PAPER

The Formulae of the Characteristic Polarization States in the Co-Pol Channel and the Optimal Polarization State for Contrast Enhancement

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SUMMARY For the completely polarized wave case, this paper presents the explicit formulae of the characteristic polarization states in the co-polarized radar channel, from which one can obtain the CO-POL Max, the CO-POL Saddle and the CO-POL Nulls in the Stokes vector form. Then the problem on the polarimetric contrast optimization is discussed, and the explicit formula of the optimal polarization state for contrast enhancement is presented in the Stokes vector form for the first time. To verify these formulae, we give some numerical examples. The results are completely identical with other authors', which shows the validity of the presented method.

key words: *radar polarimetry, optimal polarization, radio application, scattering matrix*

1. Introduction

As regards the characteristic polarization states of a radar target for the completely polarized wave case, Boerner et al. [1],[2] have already derived the characteristic polarization states based on the polarization transformation ratio, for which a radar receives optimum power. These states are one co-polarization maximum (CO-POL Max), one co-polarization saddle (CO-POL Saddle), two co-polarization nulls (CO-POL Nulls), two cross-polarization maximums (X-POL Maxs), two cross-polarization nulls (X-POL Nulls), and two cross-polarization saddles (X-POL Saddles). In radar polarimetry, the Poincaré sphere and the Stokes vector are used frequently because the former is a useful graphical aid for the visualization of polarization effects. So, it is important to express the characteristic polarization states in the Stokes vector's form. In the cross-polarized radar channel case, Yamaguchi et al.[3] provided a convenient method to obtain the X-POL Nulls, X-POL Maxs and X-POL Saddles (in the Stokes vector's form) based on eigenvalue problem. For obtaining the CO-POL Max, CO-POL Saddle and CO-POL Nulls, on the other hand, some authors used the Lagrangian multiplier method and then solved nonlinear equations [2], [4]. Obviously, this kind of method is tedious for obtaining the characteristic polarization states in the co-polarized radar channel.

In Sect. 2, a new method is provided to obtain the CO-POL Max, CO-POL Saddle and CO-POL Nulls. From this method, the explicit formulae of the CO-POL Max, CO-POL Saddle and CO-POL Nulls are presented in the Stokes vector's form for the first time. Then, one numerical example is given, showing the results are identical with [2], [4].

In Sect. 3, the problem on the polarimetric contrast optimization will be discussed. This problem is to find radar antenna polarizations that maximize the power ratio of the desired target and clutter (or undesired target), which is highly desirous in microwave remote sensing. For solving this problem, Kostinski and Boerner [5] have provided a mathematical model and a method to obtain the optimal polarization state in the matched radar channel. Recently, Mott, Tanaka and Boerner [6] extend this problem into the case of two time-varying targets (the target and clutter). Up to now, there exists no explicit formula of the optimal polarization state for contrast enhancement. In this paper, we will transform Kostinski's model into another form expressed by the Stokes vector. Then, the explicit formula of the optimal polarization state (in Stokes vector's form) will be presented. Besides, this method can also be used for solving for the case of two time-varying targets [6]. To verify the formula, we will give two numerical examples in this section, showing the results are identical with [5] and [6].

2. The Formulae for the Characteristic Polarization States in the Co-Polarized Channel

2.1 The Formulae of CO-POL Max and CO-POL Saddle

Let

$$S = \begin{bmatrix} s_1 & s_2 \\ s_3 & s_4 \end{bmatrix} \tag{1}$$

denote *the symmetric / asymmetric scattering matrix* of a radar target and **a** denote the polarization state of the transmitter ($\|\mathbf{a}\| = 1$). Then the received power in the co-polarized radar channel is given by

$$P_{co} = | S\mathbf{a} \cdot \mathbf{a} |^2 \tag{2}$$

and the received power in the matched radar channel is given by

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$$P_m = \| S\,\mathbf{a} \|^2 = S^+ S\,\mathbf{a} \cdot \mathbf{a}^* \tag{3}$$

where the superscript + denotes conjugate transpose and * denotes conjugation. Let

$$\mathbf{g} = \left(1,\ g_1,\ g_2,\ g_3 \right)^t \tag{4}$$

denote the Stokes vector of **a**, where t denotes transpose. Then the received power in the matched radar channel can be rewritten as

$$P_m = \frac{1}{2}\left(|s_1|^2 + |s_2|^2 + |s_3|^2 + |s_4|^2 \right) + v_1 g_1 + v_2 g_2 + v_3 g_3 \tag{5}$$

where

$$v_1 = \frac{1}{2}\left(|s_1|^2 + |s_3|^2 - |s_2|^2 - |s_4|^2 \right),$$

$$v_2 = \mathrm{Re}\,(s_1 s_2^* + s_3 s_4^*),$$

$$v_3 = \mathrm{Im}\,(s_1 s_2^* + s_3 s_4^*),$$

$$v = \sqrt{v_1^2 + v_2^2 + v_3^2}\,. \tag{6}$$

For the symmetric scattering matrix ($s_2 = s_3$) case, as we have known, the CO-POL Max is the same as the Matched-POL Max. Using the Cauchy-Schwarz inequality to (5), we know that P_m will be maximal if and only if

$$g_i = \frac{v_i}{v}, \qquad i = 1, 2, 3\,. \tag{7}$$

So, the CO-POL Max is

$$\boldsymbol{g} = \left(1,\ \frac{v_1}{v},\ \frac{v_2}{v},\ \frac{v_3}{v} \right)^t \tag{8}$$

where v_i and v are given by (6).

Similarly, since the CO-POL Saddle is the same as the Matched-POL Min, P_m will be minimal if and only if

$$g_i = -\frac{v_i}{v}, \qquad i = 1, 2, 3\,. \tag{9}$$

So, the CO-POL Saddle is

$$\boldsymbol{g} = \left(1, -\frac{v_1}{v}, -\frac{v_2}{v}, -\frac{v_3}{v} \right)^t. \tag{10}$$

For *the asymmetric scattering matrix* ($s_2 \neq s_3$) case, the power expression in the co-polarized radar channel remains the same if the scattering matrix S is replaced by the following *symmetric scattering matrix* S'

$$S' = \begin{bmatrix} s_1 & \dfrac{s_2 + s_3}{2} \\ \dfrac{s_2 + s_3}{2} & s_4 \end{bmatrix}. \tag{11}$$

In this way, we can also obtain the CO-POL Max and the CO-POL Saddle by the above method.

2.2 The Formula of CO-POL Nulls

It is straightforward to prove that $P_{co} = | S\,\mathbf{a} \cdot \mathbf{a} |^2$ becomes zero if and only if

$$S\,\mathbf{a} = \lambda \begin{bmatrix} a_2 \\ -a_1 \end{bmatrix} = \lambda \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \mathbf{a},$$

or

$$\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} S\,\mathbf{a} = \lambda\,\mathbf{a}\,. \tag{12}$$

Obviously, this eigenvalue problem can be solved easily. The two eigenvectors are associated with the CO-POL Nulls. From (12), we have

$$\lambda_{1,2} = \frac{1}{2}\left(s_2 - s_3 \pm \sqrt{(s_2 - s_3)^2 - 4\,(s_1 s_4 - s_2 s_3)} \right) \tag{13}$$

and

$$\mathbf{a} = \frac{1}{\sqrt{| s_4 |^2 + | \lambda_{1,2} + s_3 |^2}} \begin{bmatrix} -s_4 \\ \lambda_{1,2} + s_3 \end{bmatrix}$$

$$\left(| s_4 |^2 + | \lambda_{1,2} + s_3 |^2 \neq 0 \right), \tag{14a}$$

or

$$\mathbf{a} = \frac{1}{\sqrt{| s_1 |^2 + | \lambda_{1,2} - s_2 |^2}} \begin{bmatrix} \lambda_{1,2} - s_2 \\ s_1 \end{bmatrix}$$

$$\left(| s_4 |^2 + | \lambda_{1,2} + s_3 |^2 = 0 \right). \tag{14b}$$

Using the following expression for the Stokes vector elements in terms of Pauli matrices [11] I, J, K and L (see Appendix)

$$g_1 = i L\,\mathbf{a} \cdot \mathbf{a}^*, \quad g_2 = -i K\,\mathbf{a} \cdot \mathbf{a}^*, \quad g_3 = i J\,\mathbf{a} \cdot \mathbf{a}^*, \tag{15}$$

we have the following results:

(i) If $| s_4 |^2 + | \lambda_{1,2} + s_3 |^2 \neq 0$, the CO-POL Nulls are

$$g_1 = \frac{| s_4 |^2 - | \lambda_{1,2} + s_3 |^2}{| s_4 |^2 + | \lambda_{1,2} + s_3 |^2}, \tag{16a}$$

$$g_2 = \frac{-2\,\mathrm{Re}\left(s_4^*\left(\lambda_{1,2}+s_3\right)\right)}{\left|s_4\right|^2+\left|\lambda_{1,2}+s_3\right|^2}, \qquad (16b)$$

$$g_3 = \frac{-2\,\mathrm{Im}\left(s_4^*\left(\lambda_{1,2}+s_3\right)\right)}{\left|s_4\right|^2+\left|\lambda_{1,2}+s_3\right|^2}. \qquad (16c)$$

(ii) If $\left|s_4\right|^2+\left|\lambda_{1,2}+s_3\right|^2=0$, the CO-POL Nulls are

$$g_1 = \frac{\left|\lambda_{1,2}-s_2\right|^2-\left|s_1\right|^2}{\left|s_1\right|^2+\left|\lambda_{1,2}-s_2\right|^2}, \qquad (17a)$$

$$g_2 = \frac{2\,\mathrm{Re}\left(s_1^*\left(\lambda_{1,2}-s_2\right)\right)}{\left|s_1\right|^2+\left|\lambda_{1,2}-s_2\right|^2}, \qquad (17b)$$

$$g_3 = \frac{-2\,\mathrm{Im}\left(s_1^*\left(\lambda_{1,2}-s_2\right)\right)}{\left|s_1\right|^2+\left|\lambda_{1,2}-s_2\right|^2}. \qquad (17c)$$

Note that in the symmetric scattering matrix case ($s_2=s_3$), (13) can be simply rewritten as

$$\lambda_{1,2} = \pm\sqrt{s_2^2-s_1 s_4}. \qquad (18)$$

In *the asymmetric scattering matrix* case, the best way is to replace *the asymmetric scattering matrix* by *the symmetric scattering matrix*

$$S' = \begin{bmatrix} s_1 & \frac{s_2+s_3}{2} \\ \frac{s_2+s_3}{2} & s_4 \end{bmatrix},$$

then to use the above formulae for obtaining the CO-POL Nulls.

Example 1

If a scattering matrix is given as

$$S = \begin{bmatrix} 2i & 0.5 \\ 0.5 & -i \end{bmatrix},$$

which is taken from [1], [2] for the sake of comparison, we obtain the CO-POL Max and the CO-POL Saddle according to (8) and (10) as

$$\mathbf{g} = \left(1,\ \frac{\sqrt{2}}{2},\ 0,\ \frac{\sqrt{2}}{2}\right)^t$$

and

$$\mathbf{g} = \left(1,\ -\frac{\sqrt{2}}{2},\ 0,\ -\frac{\sqrt{2}}{2}\right)^t,$$

respectively. From (16) and (18), we can obtain the CO-POL Nulls as

$$\mathbf{g} = \left(1,\ -\frac{1}{3},\ \pm\frac{\sqrt{7}}{3},\ -\frac{1}{3}\right)^t.$$

These results are identical with [2], [4]. The power signature as a function of the transmitting polarization state, tilt angle τ and ellipticity angle ε, is illustrated in Fig. 1(a). One can find four stationary points in Fig.1(a) which correspond to the characteristic polarization states (the CO-POL Max, CO-POL Saddle and CO-POL Nulls) in the co-polarized radar channel. Fig. 1(b) shows these points on the Poincaré sphere.

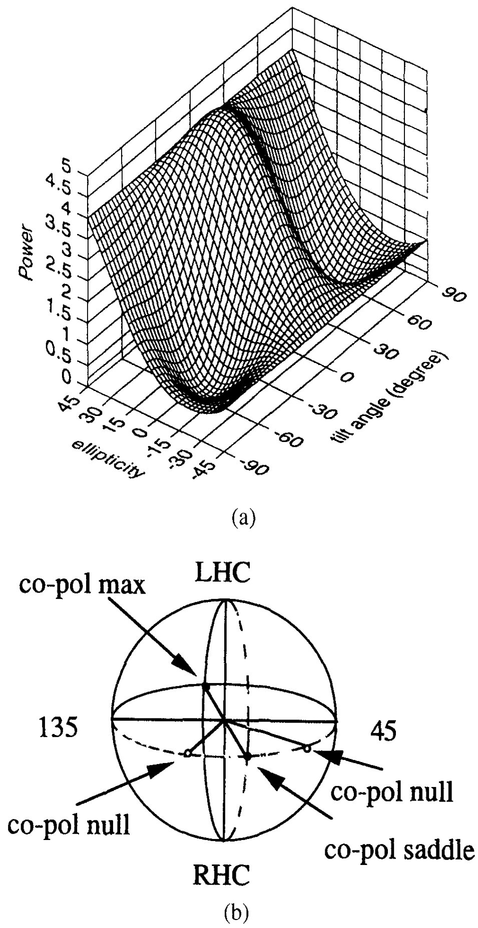

Fig. 1 (a) The CO-POL power signature.
(b) The CO-POL Max and CO-POL Saddle on the Poincaré sphere.

3. The Formula of the Optimal Polarization State for Contrast Enhancement

3.1 The Problem on the Polarimetric Contrast Enhancement Optimization

In polarimetric remote sensing, it is very important to find radar antenna polarizations that maximize the contrast between the desired target and clutter (undesired target). This is so-called the problem on the polarimetric contrast enhancement optimization. Here, let us consider the following model [5] to find $\mathbf{a}$ ($\|\mathbf{a}\|=1$) such that

$$D = \frac{\mathbf{a}^+ S_1^+ S_1 \mathbf{a}}{\mathbf{a}^+ S_2^+ S_2 \mathbf{a}} \tag{19}$$

will be maximal, where S_1 and S_2 are the scattering matrices of the target and clutter, respectively. Usually, S_2 is not supposed to be a singular matrix. On the other hand, it should be pointed out that S_1 and S_2 can be asymmetric.

Let $\mathbf{g}$ denote the Stokes vector of $\mathbf{a}$. By use of the expression (5), we can rewrite (19) as the following form

$$D = \frac{A_0 + A_1 g_1 + A_2 g_2 + A_3 g_3}{B_0 + B_1 g_1 + B_2 g_2 + B_3 g_3} , \tag{20}$$

where A_i and B_i can be obtained from (5) and (6).

Let D_m be the maximum of the above expression, then we have for any $\mathbf{g}$ that

$$D_m \geq \frac{A_0 + A_1 g_1 + A_2 g_2 + A_3 g_3}{B_0 + B_1 g_1 + B_2 g_2 + B_3 g_3} , \tag{21}$$

or

$$A_0 - D_m B_0 + (A_1 - D_m B_1) g_1 + (A_2 - D_m B_2) g_2 + (A_3 - D_m B_3) g_3 \leq 0 . \tag{22}$$

The problem here is to find $\mathbf{g}$ such that the left-hand side of (22) will be maximal.Obviously, $A_0 - D_m B_0 + (A_1 - D_m B_1) g_1 + (A_2 - D_m B_2) g_2 + (A_3 - D_m B_3) g_3$ becomes zero if and only if

$$g_i = \frac{A_i - D_m B_i}{\sqrt{\sum_{i=1}^{3} (A_i - D_m B_i)^2}} \qquad (\, i = 1, 2, 3 \,) , \tag{23}$$

which yields

$$A_0 - D_m B_0 + \sqrt{\sum_{i=1}^{3} (A_i - D_m B_i)^2} = 0 . \tag{24}$$

From this equation, we have

$$D_m = \frac{z_{12} + \sqrt{z_{12}^2 - z_1 z_2}}{z_2} , \tag{25}$$

where $z_1 = A_0^2 - A_1^2 - A_2^2 - A_3^2$, $z_2 = B_0^2 - B_1^2 - B_2^2 - B_3^2$ and $z_{12} = A_0 B_0 - A_1 B_1 - A_2 B_2 - A_3 B_3$.

Substituting (25) into (23), one can obtain the optimal polarization state $\mathbf{g}$ easily.

Example 2

Let

$$S_1 = \begin{bmatrix} 0.192 + 0.445\,i & -0.083 - 0.405\,i \\ -0.083 - 0.405\,i & -0.064 - 0.148\,i \end{bmatrix}$$

and

$$S_2 = \begin{bmatrix} -0.047 - 0.497i & -0.166 + 0.265i \\ -0.166 + 0.265i & 0.393 + 0.633i \end{bmatrix}$$

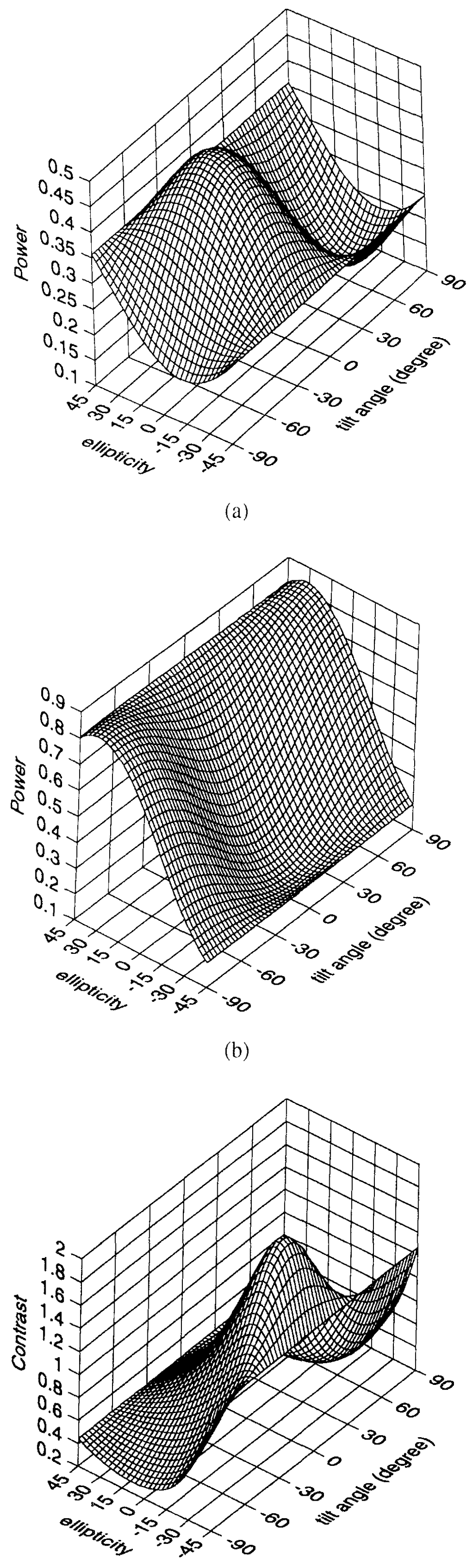

Fig. 2 (a) The signature of the scattered power density of the target.
(b) The signature of the scattered power density of the clutter.
(c) The power contrast between the target and clutter.

be the scattering matrices of the target and clutter, respectively. Using the method in this section, we can obtain

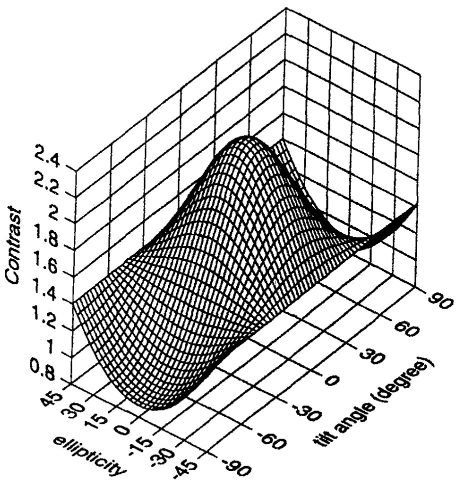

Fig. 3 The power contrast between the time-varying target and clutter.

$D_m = 1.9787$ and the optimal polarization state $\mathbf{g} = (1,\ 0.4071,\ -0.0886,\ -0.5474)^t$ The signatures of the scattered power densities (corresponding to the target and clutter) are illustrated in Fig. 2(a) and Fig. 2(b), respectively. Fig. 2(c) shows the power contrast between the target and clutter, from which one can find the optimal polarization state for the contrast enhancement. From [5], the same result can be obtained. This shows the validity of our formula.

3.2 Time-Varying Target Case

Next, let us consider the problem on the polarimetric contrast optimization in the case of two time-varying targets which was first studied by Mott, Tanaka and Boerner [6]. In this case, the targets are characterized by the time-averaged Kronecker matrices, from which the Graves matrices can be obtained by the following expression

$$G = \begin{bmatrix} k_{11} + k_{41} & k_{13} + k_{43} \\ k_{12} + k_{42} & k_{14} + k_{44} \end{bmatrix} \equiv \begin{bmatrix} \sigma_1 & \sigma_2 \\ \sigma_3 & \sigma_4 \end{bmatrix}, \qquad (26)$$

where G denotes Graves matrix and k_{ij} denotes the elements of the time-averaged Kronecker matrix. By use of (19), Mott et al.[6] extended Kostinski's model into the following form. The problem is to find $\mathbf{a}$ ($\|\mathbf{a}\| = 1$) such that

$$D = \frac{\mathbf{a}^+ G_1 \mathbf{a}}{\mathbf{a}^+ G_2 \mathbf{a}} \qquad (27)$$

will be maximal, where G_1 and G_2 are the Graves matrices of two time-varying targets (the target and clutter), respectively. Using the following expression (see Appendix)

$$\mathbf{a}^+ G\, \mathbf{a} = \frac{1}{2}(\sigma_1 + \sigma_4) + \frac{1}{2}(\sigma_1 - \sigma_4)\, g_1 + \frac{1}{2}(\sigma_2 + \sigma_3) g_2 + i\frac{1}{2}(\sigma_2 - \sigma_3)\, g_3 \,, \qquad (28)$$

one can rewrite (27) to the form of (20). So, this problem can also be solved by the above method.

Example 3

Let

$$G_1 = \begin{bmatrix} 6.2 & 0.3 - 0.09\,i \\ 0.3 + 0.09\,i & 4 \end{bmatrix}$$

and

$$G_2 = \begin{bmatrix} 2.7 & 0.26 - 0.1\,i \\ 0.26 + 0.1\,i & 4.5 \end{bmatrix}$$

be the time-averaged Graves matrices of target and clutter, respectively, which are obtained from the time-averaged Kronecker matrices of [6]. According to (27) and (28), we can write the ratio of the scattered power densities as

$$D = \frac{5.1 + 1.1 g_1 + 0.3 g_2 + 0.099 g_3}{3.6 - 0.9 g_1 + 0.26 g_2 + 0.1 g_3} \,.$$

By use of the above method (Sec. 3.1), we can obtain that $D_m = 2.3025$ and the optimal polarization state $\mathbf{g} = (1,\ 0.9948,\ -0.0936,\ -0.0412)^t$. This result is identical with [6]. Figure 3 shows the power contrast between the target and clutter, from which one can find the optimal polarization state for the contrast enhancement.

4. Conclusion

In the field of radar polarimetry, the Mueller matrix and the Stokes vectors (of the transmitter and the receiver) are employed to express the received power frequently. After the characteristic polarization states was derived by Boerner et al. [1], [2], some authors used this kind of power expression for obtaining the characteristic polarization states in the Stokes vector's form [2]-[4]. However, there exist neither explicit formula for the characteristic polarization states in co-pol channel, and nor for the optimal polarization state for contrast enhancement. In this paper, we presented four explicit formulae in terms of the Stokes vector, which are very easy to obtain the CO-POL Max, CO-POL Saddle, CO-POL Nulls and the optimal polarization state for contrast enhancement. To verify the formulae, we compared some numerical examples with other authors' [2], [4]-[6]. The results are completely identical with them, which shows the validity of our formulae.

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Appendix: The proof of Expression (28)

The Graves power matrix is defined as

$$G = S^+ S = \begin{bmatrix} \sigma_1 & \sigma_2 \\ \sigma_3 & \sigma_4 \end{bmatrix}. \qquad (A \cdot 1)$$

This can be expanded as

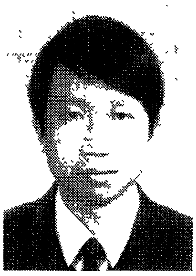
$$G = \frac{1}{2}(\sigma_1 + \sigma_4) + \frac{1}{2}(\sigma_1 - \sigma_4)\, i L - \frac{1}{2}(\sigma_2 + \sigma_3)\, i K + i\frac{1}{2}(\sigma_2 - \sigma_3)\, i J \qquad (A \cdot 2)$$

where I, J, K and L are Pauli matrices [11],

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \qquad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},$$

$$K = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix}, \qquad L = \begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix}.$$

Using (A · 2) and (15), one can obtain (28). This expansion can also be used to prove (5).



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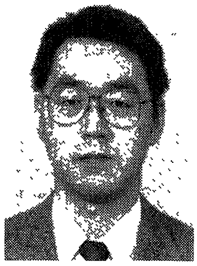

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