Operating Voltage of Optical Instruments based on Polymer-dispersed Liquid Crystal for Inspecting Transparent Electrodes

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Optical instruments based on polymer-dispersed liquid crystal (PDLC) have been used to inspect transparent electrodes. Generally the operating voltage of an inspection instrument using PDLC is very high, over 300 V, reducing its lifetime and reliability. The operating-voltage issue becomes more serious in the inspection of touch-screen panel (TSP) electrodes, due to the bezel structure protruding over the electrodes. We have theoretically calculated the parameters affecting the operating voltage as a function of the distance between the TSP and the PDLC, the thickness, and the dielectric constant of the sublayers when the inspection module was away from the TSP electrodes. We have experimentally verified the results, and have proposed a way to reduce the operating voltage by substituting a plastic substrate film with a hard coating layer of smaller thickness and higher dielectric constant.

Keywords: Optical inspection, Transparent electrode, Polymer-dispersed liquid crystal, Scattering

OCIS codes: (163.3710) Liquid crystals; (120.4630) Optical inspection; (120.2040) Displays

I. INTRODUCTION

Touch-screen panels (TSP) are widely used in mobile electronic devices such as smart phones and tablet computers. Various kinds of TSP modules using different principles of operation have been developed. Among them, methods sensing the change in resistance or capacitance are commonly used these days [1-3]. In spite of the growth in TSP-embedded products, the TSP market has become very crowded these days; hence the inspection and repair of defective TSP electrodes is essential for cost reduction. For display applications, the TSP electrodes required to sense a change in impedance should be transparent. For this reason, inspection of TSP electrodes by the naked eye is difficult. Although inspection by electrical probe tip can be used, it takes a very long time to check the entire area of a TSP panel, due to its narrow probe area [4, 5].

As another means to inspect TSP electrodes, polymer-dispersed liquid crystal (PDLC) can be used [6-11]. The PDLC is a switchable film in which liquid crystal (LC) droplets are dispersed in a polymer matrix (Fig. 1). In the zero-field state, the LC droplets are randomly oriented and the incident light is scattered due to mismatch of the refractive indices of LC (n_LC) and polymer (n_p) (Fig. 1(a)). In an applied electric field, the LC molecules are vertically aligned along the field and n_LC matches n_p, resulting in the transmission of light (Fig. 1(b)).

Figure 2 shows the operation principle for TSP electrode inspection using the PDLC. The proposed PDLC inspection module is composed of an indium tin oxide (ITO)-covered...
FIG. 2. Operation principle for TSP electrode inspection using PDLC. Light propagation through the TSP electrode, (a) without a disconnection and (b) with a disconnection.

Although there have been several reports about the application of PDLC to the inspection module [12, 13], the high operating voltage of the PDLC has not been completely resolved. Generally, the switching voltage needed to obtain the transparent state of the PDLC is very high: over 30 V, when the PDLC is sandwiched between ITO glasses with a cell gap of 10 µm. Moreover, the PDLC inspection module should be separated from the TSP electrode, typically over 10 µm, due to the bezel structure protruding above the electrode plane (see Fig. 2). Consequently, the operating voltage of the typical PDLC inspection module is over 300 V. If the capacitance of the TSP is too large, such a high operating voltage cannot be supplied by a power source. In addition, the high operating voltage often reduces the lifetime and reliability of the inspection module and the object of inspection.

The purpose of this paper can be summarized as follows. First, we theoretically calculate the parameters affecting the operating voltage of the inspection instrument. Although there is previous literature about calculating the operating voltage of a PDLC, there the PDLC module was in contact with the transparent electrode [12, 13]. However, as described above, the TSP electrodes should be away from the PDLC module, due to the bezel structure at the boundary of the TSP (Fig. 2). Thus, we derived a more general expression for the operating voltage of the PDLC inspection module, considering the distance between the TSP and the PDLC module.

As the second purpose of this paper, we propose a method to reduce the operating voltage of the TSP inspection module. As described above, the operating voltage of a PDLC module that is separated from the TSP is much increased, compared to the contact case. To reduce the voltage, we replace the top substrate film with a HC layer. The HC layer has a smaller thickness as well as a greater dielectric constant compared to the plastic film, and the operating voltage can be effectively reduced. We also calculate the operating voltage of the PDLC module as a function of the thicknesses and dielectric constants of the sublayers.

II. METHODS

A commercial nematic LC mixture (ZKC-5109XX, JNC) was mixed with a UV-reactive monomer mixture (NOA65, Norland products) at a weight ratio of 6:4. The LC mixture has a large optical birefringence $\Delta n = 0.25$ at a wavelength of 589 nm, and $\Delta \varepsilon = 20.2$ at an electric field of 1 kHz. The extraordinary and ordinary refractive indices of the ZKC-5109XX are 1.771 and 1.521 respectively. The LC-monomer mixture was stirred at 80°C for 10 minutes and cooled to room temperature at a cooling rate of 5°C/min. The mixture was then spin-coated on the ITO glass at 1500 rpm for 20 seconds. The mixture was then spin-coated on the ITO glass at 1500 rpm for 20 seconds. The coated substrate was exposed to UV light with an intensity of 30 mW/cm² for 10 minutes with a nitrogen-gas purge. Then, a commercial HC layer (SE8110, fotopolymer) was overcoated on the PDLC layer at 3000 rpm for 20 seconds. The HC layer was also exposed to the UV light under the same conditions above. Figure 3 shows the reflective optical microscopy image of the fabricated PDLC module. The HC layer is well separated from the
PDLC layer. The thicknesses of the HC and the PDLC layers were 9.6 and 13.9 µm respectively. The relative dielectric constants of the HC and PDLC layers were $\varepsilon_{rh} = 4.98$ and $\varepsilon_{rp} = 6.57$, measured from the capacitance value with a LCR meter (ZSM2376, NF) at 1 kHz [14, 15].

For the inspection test, we used a commercial capacitive-type TSP module (ER-TPC043-2, Eastrising). The column and row ITO electrodes are orthogonally crossed beneath and under a glass substrate in this TSP module. The PDLC module was placed on the TSP module, and a 1 kHz square bipolar voltage generated from a function generator (33210, Agilent) was applied through a voltage amplifier (TREK2210, TREK). The optical image during inspection was obtained using a polarizing optical microscope (50iPol, Olympus).

### III. RESULTS and DISCUSSION

Before investigating the switching property of the PDLC module, we first measured the basic switching property of the PDLC that was sandwiched between two ITO substrates. In this case, the PDLC layer is contacted between the ITO layers. Figure 4 shows the normalized transmittance (TR) of the PDLC versus applied electric field. Here “normalized TR” means the transmitted intensity normalized to the maximum TR value with a 4.0 V/µm electric field applied. The maximum intensity of the transmitted light with a 4.0 V/µm electric field applied was about 80% of the input beam intensity. The normalized TR was minimal in the zero-field state and gradually increased with increasing electric field. The electric field allowing 90% of the normalized TR was 1.3 V/µm. The insets of Fig. 4 show the PDLC sample on paper; one can easily distinguish the scattering state (0 V/µm) and the transparent state (1.3 V/µm) states.

The arrangement of the PDLC inspection module and TSP electrodes is illustrated in Fig. 5. From the boundary condition, the electric field applied across the air gap ($E_1$) and that across the dielectric layers including the HC and the PDLC layers ($E_2$) can be related as

$$E_1 = \frac{\varepsilon_{r1} E_2}{\varepsilon_{r1} - \varepsilon_{r2}}$$

where $\varepsilon_{r1}$ and $\varepsilon_{r2}$ are the relative dielectric constants of the air and the HC-PDLC layer respectively [16, 17]. Integrating the field from the TSP electrode to the other ITO should yield the applied voltage $V$ from the external power source:

$$E_1 d_a + E_2 (d_h + d_p) = V$$

where $d_a$, $d_h$, and $d_p$ are the thicknesses of the air gap, HC, and PDLC layers respectively. Eliminating $E_1$ from Eqs. (1) and (2), $E_2$ is given by

$$E_2 = \frac{\varepsilon_{r1} E_2}{\varepsilon_{r2} - \varepsilon_{r1}} \left( \frac{V}{d_a + d_h + d_p} \right)$$

Applying the boundary condition at the interface between the HC and the PDLC layer, the electric field applied across the HC ($E_h$) and PDLC ($E_p$) layers can be related as
\[ e_{rh}E_h = e_{rp}E_p \]  
\[ E_h + E_p = E_2 \]

where \( e_{rh} \) and \( e_{rp} \) are the relative dielectric constants of the HC and PDLC layers respectively [16, 17]. Eliminating \( E_h \) in Eqs. (4) and (5), \( E_p \) is given by

\[ E_p = E_2 - E_h = \frac{E_2}{e_{rp} + 1} \]  
\[ (6) \]

Considering a capacitor in which the HC and PDLC layers are serially connected between two electrodes, the capacitance \( C_2 \) is given by

\[ C_2 = \frac{e_{rp}e_{rh}A}{d_h + d_p} \]  
\[ (7) \]

where \( A \) is the area of the capacitor. Eq. (7) also equals

\[ C_2 = \frac{C_hC_p}{C_h + C_p} = \frac{e_{rh}e_{rp}A}{e_{rh}d_h + e_{rp}d_p} \]  
\[ (8) \]

Manipulating Eqs. (7) and (8), \( e_{r2} \) can be written as,

\[ e_{r2} = \frac{e_{rh} + e_{rp}}{d_h + d_p} \]  
\[ (9) \]

Substituting the result of Eq. (9) in Eqs. (3) and (6), we finally obtain \( E_p \) as a function of the experimental parameters:

\[ E_p = \frac{1}{(d_h + d_p)(d_h + e_{rh}e_{rp} + 1)(e_{rp} + 1)} V \]  
\[ (10) \]

Figure 6 shows the calculated \( E_p \) value versus applied voltage \( V \) using Eq. (10). Figure 6(a) shows the calculated result for \( E_p \) with \( d_a \) varied. For this calculation, \( d_h \) and \( d_p \) were set to be 10 µm and experimentally measured \( e_{rh} = 4.98 \) and \( e_{rp} = 6.57 \) were substituted. \( E_p \) diminished rapidly with increasing \( d_a \). The electric field to obtain 90% TR was 1.3 V/µm in Fig. 2; thus \( d_a \) should be smaller than 20 µm to apply an electric field over 1.3 V/µm, provided that the applied voltage is less than 400 V. Figure 6(b) depicts the \( E_p \) value with \( d_a \) varied. In this calculation, \( d_h \) and \( d_p \) were set to be 10 µm. It is observed that an \( E_p \) over 1.3 V/µm can be obtained, provided that \( d_a \) is smaller than 30 µm for an applied voltage of 300 V. Figure 6(c) shows the \( E_p \) value with \( d_p \) varied. It is observed that an \( E_p \) over 1.3 V/µm can be obtained, provided that \( d_p \) is smaller than 30 µm for a 300 V external field. It is also concluded that the dependence of \( E_p \) on \( d_a \) was more significant than that on \( d_h \) or \( d_p \). This is due to the higher dielectric permittivities of the HC and PDLC layers (\( e_{rh} = 4.98 \) and \( e_{rp} = 6.57 \)) than that of the air (\( e_{rl} = 1 \)), which is also consistent with Eq. (10). Figure 7 shows the calculated \( E_p \) value versus applied voltage \( V \) with \( e_{rh} \) and \( e_{rp} \) varied. We used sublayer thicknesses \( d_h = 10 \) µm, \( d_r = 9.6 \) µm, and \( d_p = 13.9 \) µm, which were measured in Fig. 3. \( E_p \) increased with increasing \( e_{rh} \) (Fig. 7(a)), while \( E_p \) decreased with increasing \( e_{rp} \) (Fig. 7(b)). The dependence of \( E_p \) on \( e_{rp} \) was greater than on \( e_{rh} \), due to \( d_p \) being smaller than \( d_h \). It is observed that an \( E_p \) over 1.3 V/µm can be obtained, provided that \( e_{rh} \) is greater than 2.98 with 260 V applied (Fig. 7(a)). The same \( E_p \) can be obtained using a PDLC with \( e_{rp} \) smaller than 8.57 with 260 V applied (Fig. 7(b)). Thus, it is favorable to use a HC layer with a high \( e_{rh} \) value and a PDLC with a low \( e_{rp} \), to reduce the operating voltage of the inspection module. Doping a small amount of nanoparticles with high dielectric constant into the HC layer could be a useful solution for reducing the operating voltage.

To confirm the validity of the theoretical calculations, we fabricated the PDLC module and investigated the operating voltage using the TSP electrodes. Figure 8 shows the normalized TR of the PDLC-TSP module versus applied voltage. A square voltage at 1 kHz was applied across the PDLC,
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FIG. 7. Calculated electric field applied across the PDLC layer versus applied voltage from the power supply. (a) \( \varepsilon_{rh} \) and (b) \( \varepsilon_{rp} \) were varied in the calculation. \( d_a = 10 \) µm, \( d_b = 9.6 \) µm, and \( d_p = 13.9 \) µm in this calculation.

FIG. 8. Normalized TR versus applied voltage for a PDLC module 10 µm away from the TSP module.

FIG. 9. Transmissive optical image of the TSP-PDLC inspection module with (a) 0, (b) 50, (c) 100, (d) 150, (e) 200, and (f) 250 V applied. The width of the electrode is 200 µm.

IV. CONCLUSION

To summarize, we theoretically calculated the operation voltage of a PDLC module for inspecting TSP electrodes. Considering the bezel structure of the TSP module, we derived a more general expression for the operating voltage when the PDLC module was separated from the TSP electrodes. We investigated the effects of changing various parameters, such as the distance between the TSP and the PDLC, the thicknesses of the sublayers, and the dielectric constants of the materials used. We experimentally confirmed that the calculated operating voltage was a good approximation to the experimental value. In addition, the operating voltage of the inspection module could be decreased from...
310 to 200 V by substituting one substrate film with an HC layer of smaller thickness and greater dielectric constant. The suggested results will be helpful for the design and development of transparent-electrode inspection systems.

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