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New Coating Polarizer with High Polarization Performance and Dimensional Stability

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Abstract

We have successfully developed a coating polarizer with an order parameter of over 0.97, transmittance of 42.3%, and polarization degree of 99.9%, in addition to outstanding heat resistance. These were achieved by crystallizing dye aligned along the liquid crystals, at a nano-sized scale. The polarizer does not require elongation, preventing shrinkage from temperature or humidity and ensuring dimensional stability. These properties make it ideal for large and flexible displays.

Author Keywords

liquid crystal; polarizer; dichroic dye; dimensional stability; high durability; flexible

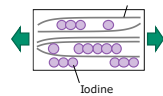
1. Objective and Background

Recently, the development of digital connected technologies has led to a diversification of display applications^{1,2}. For example, various in-vehicle displays have been proposed. Seamless integration into the vehicle surfaces, eliminating a hindrance to realization of pleasurable interior designs, calls for the application of OLEDs offering excellent flexibility for variously shaped displays³. Circular polarizers, consisting of a $\lambda/4$ phase difference plate and a linear polarizer, are used in OLEDs to prevent external light reflection. Poly vinyl alcohol (PVA) polarizers, created by stretching PVA resin doped with iodine dye, are commonly used as linear polarizers⁴. Due to the stretching process, PVA polarizers shrink when the temperature or humidity changes, and this can cause panel distortion in flexible displays⁵. This shrinkage can be reduced by thinning the PVA resin layer and the adjacent protective layer. However, if the polarizer can be made without stretching, the problem of shrinkage can be completely solved.

Non-stretched coating polarizers utilizing the alignment ability of liquid crystals are well known⁶⁻⁸. By making use of guest-host interactions between an organic dichroic dye (guest) and liquid crystal (host), it is possible to align the dye along the liquid crystals. Because cross-linked liquid crystal films do not require shape changes to express their desired functions and are known for their outstanding dimensional stability, this coating polarizer also exhibits exceptional dimensional stability. However, it is known that the polarization properties of conventional coating polarizers have a poor order parameter (S) of 0.93 due to the difficulty in controlling high order alignment of the host liquid crystal and disorientation of the dye when the liquid crystal is cross-linked⁶⁻⁸ (Table 1).

In this paper, we have realized a coating polarizer with excellent polarization properties and outstanding dimensional stability by utilizing nano-sized crystals of dye.

Table 1. Pros and cons of PVA and coating polarizers.

	PVA polarizer	Coating polarizer
Structure	Matrix	Poly vinyl alcohol (PVA)
	Dichroic dye	Iodine
	Process	Stretching
	Schematic diagram	
Property	Polarization property	Good
	Dimensional stability	Poor

2. Results

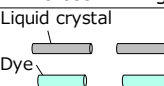
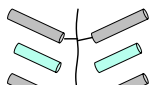

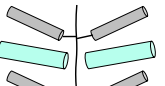
2-1. Polarizer Design

It is known that the primary cause of the poor polarization properties of coating polarizers is the disorientation of the dye when the liquid crystal is cross-linked⁶⁻⁸. If the host liquid crystal is not cross-linked, superior polarization properties in order parameter (S) over 0.97 can be achieved. However, if it is not cross-linked, the orientation of the dye will be disrupted by temperature and humidity, resulting in poor polarization properties^{6,7}. In order to achieve excellent polarization properties in any environment, it is necessary to cross-link the host liquid crystal to immobilize the dye while suppressing the orientation disorder of the dye during the cross-linking of the liquid crystal. The orientation of the liquid crystal deteriorates due to shrinkage during curing for cross-linking, which in turn leads to the disorientation of the dye as well^{6,7}. In this study, we considered the mobility of a particle, here a dye molecule, in a fluid, here liquid crystals, using the Stokes-Einstein equation⁹ (1)

$$D = \frac{k_B T}{6\pi\eta r} \quad (1)$$

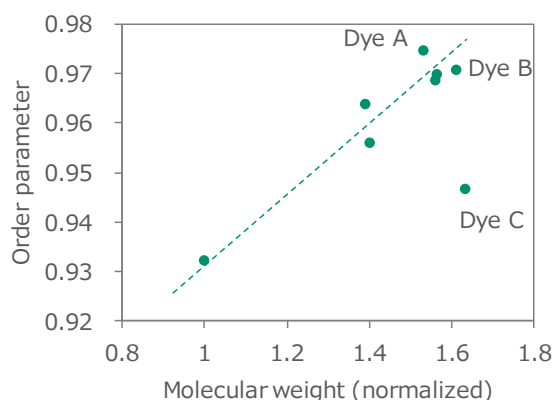
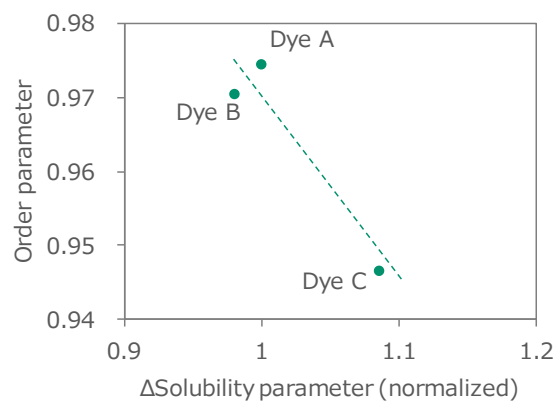
where D is the diffusion coefficient of the dye molecule, k_B is the Boltzmann constant, T is the absolute temperature, r is the radius of the dye molecule in terms of an equivalent spherical shape, and η is the dynamic viscosity of the liquid crystal. From Equation (1), it can be inferred that the dye mobility in the fluid decreases as the molecular size increases (Table 2). Since the molecular size generally correlates with the molecular weight of a compound, we explored the approach of increasing the molecular weight of the dye to suppress disorientation during the cross-linking of the liquid crystals.

Table 2. Effect of dye molecular size on alignment disturbance during cross-linking of liquid crystal (simple model).

		Before cross-linking	After cross-linking
Dye molecular size	Small		
	Large		

2-2. Preparation of Coating Polarizer

In the case of coating polarizer, dichroism is achieved by the alignment of dichroic dye molecules along the orientation of liquid crystal molecules due to the intermolecular interaction between the dye and the liquid crystal⁶⁻⁸. In this study, we used an azo compound as the dichroic dye, which is known to have a high affinity with liquid crystals and to exhibit high dichroism due to its large aspect ratio⁶⁻⁸. To examine the effect of molecular weight in detail, we synthesized dyes with the same backbone but different substituents and prepared coating polarizers using each dye. As expected, increasing the molecular weight tended to improve the order parameter, but Dye C had a low order parameter that deviated from this trend (Figure 1). From a comparison of the physical properties of Dye B and Dye C, which have similar molecular weights, we inferred that the affinity between the liquid crystal and dye affects the order parameter. When the Hansen Solubility Parameters¹⁰(SP) of the liquid crystals and dyes were calculated and the difference between them (Δ SP) was analyzed, a negative correlation between the order parameter and Δ SP was found (Figure 2). A large Δ SP indicates reduced affinity between the liquid crystal and dye, suggesting that the order parameter decreases with a weakened guest-host interaction.

**Figure 1.** Relationship between dye molecular weight and order parameter.**Figure 2.** Order parameter and Δ SP of coating polarizer using dye A, B, or C.

On the other hand, when the molecular weight and Δ SP are plotted in the area where the order parameter is over 0.95, it is surprisingly suggested that a higher molecular weight and a larger Δ SP result in a higher order parameter (Figure 3). Table 3 shows schematic diagrams of the dye alignment before and after cross-linking of liquid crystal in areas (I) to (III). In area (II), where the best polarization properties were observed, an order parameter of >0.97 was achieved. To investigate the properties of area (II), differential scanning calorimetry (DSC) measurements were performed on the polarizer using dye A, and an endothermic peak was detected, suggesting that the dye formed crystals in the coating polarizer (Figure 4). It is inferred that within the range where the liquid crystals and dye can engage in guest-host interactions, the dye becomes immiscible, crystallizes among the liquid crystals, forms large structures, and exhibits poor affinity, thus demonstrating a synergistic effect concerning molecular weight. Since the order parameter of the liquid crystal was <0.85 , which was lower than that of the dye, the hypothesis that the high order parameter of the polarizer is due to dye crystallization was supported. Additionally, this coating polarizer exhibited a low haze of 0.4%, indicating high transparency and suggesting that the dye crystals were nano-sized crystals that do not affect the visible region. In area (I), the Δ SP is too large, weakening the guest-host interaction between the dye and the liquid crystal, which results in a low order parameter. Conversely, in area (III), the Δ SP is small, preventing the formation of dye nano-sized crystals, which also leads to a low order parameter.

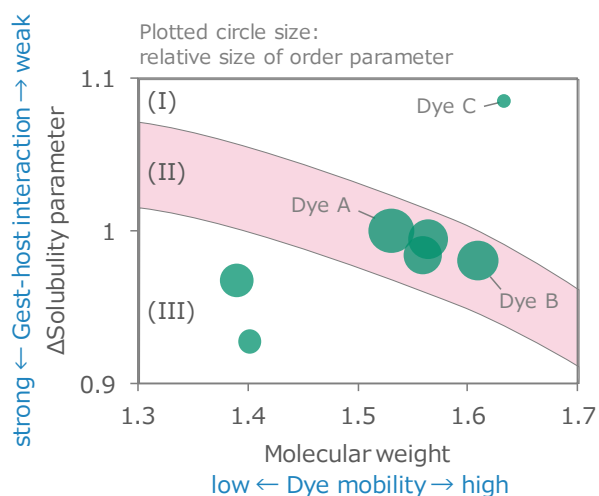


Figure 3. Effect of dye molecular weight and ΔSP on order parameter.

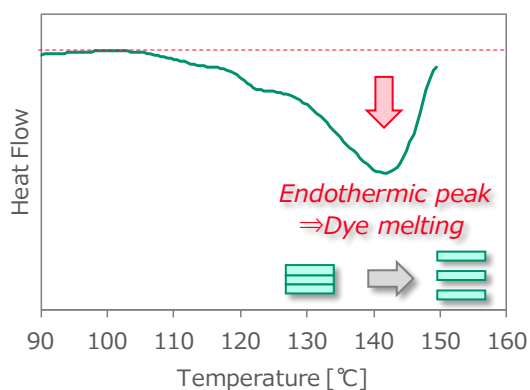


Figure 4. DSC chart of coating POL using dye A

Table 3. Schematic explanation of the effect of dye molecular weight and ΔSP on alignment disturbance during cross-linking of liquid crystal.

Before and after cross-linking of liquid crystal		ΔSP (between dye and liquid crystal)		
		Small	Large	Very large
Dye molecular weight	Small	<p>Order parameter: <0.93</p>		
	Large	<p>Order parameter: around 0.95</p>	<p>Order parameter: >0.97 Best situation (ex. Dye A)</p>	<p>Order parameter: around 0.95 Weak interaction (ex. Dye C)</p>



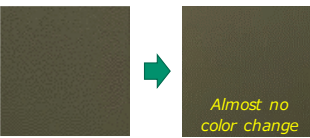
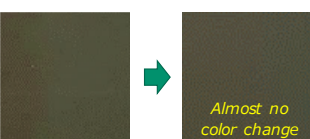
2-3. Performance of coating polarizer

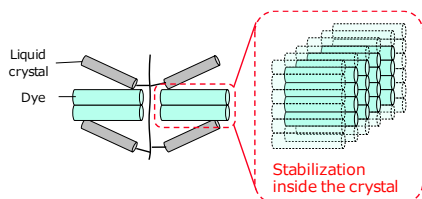
The optical properties of our coating polarizer are shown in Table 4. We have developed a polarizer with better optical properties than existing coating polarizers⁶⁻⁸. When the polarizer was bonded to a flexible substrate and heated, it was found to have excellent dimensional stability with almost no deformation. In addition, it is known that PVA polarizers generally discolor at high temperature by sandwiched between glass, or fade in color under high humidity¹¹, but our polarizers exhibited excellent robustness, with almost no discoloration or fading under the above conditions. Furthermore, they also demonstrated excellent resistance to light fading, which is known to occur easily with azo dyes (Table 5). It is thought that these excellent properties are due to the nano-sized crystals of the dye, which improve the stability of the dye molecules inside the crystals¹² (Figure 5).

Table 4. Optical properties of new coating polarizer.

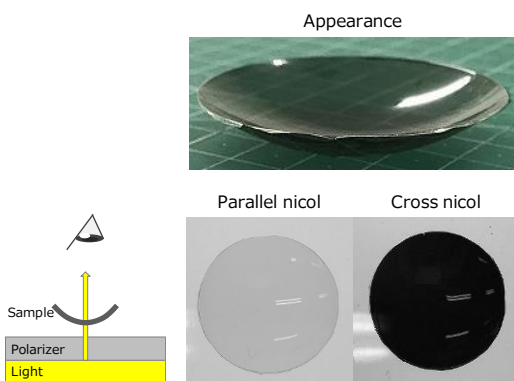
	New Coating Pol
Transmittance [%]	42.3
Polarization degree [%]	99.9
Order parameter	>0.97
Haze [%]	0.4

Table 5. Dimensional stability and heat, moisture, and light resistance of our coating polarizer (% is relative humidity).

	Our coating polarizer
Dimensional stability @60°C90% 12h	
Heat resistance @105°C 500h (Sandwiched between glass)	
Moisture resistance @60°C90% 500h	
Light resistance @Xenon Arc 250h	

**Figure 5.** Schematic explanation of improved reliability due to crystallization.

Additionally, the polarizer is a low-elasticity film of only 3µm thickness (including the polarizer protective layer), making it flexible enough to be stretched by more than 10% even at room temperature while maintaining high optical characteristics after stretching (Figure 6). These characteristics make it promising for use in displays with irregular shapes, such as 3D curved surfaces.

**Figure 6.** Appearance of our coating POL after 3D-forming: (Top) normal appearance, (Bottom) parallel and crossed polarization states.

3. Conclusion

Based on our unique dye design, we have developed a new orientation control system that crystallizes the dye into nano-sized crystals. This innovation results in a coating polarizer with excellent polarization properties ($S > 0.97$), which are superior to those of existing coating polarizers ($S \leq 0.93$). The performance is comparable to that of PVA polarizers, and we believe that it could be applied to LCD internal polarizers in the future. The polarizer is made without stretching, resulting in outstanding dimensional stability and preventing panel distortion when used in large flexible panels. Additionally, it exhibits excellent heat resistance, making it suitable for displays that require high reliability, such as automotive applications. Furthermore, it exhibits excellent flexibility due to its low elastic modulus, allowing it to be formed into 3D curved surfaces. We believe that this innovative polarizer significantly expands the possibilities for next-generation displays

4. References

- Weier M, Stengel M, Roth T, Didyk P, Eisemann E, Eisemann M, et al. Perception-driven Accelerated Rendering. *Comput. Graph. Forum.* 2017;36.
- Joo W, Brongersma M. Creating the ultimate virtual reality display. *Science.* 2022;377:1376-8.
- Huang Y, Hsiang E, Deng M, Wu S. Mini-LED, Micro-LED and OLED displays: present status and future perspectives. *Light Sci. Appl.* 2020;9.
- Ma J, Ye X, Jin B. Structure and application of polarizer film for thin-film-transistor liquid crystal displays. *Displays.* 2011;32(2):49-57.
- Goto S, Miyatake M, Saiki Y. 40-1: Distinguished Paper: A Novel Ultra-Thin Polarizer to Achieve Thinner and More-Flexible Displays. *SID Symp. Dig. Tech. Pap.* 2016;47:510-3.
- Peeters E, Nothofer HG, Diesing M, Schmitz KS, Karau F, Menzel H, et al. High-contrast thin-film polarizers by photo-crosslinking of smectic guest-host systems. *Adv. Mater.* 2006;18(18):2412-7.
- Pinol R, Serrano JL, Sierra T, Piñol M. Synthesis, properties, and polymerization of new liquid crystalline monomers for highly ordered guest-host systems. *Chem. Mater.* 2008;20(19):6076-86.
- He R, Zeng X, Chen D, Yang H. Fabrication of highly efficient coatable polarizer from tolane-based smectic reactive mesogen. *Polymer.* 2019;176:51-9.
- Einstein A. Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen. *Annalen der Physik.* 1905;4.
- Hansen CM. Hansen solubility parameters: a user's handbook. CRC Press; 2007.
- Han MH, Lyoo WS. Preparation of syndiotacticity-rich high molecular weight poly (vinyl alcohol)/iodine polarizing film with high water resistance. *J. Appl. Polym. Sci.* 2010;115(2):917-22.
- Weissbein L, Coven GE. The physical state of direct dyes in viscose and its influence on lightfastness. Part I: a method of examining the physical state of direct dyes in viscose. *Textile Res J.* 1960;30(1):58-62.