LETTER

A Novel 10 MHz-4 GHz Wilkinson Power Divider Using Lumped Compensation Elements

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Abstract Future cable television (CATV) and satellite-television receiver systems require the development of wideband power dividers (PDs) covering a few megahertz to a few gigahertz. Conventional PDs designed using either distributed circuits or lumped elements cannot accomplish this purpose. In this paper, a novel ultrawideband wideband PD is developed with a combined design of both the distributed transmission line Wilkinson power divider (WPD) and the lumped compensation elements. The WPD is designed at 2.2 GHz with a small configuration, while the loaded chip resistors and capacitors compensate its performance well at frequencies down to megahertz. The configuration and design method of the proposed divider is described, and a microstrip WPD is fabricated and measured. The simulated and measured responses of the WPD agree well over 10 MHz ~ 4.0 GHz, and both satisfy well the design specifications. To our knowledge, this is the first report of a WPD that covers an ultrawide frequency band from a few megahertz to a few gigahertz.

key words: Wilkinson power divider (WPD), ultra-wideband, megahertz, gigahertz, distributed transmission line, compensation element, lumped resistor and capacitor.

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

In Japan, the current cable television (CATV) transceivers are designed working over 10 MHz ~ 77 MHz. On the other hand, in order to accommodate the 4K8K broadcasting services, the intermediate frequency (IF) for satellite-television receivers is now extended to 3.224 GHz from the present 1.032GHz ~ 2.071GHz. This work is thereby tried to develop an ultra-wideband power divider covering 10 MHz ~ 3.224 GHz or even wider frequency band, so that it can be used for future television receiver systems.

The Wilkinson power divider (WPD) is widely used in communication systems because of its many advantages like low-insertion loss, even power distribution, and simple structure [1]-[3]. The conventional one-section two-way WPD consists of simply a pair of quarter-wavelength transmission lines and an absorbing resistor, but its operating frequency band is very narrow [1]-[3]. To broaden

the bandwidth, WPDs with multi-sections of quarter-wavelength transmission lines and multiple absorbing resistors are developed [4]-[11]. However, the multi-section WPDs cannot be designed to work at tens of megahertz, because at such low frequencies, the wavelength is so long that the circuit size of the WPD becomes unacceptable. Moreover, even a very large number of transmission line sections are used, e.g., more than 10 sections of transmission lines are used, the designed WPD still fails to show good performance at tens of megahertz when it is designed to work over 10 MHz ~ 3.224 GHz. The same is true with many other reported works. In [12] and [13], slot lines and defected ground structures are used, in [14]-[17], additional isolation networks are introduced, and in [18]-[21], complex termination impedances are employed, in order to broaden the bandwidth of WPDs. However, all fail to reach good performance, especially good isolation at both the lower megahertz and upper gigahertz of frequencies.

Another possible method to design WPDs with acceptable circuit size at tens of megahertz of frequencies is using lumped element circuits, as reported in [22]-[29]. However, the parasitic effects and loss associated with the lumped elements increase rapidly with frequency, and the performance of this type of WPDs deteriorates drastically at frequencies up to gigahertz. [30] reported quadrature hybrids, another type of commonly used power dividers, at frequencies as low as a few megahertz to a few hundreds of megahertz. But ferrite cores and hand-made copper inductor coils are used, which are time-consuming, costly, unstable in performance, weak to vibration, and cannot work at frequencies up to gigahertz.

In this paper, a novel ultrawideband WPD is proposed by loading lumped compensation elements to the output ports of a conventional WPD. The WPD is designed at frequencies of gigahertz, so its size is small. On the other hand, the lumped compensation elements improve the performance of the WPD significantly at low frequencies of a few megahertz. As a result, the proposed WPD can work well from a few megahertz to a few gigahertz. A 5-section microstrip WPD is designed for operation over 10 MHz ~ 3.224 GHz, and its measured response agrees well with the predicted one. The proposed WPD is easy for fabrication at very low price because it can be simply printed on a small piece of dielectric substrate with the soldering of a few chip-resistors

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and chip-capacitors, and no ferrite cores and hand-made copper coils are needed. Therefore, it is suitable for many possible applications requiring the simultaneous use of both the low megahertz and the high gigahertz of frequencies.

2. Configuration and Design of the Proposed WPD

At first, the design specifications of the WPD are given below, which is aimed at future possible applications requiring a frequency band ranging from a few megahertz to a few gigahertz of frequencies.

- (i) Operating frequency band: 10 MHz ~ 3.224 GHz
- (ii) VSWR < 2.0, i.e., $|S_{ii}| < 10.0$ dB ($i=1, 2, 3$)
- (iii) Maximum insertion loss, i.e., $\text{Max}(|S_{21}|, |S_{31}|) < 5.0$ dB
- (iv) Isolation between the output ports $|S_{23}| = |S_{32}| > 10.0$ dB

Next, the configuration of the proposed WPD is given in Fig. 1. It consists of five-sections of transmission lines connected with five absorbing resistors, and is loaded with lumped shunt resistor R_s and capacitor C_s at the two output ports. A five-section WPD is chosen as a trade-off between the circuit size and the bandwidth required by the design specifications. The lumped R_s and C_s elements are added for compensation of the performance of the WPD at low frequencies of a few megahertz. The design of the proposed WPD is carried out in three steps described below.

Fig. 1 Schematic of the proposed five-section WPD with lumped RC elements for compensation of its performance.

(1) Step-1: Design of a 5-section WPD

In this step, the 5-section WPD shown in Fig. 1, without loading the compensation R_s and C_s elements, is designed using the conventional even- and odd-mode method [2][3][31]. The center frequency of the WPD is chosen as $f_0 = 2.2$ GHz, the fractional bandwidth of the Chebyshev equal-ripple passband is $FBW = 150\%$, and the maximum return loss in passband is $RL = 20.0$ dB. Also, in the design, $Z_s = Z_L = 50.0 \Omega$. The finally obtained circuit parameters, including the characteristic impedance of the 5-section transmission lines and the absorbing resistors are given in TABLE I. The electrical length of all the transmission lines is $\theta = \pi/2$ @ 2.2 GHz, i.e., a quarter-wavelength at the center frequency of the passband.

TABLE I Obtained parameters of the circuit in Fig. 1.

i	1	2	3	4	5
$Z_i(\Omega)$	87.26	79.10	70.71	63.21	57.30
$R_i(\Omega)$	143.82	178.59	276.20	417.71	392.34

(2) Step-2: Determination of the compensation elements

After the circuit parameters in Fig.1 are determined, the compensation shunt resistor R_s and capacitor C_s are loaded at the output ports, Port 2 and Port 3. In [32], compensation resistors and capacitors were added at the input side of the transmission lines of the WPD. However, we found that the configuration in [32] failed to improve the performance of the WPD well at low frequencies. In this work, we propose to load shunt resistors and capacitors at the output side of the transmission lines of the WPD, as shown in Fig. 1. The values of R_s and C_s are determined by analyzing the odd-mode equivalent circuit of the WPD in Fig. 1 and using the impedance matching condition of the circuit [3][31]. Then a circuit simulator, e.g., ADS, is used to investigate the performance of the WPD, and minor tuning of R_s and C_s is made to get the optimal values of R_s and C_s as a trade-off between the circuit performance and the design specifications. The final solution is $R_s = 30.0 \Omega$ and $C_s = 33.0$ pF.

(3) Step-3: Design of the microstrip WPD

Based on the above-obtained circuit parameters of the WPD, we design the microstrip WPD using the AD1000 substrate with a relative dielectric constant of $\epsilon_r = 10.2$, a loss tangent of $\tan \delta = 0.023$, and a thickness of $t = 0.635$ mm. An electromagnetic (EM) simulator, Sonnet *em*, is used to determine the physical dimensions of the microstrip lines and simulate the response of the WPD loaded with R_s and C_s . The finally obtained circuit configuration with geometrical dimensions is shown in Fig. 2.

A comparison of the simulated frequency responses of the WPD is shown in Fig. 3. The solid and broken lines are the results simulated by the EM simulator Sonnet *em* and the circuit simulator ADS, respectively. It is seen that over 10 MHz ~ 4.0 GHz, the return loss at all three ports, including S_{11} , S_{22} , and S_{33} ($= S_{22}$) at Port 1, Port 2, and Port 3, are all below 10.0 dB. The power division S_{21} and S_{31} ($= S_{21}$) at Port 2 and Port 3 is within 3.3 ~ 5.0 dB. The isolation S_{23} between the two outputs is larger than 10.0 dB over the whole operating frequency band except a few very low frequencies. The discrepancy between the solid and broken lines are mainly due to the following facts: (1) In the EM simulation, all the losses, including the conductor loss, the dielectric loss, and the radiation loss of the circuit are considered while they are ignored in the circuit simulation. (2) The influence associated with the T-junction and the folding of the microstrip lines are all included in the EM computation, while they are also neglected in the circuit simulation.

3. Measurement of the Designed Microstrip WPD

A photograph of the fabricated WPD is shown in Fig. 4. The WPD is tested by an Anritsu MS46122A vector network analyzer. The measured responses of the WPD are drawn in Fig. 5 in solid lines, and are compared with the EM simulation results in broken lines.

Fig. 2 Configuration and geometrical dimensions of the designed microstrip WPD loaded with compensation RC chip elements.

Fig. 3 Comparison of the circuit and EM simulation results of the WPD.

It is seen that the measured and simulated results agree favorably over the whole frequency band. The discrepancy is mainly due to the fabrication precision and soldering of the connectors, absorbing resistors, and the shunt compensation chip resistors and capacitors. Over 10 MHz ~ 4.0 GHz, the return losses at all three ports, including S_{11} , S_{22} , and S_{33} ($= S_{22}$) at Port 1, Port 2, and Port 3, are all below 10.0 dB, which means that the VSWRs at all three ports are below 2.0. The power division at Port 2 and Port 3 is within 3.3 ~ 5.0 dB. The isolation S_{23} between the two outputs is better than 10.0 dB over the whole operating frequency band except a few very low frequencies. All the design specifications given at the beginning of Sec. 2 are satisfied.

4. Conclusion

A novel ultrawideband microstrip WPD loaded with lumped compensation resistors and capacitors is proposed. Both the simulated and measured performances of the WPD satisfy well the design specifications over a wide frequency band ranging from 10 MHz to 4.0 GHz. The configuration of the WPD is simple with moderate geometrical dimensions and is easy for low-cost chemical etching. No ferrite cores, hand-made copper coils are used, so the proposed WPD is a good candidate for many possible applications like the future television receiver systems.

Fig. 4 Photograph of the fabricated microstrip WPD.

Fig. 5 Comparison of the EM simulation and measured responses of the microstrip WPD.

References

- [1] E. J. Wilkinson: "An n-way hybrid power divider," IRE Transactions on Microwave Theory and Techniques 8 (1960) 116 (DOI: 10.1109/TMTT.1960.1124668).
- [2] G. L. Matthaei, Leo Young and E. M. Jones: Microwave Filters Impedance-Matching Networks and Coupling Structures (McGraw-Hill, New York, 1964)1st ed.
- [3] D. M. Pozar: Microwave Engineering (John Wiley & Sons, New York, 2011) 4th ed.
- [4] A. Altaf, G. Mehdi, C. Xi and J. Miao: "Design and analysis of three stage one into four-way equal Wilkinson Power Divider," 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST) (2019) 908 (DOI: 10.1109/IBCAST.2019.8667201).
- [5] X. Ou and Q. Chu: "A modified two-section UWB Wilkinson power divider," 2008 International Conference on Microwave and Millimeter Wave Technology (2008) 1258 (DOI: 10.1109/ICMMT.2008.4540663).
- [6] S. B. Cohn: "A class of broadband three-port TEM-mode hybrids," IEEE Trans. Microw. Theory Techn. 16 (1968) 110 (DOI: 10.1109/TMTT.1968.1126617).
- [7] H. Oraizi and A. -R. Sharifi: "Design and optimization of broadband asymmetrical multisection Wilkinson power divider," IEEE Trans. Microw. Theory Techn. 54 (2006) 2220 (DOI: 10.1109/TMTT.2006.872786).
- [8] M. M. Honari, L. Mirzavand, R. Mirzavand, A. Abdipour and P. Mousavi: "Theoretical design of broadband multisection Wilkinson power dividers with arbitrary power split ratio," IEEE Trans. Compon., Packag., Manuf. Technol. 6 (2016) 605 (DOI: 10.1109/TCPMT.2016.2518581).
- [9] C. Bao, X. Wang, Z. Ma, C. -P. Chen and G. Lu: "An optimization

- algorithm in ultrawideband bandpass Wilkinson power divider for controllable equal-ripple level,” *IEEE Microw. Wirel. Compon. Lett.* (2020) 861 (DOI: 10.1109/LMWC.2020.3011516)
- [10] X. Wang, Z. Ma, T. Xie, M. Ohira, C. -P. Chen and G. Lu: “Synthesis theory of ultra-wideband bandpass transformer and its Wilkinson power divider application with perfect in-band reflection/isolation,” *IEEE Trans. Microw. Theory Techn.* 67 (2019) 3377 (DOI:10.1109/TMTT.2019.2918539).
- [11] X. Wang, Z. Ma, T. Xie, M. Ohira, C. -P. Chen and G. Lu: “Synthesis theory of ultra-wideband bandpass transformer and its Wilkinson power divider application with perfect in-band reflection/isolation,” *IEEE Trans. Microw. Theory Techn.* 67 (2019) 3377 (DOI:10.1109/TMTT.2019.2918539).
- [12] K. Song and Q. Xue: “Novel ultra-wideband (UWB) multilayer slotline power divider with bandpass response,” *IEEE Microw. Wirel. Compon. Lett.* 20 (2010) 13 (DOI: 10.1109/LMWC.2009.2035951).
- [13] T. Yu: “A broadband Wilkinson power divider based on the segmented structure,” *IEEE Trans. Microw. Theory Techn.* 66 (2018) 1902 (DOI: 10.1109/TMTT.2018.2799579).
- [14] J. Kao, Z. Tsai, K. Lin and H. Wang: “A modified Wilkinson power divider with isolation bandwidth improvement,” *IEEE Trans. Microw. Theory Techn.* 60 (2012) 2768 (DOI: 10.1109/TMTT.2012.2206402).
- [15] V. Tas and A. Atalar: “An optimized isolation network for the Wilkinson divider,” *IEEE Trans. Microw. Theory Techn.* 62 (2014) 3393 (DOI: 10.1109/TMTT.2014.2365533).
- [16] C. J. Trantanella: “A novel power divider with enhanced physical and electrical port isolation,” 2010 IEEE MTT-S International Microwave Symposium (2010) 129 (DOI: 10.1109/MWSYM.2010.5515817).
- [17] T. Chang, T. Huang and H. Hsu: “Miniaturized Wilkinson power divider with complex isolation network for physical isolation,” 2017 47th European Microwave Conference (EuMC) (2017) 396 (DOI: 10.23919/EuMC.2017.8230873).
- [18] X. Wang, I. Sakagami, A. Mase and M. Ichimura: “Wilkinson power divider with complex isolation component and its miniaturization,” *IEEE Trans. Microw. Theory Techn.* 62 (2014) 422 (DOI: 10.1109/TMTT.2014.2300835).
- [19] H. Ahn and S. Nam: “3-dB power dividers with equal complex termination impedances and design methods for controlling isolation Circuits,” *IEEE Trans. Microw. Theory Techn.* 61 (2013) 3872 (DOI: 10.1109/TMTT.2013.2281101).
- [20] X. Wang, I. Sakagami, A. Mase and M. Ichimura: “Trantanella Wilkinson power divider with additional transmission lines for simple layout,” *IET Microw. Antennas Propag.* 8 (2014) 666 (Doi: 10.1049/iet-map.2013.0454).
- [21] S. W. Wong and L. Zhu: “Ultra-wideband power divider with good in-band splitting and isolation performances,” *IEEE Microw. Wireless Compon. Lett.* 18 (2008) 518 (DOI: 10.1109/LMWC.2008.2001009).
- [22] Y. Okada, T. Kawai and A. Enokihara: “Design method for multiband WPDs using multisection LC -ladder circuits,” *IEEE Microw. Wirel. Compon. Lett.* 27 (2017) 894 (DOI: 10.1109/LMWC.2017.2746681).
- [23] T. Kawai, I. Ohta and A. Enokihara: “Design method of lumped-element dual-band Wilkinson power dividers based on frequency transformation,” 2010 Asia-Pacific Microwave Conference (2010) 710 (DOI: None).
- [24] Y. Okada, T. Kawai and A. Enokihara: “Design method of unequal Wilkinson power divider using LC-ladder circuits for multi-way power dividers,” 2016 Asia-Pacific Microwave Conference (APMC) (2016) 1 (DOI: 10.1109/APMC.2016.7931419).
- [25] T. Kawai, K. Nagano and A. Enokihara: “Dual-band semi-lumped-element power dividers at uhf/shf bands,” 2020 50th European Microwave Conference (EuMC) (2021) 844 (DOI: 10.23919/EuMC48046.2021.9338021).
- [26] T. Kawai, H. Mizuno, I. Ohta and A. Enokihara: “Lumped-element quadrature Wilkinson power divider,” 2009 Asia Pacific Microwave Conference (2009) 1012 (DOI: 10.1109/APMC.2009.5384352).
- [27] T. Kawai, K. Nagano, and A. Enokihara: “A 920MHz lumped-element Wilkinson power divider utilizing LC-ladder circuits,” *IEICE Trans. Electron.* E101-C (2018) 801 (DOI: 10.1587/transele.E101.C.801).
- [28] Y. Okada, T. Kawai and A. Enokihara: “Wideband lumped-element Wilkinson power dividers using LC-ladder circuits,” 2015 European Microwave Conference (EuMC) (2015) 115 (DOI: 10.1109/EuMC.2015.7345713).
- [29] M. Heydari and S. Roshani: “Miniaturized unequal Wilkinson power divider using lumped component elements,” *IET Electron. Lett.* 53 (2017) 1117 (Doi: 10.1049/el.2017.2118)
- [30] D. Andrews: *Lumped Element Quadrature Hybrids* (Artech House, Norwood, 2006).
- [31] S. B. Cohn: “Optimum design of stepped transmission-line transformers,” *IRE Trans. Microw. Theory Tech.* 3 (1955) 16 (DOI: 10.1109/TMTT.1955.1124940).
- [32] I. J. Bahl, “Ultrabroadband and compact power dividers/combiners on gallium arsenide substrate [Application Notes],” *IEEE Microwave Magazine* 9 (2008) 96 (DOI: 10.1109/MMM.2008.915337).