Published in final edited form as:

J Phys Chem Biophys. 2016 August 11; 120(31): 17722–17725. doi:10.1021/acs.jpcc.6b05631.

Isotropic Elastic Stress Induced Large Temperature Range Liquid Crystal Blue Phase at Room Temperature

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Abstract

A thermodynamically stable blue phase (BP) based on the conventional rod like nematogen is demonstrated for the first time at room temperature by only diluting a chiral–nematic mixture with the help of some nonmesogenic isotropic liquid. It is observed that addition of this isotropic liquid does not only stabilize the BPs at room temperature, but also significantly improves the temperature range (reversible during heating and cooling) of the BPs to the level of more than 28 °C. Apart from that, we have observed its microsecond electro-optic response time and, external electric field induced wavelength tuning, which are the two indispensable requirements for next generation optical devices, photonic displays, lasers, and many more. Here we propose that the isotropic liquid plays two crucial roles simultaneously. On one hand, it reduces the effective elastic moduli (EEM) of the BP mixtures and stabilizes the BPs at room temperature, and on the other hand, it increases the symmetry of the mutual orientation ordering among the neighboring unit cells of the BP. Hence, the resultant mixture becomes better resistive to some microscopic change due to the change in temperature, even over a large range.

Graphical Abstract

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Notes

The authors declare no competing financial interest.

1. INTRODUCTION

It is well-known that the BP liquid crystals (BPLCs) is a coexisting state of cubic lattices and defects.^{1–4} Thermodynamic stability of this phase is found to exist over a very narrow temperature range ($<2\text{ }^{\circ}\text{C}$).^{2–6} Moving slightly away from this temperature range leads to a strong frustration, which causes generation of some defects promptly in the system.^{3,4} Since generation of defects is associated with some energy consumption of the system, the entire system becomes unstable. Normally, the gain from a strong twist energy reduces this consumption and makes the whole system stable.⁴ So, the BP is often found in a high chiral nematic LC systems.^{4–6} It is also noted that, the successful transfer of the chiral twist energy into the defect modes happens only at some specific temperature T . This temperature is usually higher than a room temperature for most of the commercially available nematic LC host used for BP.^{2–6} An experimental study shows that elastic moduli (EM) of a nematic LC host become lower with increasing temperature.^{7–9} In a similar way, while working with a chiral–nematic mixture for preparation of BPs, usually application of some high temperature (required to stabilize the BP) can be argued to reduce the effective elastic moduli (EEM) of the entire chiral–nematic mixture composite. At certain temperatures (usually higher than a room temperature but, lower than the nematic to isotropic transition temperature T_N), the reduced-EEM (r-EEM) eventually becomes responsible to form a double twisted helix along with some defect modes,^{4–6} which is commonly known as BPs.

However, if we are interested to bring this high stabilizing temperature of BPs down to the room temperature, we need to supply the corresponding (to the higher temperature) r-EEM or, equivalently, the microscopic ordering of the BPs at the room temperature in any case. As far as the order parameter or r-EEM is concerned, both can be reduced effectively either by increasing the temperature or by increasing the concentration of some nonmesogenic isotropic liquid solvent.^{10–12} The latter is the indispensable element of our novel approach. In this paper, our novel approach shows the existence of BPs over a wide range of temperature $T = 28\text{ }^{\circ}\text{C}$ (290–318 K) including the room temperature. Furthermore, we have measured its submillisecond electro-optics response time and wavelength tunability with application of an external electric field. Such BPLCs are much needed in developing polarization-independent adaptive lenses.^{13–16}

2. EXPERIMENTS

Commercially available nematic LC host MLC 2139 (Merck: $n = 0.19$, $T_{N-I} = 75\text{ }^{\circ}\text{C}$) is mixed with a chiral dopant R 811 (Merck, HTP: $15\text{ }\mu\text{m}^{-1}$) at different proportions (Table 1) and their transition temperature (T_{N*-BPI}) is examined under a polarizing microscope with temperature controller. It is observed that the T_{N*-BPI} of all the chiral–nematic mixtures (MLC 2139: R 811) appeared around $52\text{ }^{\circ}\text{C}$ but, the temperature range (T) varies from mixture to mixture (Figure 1a). In order to lower the value of T_{N*-BPI} down to the room temperature ($20\text{ }^{\circ}\text{C}$), PN 393 (Merck, nonmesogenic isotropic liquid) is mixed (MLC 2139:R 811:PN 393) with the above chiral–nematic mixtures as per the following concentration (Table 2). Before we did so, we have examined the effect of PN 393 separately on the pure nematic LC host MLC 2139 by observing the change in birefringence (and hence the microscopic ordering) with various concentration of PN 393. For that, we have

prepared a few antiparallel rubbing cells each of $4\mu\text{m}$ thick and filled with the mixtures (MLC 2139: PN 393) with different weight percent of PN 393 (Figure 1b). Next, we prepare the BP mixtures as per the above concentration in Table 2. Out of these mixtures, mixture 6, mixture 7, and mixture 8 show relatively larger T and are filled in three conventional liquid crystal cells, each having $20\mu\text{m}$ thickness and without any alignment layer for study of the spectroscopic, microscopic and electro-optical responses.

3. RESULTS AND DISCUSSION

Microscopic textures (Figure 2a) of mixture 6, mixture 7, and mixture 8 (20°C) show clearly that the stable BP exists in all the mixtures at the room temperature. Further, spectroscopic study (Figure 2b) confirms that all the room temperature BP mixtures possess very prominent reflection peaks. Once we confirm the existence of BPs in all the mixtures, we continued the rest of the experiments with mixture 7 only, because it shows the largest $T(28^\circ\text{C})$.

We have examined the robustness of mixture 7 by observing if there is any spectral shift with respect to the change in temperature. It is observed that the central wavelength of mixture 7 is red-shifted by $\lambda \cong 50\text{ nm}$ at 312 K before it goes to the isotropic state at 320 K (Figure 2c). The red shift in spectral wavelength inside the stable temperature range of mixture 7 might be an indication of the lattice deformation from body center cubic (BPI) to simple cubic (BPII), as resonant wavelength corresponding to a simple cubic lattice is relatively longer.¹⁹

Application of an external electric field onto BPs causes distortion in shape and size of the unit cell of BPs due to the electrostriction effect.^{17–22} We have taken a special attempt to observe the evolution of a monodomain of BP at room temperature inside a cell of $20\mu\text{m}$ thickness during a slow increment of the r.m.s. value of an externally applied electric field. It is worthy to mention here that, the field induced evolution of the monodomain is completely reversible with increasing and decreasing the field value only within the electric field range $E_{rms} = 5\text{ V}/\mu\text{m}$ (Figure 3a), continuous square pulse with an operating frequency 1 kHz . As a result, we observed a reversible tuning without any residual hysteresis (Figure 3b) in the central wavelength of mixture 7 by $\lambda \cong \pm 20\text{ nm}$. (λ_0 : $470\text{ nm} \leftrightarrow 490\text{ nm}$) within that field range. Above that field range, electrostriction completely untwists the helix and finally, homeotropic state is attained at $E_{rms} = 17\text{ V}/\mu\text{m}$. Upon reversing the field slowly to zero, we observed there is a residual hysteresis in spectral wavelength between increasing and decreasing field in the upper field region ($E_{rms} = 12\text{ V}/\mu\text{m} \rightarrow 6\text{ V}/\mu\text{m}$). In the lower field region ($E_{rms} < 6\text{ V}/\mu\text{m}$), there is no selective reflection, and the cell becomes optically scattered (Figure 3b). It is worthy to mention here that the original photonic bandgap of mixture 7 has been possible to retrieve from the scattering cell by applying thermal shock at isotropic temperature 50°C . Figure 3c shows the microscopic texture of the cell with mixture 7 during the slow increment of electric field. Electro-optic response time of the cell is measured at room temperature using a white light source and crossed polarizers. It is observed that the response time has been very fast $\sim 80\mu\text{s}$ (Figure 4a,b) in both the field regimes (above and below $5\text{ V}/\mu\text{m}$).

4. CONCLUSION

To conclude, first, an alternative way to stabilize the blue phase at room temperature is demonstrated by diluting a chiral nematic mixture with a nonmesogenic isotropic liquid, instead of its high temperature based counterpart. Upon diluting the high twisting power chiral–nematic system with addition of the isotropic liquid, it is observed that the transition temperature T_{N^*-BP} of the blue phase is shifted from 52 to 20 °C (room temperature). It is argued that the effective elastic moduli of the blue phase corresponding to 52 °C is replicated at the room temperature (20 °C) at a cost of diluted twisting power of the chiral–nematic mixture with addition of the nonmesogenic isotropic liquid.

Apart from the downward shift in transition temperature, it is also observed that the temperature range (ΔT) of the BP is widened from $\Delta T \approx 5$ °C (in pure chiral–nematic mixture, Table 1) to $\Delta T \approx 28$ °C in diluted chiral nematic mixture (Table 2). The possible reason for broadening the temperature range might be that the mutual orientational symmetry among the unit cells of the BP is increased. As a result, any microscopic change in this highly symmetric BP mixture cannot be possible or, in other word, the mixture becomes insensitive over a wide range of temperature.

Acknowledgments

This research was supported partially by the National Institutes of Health (through Grants R01EY020641, R21 EB008857, and R21GM103439) and the State of Ohio TVSF fund (through Grant TECG201604).

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Figure 1.

(a) Various chiral–nematic mixtures with their different temperature range (ΔT) of stable BPs. (b) Experimental observation on the change in birefringence (Δn) of the mixtures MLC 2139:PN 393 in some antiparallel rubbing cells, each of $4\mu\text{m}$ thickness under crossed polarizing microscope. Inset: Michel–Lévy color chart providing look-up table for birefringence vs color, with few demonstrative colors corresponding to different mixtures in the cells of surface area $5\text{ mm} \times 5\text{ mm}$.

Figure 2.

(a) Microscopic textures of BPs corresponding to mixture 6, mixture 7, and mixture 8 with different PN-393 concentrations mixed with the best chiral–nematic mix. E, and filled in some nonrubbing cells of thickness 20 μm . (b) Prominent reflection peaks from mixture 6 (red), mixture 7 (green), and mixture 8 (blue). (c) Red shift in spectral wavelength of mixture 7 at 318 K during the temperature scanning. The reason could be because of the phase transition from BPI-BPII.

Figure 3.

(a) Single monodomain of BP in mixture 7 at the room temperature (20 °C) is observed with white light illumination under polarizing optical microscope with 40× objective lens, exhibiting its different faceting with slowly increasing the externally applied electric field. (b) Electric field induced wavelength tuning in forward and reverse voltage scan. (c) A few demonstrative micrographs showing the change in texture color of mixture 7 during the slow increment of the rms value of externally applied electric field from 0 through 6 V/μm.

Figure 4. Microsecond response time of the BP mixture 7: (a) rise time $\sim 40 \mu\text{s}$; (b) fall time $\sim 85 \mu\text{s}$, irrespective of the operating voltage whether it is above or below the electrostriction field, i.e., $5 \text{ V}/\mu\text{m}$.

Table 1List of the Chiral Nematic Mixtures (MLC 2139: R 811) out of Which Mixture E Shows the Widest T

chiral–nematic mixtures	MLC 2139 (Nematic LC), wt %	R 811 (Chiral dopant), wt %	transition temperature (T_{N^*-BP}), °C	temperature range (T), °C
mixture A	64.2	35.8	52.1	1.5
mixture B	63.6	36.4	51.4	2.7
mixture C	62.2	37.8	52.4	3.4
mixture D	61.8	38.2	51.8	3.9
mixture E	60.1	39.9	52.2	5.2
mixture F	59.5	40.5	51.9	3.5
mixture G	57.7	42.3	52.4	2.2

Table 2

List of the Room Temperature BP Mixtures (MLC 2139; R 811; PN 393) out of Which Mixture 7 Shows the widest T

room temp BP mixtures	chiral-nematic host	PN 393, wt %	transition temperature (T_{N^*-BP}), °C	temperature range (T), °C
mixture 1	mixture E	0	52.1	2.2
mixture 2		0.6	51.8	2.8
mixture 3		1.1	44.8	4.1
mixture 4		1.5	38.5	6.3
mixture 5		1.9	30.4	18.2
mixture 6		2.3	25.9	20.4
mixture 7		2.7	20.3	28.6
mixture 8		3.5	12	23.2
mixture 9		4.2	8.4	9.3
mixture 10		4.6	4.3	1.8