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Polarization effect of liquid crystal on oblique light

Hirokazu Ishida,[1)] Toshihiro Chujo,[1)] Osamu Mori,[2)] Junichiro Kawaguchi[2)]

1) *Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan*
2) *Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan*

Abstract

The world first solar sail spacecraft IKAROS launched at 2010 demonstrated the attitude control by using Reflectivity Control Device (RCD) on orbit. The advanced RCD (A-RCD) currently under development realizes the reflection of vertical incidence light to oblique direction, which increases the degree of freedom of the control. However, in the Polymer Dispersed Liquid Crystal (PDLC) layer in the A-RCD, the light path is not parallel to the longitudinal direction of liquid crystals. This oblique transmission is considered to cause the attenuation of the light and hence decreases the performance of the RCD. In this study, we investigated the mechanism of the attenuation focusing on the polarization effect of the liquid crystal on oblique light transmission. Then the experimental method to evaluate the polarization effects is described. The experimental results show the correlation of the polarization effect and attenuation.

1. Introduction

Reflectivity Control Device (RCD) is a novel attitude control device for solar sails[1]. This device is thin-film-shaped and applied to the solar sail membrane. The RCD reflects sunlight diffusively and specularly, when the device is ON and OFF states, respectively. This device is applied to solar sail control by putting the two RCDs across the center of gravity of the solar sail, for example. Unlike internal momentum exchange devices which require fuel to unload, the RCD is a fuel-free device. Furthermore, unlike magnetorquer, the RCD is useful even in deep space explorations.

In the RCD, Polymer Dispersed Liquid Crystal (PDLC) layer is put between two polyimide-film, one of which is aluminum-deposited as shown in Fig. 1. The PDLC layer consists of small size droplets filled with liquid crystals (LC), and the polymers which surround the droplets. The efficacy of the RCD was demonstrated by an actual space mission named “IKAROS” launched by Japan Aerospace Exploration Agency (JAXA)[2]. The major problem arose in the operation of “IKAROS” was the deformation of the solar sail membrane that caused acceleration torque perpendicular to the solar sail membrane. This torque is harmful to stable attitude control. Counteracting these effect by thrusters requires fuels, and is become a significant problem when the mission period is long. As a solution to this problem, we are currently developing a new type RCD named Advanced-RCD (A-RCD) which reflects the sunlight obliquely instead of vertically[3]. The sunlight reflected by the A-RCD has a component parallel to the membrane, which generates the torque perpendicular to the membrane. The concept of the A-RCD is shown in Fig. 2.

This new type RCD, however, has one drawback. The obliquely reflected light from the A-RCD when ON-state somehow attenuated than the vertically reflected light from the conventional RCD. In this paper, we study the mechanism of this attenuation focusing on the polarization properties of the PDLC layer. Then we show the correlation between the attenuation and polarization by experiments. Hereinafter, this paper argues about the case only when ON-state unless otherwise specified.

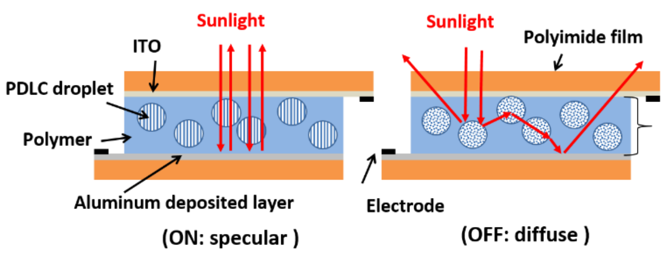

Fig. 1 Mechanism of the RCD.

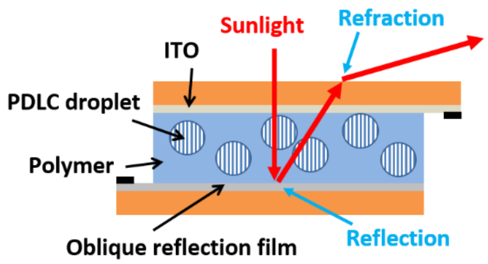

Fig. 2 Concept of the A-RCD.

2. Attenuation and polarization of light in the PDLC layer

2.1. Anisotropic properties of the liquid crystal molecule

LC can be considered as a rod-like shaped molecule, which is approximately axial symmetry as shown in Fig. 3(a). Due to the rod-like shape, the LC has an optical anisotropy. The refractive index of the LC depends on the both incident direction and polarization angle of the light through the molecule. Fig. 3(b) shows the index ellipsoid corresponding to Fig. 3 (a), in which refractive indices n_0 and n_e are respectively defined as the length of the minor and major axes of the ellipsoid. This index-ellipsoid is a diagram for calculating the magnitude of the refractive index to the light polarized and oriented particularly. The calculation procedure to get n_e' is as follows. Define the light orientation vector S and angle θ as shown in Fig. 3(b). Then cut the ellipsoid to get the cross-sectional green ellipsoid as shown in Fig. 3(b) and (c). We define n_e' as the long axis of the ellipse. Then we get the refractive index of the LC n_e' as follows

$$n_{\mathrm{LC}} = \sqrt{\frac{n_0^2 {n_e'}^2}{n_0^2 \cos^2\phi + {n_\mathrm{e}'}^2 \sin^2\phi}}. \quad (1)$$

Note that n_{LC} is the function of θ as well as ϕ because n'_e is the function of θ. From Fig. 3, n_{LC} for the light with $\theta = 0$ is constantly n_0 regardless of ϕ because the green cut-surface in Fig. 3 is a circle in this case. When $\theta \neq 0$, however, the cut-surface becomes ellipse, meaning that n_{LC} takes different values depending on ϕ. When the light with $\phi = 0$ and $\phi = \pi/2$, n_{LC} becomes n_0 and n'_e respectively.

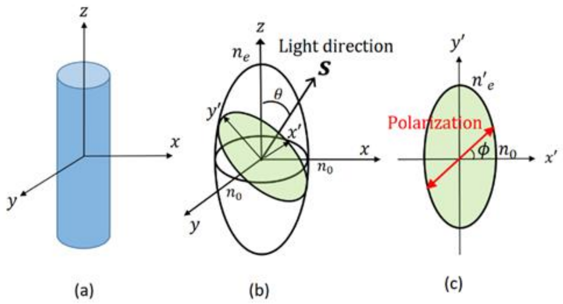

Fig. 3 Index-ellipsoid.

2.2 Relation between the attenuation and polarization in PDLC layer

The PDLC layer is a polymer-based material with many droplets[4]. Each droplet is filled with LCs. The refractive index of the polymer is typically set to n_0 which is the same value as n_0 of LC defined in Fig. 3. When an electric field is applied perpendicular to the surface of the PDLC layer (i.e. ON-state), the LC molecules in the droplets orient to the direction of the electric field. On the other hand, when no electric field is applied (i.e. OFF-state), each LC molecule is randomly oriented. From the characteristic above, when ON-state, the PDLC layer is a homogeneous medium for the light with $\theta = 0$, because the reflective indices of the polymer and the droplet take the same value.

When $\theta \neq 0$, the optical properties becomes complex. In this case, the PDLC layer becomes homogeneous when $\phi = 0$ because the $n_{\mathrm{LC}} = n_0$ for the light with $\phi = 0$. However, the PDLC layer becomes inhomogeneous when $\phi = 0$, because there is a mismatch of the refractive indices between the polymer and droplets, meaning that there are optical interfaces between the two materials. In the case of $\theta \neq 0$, the mismatch of the reflective index will be maximum and minimum when $\phi = \pi/2$ and $\phi = 0$, respectively. Unlike homogeneous mediums, light scattering occurs in inhomogeneous mediums, which causes the attenuation. Therefore, we can expect that the attenuation in the PDLC becomes highest and lowest for the light with $\phi = \pi/2$ and $\phi = 0$, respectively. In this context, the polarization properties of the PDLC is related to the attenuation of the oblique light transmission, which will be confirmed by experiments described in the following section.

3. Experiment

When light passes through a medium with the absorption coefficient μ and intensity I_0, the intensity of transmitted light $I(x)$ is expressed as follows,

$$\mu = -\frac{1}{x}\ln\left(\frac{I(x)}{I_0}\right) \tag{2}$$

where x is the passing distance of the light. Hereinafter, we refer the absorption coefficient of a medium for the P and S polarized lights to μ_P and μ_S, respectively. Since when ON-state the LCs are oriented to the perpendicular direction to the surface of a medium, P-polarized and S-polarized lights respectively correspond to the lights with $\phi = \pi/2$ and $\phi = 0$. The absorption consists of the extinction and scattering. Of these two factors, we can ignore the extinction because the both polymer and LC are colorless materials. Fron the discussion about the polarization angle of light in the PDLC and its scattering in section 2, it can be expected that PDLC has the polarization properties related to μ as following: (a) When θ is constant, μ takes the maximum value for S-polarized light and the minumum value for P-polarized light. (b) As θ increases, while μ_P takes larger values, μ_S takes constant values. In order to confirm these expectations, we proposed a method and conducted experiments to obtain μ_P and μ_S.

3.1. Method

This method considers that we can obtain the transmittance T and reflectance R of the LC device as shown in Fig. 4. The LC device is composed of the PDLC layer and two glass layers binding the PDLC. The PDLC is the same material as the actual A-RCD. Since the measured T and R of the device are the summations of the multiple reflected lights as shown in Fig. 4, T and R are calculated as follows,

$$T = \frac{I_T}{I_0} = \frac{a(1-r)^2}{1-a^2r^2}, \qquad R = \frac{I_R}{I_0} = r + \frac{a^2r(1-r)^2}{1-a^2r^2} \tag{3}$$

where a denotes the one-way attenuation rate in the interval L in Fig. 4 and r the energy reflection rate at the interface between the device and air. Note that the reflection and refraction at the interface between the glass and PDLC layer are negligible because the mismatch of the refractive indices between the two layers is small comparing to that between the air and glass. By solving the simultaneous equations Eqs. (3), we can obtain r and a. Since glass is a material with high permeability with $\mu = 1$, a is considered to be attenuation rate in the one-way pass in the PDLC layer defined as d in the Fig. 4.

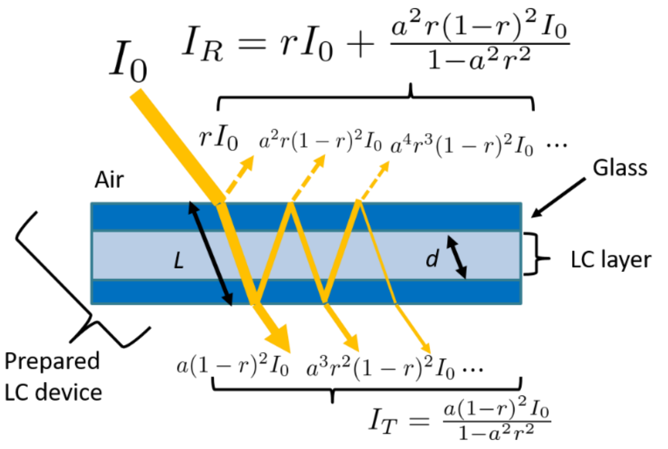

Fig. 4 Transmitted and reflected light.

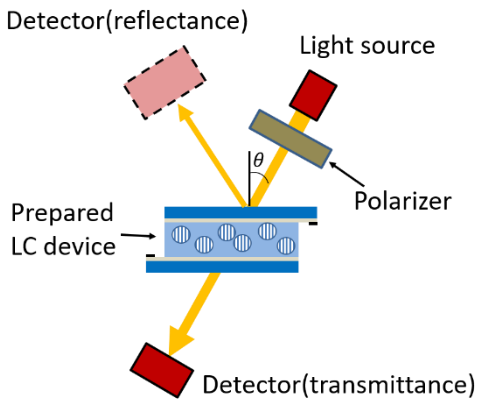

Fig.5 Experimental setup.

3.2. Experimental setup

To obtain μ_P and μ_s of the PDLC layer corresponding to the angle of incidence θ, we set the LC device shown in Fig. 4 and experimental system shown in Fig. 5. We used a spectrometer to measure the transmittance and reflectace of the device. The spectrometer emits light with 600nm wavelength, which goes through or reflects at the LC device and finally detected by the detector of the spectrometer. A polarizer is put between the device and light source, which permits perticular polarized light to go through. We can change the polarization angle by rotating the orientation of the polarizer. The angle of incident to the device θ can be changed. This θ corresponds to the θ that depicted in the Fig. 3, because when ON-state the LC molecules aligned perpendicular to the device surface.

3.3. Results and discussion

Fig. 6 plots the correlation between θ and μ for P and S polarized lights. While μ_S takes constant value regardless of θ, μ_P becomes larger as θ increases. These tendencies are the same as the expectations described in the first of section 3. These results indicate that PDLC layer has polarization properties, and it is possible to attribute the attenuation in the PDLC layer to the high value of μ_S for oblique light transmission.

Fig. 7 plots correlation between r and θ obtained from the both experimental data and theoretical values from Fresnel's law. The plot shows that there is a relatively good agreement between the experimental and theoretical values of r. Since getting r requires solving simultaneous equations, this agreement verifies the method and resulting data of r. The possible cause of the small mismatch of r is ignoring the existence of the ITO layers deposited on the glasses in the calculation. We will model the factor by the ITO layer to evaluate μ more precisely in the future work.

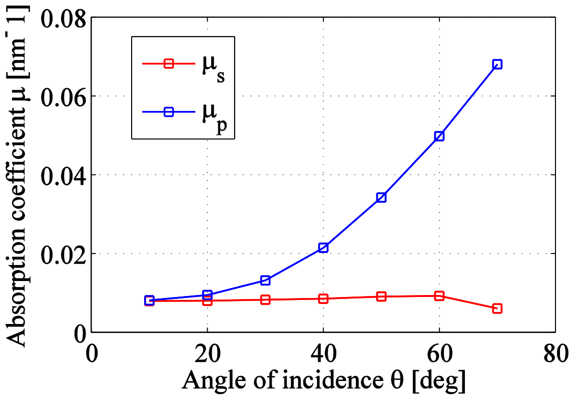

Fig. 6 Absorption coefficient of the PDLC.

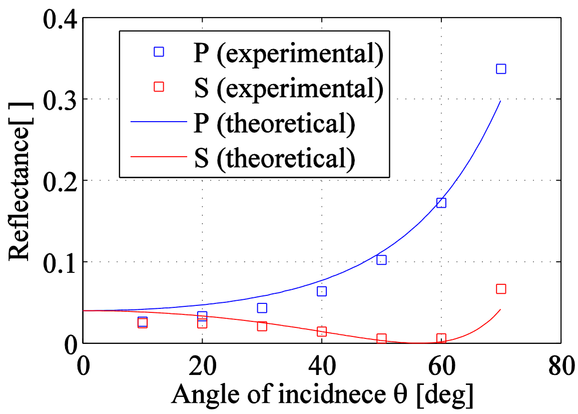

Fig. 7 Reflectance at the interface between the glass and air.

4. Conclusion

In this paper, the mechanism of the polarization effect in the PDLC layer of the A-RCD is explained. Then the experimental method to evaluate the polarization properties of PLDC layer is described. The experimental results evaluate the polarization properties of the PDLC layer. The absorption coefficient of PDLC for P-polarized light μ_P is larger than that for S-polarized light μ_S. Furthermore, as the angle of incidence θ increase, the gap between μ_P and μ_S becomes larger. Therefore, we can attribute the attenuation of oblique transmitting light in PDLC to the higher value of μ_P. These results suggest that there is a tradeoff when designing the optimal reflection angle. If the reflection angle is set to larger, the parallel component of the output becomes larger, which, however, also makes μ_P larger. Therefore, it is necessary to taking into account the polarization properties of the PDLC to design an optimal A-RCD.

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