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Polarization properties of calibration reflector system in the polarization-modulated space laser communication

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ABSTRACT

S-polarization light and p-polarization light are mutually cross orthogonal, which can be used as signal light for emitting and receiving in the polarization-modulated space laser communication, respectively. Due to the retro reflection characteristics of the corner cube retroreflector (CCR), it is widely used as a calibration reflector system in the polarization-modulated space laser communication. The polarization states of the incident light will be change owing to the total internal reflection (TIR) of uncoated rear surface, in addition, each of the six propagation trips will in general produce a different output polarization. For the calibration reflector system in the polarization-modulated space laser communication, the polarization state of the received light, especially the intensity ratio of the p-polarization component, needs to be clarified. In this paper, a framework is presented to calculate polarization by ray tracing through CCR with arbitrary input polarization states and incident angles. On this basis, the relationships between intensity ratio of the p-polarization component in the received light of each propagation trip and the incident light with different polarization states at normal incidence as well as the circular polarized light at incident angles within $\pm$ 15°analyzed. Theoretical analysis and experiments have guiding significance for the development of the polarization-modulated space laser communication.

1. Introduction

Retro reflection is one of the important properties of cube corner retroreflector that the light irradiates on the CCR at a certain angle is eventually reflected back in the direction that is counter-parallel to the incident light [1]. Because of the excellent characteristics of the CCR, it is widely used in laser range finder [2], phase-locked fiber lasers [3] and space laser communication [4].

While coated corner cubes have little effect on the input polarization state, the reflective coating results in strong thermal gradients within the corner cubes [5]. Many CCRs employ total internal reflection (TIR) by uncoated rear surfaces, however, due to the total internal reflection on each reflected surface, a different phase change of the horizontal component and the vertical component results in the change of the polarization state, and the polarization states of the emitted light are different under six different paths. There is a lot of researches on the polarization characteristics of the TIR CCR, Liu and Azzam derive the Jones matrices and eigenpolarizations of the TIR CCR at normal incidence, along with an experiment for measurements of Stokes parameters [6]. Kalibjian has present the method for the polarization analysis at the non-normal-incidence using the Stokes calculus [7]. The diffraction patterns of CCR are paid a lot of researches as well [8–10]. Their works are worthy of reference, but further work needs to do to adaptable to our needs. In the polarization-modulated space laser communication system, the *s*-polarization light is used as an emitted signal light, and the *p*-polarization light is used as a received signal light [11], through the conversion of Quarter-Wave Plate, the signal light propagate in the form of left and right circular polarized light in the link.

Therefore, in this paper, the CCR coordinate space is determined by the vector ray tracing, and the polarization characteristics of the system are described in the form of Jones matrix in Mathematics, the Jones matrix of the CCR is calculated at normal incidence, then the relationships between intensity ratio of the *p*-polarization component in the received light of each propagation trip and the incident light with different polarization states at normal incidence as well as the circular polarized light at incident angles within $\pm 15°$ analyzed. An experiment is set up to verify the theoretical analysis.

The outline of this paper is as follows. Section 2 presents a computational framework to analyze the light propagation through the TIR CCR at a certain incidence angle and input polarization states. Section 3 gives the Jones matrixes of the optical components in the calibration reflector

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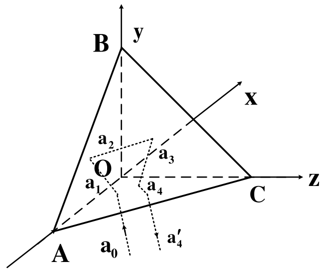

Fig. 1. Illustration of light path through a CCR.

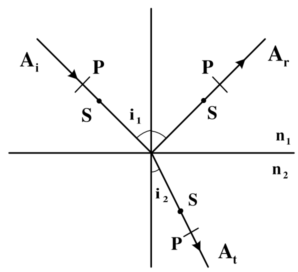

Fig. 2. Propagation vectors for the reflection and refraction.

system. Section 4 analyzes the polarization properties of the calibration reflector system: theoretical simulation. Section 5 gives the experiment results, and conclusion is made in Section 6.

2. Vectorial ray tracing of TIR CCR

In order to simplify vectorial ray tracing, the Cartesian coordinate system of CCR is set up by the three rectangular edges of the CCR, as shown in Fig. 1. The three right-angle isosceles triangles, AOB, BOC, and AOC are the TIR surface of CCR, and are respectively located in the x-y, y-z, and x-z planes. The equilateral triangle ACB is the base surface. Let $OA = OB = OC = 1$, so the unit normal vectors of the three TIR surfaces are respectively AOB: $\boldsymbol{N_1}(0,0,1)$, BOC:$\boldsymbol{N_2}(-1,0,0)$, AOC:$\boldsymbol{N_3}(0,1,0)$. The unit normal vectors of surface ABC for input light and output light are $\boldsymbol{N_0}(\frac{\sqrt{3}}{3},-\frac{\sqrt{3}}{3},-\frac{\sqrt{3}}{3})$ and $\boldsymbol{N_4}(-\frac{\sqrt{3}}{3},\frac{\sqrt{3}}{3},\frac{\sqrt{3}}{3})$.

Firstly we shall briefly introduce the direction vectors of the reflected and refracted lights with the law of reflection and Snells law. We assume the interface between two materials which are with different refractive index, n_1 and n_2 ,as shown in Fig. 2 The normal vector $\boldsymbol{N}$ is perpendicular to the interface and points toward the incident space. $\boldsymbol{A_i}$ is the unit vector of incident light, so the unit direction vectors of the reflected and refracted light , $\boldsymbol{A_r}$ and $\boldsymbol{A_t}$ are given as follows,

$$A_r = A_i - 2N(N \cdot A_i) = Rfl(N, A_i) \tag{1}$$

$$A_t = \frac{n_1}{n_2} A_i + (\sqrt{n_2^2 - n_1^2 + n_1^2 (N \cdot A_i)^2}) = Rfr(N, A_i). \tag{2}$$

We assume that the input light is in or parallel to the plane that determined by the line AC and N_4, and is reflected totally from the internal surfaces in the order of AOB, BOC, and AOC and a_0 and a_0' is the unit direction vector of input light before and after the refraction from the base surface, so the ray path through the CCR can be calculated with Eqs. (1)–(2),

$$\begin{aligned} &a_1 = a_0' = Rfr(N_0, a_0) \quad a_2 = a_1' = Rfl(N_1, a_1) \\ &a_3 = a_2' = Rfl(N_2, a_2) \quad a_4 = a_3' = Rfl(N_3, a_3) \quad a_4' = Rfr(N_4, a_4) \end{aligned} \tag{3}$$

where a_i, a_i' $(i = 1, 2, 3)$ are the unit direction vectors before and after each total internal reflection, respectively. a_4, a_4' are the unit direction vectors of the output light before and after the refraction from the base surface.

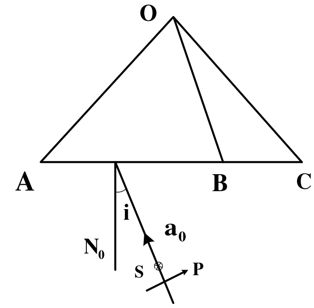

Fig. 3. Diagram of incident plane.

The electric field transfer to the direction of propagation can be described by two orthogonal vectors, expressed in the CCR coordinate system by the unit vectors of the p-polarization and s-polarization component of the light.

We define a frame for input polarization that the unit vector of the s-polarization component of the incident light S_0 is perpendicular to the plane that determined by the line AC and N_4, as shown in Fig. 3. Then the s-polarization vector in the CCR coordinate system is

$$S_0 = \frac{AC \times N_4}{|AC \times N_4|}. \tag{4}$$

According to the rotation formula of space vector the unit direction vector of input light a_0 can be rotated clockwise along vector S_0 from vector N_4,

$$a_0 = N_4 \cos i + S_0 \times N_4 \sin i + S_0 (S_0 \cdot N_4)(1 - \cos i) \tag{5}$$

where i is the angle of rotation of the vector, which can be defined as the incidence angle to the CCR. Explicitly the unit vector of the p-polarization component of the incident light is,

$$P_0 = a_0 \times S_0. \tag{6}$$

On approach to each interface, one must transform into the local s and p coordinate system corresponding to directions perpendicular and parallel to the plane of incidence, respectively. After the interface, whether refractive or reflective, the vertical vector is unchanged at a single interface, while the horizontal vector must be reevaluated by the Eq. (7) as follow, The unit direction vector of the vertical and parallel components before and after each reflection and refraction,

$$S_i = S_i' = \frac{a_i \times N_i}{|a_i \times N_i|} \qquad P_i = a_i \times S_i \qquad P_i' = a_i' \times S_i' \tag{7}$$

where a_i and a_i' are calculated by the Eq. (3), $S_i P_i$ and $S_i' P_i'$ are respectively the unit direction vectors of the s-polarization and p-polarization components before and after each reflection and refraction, based on this, different ray coordinate systems are established to describe the polarization state of light. In order to describe the polarization state of the incident light and the output light in the CCR coordinate system, the following coordinate transformation is required,

$$C_{ij} = \begin{pmatrix} P_i' \cdot P_j & S_i' \cdot P_j \\ P_i' \cdot S_j & S_i' \cdot S_j \end{pmatrix} \tag{8}$$

where C_{ij} is the rotation matrix from the coordinate system $S_i P_i$ to the coordinate system $S_i' P_i'$.

3. Jones matrices of the calibration and reflection system

In the polarization-modulated space laser communication, the s-polarization light is used as an emitted signal light, and the p-polariza