Four-Port Scattering Matrix for Dual-Polarized Wave Transmission and Reflection Network

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***Abstract*— Co-directional and bi-directional, co-polarized and cross-polarized characteristics of a lossless, matched four-port transmission network have been examined. For example, an arbitrary-inclined dielectric plate in a circular or square waveguide supporting dual-orthogonal linearly polarized modes has been analyzed, and a coordinate system is defined to apply for co-directional and bi-directional propagating circularly polarized waves. The matrix elements are polarization state and network dependent. Instead of using the terms network reciprocity and matrix symmetry, the matrix elements are discussed in terms of ratios to describe co-directional, bi-directional, co-polarized, cross-polarized, and polarization discrimination properties. Some of the ratios are equal to $1\angle 0^\circ$ and others $1\angle 180^\circ$. Applications of this analysis are described. If the properties of the four-port network are frequency dependent and integrated over a bandwidth, and/or time dependent and integrated temporally, the scattering matrix formulation is not valid due to the presence of a randomly polarized component; in these cases a Mueller matrix is used to characterize the network.**

***Index Terms*— Depolarization, four-port network, random polarization, scattering matrix.**

I. Introduction

Scattering matrices are used to describe network characteristics, and extensive applications have been published with an arbitrary number of ports [1]. The simplest network entails two-ports with a 2×2 scattering matrix comprising four matrix elements. References describing the measurement of these elements have been reported [2], [3]. Lossless three-port networks have been analyzed, and it is shown that simultaneous impedance match at all three-ports is not possible [4], [5].

A waveguide directional coupler is a four-port network characterized by a 16-element scattering matrix [1], [4], [6]. The traditional *magic tee* is a four-port network with an E-plane arm, an H-plane arm, and two coplanar arms [1], [6]. This structure has physical symmetry and reciprocal properties.

Another four-port network is an orthomode transducer (OMT) that transforms or converts orthogonal linearly polarized waves into orthogonal circularly polarized waves. A structural example of an OMT is a quarter-wave plate with an input waveguide, square or circular, propagating two orthogonal linearly polarized waves, and an output waveguide, square or circular, propagating two orthogonal circularly polarized waves [1]. The scattering matrix of this transducer is described by 16 matrix elements. A typical OMT has a dielectric plate or its equivalent oriented at an angle of 45° midway between two input orthogonal linear polarization vectors. The dielectric plate introduces a 90° differential phase shift between electric field components that are perpendicular and parallel to the plate. This structure is physically symmetrical.

To convey the purposes of this paper, a simplified structure of an arbitrary dielectric plate in a waveguide, square or circular, is analyzed and the 16 elements of its scattering matrix are presented. This arbitrary structure is not physically symmetrical because of an arbitrary angle and arbitrary differential phase shift of the plate. This transducer may be considered an “imperfect” quarter-wave plate or a generalized transducer. The perfect quarter-wave plate transducer has been analyzed previously [1], as well as an imperfect quarter-wave plate [7]. The purpose of this paper is to analyze an arbitrary, impedance-matched lossless dielectric-plate transducer, to determine all of the elements of the 4×4 scattering matrix, and to discuss their characteristics. The discussion is expanded to consider both co-directional and bi-directional propagation characteristics. It is believed that the co-directional, bi-directional, co-polarization, cross-polarization, and depolarization aspects of these networks have not all been treated adequately earlier.

The potential application of this analysis is to mitigate cross-polarization of a circularly polarized wave, propagating through rain due to canted distorted oblate-spheroid rain drops. Dual circularly polarized communication links with frequency re-use can be designed to conserve spectrum allocation. However, rain depolarization is undesired since this results in signal interference, or crosstalk. This interference and its mitigation are discussed in another paper by the author.

II. Lorentz Reciprocity Theorem

In this paper, co-directional (same) and bi-directional (opposite) wave propagation in networks are considered. The term reciprocal is used to describe network characteristics when bi-directional propagation is involved. The reciprocal nature of electromagnetic fields was formulated by Lorentz [8]–[10] and this has been applied to the coupling of two radiating antennas, which is a two-port network. The formulations have been presented in terms of volume and surface integrals. In this regard, statements are made that if a network is reciprocal then its scattering matrix is symmetrical [4], [5], [9].

III. Coordinate Systems for Bi-Directional Circularly Polarized Waves

In analyzing a network that entails circularly polarized waves propagating bi-directionally, it is essential to define a coordinate system that is consistent with the direction of circularity, or handedness, of the waves. Assume that the horizontal axis is the initial reference orientation for 0°

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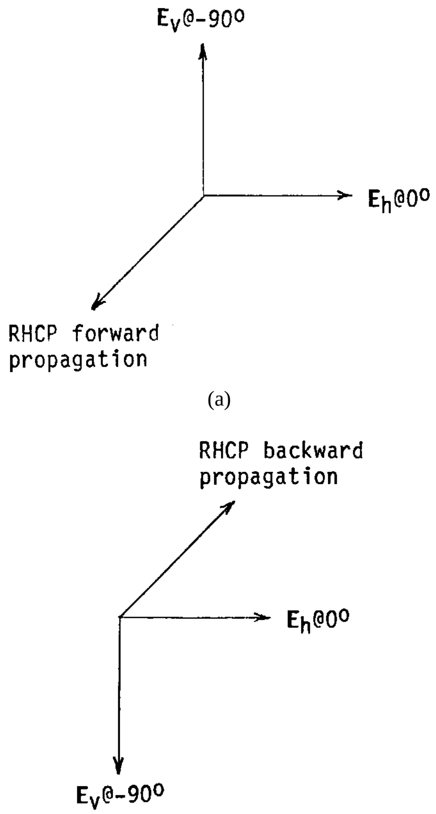
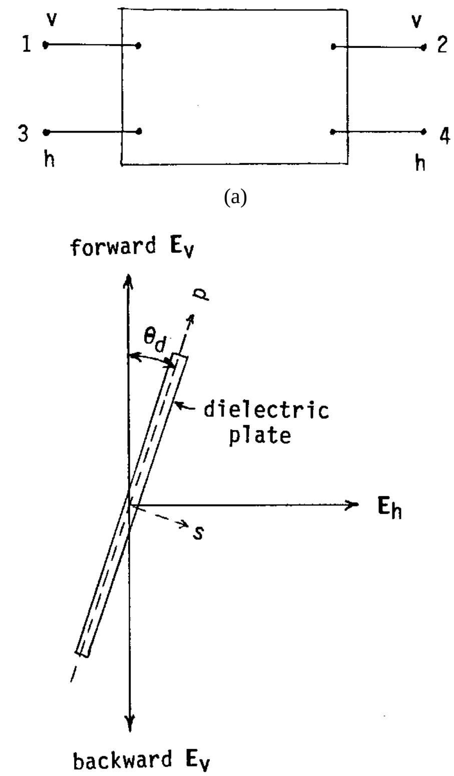


(b)

Fig. 1. Coordinate systems for (a) forward and (b) backward propagation of right-hand circularly polarized waves. With linearly polarized waves, the phases of $\boldsymbol{E}_h$ and $\boldsymbol{E}_v$ can be assumed to be 0°.



(b)

Fig. 2. (a) Four-port network and (b) coordinate axes.

phase for both right- and left-hand circularly polarized waves. In Fig. 1(a) for a forward propagating right-hand circularly polarized wave, $\boldsymbol{E}_h$ is oriented horizontally and referenced at 0° phase, and $\boldsymbol{E}_v$ is oriented vertically upward with a phase of $-90°$.

In Fig. 1(b) for a backward propagating right-hand circularly polarized wave the $\boldsymbol{E}_v$ reference vector must be oriented downward with $-90°$ phase, or oriented upward with $+90°$ phase. Thus the phase of $\boldsymbol{E}_v$ differs by 180° between forward and backward propagating for the same sense of circularly polarized wave. This opposite polarity manifests in a 180° phase difference in some element pairs in the four-port scattering matrix in this paper.

A coordinate system has been described that is dependent on the direction of propagation, and this is called "forward scattering alignment" and "backward scattering alignment" [11].

IV. Analysis

The analysis of a lossless four-port network comprising an inclined impedance-matched dielectric plate in a dual-mode waveguide, either square or circular, is treated initially with two orthogonal linearly polarized signals, which can be extended to orthogonal circularly polarized signals. The linearly polarized formulation is presented in the Appendix. The configuration and coordinate axes are shown in Fig. 2. The coordinate system is defined to anticipate application to an orthogonal dual circularly polarized application, and a distinction is made between forward and backward propagation directions, as mentioned above. Briefly, the incident vertical- and horizontal-polarized wave components with reference phases of 0° are decomposed into components aligned and perpendicular to the inclined dielectric plate. After passing through the dielectric plate the components are combined to yield the outgoing vertical and horizontal components. An output polarized component that is the same as the input is called co-polarized, whereas an output polarized component that is orthogonal to the input is called a cross-polarized (depolarized) component. The output performances of special cases are described later in this paper. The results can be applied to incident waves that are circularly polarized by a quadrature phase difference between the incident equal-amplitude vertical and horizontal components.

V. Definitions of Matrix Element Ratios for a Four-Port Network

In describing characteristics of networks, terms such as reciprocity, symmetry, and equality have been used in the literature. When dealing with two-port networks, there is little ambiguity with these terms, but some remarks have to be made in relation to four-port networks. Reciprocity conveys bidirectionality between two ports of a network. The term symmetry can describe a physical structure, such as a *magic tee*. Symmetry can also refer to a pair of elements in a scattering matrix, such as $\boldsymbol{S}_{mn} = \boldsymbol{S}_{nm}$. The term equality may be used in reference to a ratio of a pair of matrix elements such as $\boldsymbol{S}_{mn}/\boldsymbol{S}_{xy}$, and the ratio in general entails both amplitude and phase. The term equality has sometimes been used to mean equal amplitudes, but the term has also been used to mean equality in both amplitude and phase.

TABLE I

	Forward Propagation	Backward Propagation
Codirectional Co-pol	$\frac{S_{21}}{S_{43}} = 1 \angle \phi_{21} - \phi_{43}$	$\frac{S_{12}}{S_{34}} = \frac{S_{21}}{S_{43}}$
Codirectional Cross-pol	$\frac{S_{41}}{S_{23}} = 1$	$\frac{S_{14}}{S_{32}} = 1$
Codirectional XPD_a	$\frac{S_{21}}{S_{41}} = \frac{K_1}{K_2} \angle \phi_{21} - \phi_{41}$	$\frac{S_{12}}{S_{32}} = -\frac{S_{21}}{S_{41}}$
Codirectional XPD_b	$\frac{S_{43}}{S_{23}} = \frac{K_1}{K_2} \angle \phi_{43} - \phi_{41}$	$\frac{S_{34}}{S_{14}} = -\frac{S_{43}}{S_{23}}$
	Co-pol	Cross-pol
Bidirectional (a)	$\frac{S_{21}}{S_{12}} = 1$	$\frac{S_{41}}{S_{14}} = -1$
Bidirectional (b)	$\frac{S_{43}}{S_{34}} = 1$	$\frac{S_{23}}{S_{32}} = -1$

When dealing with four-port networks, the terms reciprocity and symmetry with reference to a pair of matrix elements become somewhat ambiguous. Thus, in the remainder of this paper, these terms have been avoided and are replaced with more explicit terms to convey more specificity. These terms entailing matrix element pairs represent co-directional (either forward or backward propagation), bi-directional, co-polarization, cross-polarization, and polarization discrimination.

The four-port network is assumed to be impedance matched. Thus at each port, $S_{nn} = 0$, and mutual impedances at each end of the network are also matched, such as $S_{31} = S_{13} = 0 = S_{24} = S_{42}$. The first subscript of the matrix element is the port with an outward wave, and the second subscript is the port with an inward wave. There are various ratios of elements as illustrated in Table I. In this example, a four-port network is described with vertical polarization in the top Ports 1 and 2, and horizontal polarization in the bottom Ports 3 and 4 as shown in Fig. 2. Ports 1 and 3 are on the left side, and Ports 2 and 4 on the right side. Forward propagation means power flow from Ports 1 and 3 to Ports 2 and 4. Backward propagation is in the opposite direction.

The term co-pol, meaning co-polarization, is used to describe either vv or hh, that is the input and output ports have the same polarization. In the forward direction the co-pol elements are S_{21} or S_{43}, whereas in the backward direction they are S_{12} or S_{34}.

The term cross-pol, meaning cross-polarization is used to describe either vh or hv. In the forward direction the cross-pol elements are S_{41} or S_{23}, and in the backward direction they are S_{14} or S_{32}.

The term co-directional pair means in the same direction. In the forward direction the co-pol pair is S_{21} and S_{43}. In the backward direction the co-pol pair is S_{12} and S_{34}. The co-pol element ratios have unity amplitudes but the phases are equal to ϕ_{21}–ϕ_{43}. A co-directional pair can also be applied to cross-polarization such as S_{41} and S_{23}, or S_{14} and S_{32}. These ratios are found to be equal to $1\angle 0°$.

The term bidirectional means in opposite directions between a pair of ports. For a co-pol pair, these elements are S_{12} and S_{21}, or S_{43} and S_{34}. The element ratios of these element pairs are equal to $1\angle 0°$. For a cross-pol pair these elements are S_{14} and S_{41}, or S_{23} and S_{32} and the ratios of these element pairs are equal to $1\angle 180°$. The 180° phase difference arises from the reversed coordinate system shown in Figs. 1 and 2 in order to preserve the sense of circular polarization in the two different directions.

Another very significant ratio of matrix elements is called cross-polarization discrimination (XPD). This ratio describes the amount of depolarization or cross-coupling, or interference on a circularly polarized signal, caused by asymmetry in the network or the propagation medium such as oblate spheroid raindrops [12]. XPD is the ratio of a co-pol component to a cross-pol component. It is commonly described as a scalar quantity greater than unity [13]. It is fundamentally a complex ratio with an amplitude and phase, and in this paper it is treated accordingly. Examples of XPD in the forward direction are the ratios

$$S_{21}/S_{41} \quad \text{and} \quad S_{43}/S_{23}.$$

Examples of XPD in the backward direction are the ratios

$$S_{12}/S_{32} \quad \text{and} \quad S_{34}/S_{14}.$$

For all XPD ratios, their amplitudes are equal to K_1/K_2, but the phases may not be equal as shown in the Appendix. It is noted that the phases of XPD differ by 180° between backward and forward propagation directions. This 180° phase difference arises from the selected coordinate system that preserves the handedness in dealing with circularly polarized waves in opposite directions.

VI. Polarization Dependent Matrix Elements

The values of the 4 × 4 matrix elements are examined for their dependence on the polarization state. For example, as noted above, the amplitudes of XPD are equal to the ratio K_1/K_2 and this ratio depends on the dielectric plate angle θ_d as shown in the Appendix. Specifically for the linearly polarized example, XPD becomes infinite when θ_d is 0° or 90° and hence there is no depolarization. However if the input signal is circularly polarized, XPD is not infinite even when θ_d is 0° or 90°. Thus the matrix elements differ with polarization state.

VII. Frequency Independent and Static Network

In examining the validity of the scattering matrix to a four-port network, the characteristics of the network with respect to its frequency and time dependence need to be examined. If the input signal is: 1) either monochromatic or the network characteristic does not change over the signal bandwidth and 2) the network characteristics do not change with time, that is, a static network, then the foregoing scattering matrix formulation is valid. An example of a valid network is a broadband quarter-wave plate, an OMT, that converts a linearly polarized wave into a pure circularly polarized wave over a bandwidth.

VIII. Frequency Dependent and/or Dynamic Scenario

If the network has a component or medium that is either/or both frequency and time dependent, then the foregoing scattering matrix representation is not valid as stated above. An example of an invalid network contains narrow-band resonant elements subject to wide bandwidth signals, or a network element or medium path which changes with time, such as rain along the transmission path. Another example is pulsed radar scattering where there is relative motion of either/or both the radar and scattering surface, such as encountered with a synthetic aperture radar [14]. With frequency and time dependence, the scattering matrix elements have to be formulated accordingly, and this is beyond the scope of this paper.

IX. Random Polarization

The degree of validity of a 4×4 scattering matrix formulation depends on the signal bandwidth and receiver integration period. If the integration period is significantly shorter than the dynamics of the scenario, then the scattering matrix is valid for that integration period provided there is no frequency dependence. However if the scenario is to be characterized for a longer integration period and exhibits frequency dependence there will remain a randomly polarized or unpolarized component in accordance with the Stokes' parameters [14]–[16]. To characterize these networks, a Mueller matrix formulation has been introduced [13], [17].

Examples of the importance of an unpolarized component are in the imperfect operation of rain depolarization cancellers [18], synthetic aperture radar imaging [14], and rain backscattering [19].

X. Four-Port Reflection Network

The foregoing matrix representation of a four-port transmission network can be extended to a four-port reflection network by regarding terminals 1 and 3 for the dual-polarized transmitters, and terminals 2 and 4 for the dual-polarized receivers. This is the configuration for a fully polarimetric-radar scattering scenario.

XI. Matrix Application to the Mitigation of Depolarization Caused by Rain

The 4×4 scattering matrix formulation has been applied to a conceptual design of a cross-polarization cancellation circuit operating at the signal frequency to mitigate adverse depolarization effects caused by rain on a circularly polarized signal [20]. The circuit is an arbitrary-inclined dielectric plate dual-mode transducer that combines into one component, a depolarization cancellation component followed by an ideal OMT. This mitigation technique assumes negligible frequency effects and is useful for up to moderate rain rates.

XII. Conclusion

An arbitrary-inclined dielectric plate in a dual-orthogonal mode waveguide is a four-port network that can be characterized by a 4×4 scattering matrix with 16 elements provided the elements are constant over the signal bandwidth and the network properties are constant during the integration time period. Matrix element pairs or ratios of co-directional and bi-directional, co-polarized and cross-polarized elements, and XPD are presented for a four-port orthogonal linearly polarized network. The scattering matrix elements of a given network are dependent on the polarization state. If the network properties depend on frequency and time, the scattering matrix is replaced by a Mueller matrix.

Appendix

For this analysis, the coordinate axes are shown in Fig. 2 of a generalized transducer network comprising a dielectric plate inclined at an arbitrary angle in a dual-mode waveguide, with an arbitrary differential phase delay between two orthogonal linearly polarized components. The analysis assumes a lossless impedance-matched transducer, however the formulation can be extended to media containing loss. The vertical and horizontal axes are labeled v and h, respectively, and the wave is propagating forward into the paper. The dielectric plate d is inclined at a clockwise angle of θ_d from vertical. The direction parallel to the plate surface is designated p and the surface normal is designated s for "senkrecht" which means perpendicular in German. The differential phase delay of the p component relative to the s component due to the plate is ϕ_d, and the subscript d here denotes the dielectric plate. The transducer is analyzed with linear vertical and horizontal components, however, performance of an incident i circular-polarization wave can be described in terms of linearly polarized components with a quadrature phase difference in ϕ_i of the vertical relative to horizontal component. With the wave propagating into the paper ϕ_i can assume $-/+$ 90° to designate left- and right-hand circular polarizations, respectively. After propagating through a rain path, a phase difference of ϕ_r occurs between the horizontal and vertical components of the wave incident on the network. Both ϕ_i and ϕ_r contribute to the phase of $\boldsymbol{E}_v$ relative to $\boldsymbol{E}_h$.

The following nomenclature is employed to simplify the mathematical presentation:

$$S = \sin\theta_d$$
$$C = \cos\theta_d.$$

The vertical and horizontal components of the wave incident on the transducer are $\boldsymbol{E}_{vi}$ and $\boldsymbol{E}_{hi}$, respectively. Each of these components is decomposed by the plate into p and s components, and the p component emerges with a phase ϕ_d that has a negative value representing a delay due to the dielectric. Both $\boldsymbol{E}_{vi}$ and $\boldsymbol{E}_{hi}$ will contribute to both p and s components and are added in the complex domain. Thus, from $\boldsymbol{E}_{vi}$ the plate output components assuming impedance-matched dielectric plate for both p and s components are

$$\begin{aligned} \boldsymbol{s}_{vo} &= -\boldsymbol{E}_{vi}\sin\theta_d \\ \boldsymbol{p}_{vo} &= \boldsymbol{E}_{vi}\cos\theta_d \angle\phi_d. \end{aligned}$$

From $\boldsymbol{E}_{hi}$ the plate output components are

$$\begin{aligned} \boldsymbol{s}_{ho} &= \boldsymbol{E}_{hi}\cos\theta_d \\ \boldsymbol{p}_{ho} &= \boldsymbol{E}_{hi}\sin\theta_d \angle\phi_d. \end{aligned}$$

The $\boldsymbol{p}_{vo}$ and $\boldsymbol{p}_{ho}$ components are added in the complex domain and then projected back to the v and h axes. Similar additions and projections are performed for the s components.

The output vertical and horizontal complex components $\boldsymbol{E}_{vo}$ and $\boldsymbol{E}_{ho}$ emerging from the impedance matched transducer are given by

$$\begin{aligned}\boldsymbol{E}_{vo} &= \boldsymbol{E}_{vi}C^2\angle\phi_d + \boldsymbol{E}_{vi}S^2 + \boldsymbol{E}_{hi}SC(1\angle\phi_d - 1)\\ \boldsymbol{E}_{ho} &= \boldsymbol{E}_{vi}SC(1\angle\phi_d - 1) + \boldsymbol{E}_{hi}S^2\angle\phi_d + \boldsymbol{E}_{hi}C^2.\end{aligned}$$

The scattering matrix of a four-port network is given by

$$\begin{aligned}\boldsymbol{b}_1 &= \boldsymbol{S}_{11}\boldsymbol{a}_1 + \boldsymbol{S}_{12}\boldsymbol{a}_2 + \boldsymbol{S}_{13}\boldsymbol{a}_3 + \boldsymbol{S}_{14}\boldsymbol{a}_4\\ \boldsymbol{b}_2 &= \boldsymbol{S}_{21}\boldsymbol{a}_1 + \boldsymbol{S}_{22}\boldsymbol{a}_2 + \boldsymbol{S}_{23}\boldsymbol{a}_3 + \boldsymbol{S}_{24}\boldsymbol{a}_4\\ \boldsymbol{b}_3 &= \boldsymbol{S}_{31}\boldsymbol{a}_1 + \boldsymbol{S}_{32}\boldsymbol{a}_2 + \boldsymbol{S}_{33}\boldsymbol{a}_3 + \boldsymbol{S}_{34}\boldsymbol{a}_4\\ \boldsymbol{b}_4 &= \boldsymbol{S}_{41}\boldsymbol{a}_1 + \boldsymbol{S}_{42}\boldsymbol{a}_2 + \boldsymbol{S}_{43}\boldsymbol{a}_3 + \boldsymbol{S}_{44}\boldsymbol{a}_4\end{aligned}$$

where the single subscripts refers to port numbers, the a's refer to inputs, and the b's refer to outputs. The first and second subscripts of the $\boldsymbol{S}$ terms refer to output and input ports, respectively. In this analysis, Ports 1 and 3 are the left-side ports, and Ports 2 and 4 are the right-side ports as shown in Fig. 2. Further, Ports 1 and 2 are vertically polarized, and Ports 3 and 4 are horizontally polarized. An impedance-matched network is assumed. All $\boldsymbol{S}_{nn}$ terms are zero and this may be called a co-polarized impedance match. Cross-polarized impedance matches are also assumed meaning $S_{13} = \boldsymbol{S}_{31} = 0$, as well as $\boldsymbol{S}_{24} = \boldsymbol{S}_{42} = 0$.

For simplicity, additional terms are defined:

$$\begin{aligned}K_1 &= (C^4 + S^4 + 2C^2S^2\cos\phi_d)^{0.5}\\ K_2 &= SC(2(1-\cos\phi_d))^{0.5}\\ \phi_{21} &= \tan^{-1}(C^2\sin\phi_d/(S^2 + C^2\cos\phi_d))\\ \phi_{23} &= \tan^{-1}(\sin\phi_d/(\cos\phi_d - 1))\\ \phi_{41} &= \tan^{-1}(\sin\phi_d/(\cos\phi_d - 1))\\ \phi_{43} &= \tan^{-1}(S^2\sin\phi_d/(C^2 + S^2\cos\phi_d))\\ \phi_{12} &= \phi_{21}\\ \phi_{32} &= \phi_{23} + \pi\\ \phi_{14} &= \phi_{41} + \pi\\ \phi_{34} &= \phi_{43}.\end{aligned}$$

It is noted that ϕ_{23} and ϕ_{41} are equal, by using the following definitions:

$$\begin{aligned}\boldsymbol{S}_{21} &= K_1\angle\phi_{21} = \boldsymbol{S}_{12}\\ \boldsymbol{S}_{41} &= K_2\angle\phi_{41} = -\boldsymbol{S}_{14}\\ \boldsymbol{S}_{43} &= K_1\angle\phi_{43} = \boldsymbol{S}_{34}\\ \boldsymbol{S}_{23} &= K_2\angle\phi_{23} = -\boldsymbol{S}_{32}.\end{aligned}$$

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