

# Design of Light Guides with Liquid Crystal Switches for Optical Wireless Power Transmission Receiver

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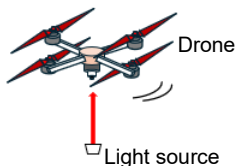
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## ABSTRACT

The logistics industry requires drone transportation with sufficient continuous flight range. Optical wireless power transmission is attracting attention as a solution. We are developing light guides with liquid crystal switch to channel light onto a power-generating element. This study examined liquid crystal alignments which are suitable for selectively directing light.

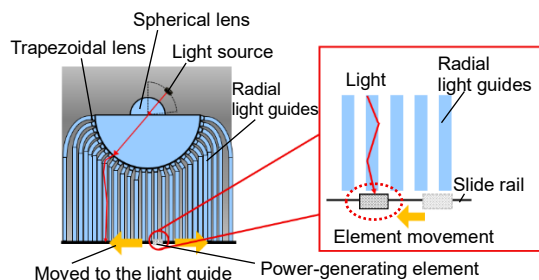
## 1 Introduction

In recent years, delivery demand has increased with the expansion of the mail-order market, while transportation capacity has decreased due to working-hour limits. Consequently, there are high expectations for the realization of drone transportation, which can reduce labor requirements through automated delivery. Truck transport can handle large-volume single-trip shipments, while drone transportation can deliver in many directions at the same time. In the future, combining the two is expected to increase transportation capacity. However, drone transportation has the problem of a limited continuous flight range [1]. Optical wireless power transmission (OWPT) offers a promising solution [2, 3]. OWPT supplies power by light energy using light transfer and photoelectric conversion through irradiation of a photoreceptor (power-generating element) (Fig. 1). Key technologies for realizing OWPT include guiding incident light from a wide area to the power-generating element and achieving high conversion efficiency with low optical loss.

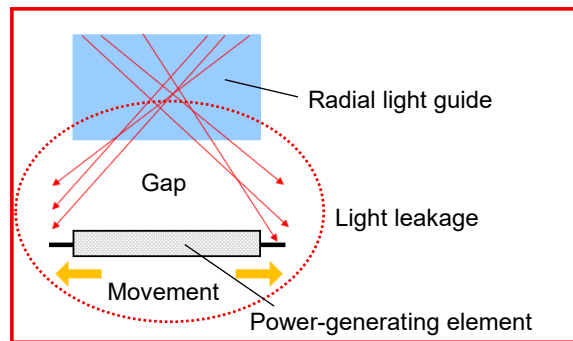


**Fig. 1 Optical wireless power transmission (OWPT)**

Our laboratory previously proposed a receiver using a spherical lens and radial light guides (Fig. 2(a)). This receiver was designed with a focusing system capable of handling wide incident angles [4]. In this system, light from the source is focused by the spherical lens, channeled into a single radial light guide, and received by a power-generating element positioned at its tip. However, the previous proposed system causes light leakage between the radial light guide and the power-generating element due to the dynamic movement of the element and



**(a) Principle of light collecting and guiding (Spherical lens + Radial light guides)**



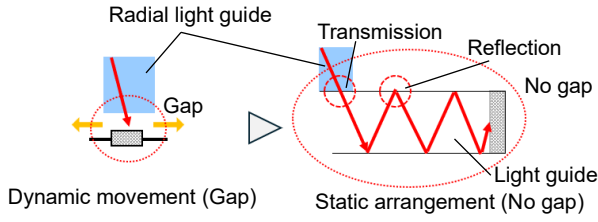
**(b) Issue of Light leakage (Radial light guide ⇔ Power-generating element)**

**Fig. 2 OWPT Receiver [4]**

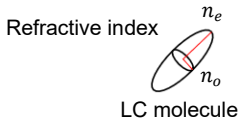
presence of gaps (Fig. 2(b)). To address light leakage caused by gaps, it is necessary to adopt a structure in which the power-generating element is statically positioned rather than dynamically moved, and light is channeled to the element (Fig. 3). This structure allows gaps to be eliminated. Therefore, we considered using liquid crystal (LC) to control light guiding. The refractive index of LC varies depending on the alignment of the LC molecules (Fig. 4). The ordinary refractive index is  $n_o$  and the extraordinary refractive index is  $n_e$ . As a result, the refractive index sensed by light changes, allowing transmission and reflection to be switched. Using this property, light guiding can be controlled.

Accordingly, this study aims to design and fabricate light guides with LC switch that use the refractive index anisotropy of LC to prevent light leakage between the radial light guide, bottom light guide, and the power-generating element. Specifically, we propose a structure for the light guides with LC switch, design LC alignments suitable for light transmission and reflection, and

evaluate interactions between LC molecules through alignment control. This new structure enables static light reception, allowing the power-generating element to receive light without moving.



**Fig. 3 Power-generating element arrangement (Dynamic (=Gap) ⇒ Static (=No gap))**



**Fig. 4 Refractive index anisotropy**

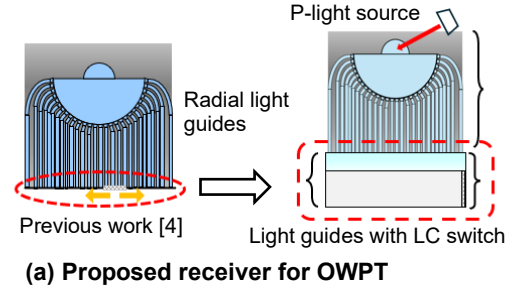
## 2 Proposal for light guides with LC switch

Fig. 5 shows the proposed method. The proposed OWPT receiver is structured so that the light guides with LC switch, which is the primary focus of this study, are positioned below the radial light guides used in previous research [4] (Fig. 5(a)).

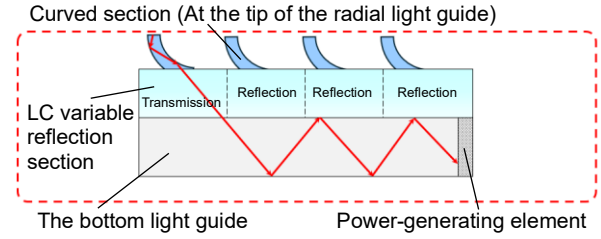
Fig. 5(b) shows that the light guides with LC switch consists of three main parts. The first part is the curved section at the tip of the radial light guide. In previous research [4], the tip of the radial light guide was straight, whereas in the newly proposed structure it is curved and attached to the LC variable reflection section. This modification determines the larger angle of incidence and reduces loss of light entering the LC variable reflection section. In light-guiding control using LC, the angle of incidence is a critical parameter, and a larger angle of incidence is required for effective control. The second part is a LC variable reflection section, where light can be switched to pass or reflect by controlling the LC. The third part is the bottom light guide, which guides light toward the power-generating element. The LC variable reflection section has voltage ON and OFF areas: the ON area transmits light, while the OFF area reflects light. By applying voltage only to the LC section that the light passes through, light is transmitted and directed to the bottom light guide. The directed light reflects again at the boundary between the LC variable reflection section and the bottom light guide at the OFF area of the LC variable reflection section. The light repeatedly reflects, until the light reaches the power-generating element at the end of the bottom light guide, realizing OWPT.

Since the control of light transmission and reflection by the LC depends on polarization, the light source uses a p-polarized laser. Polarization is unified to p-polarization using polarization conversion elements commonly found

in projectors and similar devices. Fig. 6 shows how the light path changes when the light source moves.

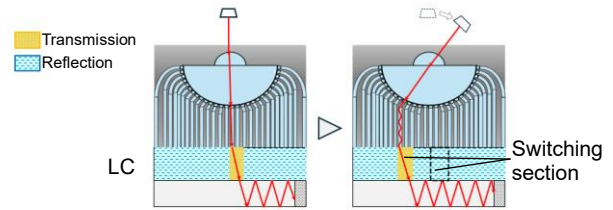


**(a) Proposed receiver for OWPT**



**(b) Light guides with LC switch for OWPT**

**Fig. 5 Proposed method**



**Fig. 6 Light path shift from light source motion**

## 3 Design of LC alignments

The LC variable reflection section is achieved by the LC layer. The LC material for the LC layer has an ordinary refractive index of  $n_o = 1.5$  and an extraordinary refractive index of  $n_e = 2.0$ , respectively. Such a high extraordinary refractive index and refractive index difference can be achieved using ZOC-A020XX ( $n_o = 1.550, n_e = 2.012$  JNC Petrochemical Co., Ltd, Japan). The LC material is rotated and this rotation angle is called the LC alignment angle  $\varphi$ . The LC alignment determines refractive index  $n(\varphi)$  in the LC layer as shown in equation (1).

$$n(\varphi) = \frac{n_e n_o}{\sqrt{n_o^2 \sin^2 \varphi + n_e^2 \cos^2 \varphi}} \quad (1)$$

We investigated the LC alignments for both light transmission and reflection. Flournoy et al. provided a formula for the reflection coefficient  $\rho_p$  as a function the angle of incidence within the glass region  $\theta_1$  for p-polarized light, as shown in equation (2) [5].

$$\rho_p = \frac{n_1 \sqrt{n_{2z}^2 - n_1^2 \sin^2 \theta_1} - n_{2x} n_{2z} \cos \theta_1}{n_1 \sqrt{n_{2z}^2 - n_1^2 \sin^2 \theta_1} + n_{2x} n_{2z} \cos \theta_1} \quad (2)$$

Fig. 7 shows a diagram of the interface where light reflects between glass as isotropic medium and LC as anisotropic medium.  $\theta_1$  is the angle of incidence in the glass region,  $n_1$  is the refractive index of the glass, and Fig. 8 shows that  $n_{2x}$ ,  $n_{2y}$ , and  $n_{2z}$  are the refractive indices in the x-, y-, and z-directions of the LC region, respectively.

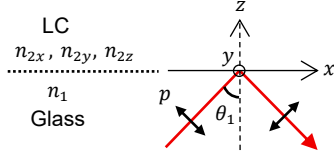


Fig. 7 Reflection interface diagram

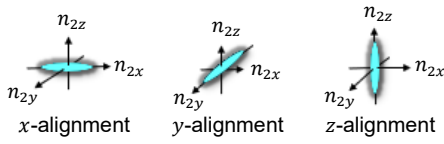


Fig. 8 Definition of LC alignment

Reflection characteristics of p-polarized light related to  $n_{2z}$  by equation (2). For x-alignment and y-alignment have low  $n_{2z}$  and for z-alignment has high  $n_{2z}$ . Thus, when glass refractive index of the bottom light guide is low and LC alignment in LC variable reflection section is x-alignment or y-alignment which  $n_{2z}$  is low, the refractive index difference between the bottom light guide and LC variable reflection section to be is transmission state. The relationship between the refractive indices of glass of the bottom light guide and LC alignment in LC variable reflection section shown in table 1.

The transmittance and reflectance are calculated using equation (2), with the LC molecular long axis oriented along the x-axis (x-alignment) and z-axis (z-alignment), are shown in Fig. 9. The x-alignment can be achieved by initial alignment at LC variable reflection section. The z-alignment can be achieved by applied voltage between top and bottom surface of LC variable reflection section. The refractive index of the glass was set to  $n_1 = 1.8$ . The critical angle for total internal reflection between  $n_o = 1.5$  and  $n_1 = 1.8$  is  $\theta_1 = 56.44^\circ$ . As shown in Table 2, for p-polarized light with incident angles of  $57^\circ \leq \theta_1 \leq 70^\circ$ , transmission occurs for the z-alignment, while reflection occurs for the x-alignment (Fig. 10). Consequently, designing the curved section so that the incident angle on the LC variable reflection section falls within  $57^\circ \leq \theta_1 \leq 70^\circ$  enables effective light-guiding control within the LC.

Table 1 The relationship between the refractive indices of glass and LC alignment

LC alignment	Glass refractive index $n_1$ : Low	Glass refractive index $n_1$ : High
x, y-alignment ( $n_{2z}$ : Low)	Transmittance	Reflection
z-alignment ( $n_{2z}$ : High)	Reflection	Transmittance

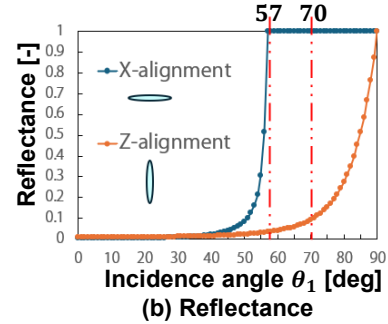
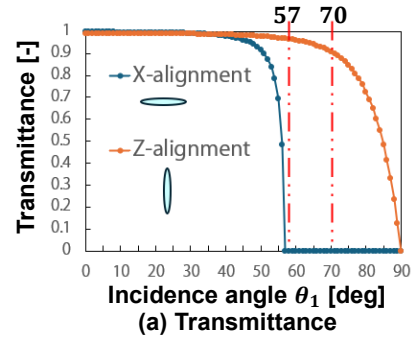


Fig. 9 Transmittance & Reflectance

Table 2 Transmittance / Reflectance of x, z alignment

$57^\circ \leq \theta_1 \leq 70^\circ$	Transmittance	Reflectance
x-alignment	0	1
z-alignment	0.9 $\uparrow$	0.1 $\downarrow$

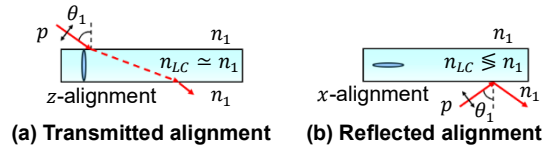
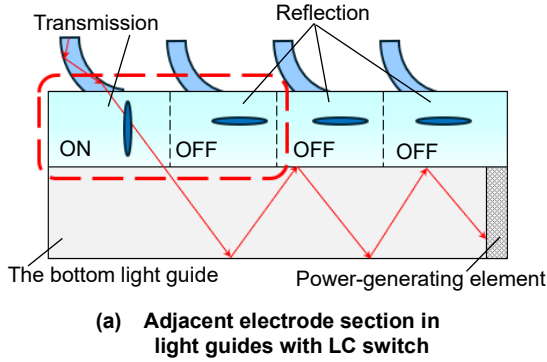


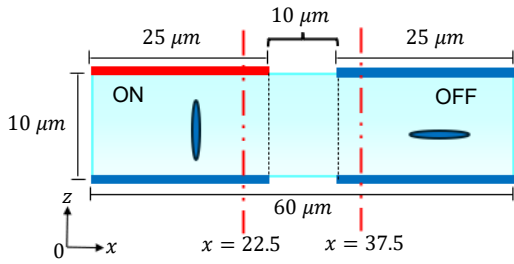
Fig. 10 LC alignment suitable for Transmittance & Reflectance

#### 4 Electrode spacing

The LC layer of the light guides with LC switch has adjacent ON and OFF electrode regions (Fig. 11). A concern is light leakage, which occurs when light reflected at the bottom of the light guide enters the space between electrodes in the LC variable reflection section (Fig. 12). For the space leakage problem, we use numerical simulations based on LC continuum elastic theory using LC alignment calculation software (LCD Master, Shintech, Ltd. Japan) were performed to examine whether adjacent electrodes have any influence. The LC layer thickness was set to 10  $\mu\text{m}$ , the pre-tilt angle to 2°, and the anchoring strength to 10<sup>-6</sup> J/m<sup>2</sup>. The electrode width was set to 25  $\mu\text{m}$ . The applied voltage was set in 0.1 V steps from 0 to 5 V.



(a) Adjacent electrode section in light guides with LC switch



(b) Enlarged view of (a)

Fig. 11 Electrode spacing

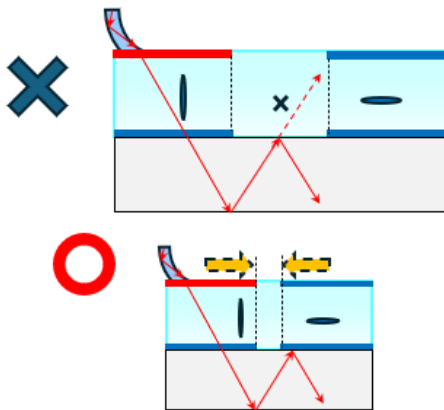


Fig. 12 Light leakage between electrodes

Figure 13 shows LC alignment control result. The LC director angle is represented by  $\theta_a$  ( $0^\circ \leq \theta_a \leq 90^\circ$ ). This angle is defined as the voltage ON state at 90% (81°) and the voltage OFF state at 10% (9°). We verified whether the LC molecules were in the voltage ON state or voltage OFF state within the 90% range of the electrode width (22.5  $\mu\text{m}$ ). At an electrode spacing of  $l = 10 \mu\text{m}$  and an applied voltage of 2.5 V, the voltage ON state is observed in the range  $0 \leq x \leq 22.5$  and the voltage OFF state is observed in the range  $37.5 \leq x \leq 60$ . This confirms proper ON and OFF operation within the 90% width range (22.5  $\mu\text{m}$ ) of the electrode. Since this structure is ultimately intended for installation on drones, a compact design is preferred. This study demonstrates controllability even with electrode spacing on the order of tens of micrometers, suggesting potential for miniaturization.

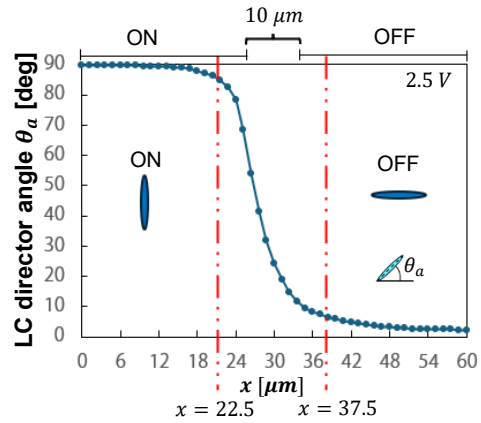


Fig. 13 LC alignment control

## 5 Conclusions

In this study, we proposed light guides with LC switch for an OWPT receiver. We designed LC alignments suitable for light transmission and reflection. With glass refractive index of  $n_1 = 1.8$  and LC refractive indices of  $n_o = 1.5$  (ordinary) and  $n_e = 2.0$  (extraordinary), transmission for p-polarized light was obtained with z-alignment (vertical) and reflection with x-alignment (horizontal) at incident angles of  $57^\circ \leq \theta_1 \leq 70^\circ$ . When the curved section is designed so that the incident angle on the LC variable reflection section is within  $57^\circ \leq \theta_1 \leq 70^\circ$ , effective light guidance is achieved, providing a basis for design guidelines. Using elastic continuum theory, we evaluated the mutual influence of adjacent electrodes in the LC layer and confirmed controllability even at electrode spacing on the order of tens of micrometers, indicating the potential for receiver miniaturization.

In future work, we plan to fabricate LC cells based on the alignment design and conduct optical experiments to verify voltage control of light transmission and reflection.

## Acknowledgements

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