A Compact Dual-band Planar 4-Way Power Divider

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Abstract **─** In this paper, an optimized approach based on T-shaped step impedance transmission line is proposed to design a compact dual band 4-way planar power divider. In the proposed structure, the 100 Ω quarter wavelength transmission lines are equaled by the T-shaped step impedance transmission lines (SITLs) which achieve the design equations with two freedom degrees. Then, the invasive weed optimization is used to find the optimized design parameters. Three power dividers with different operation frequencies ratio are designed and simulated to show the method ability. Finally, one 4-way planar power divider is fabricated and measured to verify the ability and power of the proposed approach which shows 53% compactness and proper specifications in both the operation frequencies.

Index Terms **─** Compact, dual band, planar, power divider.

I. INTRODUCTION

Power dividers are key passive components in microwave and millimeter-wave systems. The Wilkinson power divider, branch line and rate race are some examples of these passive devices [1]. These power dividers have narrow bandwidth and occupy large sizes, which limit their application and flexibility in the microwave circuits. Due to the dual band requirement in wireless communication systems, some techniques have been used to achieve the dual band attribute in these power dividers scheme such as non-uniform transmission lines, using non-uniform transmission lines, stubs and reactive components [2-5]. The 4-way power divider which is a useful component in RF applications have been considered in the literature. A 4-way Wilkinson power divider with band passes filtering response has been proposed in [6]. Very recently, a compact four-way dual-band microstrip power divider has been proposed in [7] by using RLC lumped elements which can limit the fabrication process and increase the cost. In this paper, a planar compact dual band 4-way power divider is proposed. This divider is based on the planar single band divider scheme proposed in [8] composed of four 100 Ω quarter wavelength transmission lines where its output ports are connected by 70.711 Ω resistors to enhance the output isolations. To achieve the compact and dual band specifications in this divider, the quarter wavelength transmission line segments are replaced by T-shaped step impedance transmission lines (SITLs). Using step impedance transmission line technique is a well-known approach to compact the microwave circuits as discussed in [9-11]. The proposed T-shaped SITL is composed of a stepped transmission line with an open stub in the middle which increases the freedom degrees in the design process. The T-shaped SITLs have been used previously to achieve dual band applications in some RF devices such as [12-13]. Here, a symmetric simple T-shaped SITL is used to achieve dual band and compact specifications in a planar divider. For this purpose, the equality between 100 Ω quarter wavelength transmission lines and T-shaped SITLs achieves the complex design equations. Then, a stochastic invasive weed optimization algorithm (IWO) [14-18] is used to find the best answer of the design equations, which is the desired dual band and compact planar 4-way divider. This optimization has been applied previously to compact the microwave devices such as filters [19-20], also. Three different planar compact power dividers are designed with different arbitrary operation frequencies to verify the proposed design approach. Finally, one of these cases is fabricated and measured which works at f_1=450 MHz and f_2=2.835 GHz with 56 mm×56 mm dimensions ($0.51\lambda_{g0} \times 0.51\lambda_{g0}$, where λ_{g0} is the guided wavelength at the center frequency between f_1 and f_2) which shows 53% compactness compared with one composed of two sections transmission line topology in [21]. The mean value of the insertion losses and isolation at both operation frequencies are better than 6.5 dB and 15 dB, respectively. These good specifications are comparable

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with the proposed divider in [7] but without lumped element usage limitations. The simplicity, arbitrary ratio of two operation frequencies, high enough port isolation and low insertion loss verify the ability of the proposed divider compared with the references.

II. THEORY AND DESIGN

A. Design equation

A planar 4-way power divider has been introduced in [1] which is composed of four equal 100 Ω transmission lines. The output ports are connected by 70.711 Ω resistors to enhance the output isolations. The main part of this structure is the quarter wavelength transmission lines which limit the device operation bandwidth and occupies a large area.

To achieve a compact and dual band structure, T-shaped step impedance transmission lines (SITL) are used instead of these quarter wavelength transmission lines as shown in Fig. 1. The T-shaped SITL is composed of three different transmission line segments with Z_1, Z_2 and Z_3 characteristic impedances and θ_1, θ_2 and θ_3 electrical lengths, respectively as shown in Fig. 1. These T-shaped SITLs and quarter wavelength 100 Ω transmission line should have equal properties at two different frequencies, f_1 and f_2. For this purpose, the ABCD matrices of these structures should be equaled at these two frequencies as:

$$\begin{bmatrix} 0 & j100 \\ j\dfrac{1}{100} & 0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1^{f_i}) & jZ_1\sin(\theta_1^{f_i}) \\ j\dfrac{1}{Z_1}\sin(\theta_1^{f_i}) & \cos(\theta_1^{f_i}) \end{bmatrix} \times \begin{bmatrix} \cos(\theta_2^{f_i}) & jZ_2\sin(\theta_2^{f_i}) \\ j\dfrac{1}{Z_2}\sin(\theta_2^{f_i}) & \cos(\theta_2^{f_i}) \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ j\dfrac{1}{Z_3}\tan(\theta_3^{f_i}) & 1 \end{bmatrix} \times \begin{bmatrix} \cos(\theta_2^{f_i}) & jZ_2\sin(\theta_2^{f_i}) \\ j\dfrac{1}{Z_2}\sin(\theta_2^{f_i}) & \cos(\theta_2^{f_i}) \end{bmatrix} \times \begin{bmatrix} \cos(\theta_1^{f_i}) & jZ_1\sin(\theta_1^{f_i}) \\ j\dfrac{1}{Z_1}\sin(\theta_1^{f_i}) & \cos(\theta_1^{f_i}) \end{bmatrix}, \quad (1)$$

where f_i denotes f_1 and f_2. The middle stub (Z_3, θ_3) is considered as loaded shunt impedance which is located between two transmission line segments.

Notice that the effect of discontinuities has been ignored in this relation for simplicity. Since the T-shaped SITL is considered as symmetric, reciprocal and lossless circuit, only two independent equations are achieved at each frequency from (1). The electrical lengths of T-shaped SITL segments are related to their physical length by:

$$\theta_{1,2,3}^{f_i} = \frac{2\pi}{\lambda_g^{f_i}} l_{1,2,3}, \quad (2)$$

where $\lambda_g^{f_i}$ is the guided wavelength at f_i. If the ratio of two operation frequencies are considered as K, then,

$$f_2 = Kf_1 \qquad \lambda_g^{f_2} = \frac{1}{K}\lambda_g^{f_1} \qquad \theta_{1,2,3}^{f_2} = K\theta_{1,2,3}^{f_1}. \quad (3)$$

In other words, to design a dual band divider, we have four independent equations with six unknown variables, Z_1, Z_2, Z_3, θ_1, θ_2 and θ_3. After some complex algebraic calculations, these equations can be expressed as:

$$\begin{aligned} &\left(\cos^2(\theta_1^{f_i}) - \sin^2(\theta_1^{f_i})\right)\left(\cos^2(\theta_2^{f_i}) - \sin^2(\theta_2^{f_i})\right) \\ &-\left(\frac{1}{2}\sin(2\theta_1^{f_i})\sin(2\theta_2^{f_i})\right)\left(\frac{Z_2^2 + Z_1^2}{Z_1 Z_2}\right) \\ &+\left(\frac{\tan(\theta_3^{f_i})}{2Z_3}\right)\left(Z_2(2\sin^2(\theta_1^{f_i}) - 1)\sin(2\theta_2^{f_i})\right) \\ &+\sin(2\theta_1^{f_i})\left(\frac{Z_2^2}{Z_1}\sin^2(\theta_2^{f_i}) - Z_1\cos^2(\theta_2^{f_i})\right) = 0, \end{aligned} \quad (4)$$

$$\begin{aligned} &\sin(2\theta_2^{f_i})\left(Z_2\cos^2(\theta_1^{f_i}) - (\frac{Z_1^2}{Z_2})\sin^2(\theta_1^{f_i})\right) + \\ &Z_1\sin(2\theta_1^{f_i})\left(2\cos^2(\theta_2^{f_i}) - 1\right) - \left(\frac{\tan(\theta_3^{f_i})}{Z_3}\right) \\ &\times\left(\begin{aligned} &Z_1^2\sin^2(\theta_1^{f_i})\cos^2(\theta_2^{f_i}) + Z_2^2\sin^2(\theta_2^{f_i})\cos^2(\theta_1^{f_i}) \\ &+\frac{Z_1 Z_2}{2}\sin(2\theta_1^{f_i})\sin(2\theta_2^{f_i}) \end{aligned}\right) = 100. \end{aligned} \quad (5)$$

It can be seen that there are two freedom degrees in these equation systems. An optimization algorithm is used to solve this nonlinear equation system in the next section.

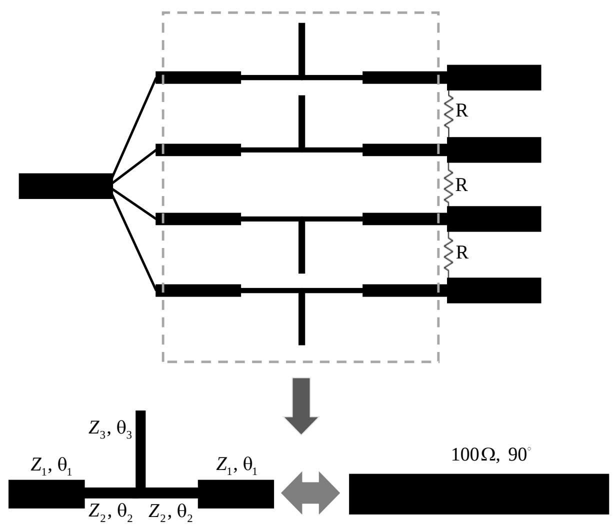


Fig. 1. (a) Structure of proposed planar dual band 4-way power divider, and (b) equivalent circuit of quarter wavelength transmission line with T-shaped SITL.

B. Optimization

The invasive weed optimization (IWO) algorithm is composed of the natural inspired behaviours of invasive weeds such as seeding, growth, and competitive exclusion to reach the rich soil area. This optimization process is initialized by random spatial dispersion of the seed population, P_{max}. After seeds growth to weeds, their fitness are calculated based on the predefined cost function. Then each weed reproduces some new seeds between S_{min} and S_{max} corresponding to its relative fitness in the weed population. This distribution is performed by a normal distribution with variable variance versus the iterations around the corresponding weed as:

$$\sigma_{iter} = \frac{(iter_{max} - iter)^n}{(iter_{max})^n}\left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final}, \quad (6)$$

where $iter$ and $iter_{max}$ are the current and maximum iteration numbers, respectively. Therefore, the dispersion variance is decreased from $\sigma_{initial}$ value to σ_{final} which leads the seeds to focus around the optimum answer. All of the new grown seeds and old weeds compete with each other to eliminate the week members when the population is reached to the maximum allowable members, P_{max}. This process continues through the iterations to achieve the best cost function value and the global optimum problem response, consequently. This optimization method has been verified to be effective in converging to an optimal solution by employing basic properties such as seeding, growth, and competition in a weed colony. The main advantage of the IWO algorithm is its independency from the initial conditions [14].

In this problem, the optimal goal is solving (4) and (5) as well as decreasing the total circuit length to achieve a compact dual band 4-way divider which can be formulated as:

$$e_t = \sqrt{e_{A_1}^2 + e_{A_2}^2 + 0.01\times e_{B_1}^2 + 0.01\times e_{B_2}^2 + W\theta_{Total}}, \quad (7)$$

where $\theta_{Total} = 2(\theta_1 + \theta_2)$ is the total electrical length of the T-shaped SITL, and e_{A1} and e_{A2} are the differences between two sides of (4) at f_1 and f_2, respectively. In a same way, e_{B1} and e_{B2} are the differences between two sides of (5) at f_1 and f_2, respectively. This cost function should be minimized to achieve the best solution for (4) and (5) as well as compactness. Notice these errors are multiplied by 0.01 to achieve balanced values compared with e_{A1} and e_{A2}. Since there is a trade-off between the equations satisfactions (e_{Ai} and e_{Bi}) and compactness (θ_{Total}), W is considered as a weighting factor in (7) for their importance balancing. In other words, W should be chosen as high as that (4) and (5) are satisfied at both frequencies, properly. The simulation results shown that 0.25 is a good value for this coefficient.

The optimization algorithm tries to minimize this error function by proper choosing of design variables, Z_1, Z_2, Z_3, θ_1, θ_2 and θ_3. The optimization parameters are tabulated in Table 1.

Table 1: IWO optimization parameters

Parameters	Description	Range
$Z_{1,2,3}$ (Ω)	Impedance	10Ω~170Ω
$\theta_{1,2,3}$ (deg)	Electrical length	1°~30°
N	Initial population	200
P_{max}	Maximum population	200
S_{min}	Minimum seed	2
S_{max}	Maximum seed	10
$\sigma_{initial}^{Z}$	Initial impedance variance	75
$\sigma_{initial}^{\theta}$	Initial electrical lengths variance	30
$\sigma_{final}^{Z,\theta}$	Final variance	0.5
Iteration	Repeat operations	1000

III. SIMULATION AND MEASUREMENT RESULTS

A. Different cases

To validate the proposed design process, three power dividers with different K are designed as tabulated in Table 2. Also, the design parameters are reported in this table. As it can be seen, the T-shaped SITs in these three cases are compact rather than the uniform quarter wavelength transmission lines. The compactness reported in the table is achieved by comparison of each case with two sections transmission line topology, one works at the first operation frequency, f_1=450 MHz and the other one works at the second one, f_2. Notice that this technique can be used to achieve dual band operation in Wilkinson power dividers as reported in [21]. All electrical lengths reported in the table are computed respect to f_1=450 MHz, also. Figure 2 depicts the error functions versus the iterations for Case A, B and C which prove the convergence of the algorithm in different cases. Notice that the stepwise behavior depicted in Fig. 2 is due to go out of the algorithm from the local minimums and converge to the global minimum response.

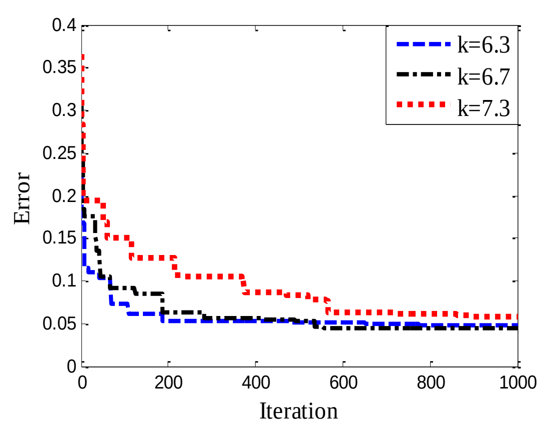


Fig. 2. The error function versus iterations in Case A.

Table 2. Characteristic impedances and electrical length of three T-shaped SITLs cases

Case	*A* *K=6.3*	*B* *K=6.7*	*C* *K=7.3*
$Z_1\,(\Omega)$	169.6	169.6	87.7
$Z_2\,(\Omega)$	148.3	162.0	169.9
$Z_3\,(\Omega)$	132.7	101.9	157.8
$\theta_1^{f_1}$ (deg)	13.5	11.1	7.2
$\theta_2^{f_1}$ (deg)	19.2	20.2	24.4
$\theta_3^{f_1}$ (deg)	29.37	32.4	44.8
θ_{Total} (deg)	65.4	62.6	63.2
Compactness	52.97%	54.75%	54.55%
Error	0.048	0.045	0.058

Figure 3 shows the simulation results of three 4-way power dividers. Theses dividers are implemented on RO4003 substrate with $\varepsilon_r = 3.55$ and 0.762 mm thickness. As it can be seen, all of these three cases are works at f_1=450 MHz, properly as it expected from the design process. The simulation results depict a very small deviation in the second operation frequencies, f_2 and small change in K, consequently. Notice that all simulations are performed by using Advance Design System Software, ADS 2011. These results verify that ignoring the step discontinuities which was not considered in the design equations, are not affected the design process, significantly.

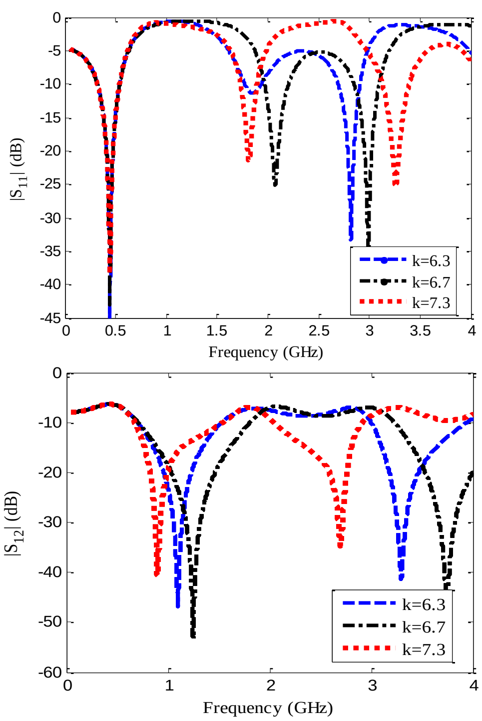


Fig. 3. The simulation results of $|S_{11}|$ and $|S_{12}|$ in three design cases.

B. Fabrication and measurement

To validate the design process, one of the proposed cases, the Case A is fabricated on RO4003 substrate with 0.762 mm thickness as shown in Fig. 4. The meander line technique is used in this 4-way power divider to achieve more compactness. Also, the 402 surface mounted resistors are used to achieve the designed isolation between the output ports. The total length of this fabricated divider is 56 mm×56 mm dimensions ($0.51\lambda_{g0} \times 0.51\lambda_{g0}$, λ_{g0} = the guided wavelength at the center frequency between f_1 and f_2) which shows 53% compactness compared with the one proposed in [21]. Notice that the meander line contribution in the power divider length reduction is about 5%.

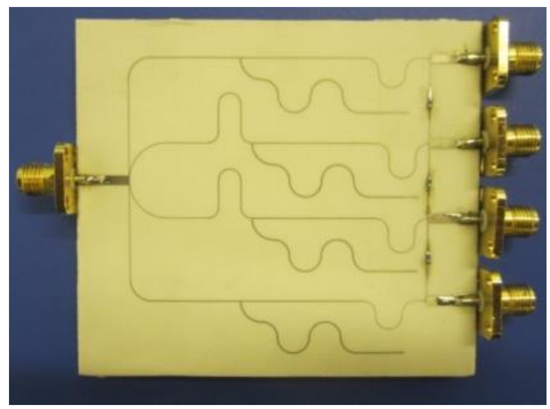
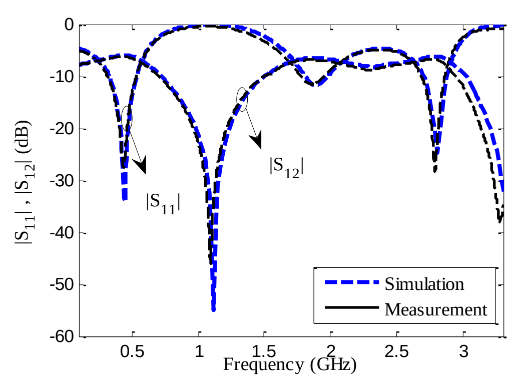


Fig. 4. The fabricated 4-way compact dual-band planar power divider (case A with *K*=6.3).

The simulation and measurement results of the proposed divider are depicted in Fig. 5. Notice that the small differences between simulation and measurement results are due to the fabrication process limitation. The mean value of the insertion losses and isolation at both operation frequencies are better than 6.3 dB and 15 dB, respectively. Therefore, this compact dual band power divider has a small insertion loss, good matching, and isolation performances at the desired dual bands. These good specifications verify the capability and ability of the proposed method.



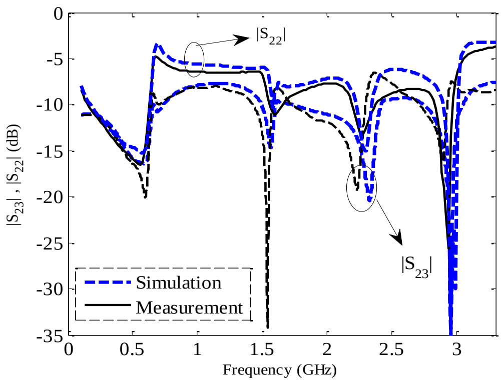


Fig. 5. Simulation and measurement results of $|S_{11}|$, $|S_{12}|$, $|S_{22}|$ and $|S_{23}|$.

IV. CONCLUSION

An optimized approach has been proposed to design a 4-way planar compact dual band power divider. In this approach, the 100 Ω quarter wavelength transmission lines have been replaced by the T-shaped SITLs. The invasive weed optimization has been used to find the optimized design parameters of the divider. Three power dividers with different frequencies ratio were designed and simulated to verify the idea. Finally, one of these dividers has been fabricated and measured which showed 53% compactness and proper specifications in both the operation frequencies.

REFERENCES

[1] D. M. Pozar, *Microwave Engineering*. 3rd ed., New York: J. Wiley & Sons, 2005.

[2] D. Hawatmeh, K. Al Shamaileh, and N. Dib, “Design and analysis of multi-frequency unequal-split Wilkinson power divider using non-uniform transmission lines,” *ACES*, vol. 27, no. 3, 2012.

[3] K.-K. M. Cheng and F.-L. Wong, “A new Wilkinson power divider design for dual band application,” *IEEE Microw. and Wireless Components Letters*, vol. 17, no. 9, pp. 664-666, September 2007.

[4] Y. Wu, Y. Liu, Y. Zhang, J. Gao, and H. Zhou, “Dual band unequal Wilkinson power divider without reactive components,” *IEEE Trans. Microwave Theory Tech. MTT*, vol. 57, no. 1, January 2009.

[5] X. Wang, I. Sakagami, K. Takahashi, and S. Okamura, “Generalized dual-band Wilkinson power divider with parallel L, C, and R components,” *IEEE Trans. Microwave Theory and Tech. MTT*, vol. 60, no. 4, April 2012.

[6] F.-J. Chen, et al., “A four-way microstrip filtering power divider with frequency-dependent couplings,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 63, no. 10, pp. 3494-3504, 2015.

[7] T. Zhang, et al., “A compact four-way dual-band power divider using lumped elements,” *Microwave and Wireless Components Letters, IEEE*, vol. 25, no. 2, pp. 94-96, 2015.

[8] A. A. M. Saleh, “Planar electrically symmetric n-way hybrid power dividers/combiners,” *IEE Transactions on Microwave Theory and Techniques MTT*, vol. 28, pp. 555-563, 1980.

[9] S. H. Sedighy and M. Khalaj-Amirhosseini, “Compact Wilkinson power divider using stepped impedance transmission lines,” *Journal of Electromagnetic Waves and Applications*, vol. 25, iss. 13, pp. 1773-1782, 2011.

[10] S. Sun and L. Zhu, “Compact dual-band microstrip bandpass filter without external feeds,” *Microwave and Wireless Components Letters, IEEE*, vol. 15, no. 10, pp. 644-646, 2005.

[11] Q.-X. Chu and F.-C. Chen, “A compact dual-band bandpass filter using meandering stepped impedance resonators,” *Microwave and Wireless Components Letters, IEEE*, vol. 18, no. 5, pp. 320-322, 2008.

[12] C. Quendo, E. Rius, and C. Person, “Narrow bandpass filters using dual-behavior resonators based on stepped-impedance stubs and different-length stubs,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 3, pp. 1034-1044, 2004.

[13] M. D. C. Velazquez-Ahumada, et al., “Application of stub loaded folded stepped impedance resonators to dual band filters,” *Progress in Electromagnetics Research*, vol. 102, pp. 107-124, 2010.

[14] A. R. Mehrabian and C. Lucas, “A novel numerical optimization algorithm inspired from weed colonization,” *Ecological Informatics*, vol. 1, iss. 4, pp. 355-366, December 2006.

[15] Y. Li, et al., “Synthesis of conical conformal array antenna using invasive weed optimization method,” *Applied Computational Electromagnetics Society Journal*, vol. 28, no. 11, 2013.

[16] B. Bahreini, A. Mallahzadeh, and M. Soleimani, “Design of a meander-shaped MIMO antenna using IWO algorithm for wireless applications,” *Applied Computational Electromagnetics Society Journal*, vol. 25, no. 7, pp. 631-638, 2010.

[17] A. R. Mallahzadeh and P. Taghikhani, “Cosecant squared pattern synthesis for reflector antenna using a stochastic method,” *Applied Computational Electromagnetics Society Journal*, vol. 26, no. 10, 2011.

[18] S. H. Sedighy, et al., “Optimization of printed Yagi antenna using invasive weed optimization (IWO),” *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 1275-1278, 2010.

[19] M. Hayati, M. Amiri, and S. H. Sedighy, "Design of compact and wideband suppression low pass elliptic filter by n-segment step impedance transmission line," *Applied Computational Electromagnetics Society Journal*, vol. 30, iss. 5, pp. 510-518, May 2015.

[20] H. Khakzad and S. H. Sedighy, "Design of compact SITLs low pass filter by using invasive weed optimization (IWO) technique," *Applied Computational Electromagnetics Society Journal*, vol. 25, no. 3, March 2013.

[21] N. Gao, G. Wu, and Q. Tang, "Design of a novel compact dual-band Wilkinson power divider with wide frequency ratio," *IEEE Microwave and Wireless Components Letters*, vol. 24, no. 2, pp. 81-83, 2014.

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