TELEMÁTICA
REVISTA DIGITAL de las Tecnologías
de la Información y las Telecomunicaciones

Revista Telemática. Vol. 20 No. 1, Enero-Marzo, 2021, p.66-75 ISSN 1729-3804

DESIGN OF AN UNEQUAL WILKINSON POWER DIVIDER FOR VHF RADAR APPLICATIONS

Ing. Daryl Ortega González[1]

[1]Universidad Tecnológica de La Habana "José Antonio Echeverría", CUJAE, 114 e/ Ciclovía y Rotonda, Marianao,
La Habana, Cuba.
[1] e-mail:fedortegag@gmail.com, dortegag@tele.cujae.edu.cu

ABSTRACT

Current radars must meet the technological demands of today's world, which is why the modernization, replacement, or design of any of its parts is a strategic step. The antenna unit does not escape this reality. In it, it is usual to find several blocks among which are the power dividers, especially in radars that use antenna arrays and in particular air exploration radars such as the P18 and P12 use an unequal Wilkinson power divider with output to the two rows that are part of its antenna array. This paper proposes the design and simulation of an unequal Wilkinson power divider at the center frequency of 160 MHz of the Very High Frequency (VHF) band with a power ratio at the output ports of 60% - 40%. The calculation of the components is carried out in Mathcad and the lumped circuit is simulated in AWR Microwave Office. From the results, Return Loss (RL) of -45.18 dB, isolation between the output ports of -49 dB, and power ratio at the output of S_{31} = -2.21 dB and S_{21}= -3.98 dB in ports 3 and 2 respectively.

KEYWORDS: Wilkinson power divider, VHF, P18, Radar.

DISEÑO DE UN DIVISOR DESIGUAL DE POTENCIA WILKINSON PARA APLICACIONES VHF DE RADAR

RESUMEN

Los radares actuales deben estar a la altura de las exigencias tecnológicas del mundo de hoy, razón por la cual la modernización, sustitución o el diseño de alguna de sus partes resulta un paso estratégico. La unidad de la antena no escapa de esta realidad. En la misma es usual encontrarse varios bloques entre los cuales están los divisores de potencia, sobre todo en los radares que emplean arreglos de antenas y en particular los radares de exploración aérea como el P18 y el P12 emplean un divisor de potencia Wilkinson con salida a las dos filas que forman parte de su arreglo plano de antenas. En el presente artículo se propone el diseño y simulación de un divisor de potencia desigual Wilkinson a la frecuencia central de 160 MHz de la banda Very High Frequency(VHF) con una relación de potencia en los puertos de salida de 60%-40%. El cálculo de los componentes se lleva a cabo en Mathcad y el circuito es simulado en AWR Microwave Office. De los resultados se extraen perdidas de retorno (RL) de -45.18 dB, aislamiento entre los puertos de salida de -49 dB y relación de potencia a la salida de S_{31}=-2.21 dB y S_{21}=-3.98 dB en los puertos 3 y 2 respectivamente.

PALABRAS CLAVES: Divisor de potencia Wilkinson, VHF, P18, Radar

1. INTRODUCTION

The development and modernization of radars that meet the demands of current surveillance systems [1-4] or the various applications in the civil field [5-7] such as meteorological control [8], requires the design and replacement of some of the Radar stages [1, 9]. This need acquires a distinctive connotation in a country like Cuba, which has a large number of radars in service, and the call from institutions to substitute imports is extended. In this context, the antenna unit is one of the parts that, due to the influence it has on the Radar range equation, is subject to improvements [10-12]. The antenna system is generally made up of several blocks, most notably the power feed network, the antenna switch, and the power dividers. In radars like the P12, P14 and P18, whose antennas are planar arrays made up of two levels, a power distribution of 60% at one level and 40% at the other is required, which implies a unequal division of power.

Manuscrito recibido: 2020-11-10, aceptado: 2020-12-20
Sitio web:http://revistatelematica.cujae.edu.cu/index.php/tele

The power dividers are passive microwave components and reciprocal devices [13] where an input signal is divided by the coupler into two (or more) signals of lesser power. Typically they are a 3 port network of the equal division (3 dB) type [14], but unequal power division ratios are also possible [15]. The lossless T-junction divider suffers from the problem of not being matched at all ports and, besides, does not have any isolation between output ports. The resistive divider can be matched at all ports, but even though it is not lossless, isolation is still not achieved [13]. The Wilkinson power divider is such a network, with the useful property of being lossless when the output ports are matched; that is, only reflected power is dissipated.

This work aims to design and simulate in the AWR Microwave Office V13 software of an unequal Wilkinson power divider with a 6/4 power division ratio to be used in antennas for air surveillance radars at the 160 MHz center frequency (VHF band).

2. INITIAL CONSIDERATIONS

The peculiarity of the Wilkinson divisor consists of putting a resistor between the two output ports (Fig.1.) since no current flows through the resistor and it does not contribute to any resistive loss. This makes an ideal Wilkinson a 100% efficient device. This resistor also provides excellent isolation even when the device is used as a combiner. Another property of the Wilkinson divider is that it is separated into quarter wavelength (λ/4) sections. At frequencies above 500 MHz, these devices are usually realized as microstrip or stripline, but at low frequencies, the sections of the λ/4 transformers are very long, so a solution is to replace these sections with their equivalent ¨π¨ circuit and in this way reduce the dimensions of the device.

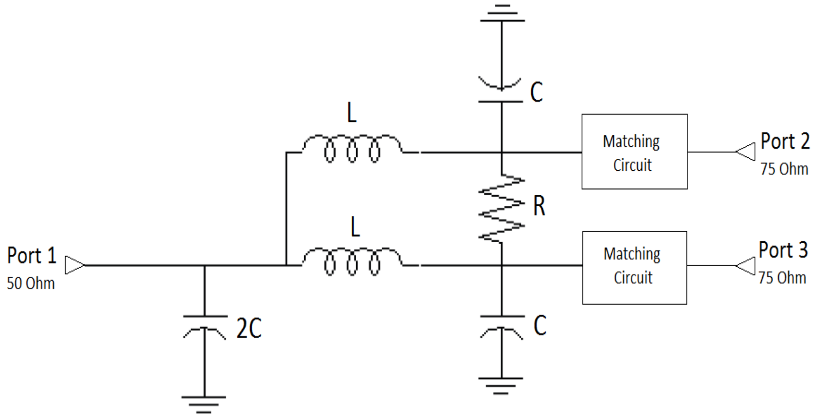

Figure1: Lumped model Wilkinson power divider.

The design in question has the particularity that the output ports must be connected to coaxial cables of 75 Ω impedance as a result of the suitably designed antenna power feed network. To simplify the circuit, L-type matching circuits of one step are designed to both ports as seen in blocks in Fig. 1.

3. THEORETICAL ANALYSIS. EVEN-ODD MODE ANALYSIS

The Wilkinson power divider can be made with arbitrary power division, but first, it will be considered the equal-split (3 dB) case. The corresponding transmission line circuit is given in Fig. 2. This circuit will be analyzed by reducing it to two simpler circuits driven by symmetric and antisymmetric sources at the output ports [13].

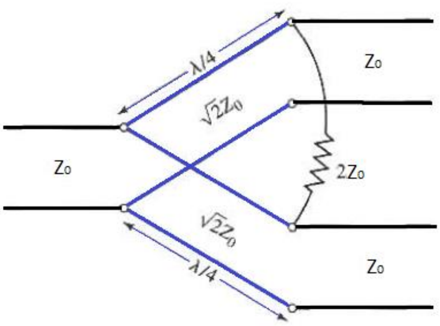

Figure 2: Wilkinson equivalent transmission line circuit.

For simplicity, all impedances will be normalized to the characteristic impedance Zo, and it is redrawn the circuit of Fig. 2. with voltage generators at the output ports as shown in Fig. 3. This network has been drawn in a form that is symmetric across the midplane; the two source resistors of normalized value 2 combine in parallel to give a resistor of normalized value 1, representing the impedance of a matched source. The quarter-wave lines have a normalized characteristic impedance Z, and the shunt resistor has a normalized value of r; for the equal-split power divider, these values should be $Z = \sqrt{2}$ and r=2, as given in Fig. 2.

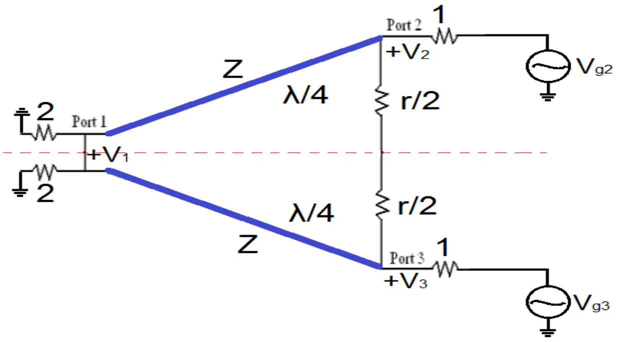

Figure 3: Symmetrical Wilkinson Power divider.

Two modes of excitation are defined for the circuit of Fig. 3.: the even mode, where $V_{g2} = V_{g3} = 2V_0$, and the odd mode, where $V_{g2} = -V_{g3} = 2V_0$. Then, by superposition of these two modes, there is an excitation of $V_{g2} = 4V_0$, $V_{g3} = 0$, from which the S parameters of the network are determined.

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Even Mode

For the even-mode excitation: $V_{g2} = V_{g3} = 2V_0$ and so $V_2{}^e = V_3{}^e$ and there is no current flow through the r/2 resistors or the short circuit between the inputs of the two transmission lines at port 1 [13]. Then it can redraw the circuit of Fig. 2. to obtain the network shown in Fig. 4.

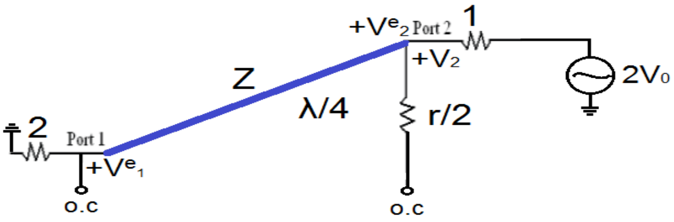

Figure 4: Even mode excitation circuit.

Then, looking into port 2, the impedance is:

$$Zin^e = \frac{z^2}{2} \tag{1}$$

The transmission line looks like a quarter-wave transformer. Thus, if $Z = \sqrt{2}$, port2 will be matched for even mode excitation; then $V_2{}^e = V_0$, since $Z_{in}{}^e = 1$. The r/2 resistor is superfluous in this case since one end is open-circuited. Next, it can be found $V_1{}^e$ from the transmission line equations. For x=0 at port 1 and x=-λ/4 at port 2, the voltage on the transmission line section can be written as:

$$V(x) = V^+\left(e^{-j\beta x} + \Gamma e^{\,j\beta x}\right) \tag{2}$$

Then

$$V^e{}_2 = V\left(-\frac{\lambda}{4}\right) = jV^+(1-\Gamma) = V_0 \tag{3}$$

$$V^e{}_1 = V(0) = V^+(1+\Gamma) = jV_0\frac{\Gamma+1}{\Gamma-1} \tag{4}$$

The reflection coefficient (Γ) is that seen at port 1, looking toward the resistor of normalized value 2, so:

$$\Gamma = \frac{2-\sqrt{2}}{2+\sqrt{2}} \tag{5}$$

$$V^e{}_1 = -jV_0\sqrt{2} \tag{6}$$

Odd Mode

For the odd-mode excitation, $V_{g2} = -V_{g3} = 2V_0$, $V_2{}^0 = -V_3{}^0$ and there is a voltage null along the middle of the circuit in Fig. 3. Thus, it can bisect this circuit by grounding it at two points on its midplane to give the network of Fig. 5. Looking into port 2, it can see an impedance of r/2 because the parallel-connected transmission line is λ/4 long and shorted at port 1 and so looks like an open circuit at port 2. Thus, port 2 will be matched for odd mode excitation for r=2 and then $V_2{}^0 = V_0$ and $V_1{}^0 = 0$. For this mode of excitation, all power is delivered to the r/2 resistors, with none going to port 1 [13].

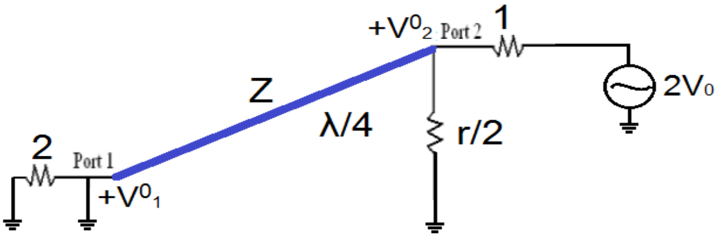

Figure 5: Odd mode excitation circuit.

Finally, it can be found the input impedance at port 1 of the Wilkinson divider when ports 2 and 3 are terminated in matched loads. The resulting circuit is shown in Fig.6. , where it is seen that this is similar to an even mode of excitation, since $V_2 = V_3$. Thus, no current flows through the resistor of normalized value 2, so it can be removed, being the circuit of Fig. 7. With the parallel connection of two quarter-wave transformers terminated in loads of unity (normalized), the input impedance is then:

$$Z_{in} = \frac{1}{2}(\sqrt{2})^2 = 1 \tag{7}$$

In summary can establish the following S parameters for the Wilkinson divider: $S_{11} = 0$, $S_{22} = S_{21} = -j/\sqrt{2}$, $S_{13} = S_{31} = -j/\sqrt{2}$, $S_{23} = S_{32} = 0$.

The preceding formula for S_{12} applies because all ports are matched when terminated with matched loads. Note that when the divider is driven at port 1, and the outputs are matched, no power is dissipated in the resistor. Thus the divider is lossless when the outputs are matched; only reflected power from ports 2 or 3 is dissipated in the resistor. Since $S_{23}=S_{32}=0$, ports 2 and 3 are isolated.

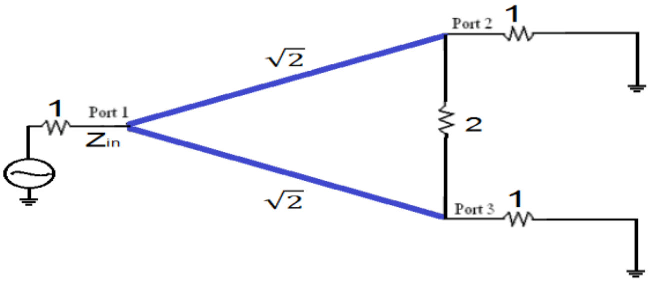

Figure 6: The terminated Wilkinson divider to find S_{11}.

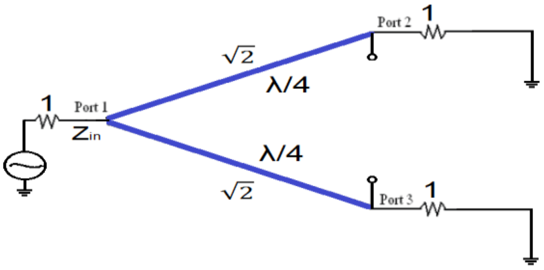

Figure 7: B section of the terminated Wilkinson divider.

Unequal Power Division

Wilkinson power dividers can also be made with unequal power splits [13]; a microstrip version is shown in Fig. 8.

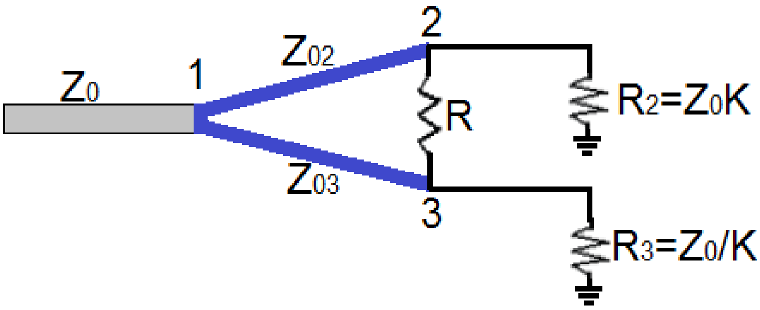

Figure 8: Unequal Wilkinson power divider.

If the power ratio between ports 2 and 3 is $K^2 = P_3/P_2$, then the following design equations apply:

$$Z_{03} = Z_0\sqrt{\frac{1+K^2}{K^3}} \tag{8}$$

$$Z_{02} = K^2 Z_{03} = Z_0\sqrt{K(1+K^2)} \tag{9}$$

$$R = Z_0\left(K + \frac{1}{K}\right) \tag{10}$$

The above results are reduced to the equal-split case for K=1. It can be observed that the output lines are matched to the impedances $R_2=Z_0K$ and $R_3=Z_0/K$. It is also highlighted that the output impedances depend on the desired power ratio, therefore, as in the case of the present design, output coupling networks must be designed to obtain the desired impedance in ports 2 and 3.

4. LUMPED ELEMENT "Π" EQUIVALENT NETWORK OF A Λ/4 TRANSMISSION LINE SECTION. TYPE-L MATCHING CIRCUIT

As previously said, above 500 MHz the Wilkinson power divider is usually realized as a microstrip or stripline but at low frequencies, the size of the quarter-wavelength segments gets exceedingly large. The conventional approach is to reduce the size of the circuit by replacing the transmission lines with its lumped components. In this sense, Fig. 9. b shows the lumped element "π" equivalent network of a quarter-wave transformer (Fig.9. a) [16].

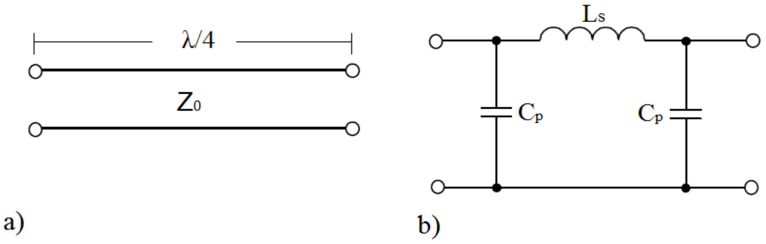

Figure 9: a) λ/4 line, b) Equivalent "Pi" lumped-element circuit.

Where the transformation equations at the design frequency are:

$$C_p = \frac{1}{2\pi f_0 Z_0} \tag{11}$$

$$L_s = \frac{Z_0}{2\pi f_0} \tag{12}$$

For the case of unequal power division as proposed in this paper (6/4), coupling networks are required at the output to obtain maximum transfer at the desired load. For applications that do not require a very large bandwidth (this is a low-quality factor, Q), a single section of an L-Type network is enough. If the configuration was chosen is that of a capacitor in parallel and an inductor in series, the circuit is as shown in Fig.10.

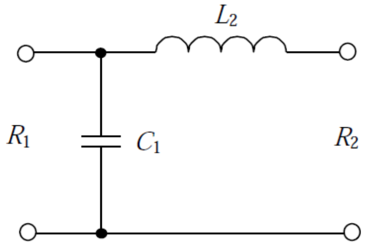

Figure 10: L-Type matching circuit.

R1 is the resistance with the highest value and where [17, 18]:

$$Q = \sqrt{\frac{R_1}{R_2} - 1} \tag{13}$$

$$\mathrm{w}C_1 = Q/R_1 \tag{14}$$

$$\mathrm{w}L_2 = QR_2 \tag{15}$$

5. DESIGN OF THE LUMPED MODEL UNEQUAL WILKINSON POWER DIVIDER

Concerning Fig. 8., the design equations (8)-(10) are used, with division relation $K_2 = P_3/P_2 = 6/4$, therefore $K_2 = 1.5$. The input port is 50Ω so Z_0 = 50Ω. In a program developed in Mathcad, the aforementioned equations are

implemented, resulting in: R = 102 Ω and output impedances: R_2 = 61.23 Ω and R_3 = 40.82Ω. The impedances of the λ/4 transformers are Z_{02} = 87.5 Ω and Z_{03} = 58.32 Ω respectively.
Knowing the characteristic impedances of the λ/4 transformers, the values of the "π" equivalent network's elements to the design frequency (f = 160 MHz) are calculated through the programmed equations (11) and (12) in Mathcad:

-For the Z_{02} network, C_3 = 11 pF and L_2 = 87 nH (see Fig. 11.)
-For the Z_{03} network, C_2 = 17 pF and L_1 = 58 nH

The impedances R_2 and R_3 need to be coupled to 75Ω impedance coaxial cables, therefore the elements of the L-type matching network are calculated from the programming of equations (13)-(15). For the central frequency of 160 MHz, it is obtained for the coupling of R_2, (C_5 = 6.28 pF; L_4 = 28.9 nH) and for the coupling of R_3, (C_4 = 12 pF; L_3 = 37nH) as seen in Fig. 11. Table 1 shows the values of the components for the design:

Table 1: Lumped elements values of the unequal Wilkinson power divider

Circuit part	Component	Value
"Pi" equivalent networks of a λ/4 transmission line sections (Z_{02}, Z_{03})	C_1	28 pF
	C_2	17 pF
	C_3	11 pF
	L_1	58 nH
	L_2	8.7 nH
Type-L matching circuit (Port 2)	C_5	6 pF
	L_4	29 nH
Type-L matching circuit (Port 3)	C_4	12 pF
	L_3	37 nH

6. SCHEMATIC SIMULATION FOR THE UNEQUAL 6:4 WILKINSON POWER DIVIDER. SIMULATION RESULTS

The lumped circuit component diagram of the unequal 6:4 Wilkinson power divider using AWR is shown in Fig. 11. The circuit shows the classical topology of the Wilkinson divider plus the two output matching networks. An input port (in this case at 50 Ω) and the two output ports at 75 Ω can be seen to be directly connected to the coaxial cables of equal impedance that go to each of the two levels of the antenna array. The two output ports are isolated from each other.

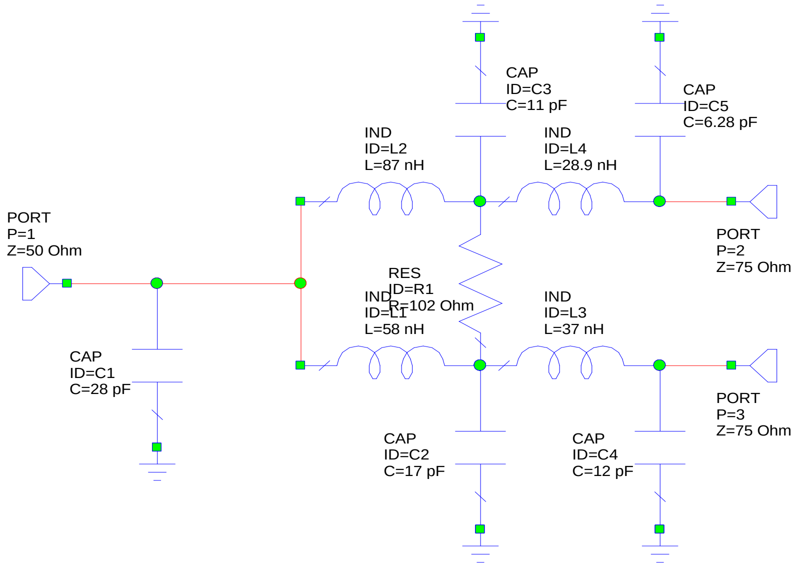

Figure 11: Unequal Wilkinson power divider in AWR Microwave Office.

The frequency response of the divider was analyzed from 100 MHz to 200MHz (Fig. 12.), where a good behavior of the RL is observed in the band of interest (140-180MHz). The parameter S_{11} of the divider at the design frequency is -45.18 dB. The 60% division ratio in port 3 and 40% in port 2 can be seen in the Insertion Loss (IL) in both ports, with parameters S_{31} and S_{21} respectively. Port 3 reaches 6/10 of the input power, this is S_{31} = -2.21 dB and port 2 reaches 4/10 of the input power (S_{21} = -3.98 dB). The values at the design frequency are marked with markers in Fig. 12.

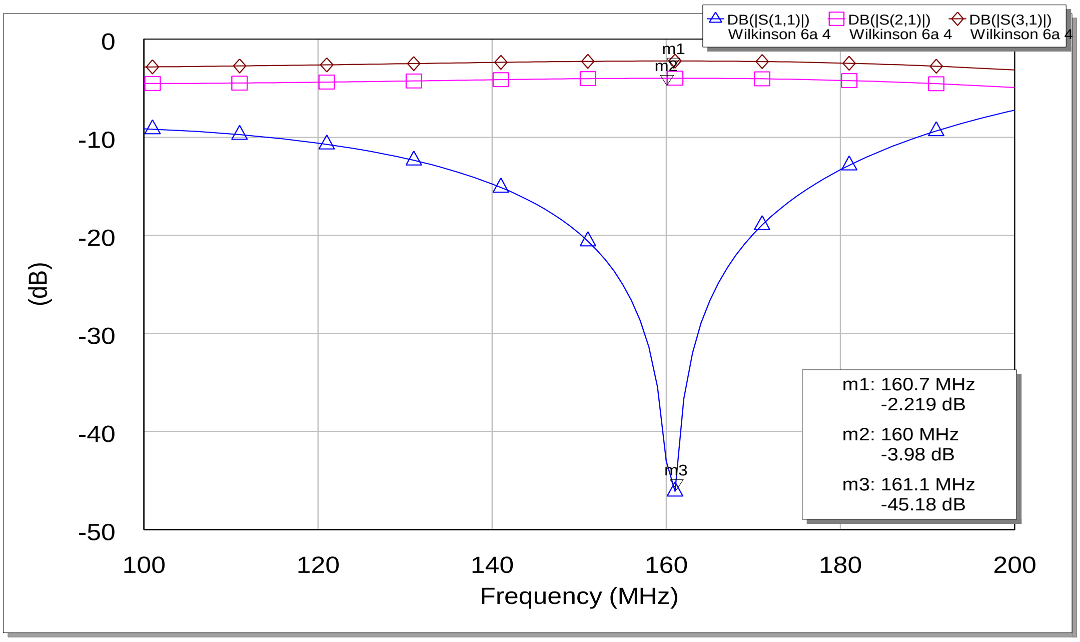

Figure 12: Frequency Responses (S_{11}, S_{21}, S_{31}).

The other elements of the scattering matrix can be seen in Fig. 13, where the isolation that exists between ports 2 and 3 is highlighted with a marker. In this sense, S_{32} = S_{23} are around -49 dB, corresponding to the characteristic of the Wilkinson splitter, nearly perfect isolation between output ports.

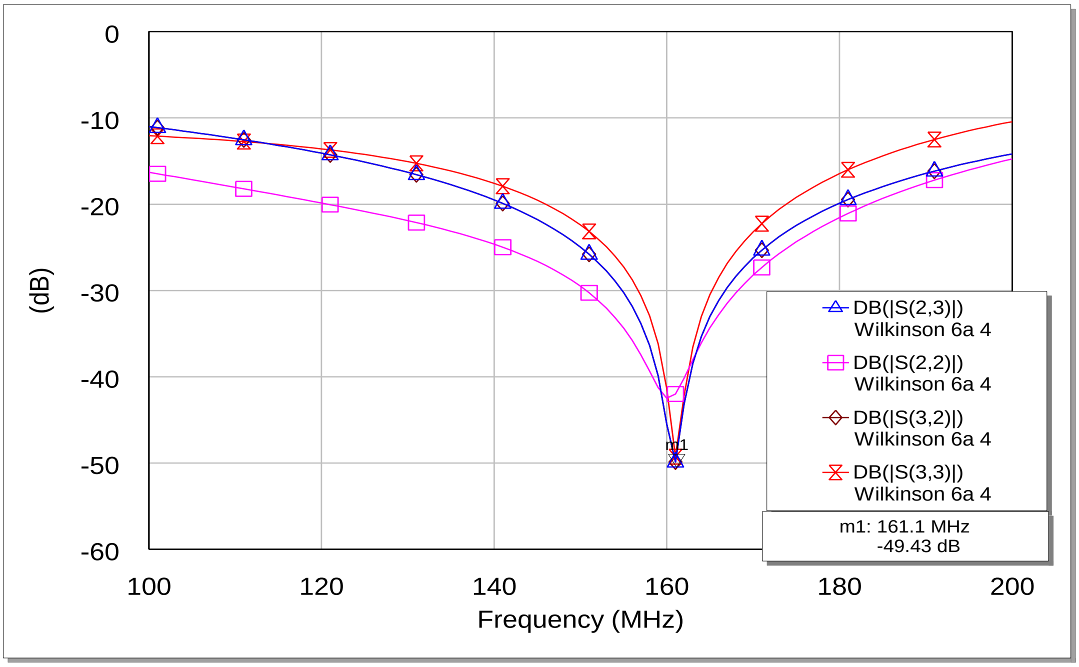

Figure 13: Frequency Responses (S_{23}, S_{22}, S_{32}, S_{33}).

7. CONCLUSIONS

Based on the theoretical foundations exposed in this paper, an unequal Wilkinson power divider was designed with a 60% -40% power output ratio at the central frequency of 160 Hz (VHF) that can be used in radar applications. The calculation of the components was carried out in a program in the Mathcad software developed for this purpose. The circuit was simulated in AWR Microwave Office. From the frequency response, it is extracted that it has an RL of -45.18 dB in the band of interest. Likewise, the desired power ratio at the output is recorded, obtaining S_{31} = -2.21 dB and S_{21} = -3.98 dB in port 3 and 2 respectively. The isolation between the output ports (S_{32} = S_{23}) is -49 dB. It features a small, easy-to-build circuit that meets the design requirements.

REFERENCES

[1] D. O. González and P. A. Morris, "Diseño de antena de bocina con corrugaciones variables para aplicaciones de Radar," presented at the Convencion Internacional Informática 2018,Vlll Simposio de Telecomunicaciones, La Habana,Cuba, 2018.

[2] N. J. G. Fonseca, E. Girard, and H. Legay, "Doubly Curved Reflector Design for Hybrid Array Fed Reflector Antennas," *IEEE Transactions on Antennas and Propagation*, vol. PP, n.º 99, pp. 1-1, 2018.

[3] H. M. E. Misilmani, M. Al-Husseini, and K. Y. Kabalan, "Design of Slotted Waveguide Antennas with Low Sidelobes for High Power Microwave Applications," *Progress In Electromagnetics Research*, vol. 56, n.º 1, pp. 15-28, 2015.

[4] Y. D. Lazo, N. C. Ferry, and P. A. Morris, "Caracterización de la antena del radar SON-9A," *Revista Cubana de Ingeniería*, vol. 6, n.º 1, pp. 57-65, 2015.

[5] H. Gao, X. Zhang, J. Zhao, and D. Li, "Technology of Intelligent Driving Radar Perception Based on Driving Brain," *CAAI Transactions On Intelligence Technology*, vol. 2, n.º 3, pp. 146-156, 2017.

[6] N. P. Bhatta and M. G. Priya, "Radar and Its Applications," *International Journal Of Circuit Theory and Applications*, vol. 9, n.º 28, pp. 1-9, 2016.

[7] M. Zajc, Z. Pogacnik, and A. Gosar, "Ground penetrating radar and structural geological mapping investigation of karst and tectonic features in flyschoid rocks as geological hazard for exploitation," vol. 67, n.º 1, pp. 78-87, 2014.

[8] L. Xumin and Y. Wue, "Research on Vectorization of Weather Radar Image," *Procedia Engineering*, vol. 15, n.º 1, pp. 1298-1302, 2011.
[9] D. O. González, P. A. Morris, and J. R. S. Gálvez, "Modification to the AU11-07N slotted waveguide antenna of the Navy-Radar 4000," *Revista de Ingeniería Electronica, Automática y Comunicaciones*, vol. 41, n.º 3, pp. 108-121, 2020.
[10] M. A. K. S. Lubis, D. P. Yusuf, F. Y. Zulkifli, and E. T. Rahardjo, "Bandwidth Improvement with Narrow Wall Slotted Waveguide Antenna," presented at the International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications, 2017.
[11] K.-R. Chou, H.-N. Lin2, W.-H. Lu, H.-W. Chang, and K.-K. Tiong, "Design and operation of an edge-wall slotted waveguide antenna with ultralow side lobes for application of off-shore Radar," *Journal of Marine Science and Technology*, vol. 23, n.º 5, pp. 620-627, 2015.
[12] S. Murugaveni and T. K. arthick, "Design of Slotted Waveguide Antenna for Radar Applications at X-Band," *International Journal of Engineering Research & Technology (IJERT)*, vol. 3, n.º 11, 2014.
[13] D. Pozar, *Microwave Engineering*, 3rd ed., 2005.
[14] B. Harathi, P. Subbalakshmi, and P. Kamaraj, "Design and Implementation of 1:2 Power Divider for Radar Applications," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 4, pp. 4779-4784, 2015.
[15] H. Elftouha, M. E. Bakkalia, N. T. Amara, A. Zakritib, Aicha, Mchbala, *et al.*, "The Unequal Wilkinson Power Divider 2:1 for WLAN Application," presented at the 13th International Conference Interdisciplinarity in Engineering (INTER-ENG 2019), 2019.
[16] A. Grebennikov, *RF and Microwave Power Amplifier Design*, 1rst ed. vol. 1: McGraw-Hill, 2005.
[17] P. Pramanick and P. Bhartia, *Modern RF and Microwave Filter Design*, 1st ed.: Artech House, 2016.
[18] G. D. Vendelin, A. M. Pavio, and U. L. Rohde, *Microwave circuit design using linear and nonlinear techniques* 2nd ed., 2005.

AUTHORS' CONTRIBUTIONS

Daryl Ortega González: Conceptualization, Data Curation, Formal Analysis, Research, Methodology, Project Management, Resources, Software, Validation-Verification, Visualization, Drafting-original draft, Drafting-reviewing and editing.

AUTHORS

Daryl Ortega González, Telecommunications and Electronic Engineer, Instructor Professor and research, Radar Group, Technological University of Havana José Antonio Echeverría (CUJAE), La Habana, Cuba, e-mail: fedortegag@gmail.com, ORCID: 0000-0002-9272-4553, currently works and interested in reflector antennas, reflectarray, phased arrays, reconfigurable antennas, adaptive antennas, and smart antennas.