Microwave Circuits Based on Six-Port Junction

Branka Jokanović[1] and Aleksandar Marinčić[2]

Abstract – **This paper describes the procedure of microwave circuits construction based on double-Y junction, which is actually a six-port circuit. The procedure is based on *S*-matrix of lossless double-Y junction. It has been demostrated how a double-Y junction can be modified into a double-Y balun and a 3dB quadrature coupler by placing open and short circuits on appropriate ports of a double-Y junction.**

Keywords **– Symmetrical Y-junction, Double-Y junction, Double-Y balun, 3dB coupler, *S*-matrix**

I. INTRODUCTION

Double-Y junctin is a six-port network consisting of three balanced and three unbalanced lines alternately deployed around a joint center. Fig. 1. shows a double-Y junction realized with CPW and slot lines. The denotation *Double-Y junction* seems to be most appropriate for such a network as in its structure there are two noticeable, separated symmtrical Y-junctions, one consisting of unbalanced CPW lines (*1-3-5*), and the other of balanced slot lines (*4-2-6*).

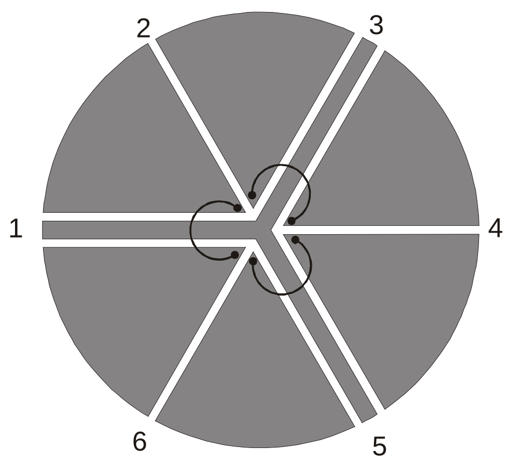

Fig. 1. Double-Y junction

If ports *2*, *3*, *5* and *6* are terminated by their characteristic impedances and if the characteristic impedances of balanced and unbalanced lines are equal to 50 Ω, the double-Y junction is matched and ports *1* and *4* are mutually isolated.

[1]Branka Jokanović is with Institute IMTEL, Bulevar Mihaila Pupina 165b, 11070 Novi Beograd, Serbia and Montenegro, E-mail: branka@insimtel.com

[2]Aleksandar Marinčić is with the Faculty of Electrical Engineering, Bulevar kralja Aleksandra 74, 11000 Beograd, Serbia and Montenegro

Therefore, looking from the port *1*, the slot lines leading to ports *2* and *6* are parallel to one another and in series to the two parallel CPW lines that lead to ports *3* and *5*. As a result of this, the input impedance, looking from port 1 is 50 Ω. The similar is valid for port *4*, as the slot lines of *2* and *6* are serially connected, and then parallelly with two serially connected CPW lines at ports *3* and *5*. Input impedance of the junction, as seen from port *4* is also 50 Ω, which can be likewise demonstrated for any pair of mutually isolated ports *2-5* and *3-6*, as the network is symmetrical.

II. S-MATRIX OF DOUBLE-Y JUNCTION

It is well known that a lossless symmetrical Y-junction is mismached, i.e. it cannot be matched at the same time at all ports. However, by combination of two such junctions, a network of six ports is obtained, which is matched. On the basis of this, an *S*-matrix of a double-Y junction can be presented by a combination of four submatrixes, of which submatrixes S_{11} and S_{22} refer to symmetrical Y-junction comprised of unbalanced, i.e. balanced lines, respectively. General form of scattering matrix of symmetrical Y-junction looks as follows:

$$S_{11}\ (S_{22}) = \begin{bmatrix} \alpha & \beta & \beta \\ \beta & \alpha & \beta \\ \beta & \beta & \alpha \end{bmatrix} \tag{1}$$

Matrix of double-Y junction[1] (with marked submatrixes) can be presented in the following way:

$$S = \begin{bmatrix} [S_{11}] & [S_{12}] \\ [S_{21}] & [S_{22}] \end{bmatrix} = \frac{1}{2} \begin{matrix} (1) \\ (3) \\ (5) \\ (2) \\ (4) \\ (6) \end{matrix} \begin{bmatrix} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} & \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \\ \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 0 & -1 & -1 \\ -1 & 0 & -1 \\ -1 & -1 & 0 \end{bmatrix} \end{bmatrix} \tag{2}$$

It should be noticed that in a symmetrical Y-junction diagonal elements are α≠0, while in *S*-matrix of double-Y junction diagonal elements of submatrixes [S_{11}] and [S_{22}] are equal to zero. Submatrixes [S_{12}] and [S_{21}] are mutually transposed and they determine relation between balanced and unbalanced ports.

The sequence of columns and rows in *S*-matrix (2) is changed in respect to the notation of ports in Fig. 1, for the purpose of better observability so that it corresponds to the following ports: *1*, *3*, *5*, *2*, *4*, *6*. The sequence of raws is marked by numbers in brackets in Eq. 2. In this way, ports referring to Y-junction, which consists of unbalanced lines, are arranged in submatrix $[S_{11}]$, and ports referring to Y-junction consisting of balanced lines in submatrix $[S_{22}]$.

On the basis of *S*-matrix of lossless double-Y junction, it is obvious that when a signal is brought to port *1*, a signal of equal amlitudes will appear at ports *2, 3, 5* i *6*, the signals at ports *2*, *3* and *5* being in phase with reference to input signal, while the signal in balanced port *6* (port adjacent to input port counterclockwise) is in antiphase. Similarly, if a signal is brought to port *4*, signals of equal amplitudes will appear at ports *2, 3, 5* and *6*, the signals at ports *2*, *5* and *6* being in antiphase in relation to the input signal, while the signal in unbalanced port *3* (port adjacent to the input port counterclockwise) is in phase. It should be noticed that ports in *S*-matrix of double-Y junction (Fig. 1.) are grouped clockwise.

If unlike *S*-matrix (2), the columns and rows are organized in the following way: *1, 5, 3, 6, 4 i 2*, which corresponds to arrangement of ports in double -Y junction counterclockwise, an *S*-matrix is obtained which has different submatrixes $[S_{21}]$, i.e. $[S_{12}]$, as given in relation (3). This matrix can be obtained by transformation of matrix (2) by replacement of the following rows and columns: *3⇒5* and *2⇒6*.

$$S=\begin{bmatrix}[S_{11}] & [S_{12}]\\ [S_{21}] & [S_{22}]\end{bmatrix}=\frac{1}{2}\begin{matrix}(1)\\(5)\\(3)\\(6)\\(4)\\(2)\end{matrix}\begin{bmatrix}\begin{bmatrix}0 & 1 & 1\\ 1 & 0 & 1\\ 1 & 1 & 0\end{bmatrix} & \begin{bmatrix}-1 & 0 & 1\\ 1 & -1 & 0\\ 0 & 1 & -1\end{bmatrix}\\ \begin{bmatrix}-1 & 1 & 0\\ 0 & -1 & 1\\ 1 & 0 & -1\end{bmatrix} & \begin{bmatrix}0 & -1 & -1\\ -1 & 0 & -1\\ -1 & -1 & 0\end{bmatrix}\end{bmatrix} \tag{3}$$

It should be pointed out that for above mentioned characteristics of a lossless double-Y junction referring to isolation between ports and to their adjustment, theoretically there is no limitation of frequency range.

If two signals are brought simultanuosly at opposite ports of double-Y junction *1* and *4* with equal amplitude and phase difference θ in respect to the signal at port *1,* the signals at other four ports are with following amplitude and phases:

$$[S][a]=[b]=\frac{1}{2}\begin{bmatrix}0 & 1 & 1 & 1 & 0 & -1\\ 1 & 0 & 1 & -1 & 1 & 0\\ 1 & 1 & 0 & 0 & -1 & 1\\ 1 & -1 & 0 & 0 & -1 & -1\\ 0 & 1 & -1 & -1 & 0 & -1\\ -1 & 0 & 1 & -1 & -1 & 0\end{bmatrix}\begin{bmatrix}1\\ 0\\ 0\\ 0\\ e^{j\theta}\\ 0\end{bmatrix}=\begin{bmatrix}0\\ b_3^\circ\\ b_5^\circ\\ b_2^\circ\\ 0\\ b_6^\circ\end{bmatrix} \tag{4}$$

$$\begin{aligned} b_2^\circ &= \sin\frac{\theta}{2}e^{j(\frac{\theta}{2}-\frac{\pi}{2})}=b_5^\circ;\\ b_3^\circ &= \cos\frac{\theta}{2}e^{j\frac{\theta}{2}};\quad b_6^\circ=\cos\frac{\theta}{2}e^{j(\frac{\theta}{2}+\pi)}\end{aligned} \tag{5}$$

Relation (5) implies that if signals of equal amplitudes and in phase (θ=0) are brought to ports *1* and *4*, there will be no signals at ports *2* and *5*, while signals at ports *3* and *6* will be in counterphase. However, if signals in counterphase (θ=π) are brought to input ports, signals at ports *2* and *5* will be in phase, while at ports *3* and *6* there will be no signals. In all other cases at all four ports there will be signals as given in relation (5).

It is interesting to see what happens when signals in quadrature (θ=π/2) are brought to opposite ports of a double-Y balun. The signal in port *4* has phase π/2 in relation to signal at port *1.* According to relation (5), the following is obtained:

$$b_2^\circ=b_5^\circ=\frac{1}{\sqrt{2}}e^{-j\frac{\pi}{4}};\quad b_3^\circ=\frac{1}{\sqrt{2}}e^{j\frac{\pi}{4}};\quad b_6^\circ=\frac{1}{\sqrt{2}}e^{j(\frac{\pi}{4}+\pi)} \tag{6}$$

Fig. 2 shows phasors of the signals at input and output ports of double-Y junction in case of two input signals (a_1 and a_4) being of the same amplitide with phase difference of θ, brought to ports *1* and *4*.

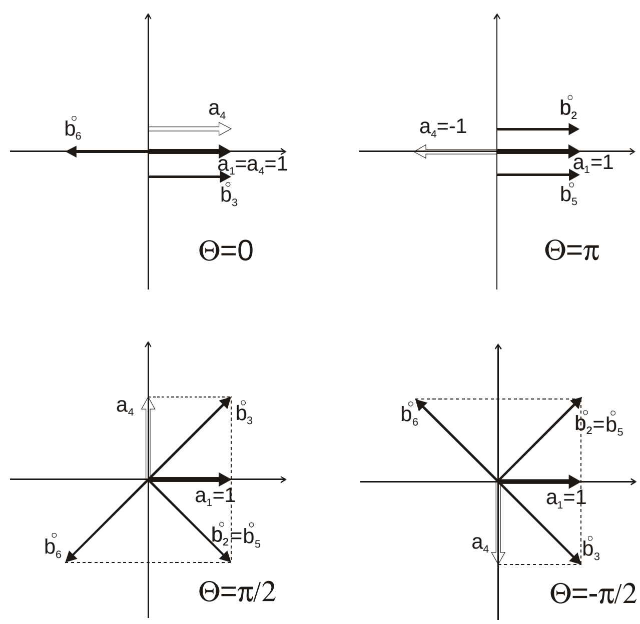

Fig. 2. Phasors of the signals at input and output ports of double-Y junction

If the signal at port *1* has phase θ in relation to signal at port *4*, signals at output ports have the following phases:

$$\begin{aligned} b_2^\circ &= \sin\frac{\theta}{2}e^{j(\frac{\theta}{2}+\frac{\pi}{2})}=b_5^\circ;\\ b_3^\circ &= \cos\frac{\theta}{2}e^{j\frac{\theta}{2}};\quad b_6^\circ=\cos\frac{\theta}{2}e^{j(\frac{\theta}{2}+\pi)}\end{aligned} \tag{7}$$

If the signal at port *1* has phase $\pi/2$ in relation to reference signal at port *4*, phases of output signals are as follows:

$$b_2^\circ = b_5^\circ = \frac{1}{\sqrt{2}} e^{j\frac{3\pi}{4}}; \quad b_3^\circ = \frac{1}{\sqrt{2}} e^{j\frac{\pi}{4}}; \quad b_6^\circ = \frac{1}{\sqrt{2}} e^{j(\frac{\pi}{4}+\pi)} \tag{8}$$

Comparing the relations given by Eq. 5. and Eq. 7. it is noticed that signals at ports *2* and *5* are π late, while signals at ports *3* and *6* are unchanged if balanced port (*4*) is chosen as a reference.

III. Double-Y Baluns

To obtan the balun function for each double-Y junction, which enables transmission of signals from nonsymmetrical line to the symmetrical one with minimal attenuation, it is necessary to make a network of two ports out of network of six ports by appropriate choice of termination. By using *S*-matrix of an ideal double-Y junction, which is given by relation (2), it is shown that it is possible to realize a balun by means of open, i.e. short circuited lines at pairs of opposite ports as the reflection coefficient of such terminations is in antiphase, i.e. it is -1 and +1 respectively. In the basic expression that gives the correlation between direct and reflected waves at ports of double-Y junction, the following conditions have been set that define an ideal balun:

- input signal at port *1* is $a_1=1$,
- reflection at this port is $b_1=0$,
- at port *4* there is no direct wave, i.e. $a_4=0$, i
- all energy from port *1* is transmitted to port *4* ($b_4=1$)

$$[S][a]=[b]=\frac{1}{2}\begin{bmatrix} 0 & 1 & 1 & 1 & 0 & -1 \\ 1 & 0 & 1 & -1 & 1 & 0 \\ 1 & 1 & 0 & 0 & -1 & 1 \\ 1 & -1 & 0 & 0 & -1 & -1 \\ 0 & 1 & -1 & -1 & 0 & -1 \\ -1 & 0 & 1 & -1 & -1 & 0 \end{bmatrix}\begin{bmatrix} 1 \\ \rho_3 b_3 \\ \rho_5 b_5 \\ \rho_2 b_2 \\ 0 \\ \rho_6 b_6 \end{bmatrix}=\begin{bmatrix} 0 \\ b_3 \\ b_5 \\ b_2 \\ 1 \\ b_6 \end{bmatrix} \tag{9}$$

In realtion (9), the reflection coefficients at ports *3*, *5*, *2* and *6* are marked with ρ_3, ρ_5, ρ_2 and ρ_6 and it is necessary to find their mutual relations. As excitation occurs only at port *1*, the following relations are valid for reflected waves *b*:

$$b_3 = S_{31} = \frac{1}{2}, b_5 = S_{51} = \frac{1}{2}, b_2 = S_{21} = \frac{1}{2}, b_6 = S_{61} = -\frac{1}{2} \tag{10}$$

After multiplication of the first and the fifth rows of *S*-matrix with column matrix [*a*] in relation (9), the following relations are obtained:

$$\begin{aligned} \rho_3 b_3 + \rho_5 b_5 + \rho_2 b_2 - \rho_6 b_6 &= 0 \\ \rho_3 b_3 - \rho_5 b_5 - \rho_2 b_2 - \rho_6 b_6 &= 2 \end{aligned} \tag{11}$$

On the basis of this relation as well as by multiplication of the second and the third rows of *S*-matrix with [*a*], expressions for reflected waves are obtained at ports *2* and *6*.

$$\begin{aligned} &\rho_3 b_3 - \rho_6 b_6 = 1 \\ &\rho_2 b_2 + \rho_5 b_5 = -1 \\ &\Downarrow \\ &1 - \rho_3 b_3 - \rho_6 b_6 = 2b_2; \\ &-1 + \rho_5 b_5 - \rho_2 b_2 = 2b_6 \\ &\Downarrow \\ &\rho_6 = -\frac{b_2}{b_6} = 1 \\ &\rho_2 = \frac{-1 - b_6}{b_2} = -1 \end{aligned} \tag{12}$$

Similar relations can be derived for reflected waves at ports *3* and *5*:

$$\begin{aligned} &1 + \rho_5 b_5 - \rho_2 b_2 = 2b_3 \\ &1 + \rho_3 b_3 + \upsilon_6 b_6 = 2b_5 \\ &\Downarrow \\ &1 + \rho_5 b_5 = 2b_3 \\ &\Downarrow \\ &\rho_5 = \frac{b_3 - 1}{b_5} = -1 \\ &1 + \rho_3 b_3 + \rho_6 b_6 = 2b_5 \Rightarrow \rho_3 b_3 = b_5 \\ &\Downarrow \\ &\rho_3 = \frac{b_5}{b_3} = 1 \end{aligned} \tag{13}$$

Consequently, if a pair of opposite ports is short circuited (*2* and *5*), and another pair of ports is open ended (*3* and *6*), the signal brought to port *1* is transmitted to port *4*, which in double-Y junction is isolated. If in relation (9), matrix (2) is replaced with matrix (3), a different balun condition is obtained, i.e. ports (*2* and *5*) should be open ended, and ports (*3* and *6*) short circuited. This only means that pairs of open, i.e. short circuited ports could be taken at liberty. However, it is crucial that opposite ports have the same reactive loading, which is reciprocal to loadings at two other opposite ports. Electrical lengths of open and short circuited sections measured from the junction center should be equal:

$$\beta_{bal} L_{bal} = \beta_{ubal} L_{ubal} \tag{14}$$

It should be borne in mind that in a real balun open and short circuited lines are not ideal and that lengths $\beta_{ubal} L_{ubal}$ and $\beta_{bal} L_{bal}$ in relation (14) mean effective electrical lengths of open and short circuited sections of symmetrical and nonsymmetrical lines.

Fig. 3. shows a double-Y junction realized by CPW and slot lines and an appropriate double-Y balun obtained by its modification. In accordance with the procedure described above and relations (11), (12) and (13), ports of double-Y junction *2* and *5* are short circuited and at ports *3* and *6* are open ended, so that CPW-slot line balun[2] is obtained. Open circuit on the slot line is realized by a circular slot (port *6*), which has the characteristics of an open circuit in a limited frequency band so that the balun band is limited too.

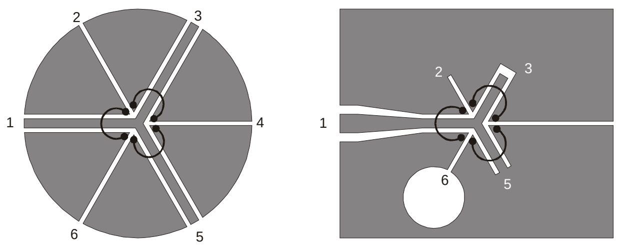

Fig. 3. DoubleY junction and corresponding CPW-slot line balun

Based on this principle, four types of double-Y baluns have been realized so far: microstrip-slot line[3], above mentioned balun CPW-slot line, CPW_{FGP}-CPS[4] and CPW_{FGP}-parallel microstrip[5].

IV. 3dB Quadrature Coupler

Using S-matrix of double-Y junction, a new 3 dB quadrature coupler could be designed, which is due to its small dimensions suitable for application at low frequencies [4]. In order to get a four-port network out of a six-port network, the signals at output ports being of equal amplitude but in quadrature, while the fourth port is isolated from the output signal, the following conditions are set that define an ideal quadrature hybrid coupler:

- signal at port *1* is $a_1=1$,
- reflection at this port is $b_1=0$,
- there is no reflection at output ports *2* and *5*.

$$[S][a]=[b]=\frac{1}{2}\begin{matrix}(1)\\(3)\\(5)\\(2)\\(4)\\(6)\end{matrix}\begin{bmatrix}0&1&1&1&0&-1\\1&0&1&-1&1&0\\1&1&0&0&-1&1\\1&-1&0&0&-1&-1\\0&1&-1&-1&0&-1\\-1&0&1&-1&-1&0\end{bmatrix}\begin{bmatrix}1\\ \rho_3 b_3\\0\\0\\0\\ \rho_6 b_6\end{bmatrix}=\begin{bmatrix}0\\b_3\\b_5^{\circ}\\b_2^{\circ}\\0\\b_6\end{bmatrix} \quad (15)$$

After multiplication of matrixes, the following relations are obtained referring to reflected wave at ports *2* and *5*:

$$\begin{aligned}&\rho_3 b_3-\rho_6 b_6=0\\&\rho_3=-\rho_6\\&1+\rho_3 b_3+\rho_6 b_6=2b_5^{\circ}\end{aligned} \quad (16)$$

$$\begin{aligned}&1-\rho_3 b_3-\rho_6 b_6=2b_2^{\circ};\\&\Downarrow\\&1+\rho_3 b_3-\rho_3 b_6=2b_5^{\circ};\\&1-\rho_3 b_3+\rho_3 b_6=2b_2^{\circ};\\&\Downarrow\\&\rho_3=2b_5^{\circ}-1;\\&\rho_3=1-2b_2^{\circ};\\&\Downarrow\\&b_5^{\circ}=1-b_2^{\circ}\Rightarrow\\&b_5^{\circ}=\frac{1-j}{2}=\frac{1}{\sqrt{2}}e^{-j\frac{\pi}{4}};b_2^{\circ}=\frac{1+j}{2}=\frac{1}{\sqrt{2}}e^{j\frac{\pi}{4}};\\&\rho_3=-j;\quad \rho_6=j\end{aligned} \quad (17)$$

It is obvious that signals at ports *2* and *5* are of the same amlitudes in quadrature, the reflection coefficents at ports *3* and *6* being of opposite signs. Unlike the double-Y balun, it is most important here that open and short circuits should be placed at distance of $\lambda_{ubal(bal)}/8+n\,\lambda_{ubal(bal)}/4$ from the junction, as in this way necessary reflection coefficients $\pm\, j$ are obtained.

If the signal is brought to port *4*, by multiplying the matrixes given in expression (18):

$$[S][a]=[b]=\frac{1}{2}\begin{bmatrix}0&1&1&1&0&-1\\1&0&1&-1&1&0\\1&1&0&0&-1&1\\1&-1&0&0&-1&-1\\0&1&-1&-1&0&-1\\-1&0&1&-1&-1&0\end{bmatrix}\begin{bmatrix}0\\-jb_3\\0\\0\\1\\jb_6\end{bmatrix}=\begin{bmatrix}0\\b_3\\b_5^{\bullet}\\b_2^{\bullet}\\0\\b_6\end{bmatrix} \quad (18)$$

the following expressions for signals at ports *2* and *5* are obtained:

$$b_5^{\bullet}=-\frac{1+j}{2}=\frac{1}{\sqrt{2}}e^{-j\frac{3\pi}{4}};\,b_2^{\bullet}=-\frac{1-j}{2}=\frac{1}{\sqrt{2}}e^{j\frac{3\pi}{4}} \quad (19)$$

Fig. 4. shows the layout of the quadrature coupler obtained by modification of CPW_{FGP}-CPS double-Y junction. At port *3* there is an open ending, while port *6* is short.circuited. According to relation (17), if a signal is brought to port *1*, the signal at port *5* (port *4* in Fig. 4.) should be $\pi/2$ late, which is also shown by electromagnetic analysis [4]. Should loadings at ports *3* and *6* change places, signal at port *5* will exceed the signal at port *2*.

It should be noticed that notation of the ports in Fig. 4. is changed in respect to that of double-Y junction (Fig. 1.): port $4\Rightarrow 3$ and port $5\Rightarrow 4$, so that elements of S^{coup}-matrix of the quadrature coupler are as follows:

$$S_{21}^{coup}=b_2^{\circ};\quad S_{41}^{coup}=b_5^{\circ};\quad S_{23}^{coup}=b_2^{\bullet};\quad S_{43}^{coup}=b_5^{\bullet} \quad (20)$$

S-matrix of the quadrature coupler $[S^{coup}]_{1245}$ whose ports *1*, *2*, *4* and *5* are marked as in Fig. 1 is as follows:

$$\left[S^{coup}\right]_{1245} = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & e^{j\frac{\pi}{4}} & 0 & e^{-j\frac{\pi}{4}} \\ e^{j\frac{\pi}{4}} & 0 & e^{j\frac{3\pi}{4}} & 0 \\ 0 & e^{j\frac{3\pi}{4}} & 0 & e^{-j\frac{3\pi}{4}} \\ e^{-j\frac{\pi}{4}} & 0 & e^{-j\frac{3\pi}{4}} & 0 \end{bmatrix} \quad (21)$$

$$\left[S^{coup}\right]_{1245} = \frac{e^{j\frac{\pi}{4}}}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 0 & -j \\ 1 & 0 & j & 0 \\ 0 & j & 0 & -1 \\ -j & 0 & -1 & 0 \end{bmatrix} \quad (22)$$

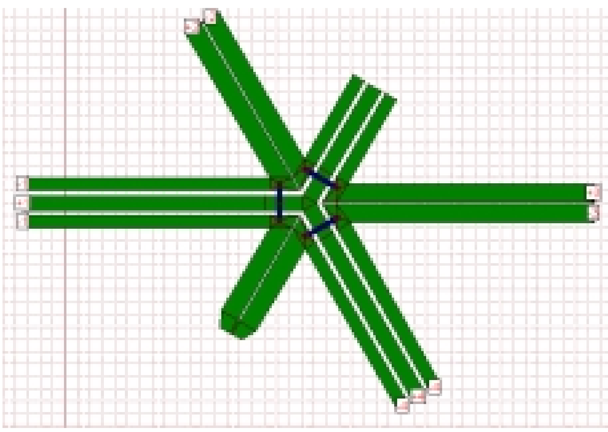

Fig. 4. Lazout of 3dB quadrature coupler

In the similar way we could obtain a matrix of coupler in case of open and short circuits are at ports *2* and *5* of double Y-junction, while output ports are *3* and *6*:

$$\begin{aligned} b_3^{\circ} &= S_{21} = b_3^{\bullet} = S_{23} = \frac{1+j}{2} = \frac{1}{\sqrt{2}} e^{j\frac{\pi}{4}}; \\ b_6^{\circ} &= S_{41} = b_6^{\bullet} = S_{43} = \frac{-1+j}{2} = \frac{1}{\sqrt{2}} e^{j\frac{3\pi}{4}} \end{aligned} \quad (23)$$

Upon formation of the coupler matrix, it should be taken into account that port marks are chaged with respect to marks in Fig. 1 in the following manner: port *3⇒2*, *4⇒3* and *6⇒4*.

$$\left[S^{coup}\right]_{1346} = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & e^{j\frac{\pi}{4}} & 0 & e^{j\frac{3\pi}{4}} \\ e^{j\frac{\pi}{4}} & 0 & e^{j\frac{\pi}{4}} & 0 \\ 0 & e^{j\frac{\pi}{4}} & 0 & e^{j\frac{3\pi}{4}} \\ e^{j\frac{3\pi}{4}} & 0 & e^{j\frac{3\pi}{4}} & 0 \end{bmatrix} \quad (24)$$

Three of four arguments of S-parameter could be changed by shifting the referent planes at input ports of the coupler, so that S-matrixes given in relations (21) and (24) can be rearranged in a suitable manner.

V. CONCLUSION

The paper describes the matrix of an ideal double-Y junction. It was also shown that only in case when the signals in phase or counterphase are brought to two opposite ports, at neighbouring clockwise ports, the signals in counterphase appear, i.e. in phase, while the rest of two ports are isolated. This shows that a double-Y junction may be used to measure phases of input signals.

It is interesting to observe that if two signals of the same amplitude but phasely shifted for angle θ are brought to opposite ports of a double-Y junction at one pair of opposite ports, the amplitude is changed as $\sin\theta/2$ and it has the same phase at both ports, while at two other ports it is changed as $\cos\theta/2$ and their phase is shifted for π, which may be useful upon demodulation of QPSK signal.

Although it was earlier percieved by intuition how a double-Y junction can be transformed into a balun, a simple and exact procedure that enables a better understanding of operation of this at first glance complicated circuit is given here.

The paper demonstrates that by placing open and short circuits at any pair of opposite ports, but at exactly determined distance, which is equal to odd multiple of $\lambda_{ubal/bal}/8$, from the junction center, a 3 dB quadrature coupler is obtained.

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