of lumped elements in radio and microwave frequencies, the distributed elements NGD circuits have also been presented in several works [9]-[12]. However, research on designing unequal power divider with predefined NGD characteristics is lacking.

In this paper, unequal power divider with high power-division ratio and predefined NGD characteristics is presented. The proposed circuit provides NGD characteristics between transmission path 3 and 1 whereas PGD between transmission path 2 and 1. The proposed power divider is proposing circuit that can be used in the dynamic power or envelope tracking PAs [6]. The NGD path can be connected to the detector path in order to compensate the time mismatch between the dynamic power supply and the signal envelope, whereas the PGD path can be directly linked to RF path.

II. ANALYSIS AND DESIGN EQUATIONS

Fig. 1 shows the proposed structure of unequal power divider with PGD and NGD characteristics, where the length of transmission line are λ/4. It also consists of branch-line where direct and coupled ports are terminated with resistors *R* [11].

In order to find the *S*-parameters of the proposed structure, modified even-and odd-mode analysis can be applied [5]. The modified even-mode equivalent circuits are illustrated in Fig. 2 and Fig. 3. From these equivalent circuits, for the matched reflection coefficients (S_{11}=0) at center frequency, the value of characteristics impedance of line can be found as (1).

$$Z_a = Z_b = \sqrt{2} Z_0 \tag{1a}$$

$$Z_c = Z_d = Z_0 \tag{1b}$$

$$Z_e = Z_0 \big/ \sqrt{2} \tag{1c}$$

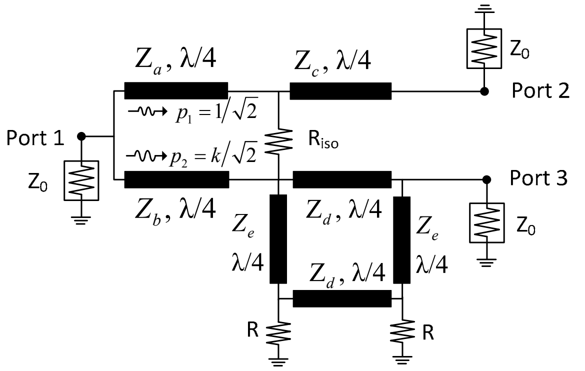


Fig. 1. Proposed structure of unequal power divider with positive and negative group delays.

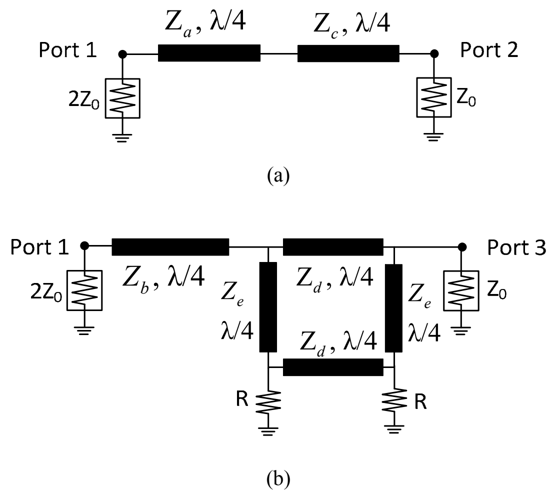


Fig. 2. Modified even-mode equivalent circuits: (a) between port 2 and 1 and (b) between port 3 and 1.

Using modified even- and odd-modes equivalent circuits [5], [11], the *S*-parameters and GDs associated with different transmission paths at $f = f_0$ are expressed as (2)

$$S_{11}\big|_{f=f_0} = S_{22}\big|_{f=f_0} = S_{33}\big|_{f=f_0} = 0 \tag{2a}$$

$$S_{21}\big|_{f=f_0} = \frac{1}{\sqrt{2}} \tag{2b}$$

$$S_{31}\big|_{f=f_0} = \frac{1}{\sqrt{2}}\left|\frac{Z_0 - R}{Z_0 + R}\right| \tag{2c}$$

$$\tau_{21}\big|_{f=f_0} = \frac{0.5152}{f_0} \tag{2d}$$

$$\tau_{31}\big|_{f=f_0} \approx -2.0759\frac{\left(R^2 - 0.4184Z_0^2\right)}{f_0\left(Z_0^2 - R^2\right)} \tag{2e}$$

where, Z_0 is port-reference impedance. Furthermore, power division ratio k is defined as (3).

$$k = \frac{S_{31}}{S_{21}}\bigg|_{f=f_0} = \left|\frac{Z_0 - R}{Z_0 + R}\right| \tag{3}$$

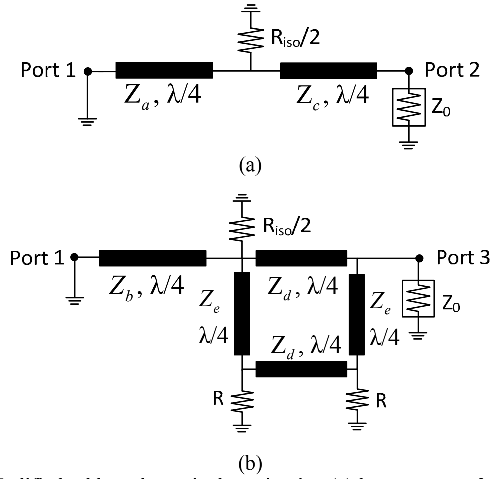


Fig. 3. Modified odd-mode equivalent circuits: (a) between port 2 and 1 and (b) between port 3 and 1.

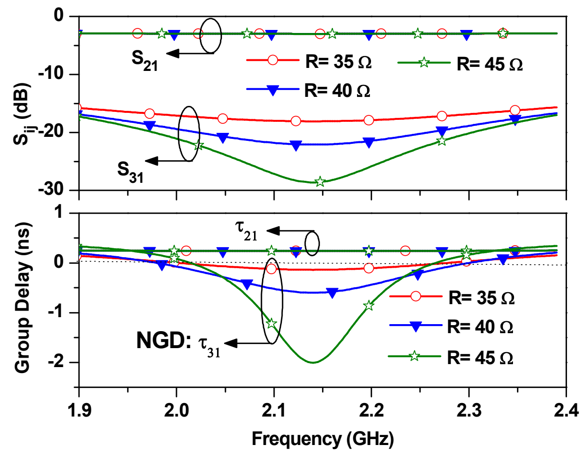


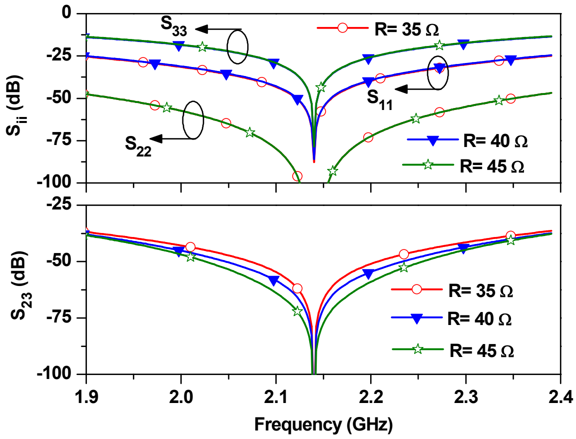
Fig. 4. Synthesized magnitude and group delay characteristics using ideal circuit parameters.

As seen from (2c) and (2e), the magnitude and GD between transmission path 3 and 1 is purely controlled by resistor *R*. As *R* is increased toward Z_0, the GD and magnitude S_{31} are increased towards high value. Therefore, power division ratio *k* and NGD can be varied only by *R*. Moreover, the magnitude and PGD between port 2 and 1 is constant and independent of *R*, as shown in (2b) and (2d).

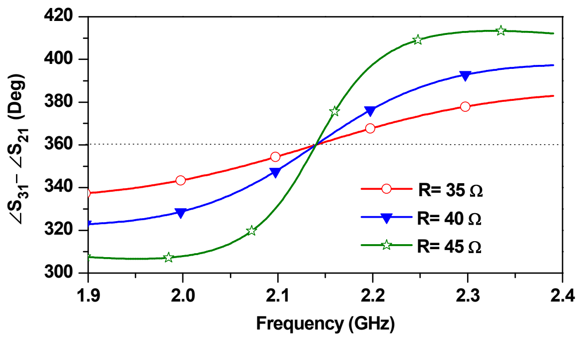
The isolation characteristic can be analyzed from the modified odd-mode equivalent circuits shown in Fig. 3. For the perfect isolation, the value of S_{23} should be equal to zero. Under this condition, the value of isolated resistor R_{iso} can be found as (4).

$$R_{iso} = 2Z_0 \tag{4}$$

On the basis of design equations, the calculated responses of the proposed circuit are shown in Fig. 4 and 5 with different values of *R*. As seen from Fig. 4, transmission coefficient and GD associated with path 3 and 1 are changed with different values of *R*. As value of *R* approaches to Z_0, the value of S_{31} and GD are moved toward high value. However, the GD and transmission coefficient between path 2 and 1 remain almost constant value and PGD. The input/output return losses are perfectly matched at f_0 as shown in Fig. 5(a) Moreover, the isolation between output ports is infinite.



(a)



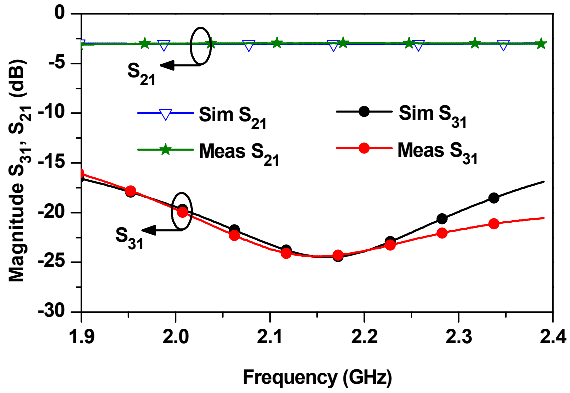
(b)

Fig. 5. Synthesized results using ideal circuit parameters: (a) return loss and isolation characteristics and (b) phase difference characteristics.

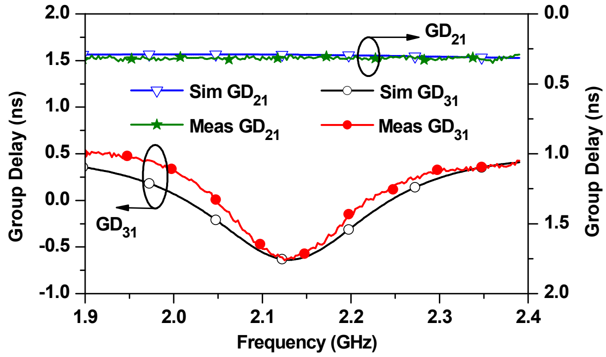
III. Simulation And Measurement Results

For experimental verification, we designed and fabricated the proposed microstrip line power divider for the specified NGD of -0.6 ns at f_0 of 2.14 GHz. The circuit was fabricated on a Rogers RT/Duriod 5880 substrate with a dielectric constant (ε_r) of 2.2 and a thickness (h) of 31 mils. The circuit was simulated and optimized using ANSYS HFSS 2014.

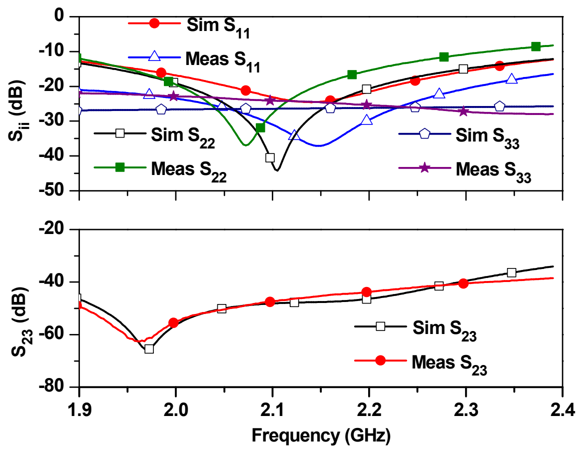
The simulated and measured the magnitudes and GDs are shown in Fig. 6(a) and 6(b). The measured results have agreement with the simulations. In Fig. 6(a), the measured values of $|S_{21}|$ and $|S_{31}|$ are determined as -2.96 dB, -24.35 dB at 2.14 GHz, respectively. Therefore, the measured power division ratio is 21.39 dB. Similarly, the measured GDs between transmission paths are determined as τ_{21} = 0.34 ns and τ_{31} = -0.529 ns, respectively as shown in Fig. 6(b). In Fig. 6(c), the measured $|S_{11}|$, $|S_{22}|$, and $|S_{33}|$ are -24.73 dB, -20.58 dB and -20.62 dB, respectively. The return loss characteristics of fabricated circuit are slightly degraded as compared to ideal results because of junction capacitance of branch-line structures. The measured isolation ($|S_{23}|$) at f_0 is -42.18 dB. The measured phase difference between the two output ports is shown in Fig.7. A photograph of fabricated circuit is shown in Fig. 8.



(a)



(b)



(c)

Fig. 6. Simulation and measurement results: (a) magnitude, (b) group delay and (c) return loss and isolation characteristics.

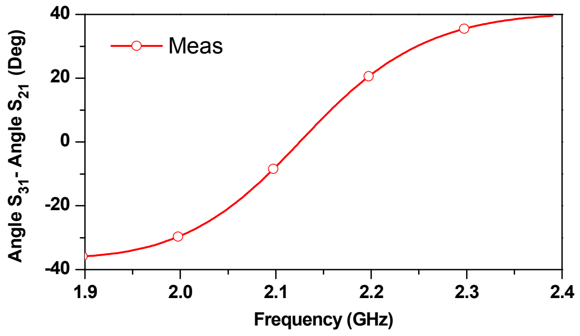


Fig. 7. Phase differences between output ports.

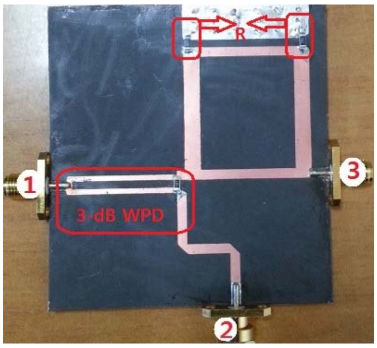


Fig. 8. Photograph of fabricated circuit.

IV. Conclusion

In this paper, unequal power divider with high power division ratio and predefined negative group delay characteristics is proposed and fabricated. Both theoretical and experimental results have been presented for verification. From analysis, it is observed that the negative group delay and power division ratio is fully controlled by termination resistance of branch-line. The simulated and measured results show its merit of negative group delay, good return loss and high isolation. In addition, the proposed power divider is promising for application in dynamic power supply or envelope tracking power amplifier to minimize the time-mismatch between the envelope and the RF signal paths.

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References

[1] C. Y. Chang and C. C. Yang, "A novel broad-band chebyshev-response rat-race ring coupler," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 4, pp. 455-462, Apr. 1999.

[2] H. Xu, G. Wand, and K. Lu, "Microstrip rat-race couplers," *IEEE Micro. Mag.*, vol. 12, no. 4, pp. 117-129, Jun. 2011.

[3] M. J. Chik and K. K. M. Cheng, "Group delay investigation of rat-race coupler design with tunable power division ratio," *IEEE Microw. Wireless Compon. Letters,* vol. 24, no. 5, pp. 324-326, May 2014.

[4] B. Li, X. Wu, and W. Wu, "A 10:1 unequal Wilkinson power divider using coupled lines with two shorts," *IEEE Microw. Wireless Compon. Letters*, vol. 19, no. 12, pp. 789-791, Dec. 2009.

[5] H. R. Ahn "Compact CVT-/CCT-unequal poer dividers for high-power division ratios and design methods for arbitrary phase differences," *IEEE Trans. Microw. Theory Tech*., vol. 62, no. 12, pp. 2954-2964, Dec 2014.

[6] B. Kim, J. Moon, and I. Kim, "Efficiently amplified," *IEEE Microwave Magazine*, vol. 11, no. 5, pp. 87-100, Aug. 2010.

[7] D. Solli and R. Y. Chiao, "Superluminal effects and negative delays in electronics, and their application," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top*., no. 5, pp. 056601 1-0566101 4, Nov. 2002.

[8] S. Lucyszyn, I. D. Robertson, and A. H. Aghvami "Negative group delay synthesizer," *IET Electronics Letters,* vol. 29, no. 9, pp. 798-800, Apr. 1993.

[9] H. Choi, Y. Jeong, C. D. Kim, and J. S. Kenney, "Efficiency enhancement of feedforward amplifiers by employing a negative group delay circuit," *IEEE Trans. Microw. Theory Tech*., vol. 58, no. 5, pp. 1116-1125, May 2010.

[10] G. Chaudhary and Y. Jeong, "Low signal attenuation negative group delay network topologies using coupled lines," *IEEE Microw. Theory Tech.,* vol. 62, no. 10, pp. 2316-2324, Oct. 2014.

[11] G. Chaudhary and Y. Jeong, "A design of reconfigurable negative group delay circuit without external resonators," *IEEE Antennas and Wireless Propag. Letters*, vol. 14, pp. 883-886, 2015.

[12] C. T. M. Wu and T. Itoh, "Maximally flat negative group delay circuit: a microwave transmission line approach," *IEEE Trans. Microw. Theory Tech.,* vol. 62, no. 6, pp. 1330-1342, Jun. 2014.