AN INVESTIGATION OF SIX-PORT PHASE-TYPE CIRCULATORS AND SWITCHES

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GENERAL

A wide variety of ferrite circulators and switches is being used in UHF channels of current wireless systems. Theory of three- and four-port circulators and switches has reached a fairly advanced development stage. Appropriate devices in our country and elsewhere have parameters that are pretty close to the maximum attainable. Nevertheless, the problems concerning the improvement of electric strength and reduction of losses continue to be topical. They are especially urgent when operational peculiarities of the system call for a considerable number of such devices.

The currently known junction patterns for several circulators, though lending considerable operational possibilities, are on the other hand not optimal from the point of view of electric strength (each circulator carries full power) and losses (the circulator losses are added). Increase in the number of circulators or switches also leads to reduction of reliability of the set as a whole. Therefore it is but natural to attempt a combination of functions of a number of circulators (switches) in a single device.[1,2] This paper deals with six-port devices permitting an increase of electric strength as well as reduction of losses.

1. SIX-PORT DEVICES WITH PERFECT TRANSMISSION

Consider a junction (Figure 1) represented by a cascade combination of three six-port block elements: two bridges[3,4] and a phase-shifter in between. The latter consists of three not interconnected transmission lines, nonreciprocal in phase, as a general case. The phase shifts in these lines, in principal and in reverse directions are shown as θ_k (K = 1,2,. . . ,6). Any losses in these lines are being neglected. The bridges are regarded as ideal. Regardless of the construction every six-port bridge has a pair of twin (symmetrical) output arms and one arm being non-pair in relation to any input port. A signal incoming to any arm is distributed equally between three ports on the opposite side of the bridge, the two other ports being disjoined with the input one. Signals in the twin arms of the bridge are mutually in-phase and are shifted in relation to the phase in the non-pair arms by 120°. The sense of the shift depends upon the design of the bridge.

NOTES

By means of waveguide transmission matrices one may determine the transmission matrix of the six-port junction under consideration as:

$$\begin{Vmatrix} 0 & \Sigma^* t_3 & 0 & \Sigma^* t_5 & 0 & t_1 \\ \Sigma t_4 & 0 & \Sigma t_6 & 0 & t_2 & 0 \\ 0 & \Sigma^* t_1 & 0 & t_3 & 0 & \Sigma^* t_5 \\ \Sigma t_2 & 0 & t_4 & 0 & \Sigma t_6 & 0 \\ 0 & t_5 & 0 & \Sigma^* t_1 & 0 & \Sigma^* t_3 \\ t_6 & 0 & \Sigma t_2 & 0 & \Sigma t_4 & 0 \end{Vmatrix} \qquad (1)$$

where

$$t_1 = \frac{1}{3}(\Sigma\alpha_3^* + \alpha_2^* + \alpha_1^*) \qquad t_4 = \frac{1}{3}(\alpha_4 + \Sigma^*\alpha_5 + \alpha_6)$$

$$t_2 = \frac{1}{3}(\Sigma^*\alpha_4 + \alpha_5 + \alpha_6) \qquad t_5 = \frac{1}{3}(\alpha_3^* + \alpha_2^* + \Sigma\alpha_1^*)$$

$$t_3 = \frac{1}{3}(\alpha_3^* + \Sigma\alpha_2^* + \alpha_1^*) \qquad t_6 = \frac{1}{3}(\alpha_4 + \alpha_5 + \Sigma^*\alpha_6)$$

$$\Sigma = \exp(\pm j\, 120°);\ \alpha_n^* = \exp(j\,\theta_n)\ (n = 1, 2, 3);\ \alpha_m = \exp(-j\,\theta_m)\ (m = 4, 5, 6) \qquad (2)$$

From here on we shall consider only such devices, where a signal incoming to any arm on one side of the junction is completely transmitted to one of the three arms on the opposite side. We shall name them "perfect transmission devices". Their transmission matrices must contain a single, and only a single, non-zero element equal to unity in absence of losses.

Evidently, the perfect transmission condition is satisfied only by 9 varieties of matrices as given by[4]:

1. $\lvert t_1\rvert = \lvert t_6\rvert = 1$	4. $\lvert t_2\rvert = \lvert t_3\rvert = 1$	7. $\lvert t_1\rvert = \lvert t_2\rvert = 1$	
2. $\lvert t_2\rvert = \lvert t_5\rvert = 1$	5. $\lvert t_3\rvert = \lvert t_6\rvert = 1$	8. $\lvert t_3\rvert = \lvert t_4\rvert = 1$	(3)
3. $\lvert t_1\rvert = \lvert t_4\rvert = 1$	6. $\lvert t_4\rvert = \lvert t_5\rvert = 1$	9. $\lvert t_5\rvert = \lvert t_6\rvert = 1$	

Tracks of signals through the device are illustrated in Figure 2. Six varieties of matrices serve to describe non-reciprocal devices (diagrams 1 through 6) and three others–reciprocal devices (diagrams 7, 8, 9).

2. SIX-PORT PHASE CIRCULATOR

Non-reciprocal diagrams in Figure 2 show the passage of signals through six-port circulators. Expressions (1), (2), (3) enable one to determine the phase shifts in the shifter block lines necessary for realization of the diagrams 1 through 6. An analysis of the expressions proves that the phases for both principle, as well as reverse directions, may have an arbitrary relative shift. This fact lends a possibility for not a single way of realizing the diagrams 1 through 6. Minimum differential phase shifts are obtained when one of the shifters is reciprocal, while the other two are non-reciprocal. Here the distinct forms of diagrams 1 through 6 differ in the relative position of the reciprocal channel. For example, when channel 1-6 is reciprocal, the signal passes the ciculator according to diagram 3 or 4 (depending on the sense of the magnetic field). When channel 3-4 is reciprocal, diagram 5 or 6 is used.

Results of phase-shift calculations for the shifter block utilizing $-2/3\,\pi$, and $+2/3\,\pi$-bridges are given in Tables I and II respectively. Here θ_n denotes phase-shifts for the principal direction (θ_4, θ_5, θ_6,) and θ_{ob} – for the reverse direction (θ_1, θ_2, θ_3) (see Figure 1); $\Delta\theta = \theta_n - \theta_{ob}$.

Table I

Direction of Circulation	1→6→2→4→3→5→1			1→5→3→4→2→6→1		
Phase-shift	θ_n	θ_{ob}	$\Delta\theta$	θ_n	θ_{ob}	$\Delta\theta$
Channel 1-5	$\theta_o + 120^\circ$	θ_o	$+120^\circ$	θ_o	$\theta_o + 120^\circ$	-120°
Channel 2-5	θ_o	θ_o	0°	θ_o	θ_o	0°
Channel 3-4	θ_o	$\theta_o + 120^\circ$	-120°	$\theta_o + 120^\circ$	θ_o	$+120^\circ$

Table II

Direction of Circulation	1→6→2→4→3→5→1			1→5→3→4→2→6→1		
Phase-shift	θ_n	θ_{ob}	$\Delta\theta$	θ_n	θ_n	$\Delta\theta$
Channel 1-6	$\theta_o -120^\circ$	θ_o	-120°	θ_o	$\theta_o -120^\circ$	$+120^\circ$
Channel 2-5	θ_o	θ_o	0°	θ_o	θ_o	0°
Channel 3-4	θ_o	$\theta_o -120^\circ$	$+120^\circ$	$\theta_o -120^\circ$	θ_o	-120°

The difference between circulators utilizing $-2/3\,\pi$ and $+2/3\,\pi$-bridges, consists in the fact that in the first instance the phase-shift in a reciprocal channel must be equal to the minimum non-reciprocal phase-shift, and in the second instance–to the maximum shift (see Figure 3).

3. THREE-THROW SWITCH

Analysis of reciprocal diagrams 7, 8, 9 by means of expressions (1), (2), (3), proves that they describe three distinct states of the six-port switch. It has been found that the switch is realizable with both reciprocal and non-reciprocal phase-shifters. However, minimum phase shifts in the shifters are obtained when all three of them are reciprocal. Thus, by adjusting the electric length of one of the phase-shifters by 120° in relation to the other two, one may switch any entrance port of the device to any of it's exit ports. In absence of a magnetic field the electric length of the phase-shifters equals θ_0. When the field is applied, the electric length must be $\theta_0 \pm 120^\circ$, depending on the sign $(2/3\,\pi)$ of the bridge.

4. ELEMENTS OF SIX-PORT FERRITE DEVICES

Problems concerning the realization of ferrite phase-shifters have been profoundly studied, so there is no need here to enter in details. On the other hand, the realization of six-port bridges should be discussed at some length. For the sake of convenience in arranging phase devices, the six-port bridges must satisfy certain conditions regarding the type of symmetry. The most efficient way of arranging such devices is based on three-dimensional design of six-port bridges. 3D-bridges utilizing coaxial transmission lines are known.[4]

A six-port waveguide bridge has been developed specially for the centimeter band.[3] This bridge (Figure 4) is formed by three rectangular waveguides spaced 120° and touching each other with their narrow walls. On a certain length (Figure 4) the walls are absent, thus forming a star cross-section cavity. The butt-ends of this cavity are formed by metal walls shaped as an equilateral triangle. The butt-ends are joined by a cylindrical metal rod crossing the center of the cavity.

5. EXPERIMENTAL

The possibility of technological realization of six-port ferrite devices with perfect transmission has been checked for the centimeter band on a laboratory model (Figure 5). Parameters of the model were:

Direct losses	–	not over 1 dB,
Return losses	–	not less than 18 dB,
VSWR	–	not over 1.3:1
Electric strength	–	1.5 times that of four-port ferrite devices.

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4. L. G. Dorfman. "On the Theory of Three-Dimensional 12-Pole Devices with Symmetry." *Electrosvjaz*, 1963, N12, pp. 23-31.

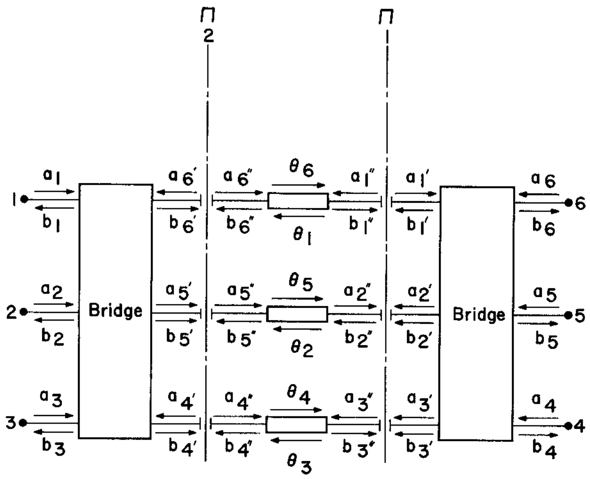

Figure 1. Phase Shifter Block Elements

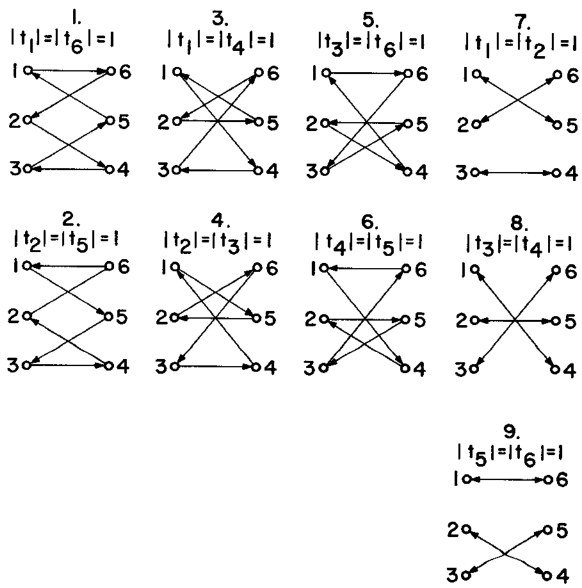

Figure 2. Non-Reciprocal Diagrams Showing Passage of Signals Through Six-Port Circulators

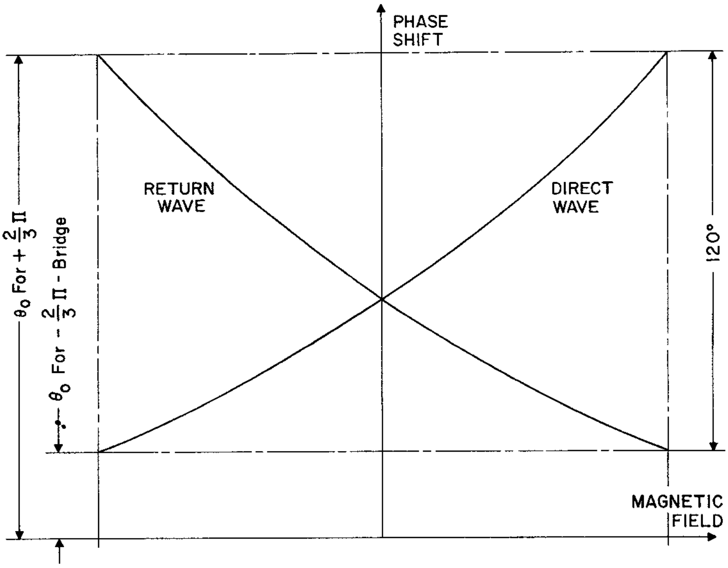

Figure 3. Phase Shift in Circulators Utilizing $-2/3\,\pi$, $+2/3\,\pi$ Bridges

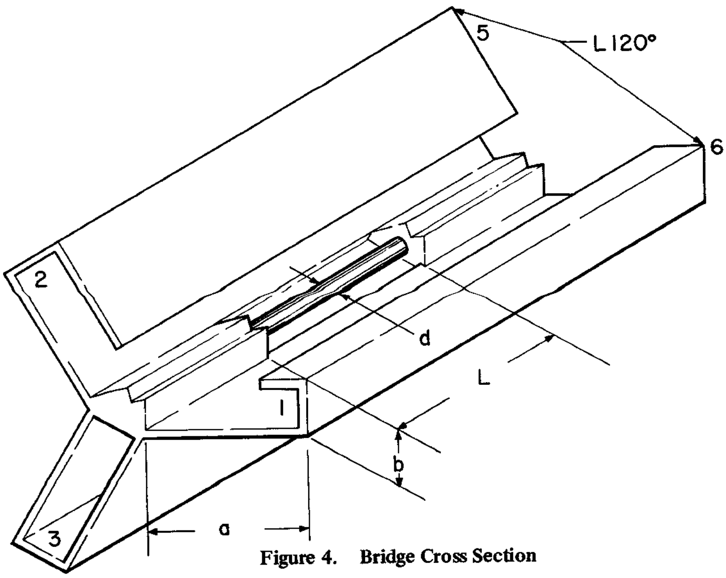

Figure 4. Bridge Cross Section

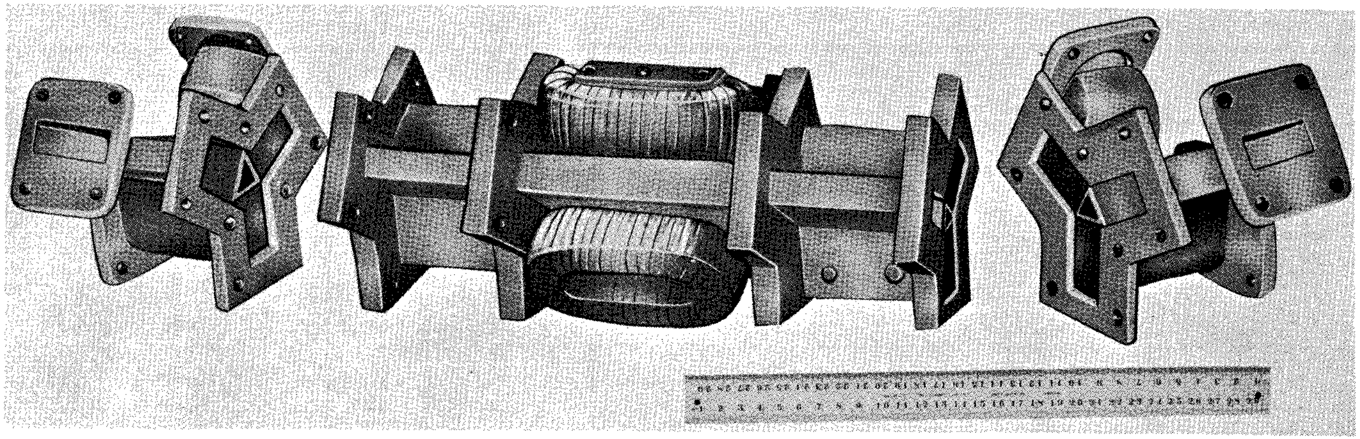

Figure 5. Laboratory Model of Six-Port Phase-Type Circulator/Switch