Progress In Electromagnetics Research Letters, Vol. 71, 37–43, 2017

Miniaturized Gysel Power Dividers Using Lumped-Element Components

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Abstract—This letter presents miniaturized Gysel power dividers using lumped-element components. The characteristic impedances of all the equivalent transmission lines in these dividers are fixed to the same values based on even and odd mode analysis, thus simplifying the design procedure and miniaturizing the Gysel power dividers. The ideal divider designed at a frequency of 590 MHz exhibits power splits of -3.2 ± 0.2 dB and return losses of greater than 15 dB for the frequency range of 460 to 650 MHz. Furthermore, isolation between output ports is greater than 15 dB for the frequency range of 500 to 680 MHz. The fabricated miniaturized Gysel power divider achieves broadband characteristics and is very compact, occupying only about 15% of the area of a conventional Gysel power divider.

1. INTRODUCTION

Power dividers play an important role in many wireless communication circuits. Because of the high isolation between output ports, they are used in many devices, including power amplifiers, vector modulators, mixers, phased array antennas, and linearizers. According to their operating power, power dividers can be classified into two groups: low-power dividers, such as the Wilkinson power divider [1], and high-power dividers, such as the Gysel power divider [2]. The Gysel power divider has recently attracted increased attention because of advantages such as its high power handing capabilities; in this aspect, it outperforms the Wilkinson power divider. However, the conventional Gysel power divider typically consists of six 90° transmission lines with a design frequency of f_0, requiring the divider to have a large area. The reduction method depends on the equivalent circuit of these transmission lines [3]. Using composite right- and left-handed transmission lines [4] reduced the size of the Gysel power divider by 81.8%, and the 15 dB bandwidth isolation was approximately 27.5%. Furthermore, Gysel power divider using equivalent lumped-element components [5] was smaller than that using composite right- and left-handed transmission lines, and the 15 dB bandwidth isolation was approximately 30%.

This letter describes miniaturized lumped-element Gysel power dividers constructed with a minimal number of lumped elements. Miniaturized lumped-element power dividers and rat-race (or ring) hybrids which utilizes the elimination of inductors and capacitors and unequal power-divider design which utilizes the elimination of an open stub and a short stub were presented [6–10]. However, to the best our knowledge, there is no report about Gysel power dividers which utilizes the elimination of inductors and capacitors positively, while setting the characteristic impedances of all the equivalent transmission lines the same values, to simplify the design procedure and for miniaturization of the Gysel power dividers with low insertion loss.

2. DESIGN AND THEORETICAL ANALYSIS

The configuration of a conventional Gysel power divider is shown in Fig. 1. It consists of six 90° transmission lines with a design frequency of f_0 and two isolation resistors. Its characteristic impedances,

Received 18 August 2017, Accepted 29 September 2017, Scheduled 10 October 2017
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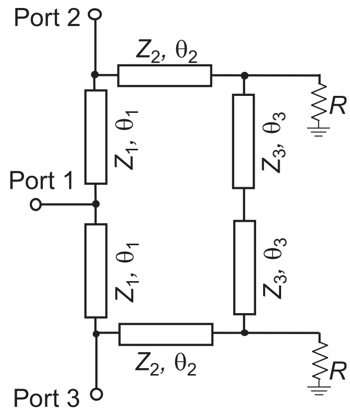


Figure 1. Configuration of Gysel power divider.

electrical lengths, and resistance are $Z_1 = \sqrt{2}Z_0$, $Z_2 = Z_0$, and $Z_3 = Z_0/\sqrt{2}$; $\theta_1 = \theta_2 = \theta_3 = 90°$; and $R = Z_0$, respectively. Here, Z_0 is the reference characteristic impedance. The area it occupies is approximately $\lambda/2 \times \lambda/4$, where λ is the wavelength on the substrate at the design frequency. Thus, we analyze the Gysel power divider with the electrical lengths of $\pm 90°$ based on even- and odd-mode analysis [11].

2.1. Even-Mode Analysis

Even-mode circuit model of the Gysel power divider is shown in Fig. 2(a). Admittance Y_{in1} can be written as

$$Y_{in1} = \frac{j\frac{1}{Z_2}\sin\theta_2 + \left(\frac{1}{R} + j\frac{1}{Z_3}\tan\theta_3\right)\cos\theta_2}{\cos\theta_2 - \frac{Z_2}{Z_3}\tan\theta_3 \sin\theta_2 + j\frac{Z_2}{R}\sin\theta_2}. \tag{1}$$

Because Y_{in1} becomes zero at electrical lengths of $\theta_2 = \theta_3 = \pm 90°$ or $\theta_2 = -\theta_3 = \pm 90°$, the circuit seen from this point can be regarded as an open circuit. Moreover, it is interesting to see that the impedances Z_2, Z_3, and resistance R do not contribute to the value of the impedance Y_{in1} for $\theta_2 = \theta_3 = \pm 90°$ or $\theta_2 = -\theta_3 = \pm 90°$. Therefore, the circuit shown in Fig. 2(a) can be reduced to the network shown in Fig. 2(b). For the impedance to match at ports 1 and 2, the following condition must be fulfilled:

$$2Z_0 = Z_1 \frac{Z_0 + jZ_1 \tan\theta_1}{Z_1 + jZ_0 \tan\theta_1}. \tag{2}$$

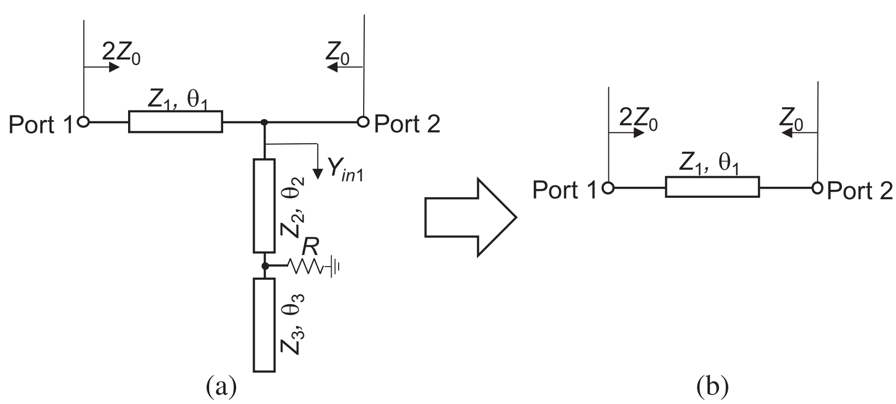


Figure 2. Circuit of power divider shown in Fig. 1 under even-mode excitation.

Setting $\theta_1 = \pm 90°$ at the center frequency yields

$$Z_1 = \sqrt{2} Z_0. \tag{3}$$

2.2. Odd-Mode Analysis

Odd-mode circuit model of the Gysel power divider is shown in Fig. 3(a). Admittances Y_{in2} and Y_{in3} can be written as

$$Y_{in2} = -j\frac{\cot\theta_1}{Z_1}, \quad Y_{in3} = -j\frac{\cot\theta_3}{Z_3}. \tag{4}$$

Because Y_{in2} and Y_{in3} become zero at electrical lengths of $\theta_1 = \theta_3 = \pm 90°$ or $\theta_1 = -\theta_3 = \pm 90°$, the circuit shown in Fig. 3(a) can be reduced to the network shown in Fig. 3(b). For impedance matching at port 2, the following condition must be fulfilled:

$$Z_0 = Z_2\frac{R + jZ_2\tan\theta_2}{Z_2 + jR\tan\theta_2}. \tag{5}$$

Subsequently choosing $\theta_2 = \pm 90°$ at the center frequency yields

$$Z_2 = \sqrt{RZ_0}. \tag{6}$$

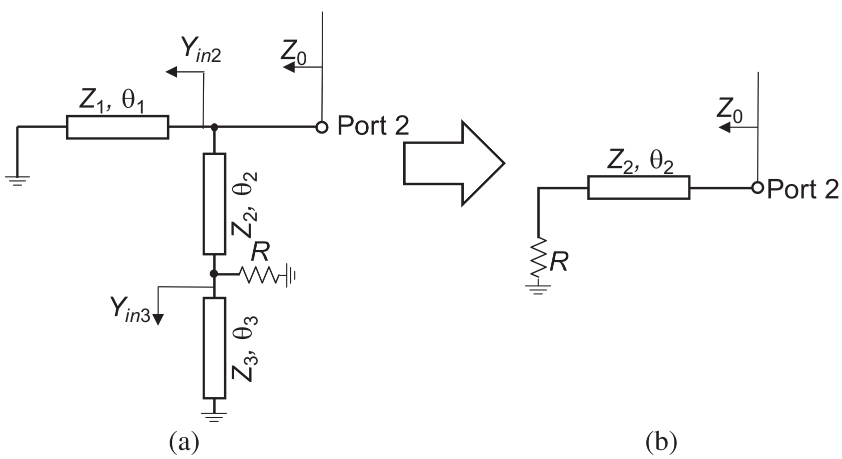


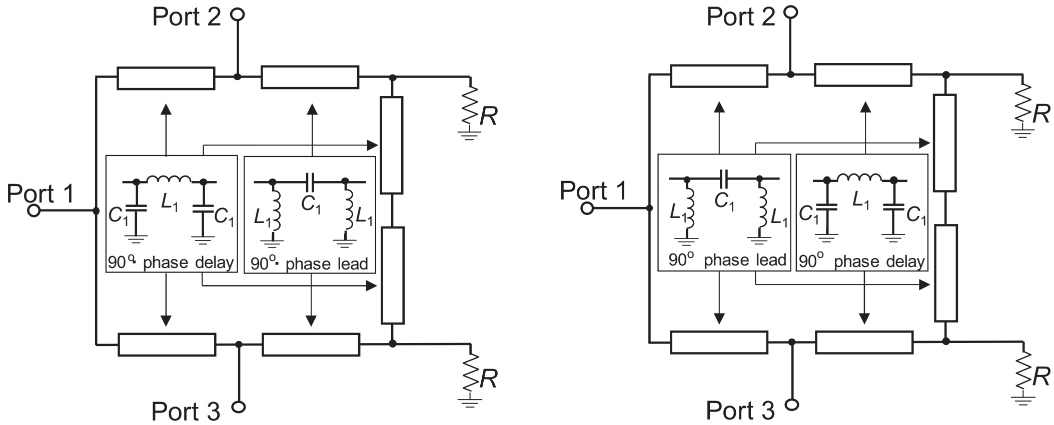
Figure 3. Circuit of power divider shown in Fig. 1 under odd-mode excitation.

Thus, the parameter of the proposed Gysel power divider should satisfy Equation (3) and Equation (6). These equations demonstrate that the characteristic impedance Z_3 can be selected arbitrarily. Thus, we assume that the characteristic impedances of all the equivalent transmission lines are fixed to the same values ($Z_3 = \sqrt{2}Z_0$ and $R = 2Z_0$). Typical Gysel power divider sets Z_3 to $Z_0/\sqrt{2}$ and R to Z_0, respectively, while the proposed Gysel power divider sets Z_3 to $\sqrt{2}Z_0$ and R to $2Z_0$. To the best of our knowledge, Gysel power divider which sets the same characteristic impedances of all the transmission-line section has not been reported yet.

Figure 4 shows the examples of lumped-element Gysel power dividers incorporating a lumped-element equivalent. π-network. In these circuits, capacitors with capacitances of $C_1 = \frac{1}{2\sqrt{2}\pi f_0 Z_0}$ and inductors with inductances of $L_1\frac{Z_0}{\sqrt{2}\pi f_0}$ are used.

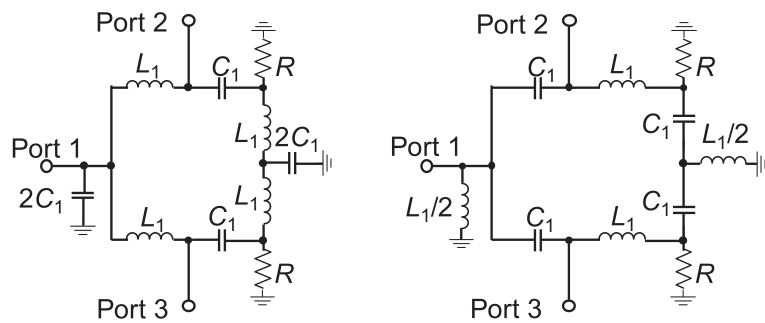
Because adjacent inductors and capacitors in the dividers shown in Fig. 4 form parallel resonant circuits whose input impedances are infinite at the center frequency, the elimination of the inductors and capacitors, as shown in Fig. 5, does not affect the electrical distribution and coupling characteristics at the center frequency. Furthermore, the proposed topology does not obey the low-pass or high-pass characteristics. This contributes to the achievement of the broadband characteristics.

In general, the power-handling capability depends on the performance of the isolation resistors to transfer the heat to the ground [12]. The proposed Gysel power dividers are superior to the Wilkinson divider.



(a) (b)

Figure 4. Examples of lumped-element Gysel power dividers using equivalent π-network.



(a) (b)

Figure 5. Novel configuration of proposed Gysel power dividers using lumped-element components.

3. SIMULATION AND EXPERIMENTAL RESULTS FOR THE PROPOSED GYSEL POWER DIVIDERS

The validity of the proposed circuit configuration was confirmed by simulating the frequency characteristics of the proposed Gysel power dividers using Microwave Office and ADS. We focus on the 470–790 MHz UHF band, which is used predominantly for TV broadcasting in Europe [13]. We assumed that the design frequency f_0 was 590 MHz, the reference characteristic impedance Z_0 was $50\,\Omega$, the capacitance of capacitor C_1 was 3.81 pF, and the inductance of inductor L_1 was 19.08 nH.

Figure 6 shows the simulation results for the proposed miniaturized Gysel power dividers shown in Fig. 5. These simulation results were obtained using ideal loss-less lumped elements. As shown in Fig. 6(a), the ideal divider exhibits power splits of -3.2 ± 0.2 dB and return losses of greater than 15 dB for the frequency range of 460 to 650 MHz. Furthermore, isolation between output ports is greater than 15 dB for the frequency range of 500 to 680 MHz. Furthermore, as shown in Fig. 6(b), the ideal divider exhibits power splits of -3.2 ± 0.2 dB and return losses of greater than 15 dB for the frequency range of 540 to 750 MHz. Furthermore, isolation between output ports is greater than 15 dB for the frequency range of 520 to 700 MHz. The simulation results indicate that good isolation and matching are achieved in the passband.

The feasibility of circuit operation was experimentally investigated by fabricating the proposed power divider on a commercially available 1.6 mm-thick 4-layer FR4 substrate (dimensions of $2.75\,\text{cm} \times 1.94\,\text{cm} = 5.34\,\text{cm}^2$) [14]. A photograph of the fabricated miniaturized Gysel power divider is shown in Fig. 7. The relative permittivity and loss tangents at 1 GHz were typically between 4.0 and 4.2 and

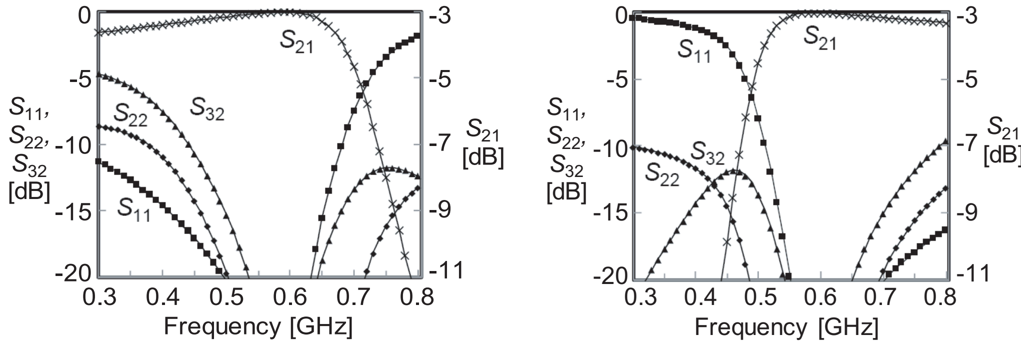


Figure 6. Simulation results for proposed miniaturized Gysel power dividers shown in (a) Fig. 5(a) and (b) Fig. 5(b).

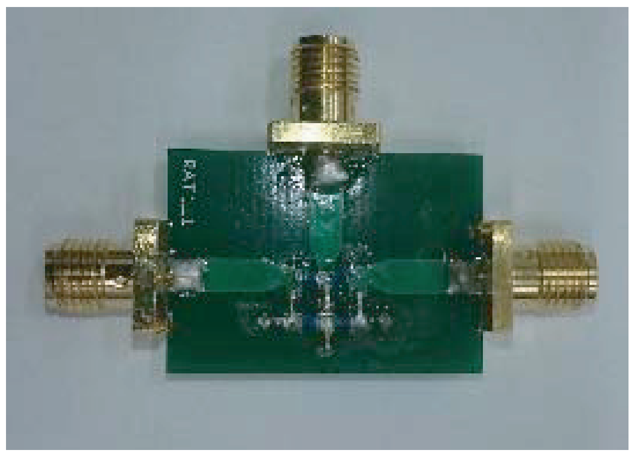


Figure 7. Photograph of fabricated miniaturized Gysel power divider shown in Fig. 5(a).

between 0.012 and 0.014, respectively. The chip capacitors, chip inductors, and chip resistors used in the circuit were hand-soldered. The chip capacitors with 1005 size and chip inductors with 1608 size were from Murata Manufacturing Company Ltd. Q value of the chip inductors is 80.65 at frequency 590 MHz.

In this work, we selected a rated voltage of 50 V_{dc} for the chip capacitors and chip inductors. Furthermore, a rated current max of 1400 mA for the chip inductors (Namely, a maximum handling power is 70 W.) and a maximum working voltage of 75 V and a maximum handling power of 0.1 W for the chip resistors. However, we can select larger lumped elements or can use external resistors if we need larger power-handling capability.

The measurement results shown in Fig. 8 indicate a bandwidth of about 30% with better than 15 dB isolation from 510 to 690 MHz and a bandwidth of about 27% with better than 15 dB return losses and insertion losses of 3.7 ± 0.5 dB from 460 to 620 MHz. There is good agreement between the simulation and measurement results. Table 1 compares the results of this study and various reported Gysel power divider characteristics. This comparison demonstrates that the proposed device achieved both miniaturization and sufficient broadband characteristics. Furthermore, by reducing the number of lumped elements from 25 [5] to 8, we improved the insertion losses of about 0.5 dB at 540 MHz while maintaining broadband characteristics. In this work, we fabricated the circuit with hand soldering. If we adopt the surface mount technology, we can further improve the insertion loss. The proposed miniaturized Gysel power divider achieves broadband characteristics and is very compact, occupying only about 15% of the area of a conventional Gysel power divider.

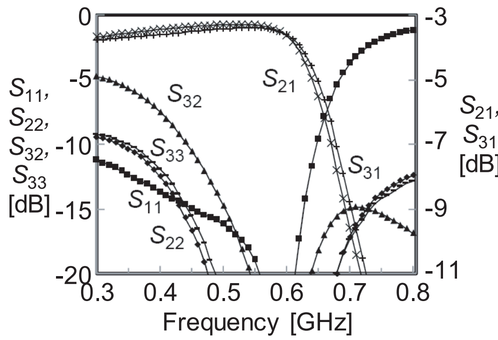


Figure 8. Measured results for the fabricated miniaturized Gysel power divider shown in Fig. 7.

Table 1. Performance comparison of proposed and previously reported Gysel power dividers.

Type	Size [$\lambda \times \lambda$]	15 dB bandwidth of isolation	Power ratio	Design frequency [GHz]	ε_r/h of substrate
Proposed Gysel power divider	0.17×0.11	30%	-3 dB (equal)	0.59	4.2/1.6 mm
[4]	0.19×0.12	27.5%	-3 dB (equal)	0.9	3.5/0.508 mm
[15]	0.5×0.25	30%	arbitrary	2	2.65/0.8 mm
[16]	0.83×0.58	62%	-3 dB (equal)	1.5	10.2/1.27 mm

4. CONCLUSION

This letter proposes miniaturized lumped-element Gysel power dividers using lumped-element components. The fabricated power divider achieved about 15% of the area of a conventional Gysel power divider, a bandwidth of about 30% with better than 15 dB isolation, and a bandwidth of about 27% with better than 15 dB return losses. The proposed design is very simple yet is still able to achieve both miniaturization and sufficient broadband characteristics with low insertion loss.

ACKNOWLEDGMENT

The results are based on the outcome of contract research for SCOPE (Strategic Information and Communications R&D Promotion Programme). This work was supported in part by the VLSI Design and Education Center (VDEC) at the University of Tokyo in collaboration with Keysight Technologies Japan, Ltd.

REFERENCES

1. Wilkinson, E. J., "An N-way hybrid power divider," *IRE Trans. Microw. Theory Techn.*, Vol. 8, No. 1, 116–118, Jan. 1960.
2. Gysel, U. H., "A new N-way power divider/combiner suitable for high-power application," *IEEE MTT-S Int. Microw. Symp. Dig.*, 116–118, May 1975.
3. Ahn, H. R. and B. Kim, "Small wideband coupled-line ring hybrids with no restriction on coupling power," *IEEE Trans. Microw. Theory Techn.*, Vol. 57, No. 7, 1806–1817, Jul. 2009.
4. Ren, X., K. Song, F. Zhang, and B. Hu, "Miniaturized Gysel power divider based on composite right/left-handed transmission lines," *IEEE Microw. Wireless Compon. Lett.*, Vol. 25, No. 1, 22–24, Jan. 2015.

5. Tang, B., H. Hayashi, and R. Ueda, "Reduced-size gysel power dividers using lumped-element components," *Microw. Opt. Technol. Lett.*, Vol. 58, No. 10, 2341–2344, Oct. 2016.
6. Hayashi, H., T. Nakagawa, and K. Araki, "Power distributing/combining circuit," *Japanese Patent Application Publication No. 2002-064353*, 2002.
7. Hayashi, H. and M. Kawashima, "Miniaturized lumped-element power dividers with a filtering function," *IEICE Trans. Electron.*, Vol. E91-C, No. 11, 1798–1805, Nov. 2008.
8. Hirota, T., A. Minakawa, and M. Muraguchi, "Reduced-size branch-line and rat-race hybrids for uniplanar MMIC's," *IEEE Trans. Microw. Theory Techn.*, Vol. 38, No. 3, 270–275, Mar. 1990.
9. Ahn, H.-R., I.-S. Chang, and S.-W. Yun, "Miniaturized 3-dB ring hybrid terminated by arbitrary impedances," *IEEE Trans. Microw. Theory Techn.*, Vol. 42, 2216–2221, Dec. 1994.
10. Li, P. W. and K. K. M. Cheng, "A new unequal power-divider design with enhanced insertion loss flatness," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 12, 786–788, Dec. 2009.
11. Zhang, H. and Q. Xue, "A novel Gysel power divider with arbitrary power ratio for high-power application," *Proc. IWS 2013*, 1–4, Beijing, 2013.
12. Hayati, M., S. A. Malakooti, and A. Abdipour, "A novel design of triple-band Gysel power divider," *IEEE Trans. Microw. Theory Techn.*, Vol. 61, No. 10, 3558–3567, Oct. 2013.
13. Oh, S. W., Y. Ma, M. H. Tao, and E. C. Y. Peh, "An overview and comparison of TV White Space regulations worldwide," *Proc. ICFCNA 2014*, 1–6, Kuala Lumpur, Malaysia, 2014.
14. Hayashi, H., "Tandem Lange 3-dB 90° hybrid implemented on FR4 substrate," *Proc. 2014 NORCHIP*, 1–3, Tampere, Finland, 2014.
15. Wu, Y., Y. Liu, and S. Li, "A modified Gysel power divider of arbitrary powerratio and real terminated impedances," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No. 11, 601–603, Nov. 2011.
16. Oraizi, H. and A. Sharifi, "Optimum design of a wideband two-way gysel power divider with input-output impedance matching," *IEEE Trans. Microw. Theory Techn.*, Vol. 57, No. 9, 2238–2248, Sep. 2009.