# Dielectric characterization and voltage holding ratio of blue-phase cells

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## ARTICLE INFO

## ABSTRACT

The phase behaviors of a blue-phase (BP) liquid crystal in a planar-aligned cell were investigated by means of temperature-dependent dielectric spectroscopy. With auxiliary observations of optical transmission spectra and birefringent textures, we found that the transition temperatures of two adjacent mesophases, including the cholesteric-to-BPI, the BPI-to-BPII, and the BPII-to-isotropic, can clearly be distinguished by the first and second derivatives of the real-part dielectric permittivity function to the temperature at a specific frequency. Furthermore, an attempt to evaluate the device performance of a polymer-stabilized BP, derived from the photopolymerization of two monomers (RM257 and TMPTA), was achieved with a new circuital design for the voltage-holding-ratio (VHR) measurement. Preliminary results of the VHRs of samples at 180 Hz and their temperature dependence were obtained accordingly.

## 1. Introduction

Blue phases (BPs) are liquid–crystal (LC) mesophases, existing between chiral nematic and isotropic liquid phases. According to the structural feature of self-assembly of three-dimensional cubic lattices and double-twisted cylinders (DTCs) separated by disclinations, three types of BPs, designated BP-III with isotropic symmetry, BP-II with simple cubic symmetry and BP-I with body-centered cubic symmetry, can sequentially be found on cooling from the isotropic phase [1–3]. Owing to the frustrated-phase limitations, the temperature range of BPs is quiet narrow, typically 1–2 °C. The detailed phase behaviors of BPs thus play a critical role for carrying out BP-related research. Even when the temperature range of BPs can readily be widened by the polymer stabilization (PS) [4,5], a simple and precise examination on the phase behaviors of a PSBP system is helpful to enhance the reliability and the yield for the photopolymerization process for specific BPs. In this regard, some well-known techniques, such as the differential scanning calorimetry (DSC) [6] and the polarizing optical microscopy (POM), measurements of the Kössel diagrams [7], transmission/reflection spectra [8], and image processing [9], have been proposed to characterize the temperature regime as well as the type of BPs. Moreover, because the material properties of LCs are generally dependent of the temperature, the recognition of the phase diagram of BPLCs has been also reported based on the temperature dependence of the refractive index [10] or dielectric constant [11].

BPLCs with intriguing structural and optical features reveal several advantages such as no need of alignment layers, excellent dark appearance in the field-off state, wide viewing angle, insensitivity of driving voltage to the cell gap, and sub-microsecond gray-to-gray response time. These benefits allow BPLCs to hold promise for realizing next-generation displays. Consequentially, most of researchers from both academia and industry pay much attention to the development of BPLC materials and displays. As thus, some alluring approaches for solving fatal drawbacks, especially the narrow temperature range [4,5] and the high operating voltage [12–16], have successively been proposed to boost the commercialization. On the other hand, when a BPLC cell is treated with surface alignment, the uniformity of BP morphologies can considerably be promoted owing to the presence of surface anchoring force and thus the induction of pinning effect on the BP platelets. Moreover, improvement on the operating voltage, hysteresis, response time, and the profile of reflection band of planar-aligned BPLC cells have recently been established in comparison with a conventional BPLC cell without surface treatment [17–20]. Apart from aforementioned approaches for the development of BPLC devices, the measurement of voltage holding ratio (VHR) for BPLC displays stemming from the point of view of prospective consideration is essential in that the VHR of a LC display is one of reliable parameters for evaluating the strength of ionic effect and thus the display performance as well as image qualities [21,22]. Ideally, the VHR is defined as the fraction of the residual voltage after a certain duration in open circuit to the initially applied voltage. Sufficiently high VHR indicates high reliability of image quality with uniform contrast ratio and stable image without flicking. In view

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of currently available instruments for VHR measurements, the voltage of data-line signal supplied for the charging process in a LC cell is typically 10 V, which is much smaller than the operating voltage of BPLC cells. Nevertheless, various circuit designs, enabling the maximum voltage across the BPLC cell up to 30 V, have been demonstrated very recently [23–25]. These innovations could be regarded as pathways for the development of new driving circuits with high data-line voltage to measure the VHR of BPLCs.

In this study, we extended our previous work on LC phase behaviors [11], presenting a feasible and reliable approach for phase identification based on temperature-dependent dielectric spectroscopy. By subjecting a BPLC mixture into planar-aligned cells, the accuracy and reliability for the examination of transition temperatures between two adjacent phases are clarified according to the first-order and second-order derivatives of the real-part dielectric permittivity with respect to the temperature. Moreover, in considering the prospect for the development of next-generation displays in the LC industry, we proposed a VHR circuit enabling the supply of data-line voltage up to 40 V and frame rate of 180 Hz that attempts to investigate the VHR of various PSBP cells. The comparison of VHR between the PSBP and its host LC counterpart is presented. The behavior of temperature-dependent VHR of both cells is briefly clarified in a given temperature regime.

## 2. Experimental

The BPLC mixture used is composed of a nematic LC host (HDE) doped with a right-handed chiral additive (R5011) at a weight ratio of 3.2 wt%. The specifications of HDE, including birefringence $\Delta n$, dielectric anisotropy $\Delta \varepsilon$ and the clearing point $T_{NI}$, are $\Delta n = 0.204$ (HCCH datasheet) at the wavelength of 589 nm and temperature of 20 °C, $\Delta \varepsilon = 60.64$ (measured from a 15-µm-thick planar cell at 40 V and 0 V in this laboratory) at the frequency of 1 kHz and temperature of 25 °C and $T_{NI} = 97$ °C. In addition, a BPLC/monomer mixture was prepared by mixing two kinds of ultraviolet (UV)-curable monomers (RM257 and TMPTA) and a photoinitiator (Irgacure184) with the BPLC. The weight ratios of RM257, TMPTA and Irgacure184 to the BPLC are 4.6, 3.1 and 0.3 wt%, respectively. In this study, the BPLC was injected into planar-aligned cells with an electrode area ($A$) of 0.25 cm$^2$ and cell gap ($d$) of 15 ± 0.5 µm for dielectric investigations whereas the BPLC/monomer mixture and the pristine nematic LC (HDE) counterpart were individually subjected into non-aligned (i.e., without polyimide) and planar-aligned (i.e., with polyimide) cells with $A = 1.0$ cm$^2$ and $d = 4.5 ± 0.5$ µm for comparison of their VHR data. To fabricate PSBP samples from the BPLC/monomer mixture, each BPLC/monomer cell was cooled slowly from the isotropic to the BPI phase with a cooling rate of 0.1 °C/min using a temperature controller (Linkam T95-PE). When reaching the temperature where the cell exhibited the BPI phase, the photopolymerization process was performed by using a UV lamp with wavelength of 365 nm. The UV intensity and the exposure time were 2 mW/cm$^2$ and 30 min, respectively.

The temperature of all investigated cells for measurements was controlled using Linkam T95-PE, too. Here, both the cooling and heating rates were 0.1 °C/min. Because the cell is set in a nearly air-tight stage of the temperature controller, the moisture and ions from the air [26], enabling the deterioration of BPLC material, can considerably be blocked. Moreover, according to a relevant paper concerning the time-varying ionic properties of a LC cell [27], cells for the measurement of VHR were kept undisturbed for one day after the LC injection. The frequency ($f$) dependence of the complex dielectric function, defined as $\varepsilon^*(f) = \varepsilon'(f) - i\varepsilon''(f)$, where $\varepsilon'$ is the real-part and $\varepsilon''$ the imaginary-part dielectric permittivity, was acquired in the frequency regime between 20 Hz

to $2 \times 10^6$ Hz using a LCR meter (Agilent E4980A). The probe voltage was as small as 0.05 $V_{rms}$ in the sinusoidal waveform to avoid the contribution of field-induced molecular reorientation to the dielectric data. To manifest the phase diagram of the BPLC cell derived from dielectric data, auxiliary approaches, including the observation of texture images and measurement of transmission spectra, were employed. The optical textures at given temperatures were obtained by means of a polarizing optical microscope (Olympus BX51). Note that the rubbing direction of the planar-aligned BPLC cell was set parallel to the transmission axis of the polarizer. The transmission spectra of BPLC cells in the wavelength range between 400 and 700 nm were acquired with a high-speed fiber-optic spectrometer (Ocean Optics HR2000+) in conjunction with a halogen light source (Ocean Optics HL2000). In regard to the measurement of the VHR, Fig. 1 illustrates a newly designed circuit specifically tailored for simulating the charging and discharging behaviors of a PSBP cell. Compared with currently available commercial instruments for the VHR measurement, the maximum voltage of the data-line signal in our circuit is promoted to +40 V, which is more applicable to the driving of a typical BPLC or PSBP cell. However, since a commercially available field-effect-transistor instead of an integrated circuit is used as the element to provide high enough voltage for the charging behavior of the BPLC sample, the generation of data-line voltage is limited to direct-current signals. This could lead to the accumulation of ionic impurities on the substrates and thus reduce the effective voltage across in the BPLC cell when measuring the VHR. Consequently, it should be emphasized here that the VHR measured based on the proposed circuit is a relative value containing errors contributed by the system-generated ionic effect. The scan line was 5 V with an offset of 2.5 V in the square waveform with a frame time of 5.56 ms (corresponding to a frequency of 180 Hz) and the pulse width of the scan line ($t_1$) was 5.14 µs at 180 Hz. The data-line and scan-line signals were supplied by an arbitrary function generator (Tektronix AFG-3022B) and a power supply (GW INSTEK GPS-3303), respectively. According to the resulting VHR curve obtained with an oscilloscope (Agilent Technologies DSO5054A), the VHR can be defined as [28]:
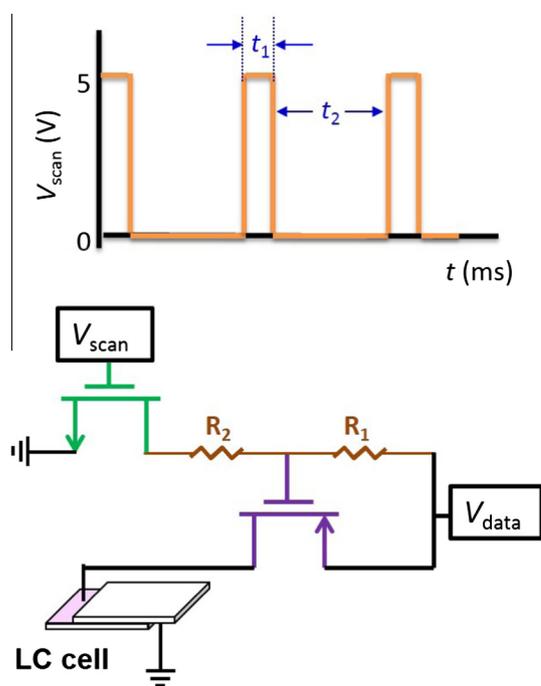


**Fig. 1.** Schematic of the equivalent circuit used for the VHR measurement.