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DESIGN OF AN ULTRA-WIDEBAND POWER DIVIDER VIA THE COARSE-GRAINED PARALLEL MICRO-GENETIC ALGORITHM

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Abstract—An ultra-wideband (UWB) power divider is designed in this paper. The UWB performance of this power divider is obtained by using a tapered microstrip line that consists of exponential and elliptic sections. The coarse grained parallel micro-genetic algorithm (PMGA) and CST Microwave Studio are combined to achieve an automated parallel design process. The method is applied to optimize the UWB power divider. The optimized power divider is fabricated and measured. The measured results show relatively low insertion loss, good return loss, and high isolation between the output ports across the whole UWB (3.1–10.6 GHz).

1. INTRODUCTION

Since the Federal Communication Commission (FCC) of the United States allocated the spectrum 3.1–10.6 GHz for commercial use in 2002, many ultra-wideband (UWB) devices have been gained a lot of interest among researchers and the wireless industry [1, 2]. The power divider is one of the key passive components in the design of microwave circuits and antenna arrays, but due to the limitation on frequency bandwidth, which is not suitable for the UWB systems [3–5]. So wideband power dividers are needed. Some UWB power dividers with different design methodologies have been proposed [6–15]. A UWB power divider by installing a pair of stepped-impedance open-circuited stubs and parallel-coupled lines was presented in [6]. In [7–9], improved Wilkinson UWB power dividers were proposed. Based

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on a T-junction in output ports combined with a slotline, a planar UWB out-of-phase power divider was presented in [10, 11]. A UWB power divider consisting of three T-shaped microstrip lines and an H-shaped slot etched was presented in [12]. A UWB multilayer slotline power divider was introduced [13]. According to [14], a UWB power divider exploiting broadside coupling via multilayer microstrip/slot configuration was implemented. Using an exponentially tapered microstrip line and three resistors, a UWB powder divider achieved good return loss and high isolation [15].

The UWB power divider design is a complex problem. Therefore global optimization methods are a good option and can be used for auxiliary design. In recent years, many evolutionary algorithms have been proposed for solving design problems in electromagnetics such as differential evolution (DE) [16], particle swarm optimization (PSO) [12, 17–19] and genetic algorithm (GA) [20–23]. Among them, the PSO [12, 17, 18] and the GA [23] have already been used in power divider designs. It is well known that the GA is easy to parallelize. For improving the performance of the GA, the parallel genetic algorithm (PGA) has been proposed [24–26]. In [24, 25], the PGAs parallelized in a master-slave model were applied to design antenna array. In the master-slave parallel model, a single population is used, but the evaluation of the individuals and sometimes the application of the genetic operators are executed in parallel. So the behaviour of the master-slave algorithm is essentially as same as a serial GA. The coarse-grained PGA was used in [26]. This parallel model divides a large population into some sub-populations, and independently performs selection, crossover and mutation on each subpopulation. A migration operator is used to send some individuals from one deme to another. The coarse-grained parallel model can accelerate the convergence rate and avoid the premature convergence. The micro-genetic algorithm (MGA) is a GA with a small population size which can speed up the converge, and has been applied to antenna design problems [27, 28] and a impedance transformer [29]. In [30], the master-slave parallel micro-genetic algorithm (PMGA) was used to optimize a frequency selective surface (FSS). The coarse-grained PMGA was applied to solve job shop scheduling problem [31] and simultaneously tune power system stabilizer in multimachine power system [32]. However, the coarse-grained PMGA has not been applied for microwave engineering design.

In this paper, a tapered microstrip line comprising exponential and elliptic sections is applied to achieve the UWB performance, instead of an exponentially tapered line in [15]. The CST Microwave Studio is used here to simulate the power divider, and the coarse-grained PMGA based on binary coding is applied to optimize the structure of the tapered microstrip line. The lengths of 29.65 mm and 18.0 mm are chosen for the tapered line of this design (the length of 29.65 mm in [15]). Two resistors are placed along the tapered line to improve the isolation and output return loss, while in [15], three resistors were used. The proposed power divider exhibits comparable performance to [15] (fabricated on the same dielectric substrate). Moreover, the isolation and output return loss of the proposed power divider are better than those of the power divider with two isolation resistors in [15].

This paper is organized as follows. Section 2 describes the structure of the power divider design. In Section 3 an example of antenna array pattern synthesis is provided to demonstrate the advantages of the coarse-grained PMGA. In Section 4, the combined method between the CST MWS and the coarse-grained PMGA is used to optimize the power divider, in addition, the numerical and experimental results are presented to validate the proposed power divider. The conclusion is given in Section 5.

2. POWER DIVIDER STRUCTURE

The configuration of the proposed UWB power divider is shown in Fig. 1. The power divider is printed on a Rogers RT/duroid 5880 substrate with thickness of 0.508 mm and relative permittivity of 2.2. The width $W_m = 1.48\,\mathrm{mm}$ of the input and output microstrip ports is determined assuming $50\,\Omega$ characteristic impedance. Two symmetrical branches are connected with port 1, each of which has a smoothly tapered line that consists of exponential and elliptic sections, as shown in Fig. 2. The tapered line is used to improve the impedance transition from $100\,\Omega$ ($W_{m1} = 0.34\,\mathrm{mm}$) to $50\,\Omega$ at the output port. The power incident at port 1 can be equally divided to port 2 and port 3 over a wide frequency band. x_s is the cut-point position. The length of the tapered line is L_t. The functions associated with each of these two sections are listed below.

1) Exponential section:

$$y = k_1 \exp(k_2 x) + k_3 x, \tag{1}$$

where $k_1 = 0.4$.

2) Elliptic section:

$$\begin{aligned} x &= a\cos(\phi)\cos(phi) - b\sin(\phi)\sin(phi) + x_c \\ y &= a\cos(\phi)\sin(phi) + b\sin(\phi)\cos(phi) + y_c, \end{aligned} \tag{2}$$

where phi is the rotation angle of the ellipse, ϕ is the ellipse sweeping angle, (x_c, y_c) is the center of the ellipse, a is the major semi-axis and b is the semiminor axis.

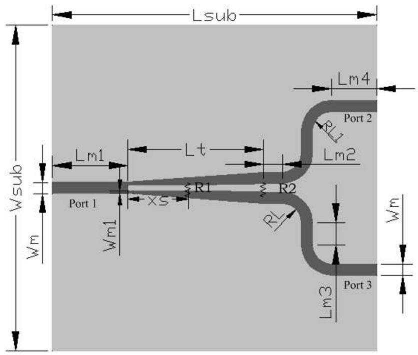

Figure 1. Geometry of the proposed power divider.

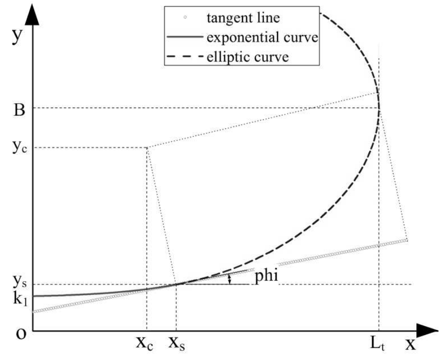

Figure 2. The structure geometry for the tapered line.

The slope of the tangent line is

$$k_s = k_1 k_2 \exp(k_2 x_s) + k_3. \tag{3}$$

So $phi = \arctan(k_s)$.

We can obtain,

$$\begin{aligned} a &= \sqrt{x_a^2 + (y_a x_a \tan(phi))^2 / \left(x_a^2 - 2 y_a x_a \tan(phi)\right)} \\ b &= y_a / \left(1 - \sqrt{1 - \frac{x_a}{a}}\right), \end{aligned} \tag{4}$$

where

$$\begin{aligned} x_a &= (L_t - x_s)/\cos(phi) + (B - y_s - k_s(L_t - x_s))\sin(phi) \\ y_a &= (B - y_s - k_s(L_t - x_s))\cos(phi), \end{aligned} \tag{5}$$

and

$$y_s = k_1 \exp(k_2 x_s) + k_3 x_s. \tag{6}$$

The center (x_c, y_c) is

$$\begin{aligned} x_c &= x_s - b\sin(phi) \\ y_c &= y_s + b\cos(phi). \end{aligned} \tag{7}$$

The design parameters for this power divider is $\{k_2, k_3, B, x_s, R_1, R_2\}$. The resistors R_1 and R_2 are placed on the cut-point position x_s and the position L_t, respectively. Other parameters of the proposed power divider are as follows: $L_{m1} = 10\,\text{mm}$, $L_{m2} = 2.5\,\text{mm}$, $RL = 4\,\text{mm}$.

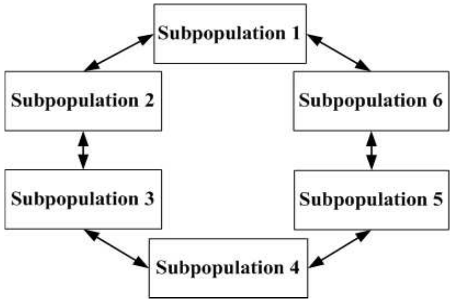

Figure 3. The ring topology of migration.

3. THE COARSE-GRAINED PARALLEL MICRO-GENETIC ALGORITHM

The MGA can be parallelized by dividing a population into several sub-populations assigned to each corresponding processor. This model is called coarse-grained, which introduces a migration operator used to send some individuals from one subpopulation to another. In this paper, We migrate the best individual of the source subpopulation to displace the worst individual in the destination subpopulation. The ring topology of migration is used, as shown in Fig. 3. The coarse-grained PMGA is implemented using C++ on a message passing interface (MPI) environment.

We use different crossover and mutation probability, as well as different methods of selection and crossover. The procedure of the coarse-grained PMGA at each processor is as follows:

Algorithm 1 Procedure of coarse-grained PMGA at each processor

Initialization:

1: $G \leftarrow 1$;

2: initialize subpopulation (N_{sub} individuals);

Iteration:

3: **while** termination conditions not met **do**

4: calculate fitness values;

5: **if** mod $(G,\, k) = 0$ **then**

6: sort the individuals according to their fitness values;

7: send the best individual I_{best} to neighbor;

8: receive the best individual I_{best1} from neighbor;

replace the worst individual I_{worst} with I_{best1};
sort the individuals according to their fitness values;
receive the best individual I_{best2} from the other neighbor;
replace the worst individual I_{worst} with I_{best2};
end if
select a set of individuals for reproduction;
recombine the new population with crossover;
mutate individuals;
if mod $(G, G_{\text{refresh}}) = 0$ **then**
keep the best individual and initialize the others;
end if
$G \leftarrow G + 1$;
end while

We carry out a linear array synthesis to demonstrate the superior of the coarse-grained PMGA. We consider a 40-element uniformly excited linear array symmetrically placed along the x-axis. Our purpose is to find the optimal positions of array elements that would afford a pattern with a minimum side-lobe level (SLL). Only half of the optimization parameters $\{x_1, \ldots x_{20}\}$ are considered. The array factor can be written as

$$AF(\theta, \bar{x}) = 2\sum_{i=1}^{20}\left(\cos\left(\frac{2\pi}{\lambda}x_i \sin\theta\right)\right). \tag{8}$$

The angle resolution of θ is 0.1°. We assume that $d_{\min} = 0.5\lambda \leq x_i - x_{i-1} \leq d_{\max} = \lambda$. The population size is set as 100. There are four sub-populations (or parallel processes) in the coarse-grained PMGA. Fig. 4 shows the average convergence rates for the coarse-grained PMGA and the MGA in 5 independent runs. We can see that the coarse-grained PMGA converges faster than the MGA, and the PMGA only needs 50,000 evaluations on each processor in contrast to 200,000 evaluations by the MGA. The minimum values of SLL obtained by the PMGA and the MGA are -22.27 dB and -21.54 dB respectively. The patterns of the best designs are shown in Fig. 5.

4. NUMERICAL RESULTS

The power divider is simulated using CST MWS. A VBA macro language is used to combine the coarse-grained PMGA and CST MWS.

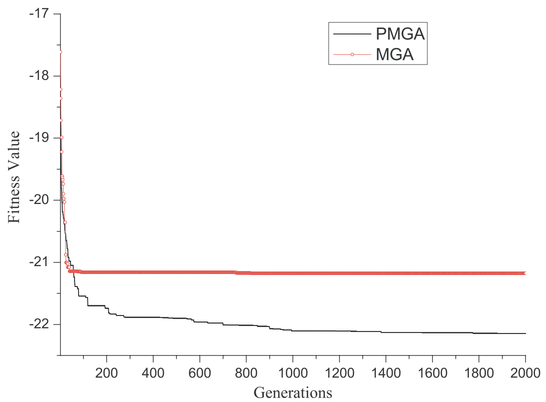

Figure 4. Comparisons of the average convergence rates for PMGA and MGA.

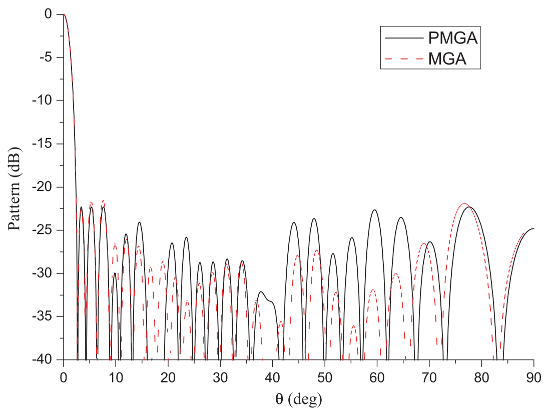

Figure 5. Best radiation patterns obtained by PMGA and MGA.

However, We found that the PMGA can not directly call the CST MWS via the VBA macro language. In order to solve this problem, we add a monitoring program on each processor. The PMGA produces individuals that are exported to a file (data file) on each processor, as well as a sign file on each processor. If the sign file is found by the monitoring program, the monitoring program calls the VBA Macro language. Then the VBA Macro language reads the data file and calls CST MWS to automatically model and calculate the fitness values.

The total population size is set to 80 and the number of subpopulations or processors is 4. The maximum iteration number is 100. We set $G_{\text{refresh}} = 5$ and $k = 3$. The crossover and mutation

Table 1. Parameters of the coarse-grained PMGA.

Subpopulation	P_c	P_m	Selection	Crossover
1	0.85	0.005	Tournament	Multiple Point
2	0.8	0.03	Roulette Wheel	Multiple Point
3	0.95	0.01	Tournament	Single Point
4	0.75	0.02	Roulette Wheel	Single Point

Table 2. Parameters optimized by the coarse-grained PMGA.

k_2	k_3	B	x_s	R_1	R_2
1.005e-9	0.05396	2 mm	11 mm	78.62 Ω	165.94 Ω

probability are P_c and P_m respectively. Table 1 shows the parameters of the PMGA on each subpopulation. The four sub-populations adopt different evolutionary strategies. According to this way, we can maintain the diversity of population. The power divider is built on a Rogers RT5880 substrate (thickness is 0.508 mm, $\varepsilon_r = 2.2$).

4.1. The Length of the Tapered Line is 29.65 mm

In order to illustrate the function of the combined exponential and elliptic curves, we optimize a similar structure as in [15]. The parameters of the power divider is as follows: $L_t = 29.65\,\text{mm}$, $L_{m3} = 20\,\text{mm}$, $L_{m4} = 0\,\text{mm}$, $W_{\text{sub}} = 52\,\text{mm}$, $L_{\text{sub}} = 56.15\,\text{mm}$, $RL_1 = 0\,\text{mm}$.

We define the design problem as the minimization of the objective function:

$$F(\bar{x}) = \{\max S_{11} + \max S_{22} + \max S_{23}, f \in [3\,\text{GHz}, 10.2\,\text{GHz}]\}, \quad (9)$$

where $\bar{x} = \{k_2, k_3, B, x_s, R_1, R_2\}$.

The solution space of the exponential section parameters is: $k_2 \in [0, 0.1]$ and $k_3 \in [-0.05, 0.1]$. The height B of the terminal tapered line ranges from 0.5 mm to 6 mm. The lower and upper bounds of the cut-point position x_s are 2 mm and 25 mm, respectively. The isolation resistors R_1 and R_2 vary from 50 Ω to 400 Ω. The design parameters for the UWB power divider obtained by the coarse-grained PMGA are shown in Table 2.

Figure 6 shows the simulated S-parameters of the power divider. The input return loss is better than 15 dB over 2.4–11 GHz (2.1–11 GHz in Ref. [15]). The output return loss is better than 14 dB from 2 GHz to 10.2 GHz, while in [15], that is only better than 10 dB over 2–7 GHz. The isolation is better than 13.6 dB over 2–10.2 GHz, in contrast to

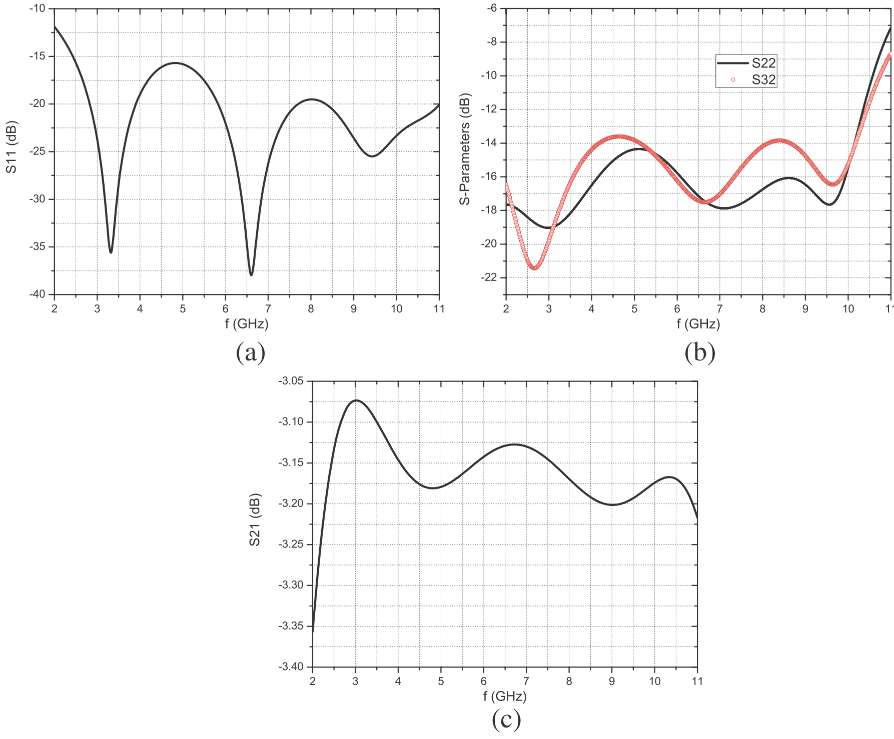

Figure 6. S-parameters of the power divider.

10 dB over 2–7 GHz in [15]. The ripple of the transmission coefficient is from 3.05 dB to 3.4 dB, while in [15], that is from 3.1 dB to 4.1 dB. So the combined exponential and elliptic curves are helpful to achieve better output return loss and isolation.

4.2. The Length of the Tapered Line is 18 mm

We set $L_t = 18\,\text{mm}$, $L_{m3} = 3\,\text{mm}$, $L_{m4} = 6\,\text{mm}$, $W_{\text{sub}} = 43.2\,\text{mm}$, $L_{\text{sub}} = 43\,\text{mm}$, $RL_1 = 4\,\text{mm}$. In the proposed power divider structure, we require that the return loss for three ports and the isolation are better than 10 dB on the entire 3.1–10.6 GHz band. In order to achieve the desired results, the design problem can be defined as the minimization of the objective function:

$$F(\bar{x}) = \{\max S_{11} + \max S_{22} + \max S_{23}, f \in [3.1\,\text{GHz}, 10.6\,\text{GHz}]\}, \quad (10)$$

where $\bar{x} = \{k_2,\ k_3,\ B,\ x_s,\ R_1,\ R_2\}$.

The solution space of the exponential section parameters is: $k_2 \in [0,\ 0.08]$ and $k_3 \in [-0.05, 0.02]$. The height B of the terminal tapered line ranges from 0.5 mm to 2 mm. The lower and upper bounds of the cut-point position x_s are 2 mm and 14 mm respectively. The isolation resistors R_1 and R_2 vary from 50 Ω to 400 Ω.

Table 3 shows the design parameters of the UWB power divider optimized by the coarse-grained PMGA. The optimized isolation resistors in the table are replaced by their nearest standard chip resistors. We select $R_1 = 75\,\Omega$ and $R_2 = 180\,\Omega$.

The fabricated power divider was tested using a HP8510C vector network analyser. The photograph of the fabricated UWB power divider is shown in Fig. 7.

The simulated and measured isolation performance of the proposed power divider is shown in Fig. 8. The isolation between

Table 3. Parameters optimized by the coarse-grained PMGA.

k_2	k_3	B	x_s	R_1	R_2
0.0594	−0.0314	0.6 mm	8 mm	75.68 Ω	181.42 Ω

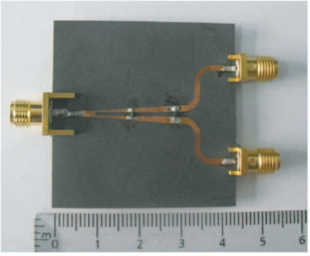

Figure 7. Photograph of the proposed power divider.

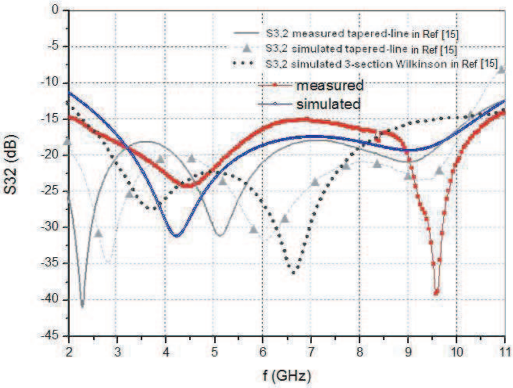

Figure 8. Comparisons of the isolation performance.

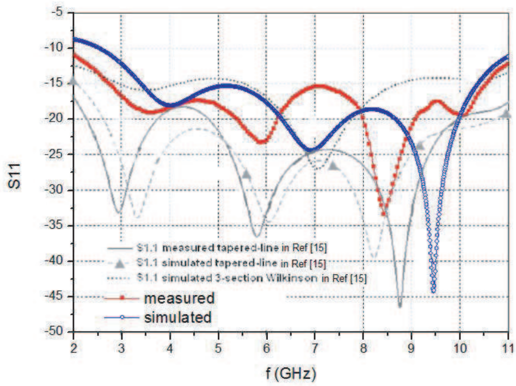

Figure 9. Comparisons of the return loss for port 1.

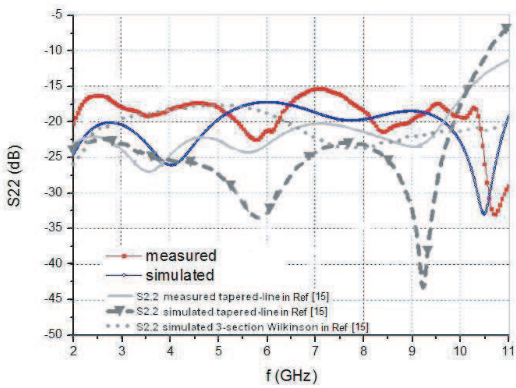

Figure 10. Comparisons of the return loss for port 2.

the output ports is better than 15 dB across frequency band of 2.1–10.8 GHz. The measured return loss of the input port, shown in Fig. 9, is better than 15 dB over 2.5–10.6 GHz. Fig. 10 shows the simulated and measured return loss at port 2. The return loss of the output port is better than 15 dB from 2 to 11 GHz. Fig. 11 compares the simulated and measured insertion loss of the power divider. The ripple of the measured insertion loss between the input and output ports is from 3.05 dB to 3.45 dB across 2–11 GHz. It can be seen that the measured results are in good agreement with those of the simulation. The discrepancy between the measured and simulated results is mainly due to the SMA connector, the manufacturing errors and minor offset in soldering positions of the isolation resistors.

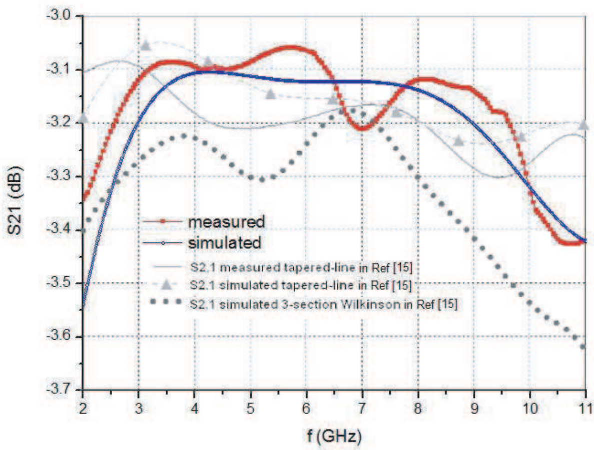

Figure 11. Comparisons of the transmission coefficient.

Table 4. Comparative results of the power dividers.

	This paper	Ref. [15] with three resistors	Ref. [15] with two resistors
The length of tapered line	18 mm	29.65 mm	29.65 mm
Band of $\vert$dB $(S_{11})\vert$ better than 15 dB	2.5–10.6 GHz	2–11 GHz	2.1–11 GHz
Band of $\vert$dB $(S_{22})\vert$ better than 15 dB	2–11 GHz	2–10.2 GHz	2–6.5 GHz
Band of $\vert$dB $(S_{32})\vert$ better than 15 dB	2.1–10.8 GHz	2–10.2 GHz	2–6.5 GHz
Ripple of $\vert$dB $(S_{21})\vert$	3.05–3.45 dB	3.05–3.3 dB	3.1–4.1 dB

In Figs. 8–11, we also compared the performance of the proposed power divider with the results of the exponentially tapered-line divider and 3-section Wilkinson divider in [15]. The substrate material in [15] is as same as that in this paper. Table 4 shows the comparative measured results of the power dividers. We can see that the isolation, the input return loss, output return loss and the insertion loss are comparable for the power dividers with two resistors in this paper and with three resistors in [15].

5. CONCLUSION

A compact UWB power divider proposed and discussed here comprises a tapered line (consists of an exponential section and an elliptic section) and two isolation resistors. The power divider was optimized using the coarse-grained PMGA combined with a numerical solver CST MWS. Across the whole UWB, the optimized power divider exhibits low amplitude ripple in the insertion loss and good impedance matching in the input port. Using two isolation resistors along the tapered line, we achieve good isolation and output return loss better than 15 dB over the entire UWB. The measured results are in good agreement with the simulation results. It is shown that the design methodology is an effective way for power divider design.

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