Microwave Circuit Element Library for Teaching RF and Microwave Engineering

Dejan V. Tošić and Vladimir V. Petrović[1]

Abstract – **This paper presents a new library of RF and microwave elements that should be included when teaching RF and microwave engineering courses. This library should help students to understand better the element characterization at microwave frequencies and provide guidance in the process of solving a microwave circuit from the student's point of view. The elements considered are assumed to be linear and time invariant.**

Keywords – **RF and microwave circuit, scattering parameters, element characterization.**

I. Introduction

RF and microwave engineering courses [1–9] are considered important in electrical engineering education and they form a solid ground for grasping concepts and phenomena of contemporary electronics, communication systems and radar systems.

New software tools [10–19] that are available nowadays have dramatically influenced the possibilities of educational technology and play an important role in teaching RF and microwave engineering. However, proper deployment of the software tools requires clear understanding of the underlying microwave theory, modeling and analysis procedures.

Students are usually somewhat confused by the conventions used for defining the signs of wave signals and their relations to the voltages and currents. Furthermore, they lack any methodology and do not have rigorous understanding of the microwave element characterization. Thence, they often come up with wrong equations or an insufficient or redundant set of equations when they try to solve a microwave circuit.

A good example of students' misunderstanding element characterizations is the characterization of the ideal amplifier. The Electric Circuit Theory defines the ideal amplifier as a voltage-controlled voltage source: the amplifier has infinite input impedance and zero output impedance. Quite opposite, in RF and microwave engineering the ideal amplifier has finite input impedance and non-zero output impedance!

In this paper, we suggest a comprehensive library of microwave elements that should be included in microwave engineering courses. The presented library focuses on precise and general element characterization, which is of prime interest for understanding both teaching material and sophisticated microwave software tools.

[1]Authors are with School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, PO Box 35-54, 11120 Belgrade, Serbia (e-mail: tosic@etf.rs, vp@etf.rs).

II. Wave Signals as Variables for Microwave Circuits

Electric circuit theory and concepts represent a special case (restricted version) of electromagnetic theory and concepts. When the time-variation of sources is relatively slow (circuit operates at comparatively low frequencies) the dimensions of a conducting network are significantly smaller than the wavelength, so the electromagnetic field is quasi-static, electromagnetic problem can be simplified to a circuit problem.

An electrical network or electrical circuit (Fig. 1) is an interconnection of electrical elements that can have two or more terminals. Each circuit element represents one of the fundamental aspects of the electrical network and it is an idealization of the physical properties of the practical devices that are available commercially. Port is a pair of element terminals such that currents in terminals are of equal magnitude and opposite directions. The reference direction of the port voltage and the reference direction of the port current of an element are said to be in the associated (standard) reference direction if a positive current enters the port by the terminal marked with a plus sign and leaves the port by the terminal marked with a minus sign.

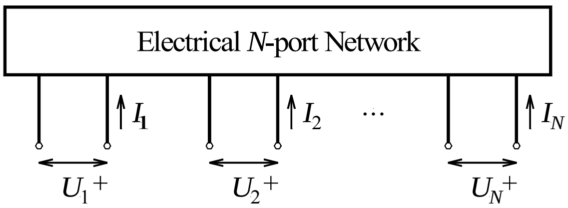

Fig. 1. Electrical network characterized by port voltages and currents.

At RF and microwave frequencies, circuit elements and electromagnetic structures can be viewed as multiport networks (Fig. 2). Therefore, a microwave circuit can be represented as an interconnection of multiport components characterized by suitable parameters determined analytically or experimentally (by measurement). Lumped element modeling is not adequate because elements' dimensions are comparable to the signal wavelength. The logical choice of circuit variables to use at these frequencies are traveling waves, referred to as wave signals, rather than total voltages and currents. The most suitable (and from the measurement viewpoint the only possible) device characterization are scattering parameters (S-parameters).

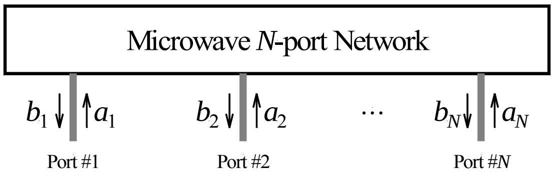

Fig. 2. Microwave network characterized by wave signals.

A linear time-invariant multiport microwave network can be characterized in the frequency domain by the wave signals as follows:

$$[b]=[s][a]+[b]_{\mathrm{g}}\,, \tag{1}$$

$$[b]=\begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix},\ [s]=\begin{bmatrix} s_{11} & \cdots & s_{1N} \\ \vdots & \ddots & \vdots \\ s_{N1} & \cdots & s_{NN} \end{bmatrix},\ [a]=\begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix},$$

and $[b]_{\mathrm{g}}$ is a column matrix of the known wave signals generated within the network, and emanating from the network ports, when all ports are matched. It is a direct consequence of the independent sources inside the network.

Relations between wave signals, nominal (reference) impedances, voltages and currents are given by

$$U_k=\left(a_k+b_k\right)\sqrt{Z_{0k}}\,, \qquad I_k=\frac{a_k-b_k}{\sqrt{Z_{0k}}}\,, \tag{2}$$

$$a_k=\frac{U_k+Z_{0k}I_k}{2\sqrt{Z_{0k}}}, \qquad b_k=\frac{U_k-Z_{0k}I_k}{2\sqrt{Z_{0k}}}\,. \tag{3}$$

When we form a microwave circuit, we often connect ports of unequal reference impedances. The junction of these ports can be viewed as a simple two-port component (Fig. 3) also referred to as the nominal impedance step.

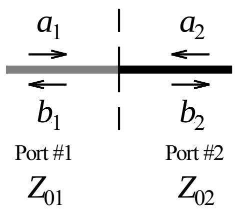

Fig. 3. Junction between two ports of different nominal impedances.

This junction is characterized by

$$[s]_{\mathrm{junct}}=\begin{bmatrix} \dfrac{Z_{02}-Z_{01}}{Z_{02}+Z_{01}} & \dfrac{2\sqrt{Z_{01}Z_{02}}}{Z_{01}+Z_{02}} \\ \dfrac{2\sqrt{Z_{01}Z_{02}}}{Z_{01}+Z_{02}} & \dfrac{Z_{01}-Z_{02}}{Z_{01}+Z_{02}} \end{bmatrix}, \tag{4}$$

or, in the special case when nominal impedances are equal, as

$$[s]_{\mathrm{junct1}}=\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},\ b_1=a_2\,,\ b_2=a_1\,.$$

Quite general, it should be emphasized that at each port a pair of variables (voltage, current) is replaced with a triplet (incident wave, reflected wave, nominal impedance).

III. Ideal Linear Microwave Elements

Initial microwave circuit design often starts with idealized microwave components that we call ideal microwave elements. A microwave circuit composed of ideal elements usually gives a good insight into the circuit operation and performance.

This section reviews ideal elements most frequently used in practice. We assume that the nominal impedances of ports are real, that all ports of an element have the same nominal impedance, and that only one mode (TEM) is propagating

The port numbering convention adopted in this paper, in some cases, might differ from the numbering of ports found in some literature.

One-port network representing a microwave load, short circuit, or open circuit (Fig. 4) is characterized by

$$[s]_{\mathrm{load}}=[s_{11}] \tag{5}$$

where

$s_{11}=\dfrac{Z-Z_0}{Z+Z_0}$, for an arbitrary load of impedance Z,

$s_{11}=0$, for a matched load (termination),

$s_{11}=-1$, for short circuit,

$s_{11}=1$, for open circuit.

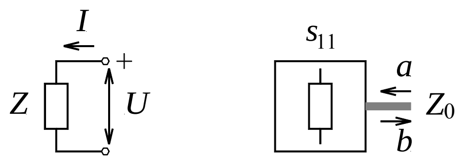

Fig. 4. One-port network, load.

Voltage source of emf U_{g} and internal impedance Z_{g} (Fig. 5) is characterized by

$$b=\frac{Z_{\mathrm{g}}-Z_0}{Z_{\mathrm{g}}+Z_0}a+\frac{U_{\mathrm{g}}\sqrt{Z_0}}{Z_{\mathrm{g}}+Z_0}=s_{11}a+b_{\mathrm{g}}\,. \tag{6}$$

If the source impedance equals the nominal impedance then $b=\dfrac{U_{\mathrm{g}}}{2\sqrt{Z_0}}=b_{\mathrm{g}}$.

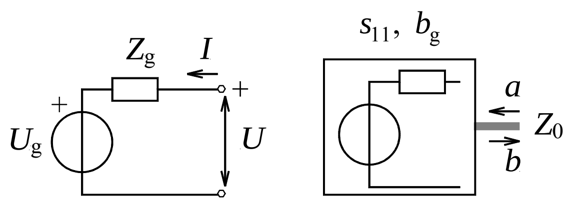

Fig. 5. Voltage source with internal impedance.

Transmission line section (Fig. 6), assuming that the line is uniform, the dielectric is homogeneous, the losses are negligible, and only one mode (TEM) is propagating, is characterized by

$$[s]_{\text{line}} = \begin{bmatrix} 0 & e^{-j\Theta} \\ e^{-j\Theta} & 0 \end{bmatrix}, \qquad (7)$$

$$\Theta = \beta D = 2\pi \frac{D}{\lambda} = \frac{f}{F_0}\Theta_0 = \frac{\omega}{\Omega_0}\Theta_0 ,$$

where Θ is the electrical length, β is the phase coefficient, D is the length, f is the operating frequency, $F_0 = \Omega_0/(2\pi)$ is the reference frequency at which the electrical length is Θ_0, $\omega = 2\pi f$ is the corresponding angular frequency, and nominal impedances are equal to the characteristic impedance ($Z_0 = Z_c$).

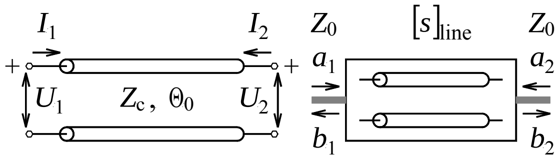

Fig. 6. Transmission line section.

Microwave amplifier (Fig. 7) is an active non-reciprocal matched two-port network characterized by

$$[s]_{\text{amp}} = \begin{bmatrix} 0 & 0 \\ G & 0 \end{bmatrix}, \qquad |G| > 1 \qquad (8)$$

The gain in decibels is $G_{\text{dB}} = 20\log_{10}|G|$.

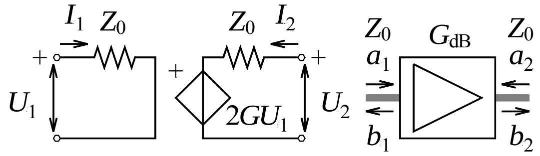

Fig. 7. Microwave amplifier.

Microwave isolator (Fig. 8) is a passive non-reciprocal matched two-port network characterized by

$$[s]_{\text{isol}} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \qquad (9)$$

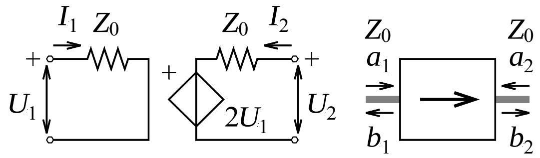

Fig. 8. Microwave isolator.

Microwave attenuator (Fig. 9) is a passive reciprocal matched two-port network characterized by

$$[s]_{\text{att}} = \begin{bmatrix} 0 & A \\ A & 0 \end{bmatrix}, \qquad |A| < 1 \qquad (10)$$

Attenuation in decibels is $A_{\text{dB}} = -20\log_{10}|A|$.

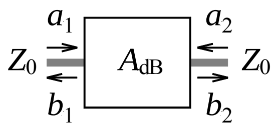

Fig. 9. Microwave attenuator.

Microwave phase shifter (Fig. 10) is a passive reciprocal matched two-port network characterized by

$$[s]_{\text{shift}} = \begin{bmatrix} 0 & e^{-j\varphi} \\ e^{-j\varphi} & 0 \end{bmatrix}, \qquad (11)$$

where φ is the phase shift also referred to as the phase delay.

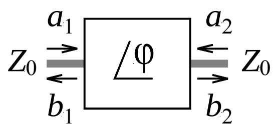

Fig. 10. Microwave phase shifter.

Ideal transformer (Fig. 11) is a passive reciprocal lossless two-port network characterized by

$$[s]_{\text{transf}} = \begin{bmatrix} \frac{n^2-1}{n^2+1} & \frac{2n}{n^2+1} \\ \frac{2n}{n^2+1} & \frac{1-n^2}{n^2+1} \end{bmatrix}, \qquad (12)$$

where n is the turn ratio. A transformer with a unit turn ratio is a matched network.

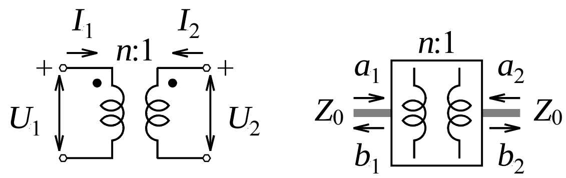

Fig. 11. Ideal transformer.

Microwave gyrator (Fig. 12) is a passive non-reciprocal matched two-port network characterized by

$$[s]_{\text{gyr}} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \qquad (13)$$

or, alternatively, by

$$[s]_{\text{gyr1}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \qquad (14)$$

when $r = -Z_0$.

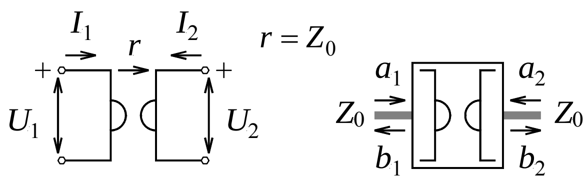

Fig. 12. Microwave gyrator.

Microwave immitance invertor (Fig. 13) is a reciprocal lossless two-port network characterized by $U_1 = zI_2$,

$I_1 = \frac{1}{z} U_2$, where z is a purely imaginary number $z = \pm \mathrm{j}K$ or $z = \frac{\pm \mathrm{j}}{J}$, that is

$$[s]_{\text{imminv}} = \begin{bmatrix} \frac{z^2 + Z_0^2}{z^2 - Z_0^2} & \frac{-2zZ_0}{z^2 - Z_0^2} \\ \frac{-2zZ_0}{z^2 - Z_0^2} & \frac{z^2 + Z_0^2}{z^2 - Z_0^2} \end{bmatrix}. \quad (15)$$

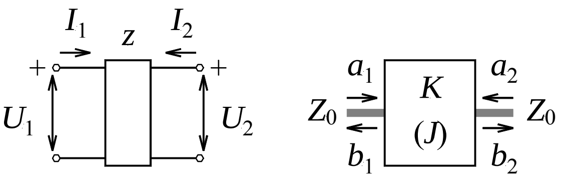

Fig. 13. Microwave immitance invertor.

Microwave circulator (Fig. 14) is a passive non-reciprocal lossless matched three-port network characterized by

$$[s]_{\text{circ}} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}. \quad (16)$$

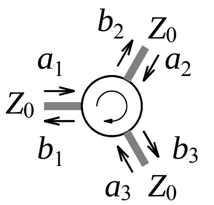

Fig. 14. Microwave circulator.

Symmetric power splitter (Fig. 15) is a passive reciprocal matched three-port network characterized by

$$[s]_{\text{symsplit}} = \frac{1}{2} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}. \quad (17)$$

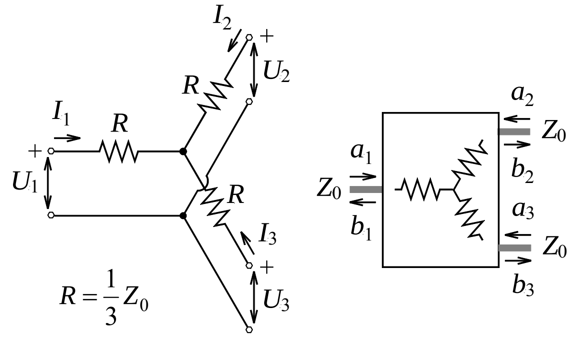

Fig. 15. Symmetric power splitter.

Parallel three-port Y-junction (ideal TEE, Fig.16) is a reciprocal lossless network characterized by

$$[s]_{\text{p3Y}} = \frac{1}{3} \begin{bmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{bmatrix}. \quad (18)$$

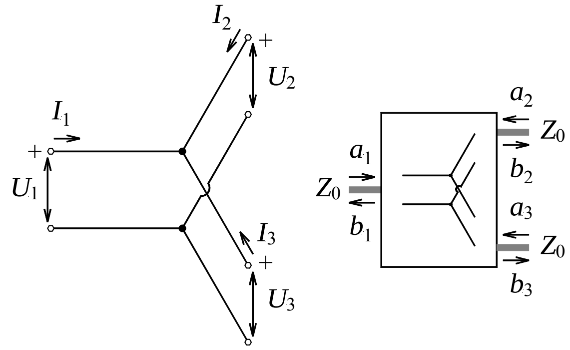

Fig. 16. Parallel three-port Y-junction.

Series three-port Y-junction (Fig. 17) is a reciprocal lossless network characterized by

$$[s]_{\text{s3Y}} = \frac{1}{3} \begin{bmatrix} 1 & -2 & -2 \\ -2 & 1 & -2 \\ -2 & -2 & 1 \end{bmatrix}. \quad (19)$$

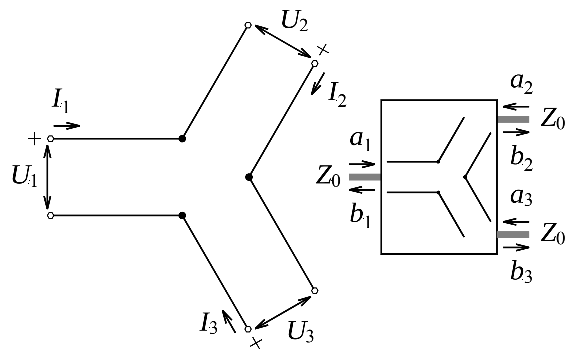

Fig. 17. Series three-port Y-junction.

Waveguide E-junction (Fig. 18) is a reciprocal lossless three-port network characterized by

$$[s]_{\text{wE}} = \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{2}}{2} & \frac{1}{2} \\ \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} \\ \frac{1}{2} & -\frac{\sqrt{2}}{2} & \frac{1}{2} \end{bmatrix}. \quad (20)$$

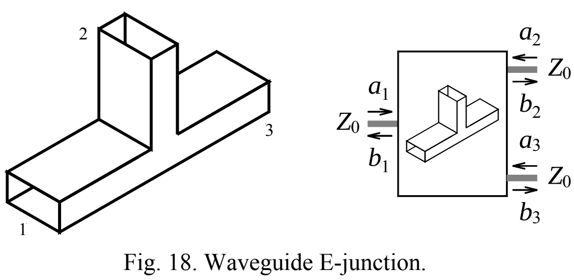

Fig. 18. Waveguide E-junction.

Waveguide H-junction (Fig. 19) is a reciprocal lossless three-port network characterized by

$$[s]_{\mathrm{wH}} = \begin{bmatrix} \frac{1}{2} & \frac{\sqrt{2}}{2} & -\frac{1}{2} \\ \frac{\sqrt{2}}{2} & 0 & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & \frac{\sqrt{2}}{2} & \frac{1}{2} \end{bmatrix}. \qquad (21)$$

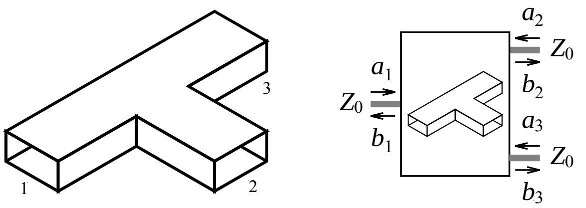

Fig. 19. Waveguide H-junction.

Parallel cross junction (Fig. 20) is a reciprocal lossless four-port network characterized by

$$[s]_{\mathrm{p4X}} = \frac{1}{2}\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}. \qquad (22)$$

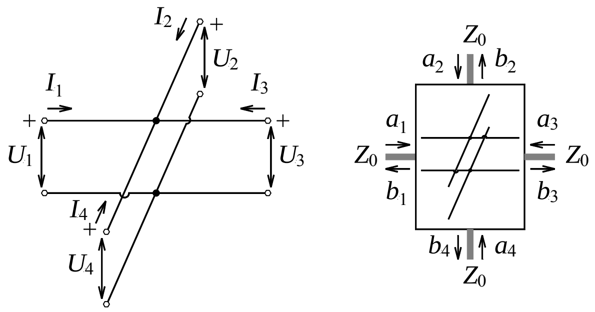

Fig. 20. Parallel cross junction.

Microwave coupler (Fig. 21) is a passive reciprocal lossless matched four-port network characterized by

$$[s]_{\mathrm{c}} = \begin{bmatrix} 0 & \alpha e^{j\varphi} & 0 & \beta e^{j\psi} \\ \alpha e^{j\varphi} & 0 & \beta e^{j\theta} & 0 \\ 0 & \beta e^{j\theta} & 0 & \alpha e^{j\eta} \\ \beta e^{j\psi} & 0 & \alpha e^{j\eta} & 0 \end{bmatrix}, \qquad (23)$$

where α, β are arbitrary real positive numbers with $\alpha^2+\beta^2=1$ and $\varphi-\theta=\psi-\eta+(2n+1)\pi$, $n=0,\pm1,\pm2,\ldots$.

Symmetric coupler is defined by $\psi-\varphi=\pm\pi/2$ and

$$[s]_{\mathrm{sc}} = e^{j\varphi}\begin{bmatrix} 0 & \alpha & 0 & \pm j\beta \\ \alpha & 0 & \pm j\beta & 0 \\ 0 & \pm j\beta & 0 & \alpha \\ \pm j\beta & 0 & \alpha & 0 \end{bmatrix}. \qquad (24)$$

It is also referred to as the symmetric quadrature coupler and is usually specified with $\varphi=0$ and the upper (plus) sign

$$[s]_{\mathrm{sc1}} = \begin{bmatrix} 0 & \alpha & 0 & j\beta \\ \alpha & 0 & j\beta & 0 \\ 0 & j\beta & 0 & \alpha \\ j\beta & 0 & \alpha & 0 \end{bmatrix}. \qquad (25)$$

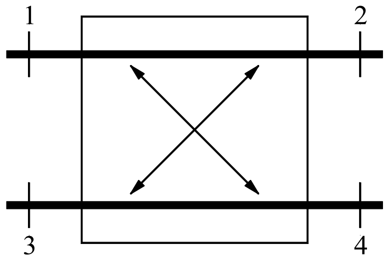

Fig. 21. Microwave coupler.

Antisymmetric coupler is defined by

$$[s]_{\mathrm{ac}} = e^{j\varphi}\begin{bmatrix} 0 & \alpha & 0 & \pm\beta \\ \alpha & 0 & \mp\beta & 0 \\ 0 & \mp\beta & 0 & \alpha \\ \pm\beta & 0 & \alpha & 0 \end{bmatrix}. \qquad (26)$$

It is usually specified with $\varphi=0$ and the upper sign,

$$[s]_{\mathrm{ac1}} = \begin{bmatrix} 0 & \alpha & 0 & \beta \\ \alpha & 0 & -\beta & 0 \\ 0 & -\beta & 0 & \alpha \\ \beta & 0 & \alpha & 0 \end{bmatrix}. \qquad (27)$$

Hybrid coupler is defined for $\alpha=\beta=1/\sqrt{2}$ and is usually characterized by

$$[s]_{\mathrm{hc}} = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & e^{j\varphi} & 0 & e^{j\psi} \\ e^{j\varphi} & 0 & e^{j\theta} & 0 \\ 0 & e^{j\theta} & 0 & e^{j\eta} \\ e^{j\psi} & 0 & e^{j\eta} & 0 \end{bmatrix}. \qquad (28)$$

Quadrature Hybrid Coupler (QHC), also referred to as the 90°-hybrid junction, is defined by

$$[s]_{\mathrm{qhc}} = \frac{e^{j\varphi}}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 0 & \pm j \\ 1 & 0 & \pm j & 0 \\ 0 & \pm j & 0 & 1 \\ \pm j & 0 & 1 & 0 \end{bmatrix}. \qquad (29)$$

Magic-T is an antisymmetric hybrid coupler characterized by

$$[s]_{\mathrm{magT}} = \frac{e^{j\varphi}}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 0 & \pm1 \\ 1 & 0 & \mp1 & 0 \\ 0 & \mp1 & 0 & 1 \\ \pm1 & 0 & 1 & 0 \end{bmatrix}. \qquad (30)$$

It is usually specified with $\varphi=0$ and the upper sign. Port 1 is the H-branch (Sigma port, Σ), Port 3 is the E-branch (Delta port, Δ), and Ports 2 and 4 are the output ports.

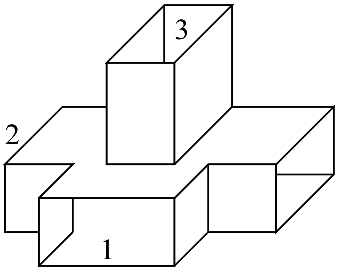

Fig. 22. Magic-T.

Hybrid ring, also referred to as the 180° hybrid junction or rat-race, is an antisymmetric hybrid coupler characterized by

$$[s]_{\text{hring}} = \frac{e^{j\varphi}}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -1 & 0 & 1 & 0 \end{bmatrix}. \quad (31)$$

It is usually assumed $\varphi = -\pi/2$.

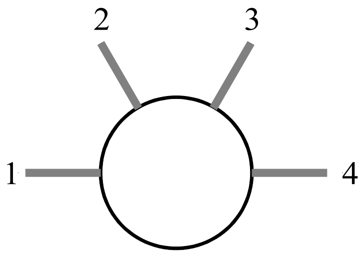

Fig. 23. Hybrid ring.

IV. Conclusion

Mastering concepts and phenomena from RF and microwave engineering is very important in understanding electronics, telecommunication systems and radar systems. If educators wish to generate interest in this field among the incoming engineering students, they should do a better job of promoting the profession by providing better teaching tools and delivery methods. New software tools that are available nowadays have dramatically influenced the possibilities of educational technology and should play a crucial role in teaching RF and microwave engineering.

It has been observed that engineering students are usually somewhat confused by the microwave circuit theory conventions used for defining the signs of wave signals and the corresponding voltages and currents. In addition, they lack any methodology and do not have rigorous understanding of the RF/microwave device characterization, so they often come up with wrong equations or an insufficient or redundant set of equations when they try to solve an RF/microwave circuit.

In this paper a comprehensive library of RF and microwave elements has been presented and organized pedagogically from the student's viewpoint. The library should be included in the RF/microwave engineering curricula and is targeted at students or educators seeking both a full element understanding in computer assisted learning and clarifying the underlying element characterization when solving microwave circuits.

Acknowledgement

This work was supported in part by the Serbian Ministry of Science and Technological Development under Grant TR-11021.

References

[1] A. R. Djordjevic, D. V. Tosic, *Microwave Engineering*, Academic Mind, Belgrade, 2006.
[2] V. V. Petrovic, D. V. Tosic, A. R. Djordjevic, *Microwave Passive Circuits*, eBook (in Serbian), 2009.
[3] D. M. Pozar, *Microwave engineering*, 3rd Ed., John Wiley, New York, 2005.
[4] L. Besser, R. Gilmore, *Practical RF Circuit Design for Modern Wireless Systems, volume I: Passive Circuits and Systems*, Artech House, Boston, 2003.
[5] R. E. Collin, *Foundations for Microwave Engineering*, McGraw-Hill, New York, 1992; reprint J. Wiley - IEEE Press, 2001.
[6] A. R. Djordjevic, et al., *Scattering Parameters of Microwave Networks with Multiconductor Transmission Lines*, Artech House, Boston, 1990.
[7] A. R. Djordjevic, et al., *Matrix Parameters for Multiconductor Transmission Lines*, Artech House, Boston, 1989.
[8] F. E. Gardiol, *Introduction to Microwaves*, Artech House, Boston, 1984.
[9] K. C. Gupta, R. Garg, R. Chada, *Computer-Aided Design of Microwave Circuits*, Artech House, Boston, 1981.
[10] *Microwave Office*, Applied Wave Research, Inc., 1960 E. Grand Avenue, Suite 430, El Segundo, CA 90245, USA. http://www.appwave.com
[11] *ADS*, Agilent Technologies, Inc., 5301 Stevens Creek Blvd, Santa Clara, CA 95051, USA. http://www.agilent.com
[12] *Genesys*, Eagleware, Agilent Technologies, Inc., 5301 Stevens Creek Blvd, Santa Clara, CA 95051, USA. http://www.eagleware.com/products/genesys/genesys.html
[13] *Ansoft Designer with Nexxim*, Ansoft, Inc., 225 West Station Square Drive, Suite 200, Pittsburgh, PA 15219, USA. http://www.ansoft.com
[14] *IE3D and MDSPICE*, Zeland Software, Inc., 48834 Kato Road, Suite 103A, Fremont, CA 94538, USA. http://www.zeland.com
[15] *PSpice*, Cadence Inc., 2655 Seely Avenue, San Jose, CA 95134, USA. http://www.cadence.com/orcad/
[16] *ICAP/4*, Intusoft Inc., 879 West 190th Street, Suite 100, Gardena, CA, USA. http://www.intusoft.com/
[17] *HSPICE*, Synopsys, Inc., 700 East Middlefield Road, Mountain View, CA 94043, USA. http://www.synopsys.com/products/mixedsignal/hspice/hspice.html
[18] *LTspice*, Linear Technologies, Inc., http://www.linear.com
[19] *WIPL-D Microwave Pro*, WIPL-D d.o.o., Gandijeva 7, Belgrade, Serbia. http://www.wipl-d.com