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Design and miniaturization of dual-band Wilkinson power dividers

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In this paper, four differently shaped Wilkinson power dividers are presented by selecting the same physical length of two-section transmission lines, dual arbitrary frequency band Wilkinson power dividers can be achieved. The 2.4 GHz (WLAN) and 5.9 GHz (DSRC IEEE 802.11p) frequency bands are selected to complement the future development of multi-band, multi-standard transceivers. To improve physical separation and electrical isolation between the two output ports a parallel RLC circuit is employed. For verification, the simulated and measured performance results of dual-band Wilkinson power dividers implemented on the Rogers 4003C laminate are presented. The measurement results for the fabricated Wilkinson power dividers were in good agreement with theoretical simulation results and show dual-band characteristics.

K e y w o r d s: dual-band, DSRC, RF/microwave circuit, Rogers 4003C, Wilkinson power divider (WPD)

1 Introduction

Wilkinson power dividers/combiners (WPD) are one of the key passive microwave components of modern microwave and RF communication systems. They are widely used for power division or combination in different microwave circuits such as power amplifiers, antenna feeding networks, I/Q vector modulators, demodulators, mixers, frequency multipliers, *etc*. WPD became popular due to their planar structure simplicity, good input and output port matching, and isolation characteristics, but conventional distributed Wilkinson power dividers require a large area at printed circuit board (PCB). For this reason, miniaturization of power dividers has become an attractive topic for microwave researchers and designers. Thereby, various structures have been proposed over the years offering dual- or multi-band WPD with improved performances: low insertion loss, improved isolation and matching, wide band-ratio, small board size [1-8], but all of these designs do not include the 5.9 GHz band. Therefore, in this paper, we present four differently shaped WPD with the same physical length of two-section transmission lines for 2.4 GHz and 5.9 GHz frequency bands, which are widely used in wireless local area network (WLAN) and dedicated short-range communications (DSRC IEEE 802.11p) applications.

We have design the four different shaped dual-band Wilkinson power dividers. The fabricated prototypes were approved by a comparison of the simulation and measured results. The appendicles contain results describing two of the four structures presented in this paper.

2 Design, equations and miniaturization

As mentioned, this work focuses on the design and implementation of a dual-band WPD with the parallel RLC circuit. The circuit schematic of this power divider is shown in Fig. 1 and consists of two pairs of transmission lines with same physical lengths l_1, l_2 and different characteristic impedances Z_1, Z_2, where (l_1, Z_1) and (l_2, Z_2) correspond to operating frequencies f_1 and f_2, respectively. The parallel connection of the resistor (R), the capacitor (C), and the inductor (L), which shunt the two output ports, are used to increase isolation between the outputs. Z_0 is the port characteristic impedance.

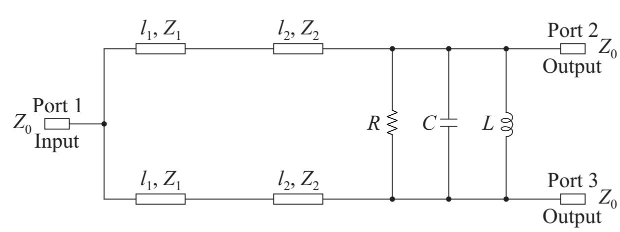

Fig. 1. Dual-band WPD with the parallel RCL isolation circuit

Methods for calculating parameters of such a power divider structure are described in various references [9-11]. According to [10], the physical length of two-section transmission lines can be obtained as

$$l_1 = l_2 = \frac{n\pi}{\beta_1 + \beta_2}, \tag{1}$$

where n is a positive integer and, in this case, is equal to 1, because the ratio of f_2/f_1 is less than 3. Here, β

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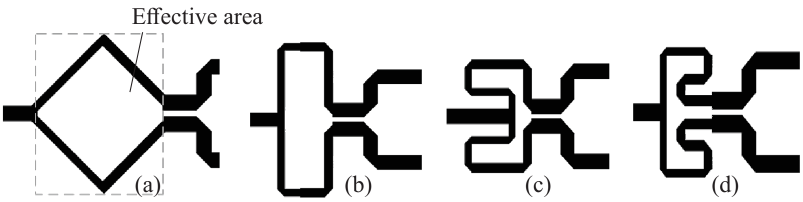


Fig. 2. Dual-band WPD configurations: (a) - rhombus type, (b) - rectangle type, (c) - l_1 -folded type, and (d) - l_2-folded type

Table 1. Design parameters of the dual-band WPD

Parameter	Value
$l_1 = l_2$	11.1 mm
W_0	1.8 mm
W_1	0.85 mm
W_2	1.1 mm
Z_0	50 Ω
Z_1	75.4 Ω
Z_2	66.3 Ω
R	100 Ω
C	0.1 pF
L	17.1 nH

is the propagation constant for f_1 and f_2 frequencies, respectively.

The characteristic impedances of the transmission lines Z_2 and Z_1, are

$$Z_2 = Z_0\sqrt{\frac{1}{2\alpha} + \sqrt{\frac{1}{4\alpha^2 + 2}}}, \tag{2}$$

$$Z_1 = \frac{2Z_0^2}{Z_2}, \tag{3}$$

where Z_0 is the ports characteristic impedance (50 Ω), and parameter is

$$\alpha = \tan^2(\beta_1 l_1). \tag{4}$$

The values of the isolation resistor, capacitor and inductor can be express by

$$R = 2Z_0, \tag{5}$$

$$C = \frac{B/\omega_1 - A/\omega_2}{2\omega_2/\omega_1 - 2\omega_1/\omega_2}, \tag{6}$$

$$L = \frac{2\omega_2/\omega_1 - 2\omega_1/\omega_2}{B\omega_1 - A\omega_2}, \tag{7}$$

where ω is the radian frequency for f_1 and f_2 frequencies, respectively, and A, B, p and q parameters can be expressed by the following equations:

$$A = \frac{Z_2 - Z_1 p^2}{Z_2 p\,(Z_1 + Z_2)}, \tag{8}$$

$$B = \frac{Z_2 - Z_1 q^2}{Z_2 q\,(Z_1 + Z_2)}, \tag{9}$$

$$p = \tan(\beta_1 l_1), \tag{10}$$

$$q = \tan(\beta_2 l_1). \tag{11}$$

Calculations were performed based on the above mentioned equations and the fact that the dual-band Wilkinson power divider will have carrier frequencies of $f_1 =$ 2.4 GHz and $f_2 =$ 5.9 GHz, and will be implemented on a 0.813 mm thick Rogers 4003C laminate. The latter laminate was considered to have a relative permittivity of 3.55, conductor cladding 17 μm in thickness on both sides, and a dissipation factor ($\tan\delta$) of 0.0021 at 2.5 GHz/23 °C, [12]. Summary of the proposed dual-band WPD segment values is tabulated in Tab. 1. Considering the fact, that the electrical lengths of l_1 and l_2 should be left constant, the only way of reducing the overall area is to fold the segments in such a way, which introduces the least amount of stray capacitance between the transmission lines, but still reduces the overall area. Thus, based on the parameters in Tab. 1, four differently shaped WPDs are presented and discussed. All the latter configurations are shown in Fig. 2. The first WPD shown in Fig. 2 (a) is the rhombus type, and the entire structure occupies an area of 3 cm^2 on the PCB. The effective area is calculated by considering only the area occupied by two-section transmission lines as highlighted by the dotted line in Fig. 2(a). The other three structures were designed to reduce this area while maintaining the calculated parameters listed in Tab. 1. The second structure is the rectangle type and shown in Fig. 2(b), covering an area of 1.4 cm^2. The remaining two reduced-size configurations are shown in Fig. 2(c) and Fig. 2(d) and are named l_1 -folded and l_2 -folded, respectively. The latter names are assigned based on which power divider transmission line pair (l_1 at the input or l_2 at the output) is symmetrically folded. The resulting areas are 1.2 cm^2 and about 1 cm^2, respectively. Thus, compared to the rhombus type configuration, the area of the latter two power dividers is reduced about three times.

3 Simulation and measurement results discussion

To verify the above mentioned power divider structures, the four different design examples are implemented on Rogers 4003C laminate. Figure 3 presents a photograph of the fabricated prototypes alongside a metric ruler. The impedances at each port have been designed to be nominal 50 Ω. The isolation resistor, capacitor and inductor are surface-mount 0402-size components and have the values of 100 Ω (1% tolerance), 0.1 pF (±0.1pF),

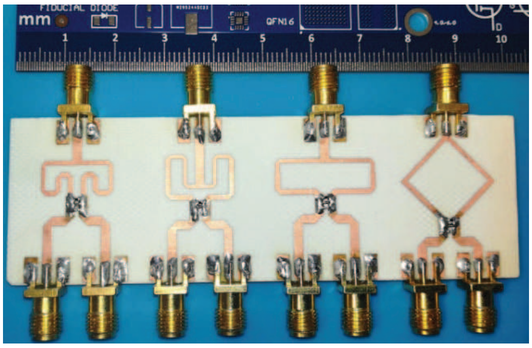


Fig. 3. Photograph of the fabricated dual-band WPD structures

and 17 nH (1% tolerance), respectively. The simulated and measured results are obtained using the Keysight ADS2017 software package and Rohde & Schwarz ZVB8 vector network analyzer (VNA), respectively. The VNA has been calibrated accounting for the length of the cable and the reference plane has been moved right after the connector, as the distance from the connector to the PCB microstrip and the loss in the connector are known [13].

The designed rhombus type WPD is set as the base structure regarding the S-parameters. The folded structures are compared to the latter to maintain the performance while reducing the effective area, marked in Fig. 2 (a). The simulations and measurements have been conducted over the frequency band ranging from 10 MHz to 8 GHz. Rectangle type WPD was found to be the best performing structure, thus the measurement and simulation results are presented alongside the base structure in Fig. 4.

Comparing the rhombus and rectangular WPD structures, the measured return loss (S_{11}) is lower than -26.1 dB and -31.8 dB for 2.4 GHz and 5.9 GHz, respectively, as shown in Fig. 4(a). The measured insertion loss (S_{21} and (S_{31}) is in the range of -3.05 dB to -3.3 dB, Fig. 4(b) and is close to the simulated values. The measurement results show and a good output return loss (S_{22} and S_{33}) which is better than -21 dB at both target frequencies, Fig. 4(c). The isolation (S_{23} and S_{32}) between Port2 and Port3 (Fig. 1) is lower than -28 dB at 2.4 GHz, and -21dB at 5.9 GHz as shown in Fig. 4(d). Thus, folding the rhombus type dual-band Wilkinson power divider in a rectangular way ensuring a minimum amount of stray capacitance between the microstrip segments reduces the effective area by 53% (in the case of this paper from 3 cm^2 to 1.4 cm^2) while maintaining almost identical performance and can lead to more compact multiband, multi-standard transceivers for vehicular communications.

Folding the rectangle WPD structure introduces parasitic stray capacitance between the microstrips, which affects the S-parameter response curves. Even though l_1 -folded type and l_2 -folded type WPD performed as expected around 2.4 GHz with an S_{11} curve minimum offset to the lower side by around a 100 MHz when compared to the simulation results, the additional stray capacitance greatly affected the performance around 5.9 GHz. The S_{11} minimum shifted to the lower frequency range by more than 250 MHz and the minimum S_{11} magnitude degraded by around 15 dB. The return loss (S_{21} and S_{31}) also increased at 5.9 GHz by more than 0.2 dB. Complete measurement results for all investigated structures are presented in Appendix A.

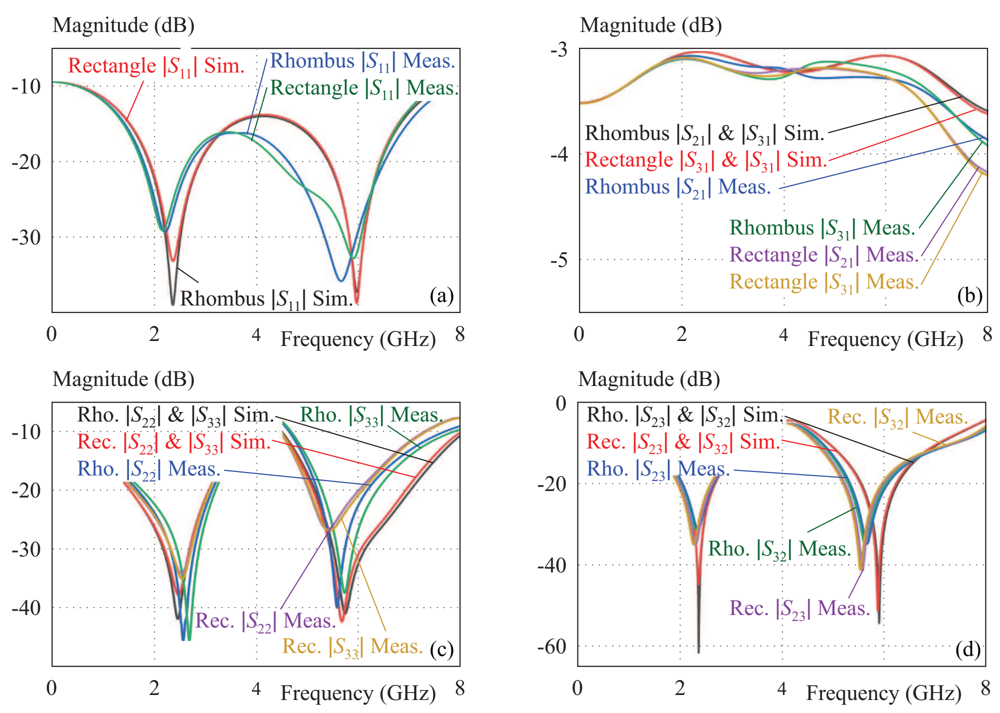
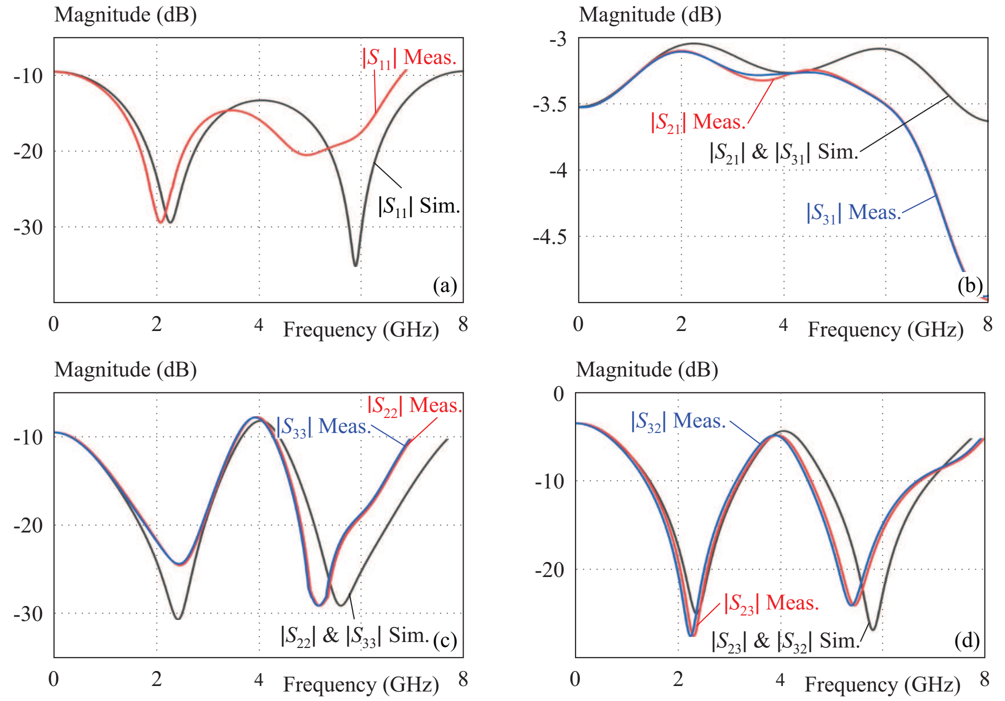
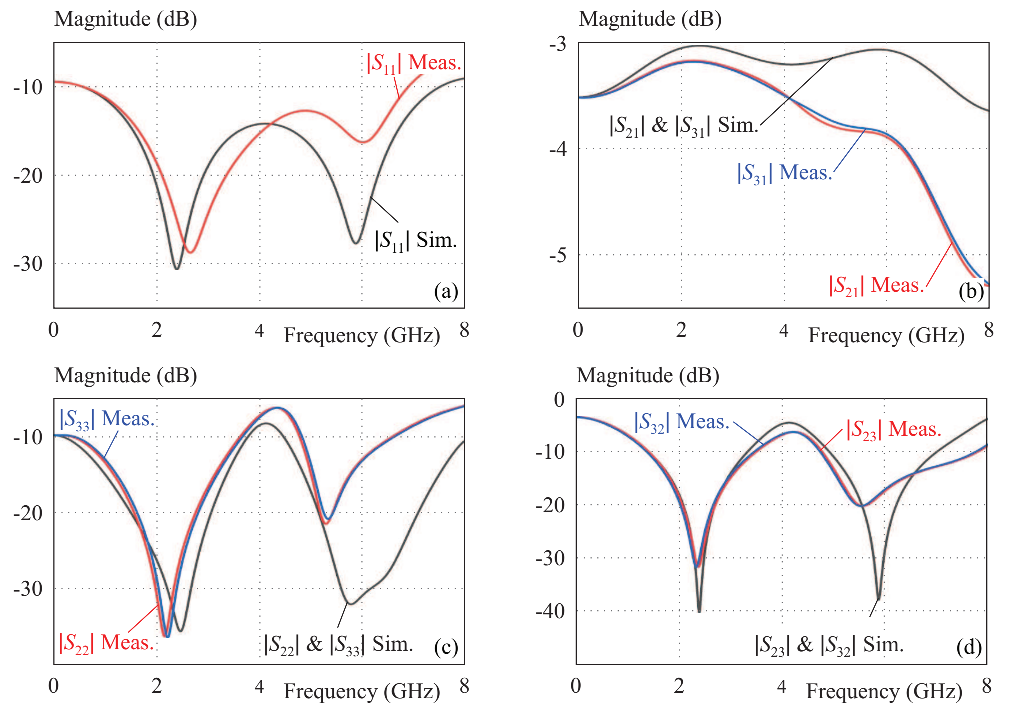


Fig. 4. Rhombus and rectangle type dual-frequency WPD S-parameter simulation and measurement results: (a) - return loss (S_{11}), (b) - insertion loss (S_{21}, S_{31}), (c) - output return loss (S_{22}, S_{33}), and (d) - output port isolation (S_{23}, S_{32})

Appendix A



l_1-folded type dual-frequency Wilkinson power divider S-parameter simulation and measurement results: (a) - return loss (S_{11}), (b) - insertion loss (S_{21}, S_{31}), (c) - output return loss (S_{22}, S_{33}), (d) - output ports isolation (S_{23}, S_{32})



l_2 -folded type dual-frequency Wilkinson power divider S-parameter simulation and measurement results: (a) - return loss (S_{11}), (b) - insertion loss (S_{21}, S_{31}), (c) - output return loss (S_{22}, S_{33}), and (d) - output ports isolation (S_{23}, S_{32})

4 Conclusions

In this paper, four different shaped Wilkinson power dividers with parallel RLC complex isolation components were presented. The size of the investigated power dividers was reduced by folding the same physical lengths two-section transmission lines. The designed rhombus type WPD was set as the performance baseline and only the rectangle type WPD maintained the performance (return and insertion loss as well as port isolation) at 2.4 GHz and 5.9 GHz arbitrary frequencies as well as reducing the effective area by 53% (in the case of this paper from $3\,\mathrm{cm}^2$ to $1.4\,\mathrm{cm}^2$). All designed WPD structures have been investigated using Keysight ADS2017 software package, fabricated on the Rogers 4003C substrate and measured using Rohde & Schwarz ZVB8 vector network analyzer. The presented dividers can be easily applied to compact multi-band, multi-standard transceivers for vehicular communications.

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