

Diluter Effects on Polymer-Stabilized Blue Phase Liquid Crystals

Yuan Chen, Jin Yan, Martin Schadt, Shih-Hsien Liu, Kung-Lung Cheng, Jyh-Wen Shiu, and Shin-Tson Wu, *Fellow, IEEE*

Abstract—Diluter effects on the phase transition temperatures, Debye relaxation frequency, and electro-optics of polymer-stabilized blue phase liquid crystal (BPLC) are investigated. Some diluters not only significantly decrease the BPLC response time but also slightly enhance the Kerr constant. For practical applications, optimal diluter concentration should be considered in order to balance the needs between response time and operation voltage.

Index Terms—Blue phase, diluter, Kerr constant, liquid crystals.

I. INTRODUCTION

POLYMER-STABILIZED blue phase liquid crystal (PS-BPLC) [1]–[3] is a promising candidate for next-generation display [4]–[6] and photonic devices [7], [8] because of its attractive features, such as submillisecond response time [9], [10], no need for surface alignment layer, and optically isotropic dark state. However, high operation voltage still hinders its widespread applications. In addition to protruded electrode device structures [6], [11], [12], BPLC materials with a large Kerr constant (K) play a crucial role because the on-state voltage is inversely proportional to \sqrt{K} [13]. From Gerber's model [14], Kerr constant is related to the birefringence (Δn), dielectric anisotropy ($\Delta\epsilon$), average elastic constant (k), and pitch length (p) of the LC host as

$$K \approx \Delta n \cdot \Delta\epsilon \frac{\epsilon_0 p^2}{\lambda k (2\pi)^2}. \quad (1)$$

From (1), increasing $\Delta\epsilon$ is a straightforward way for enhancing Kerr constant. Indeed, BPLC hosts with $\Delta\epsilon > 100$ have been developed recently [13], [15]. For comparison, a typical nematic LC has $\Delta\epsilon < 10$. Therefore, BPLC represents a paradigm shift in LC material development. The problems associated with such a huge $\Delta\epsilon$ LC are threefold: 1) its viscosity is large, so that the device response time goes back to 1-ms range and the one-drop fill panel fabrication process becomes more difficult; 2) the pixel's capacitance is increased by $\sim 10\times$, so that a longer circuit charging time is needed [16]; 3) lower relaxation frequency; e.g., JNC JC-BP01M has a relaxation frequency of 1.3 kHz, and its Kerr constant decreases by $\sim 2\times$ as

the frequency increases from 60 Hz to 1 kHz [17]. When driving this BPLC at 1 kHz for color sequential displays, two serious problems are encountered: 1) the operation voltage is increased by $\sim 40\%$, and 2) the dielectric heating effect [18]–[20] due to the imaginary part (absorption) of dielectric constant, which has a peak value at the relaxation frequency, will affect the performance stability of the BPLC device.

Diluters have been widely used for lowering the viscosity and melting temperature of a nematic LC [21]–[27]. However, diluter effect on the BPLC properties has not been investigated. Here, we report the diluter effects on a BPLC host which has a large $\Delta\epsilon$. When we dope 6 wt% of a diluter to the LC host, the mixture's viscosity (η) is dramatically reduced, while the decrease in Δn and $\Delta\epsilon$ is mild. Most diluter molecules are fairly short, while the large $\Delta\epsilon$ BPLCs have bulky and long molecules with several dipole groups. Thus, after the addition of diluters the average molecular length l is shortened. Since the relaxation frequency f_r is proportional to $1/(\eta l^3)$ [28], diluters help to increase f_r . This increased relaxation frequency is less critical to nematic LCs because their relaxation frequency is already high (> 50 kHz), but is important to BPLCs because their relaxation frequency is usually low (< 10 kHz) [14].

In this paper, several diluters, including compounds and mixtures, were employed. Doping 6% of some diluters not only reduces the response time by $2\times$ – $3\times$, but also improves the Kerr constant. To compare the performance with and without diluters, we use a Figure of Merit (FoM) defined as the ratio of Kerr constant to decay time (K/τ) [29]. Higher diluter concentration helps to further decrease the response time, but its tradeoff is the decreased Kerr constant.

II. LC HOST PROPERTIES

In experiment, we used LC1 (HTG-135200, HCCH, China) as the nematic host. Its physical properties are listed as follows: $\Delta n = 0.205$ at $\lambda = 633$ nm, $\Delta\epsilon = 99$ at 1 kHz, $\gamma_1 = 700$ mPas at 25°C , and clearing temperature $T_c = 98^\circ\text{C}$. We mixed 94 wt% of LC1 with 6% of a nonpolar diluter 5CC3 [4-pentyl-4'-propyl-1,1'-bi(cyclohexyl)]. For convenience, we call this mixture as LC2.

Both Δn , $\Delta\epsilon$, viscoelastic constant (γ_1/k_{11}) and γ_1 of the LC mixture are all temperature dependent, as described by following equation [29]–[34]:

$$\Delta n = \Delta n_0 S, \quad (2)$$

$$\Delta\epsilon = aS \exp(U/k_B T) \quad (3)$$

$$\gamma_1/k_{11} = b \cdot \exp(E_a/k_B T)/S \quad (4)$$

$$\gamma_1 = cS \exp(E_a/k_B T) \quad (5)$$

Manuscript received January 22, 2013; revised February 28, 2013; accepted March 17, 2013. Date of publication April 05, 2013; date of current version July 17, 2013.

Y. Chen, J. Yan, and S.-T. Wu are with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA (e-mail: yuanucf@knights.ucf.edu; swu@ucf.edu).

M. Schadt is with MS High-Tech Consulting, 4411 Seltisberg, Switzerland. S. H. Liu, K. L. Cheng, and J. W. Shiu are with Industrial Technology Research Institute, Hsinchu 310, Taiwan.

Color versions of one or more of the figures are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JDT.2013.2254109

TABLE I
FITTING PARAMETERS FOR LC1 AND LC2 WITH (2)–(6)

LC Host	Δn_0	β	U (meV)	a	E_a (meV)	b	c
LC1	0.297	0.226	109	2.07	550	2.9E-8	2.3E-7
LC2	0.279	0.227	109	1.87	501	1.5E-7	7.7E-7

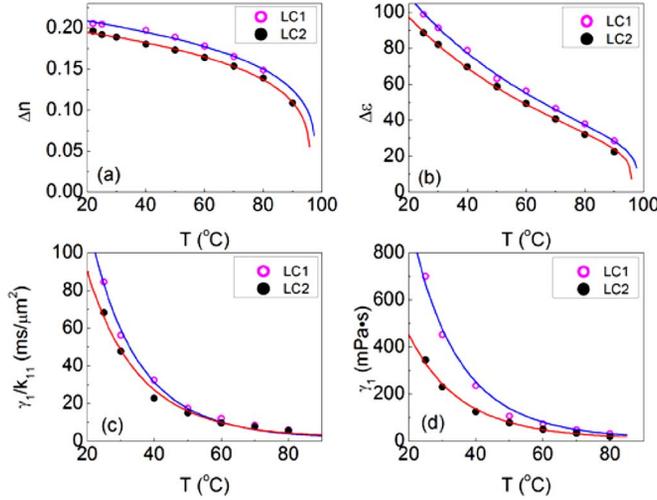


Fig. 1. Temperature dependent (a) Δn at $\lambda = 633$ nm, (b) $\Delta \varepsilon$ at 1 kHz, (c) γ_1/k_{11} and (d) γ_1 of LC1 and LC2. Dots represent the measured data and lines are fitting results according to (2)–(5), respectively.

where S denotes the order parameter, Δn_0 is the extrapolated birefringence at $T = 0$ K, U is a parameter related to dipole moment, E_a is the activation energy, k_B is the Boltzmann constant, and a , b , and c are proportionality constants. Order parameter S can be approximated by Haller's semi-empirical equation [35], [36]:

$$S = (1 - T/T_c)^\beta \quad (6)$$

where β is a material constant and T_c is the clearing point of the LC mixture. After doping 6% of 5CC3, the T_c of LC2 drops slightly from 98 °C to 96 °C.

Fig. 1 depicts the temperature dependent Δn (at $\lambda = 633$ nm), $\Delta \varepsilon$ (at 1 kHz), γ_1/k_{11} and γ_1 of LC1 and LC2. Please note that these are the LC hosts without chiral dopants and photo-curable monomers. Here, dots are experimental data and lines are fitting results with (2)–(5). Table I lists the fitting parameters. The agreement is quite good. After doping 6% 5CC3 to LC1, the Δn of LC2 is decreased by about 6%, $\Delta \varepsilon$ by 10%, and more amazingly the rotational viscosity γ_1 is reduced by 200% at 25 °C [Fig. 1(d)]. However, doping a low molecular weight diluter also lowers the elastic constant. As a result, γ_1/k_{11} is only reduced by 20% [Fig. 1(c)]. From Table I, the activation energy E_a of LC2 is about 10% smaller than that of LC1 because of the lower viscosity induced by the diluter.

III. RELAXATION FREQUENCY

For color sequential displays, a higher operation frequency (up to 1 kHz) is needed in order to suppress color breakup. In a BPLC, the relaxation frequency of Kerr constant is closely related to the dielectric relaxation frequency f_r of the LC host

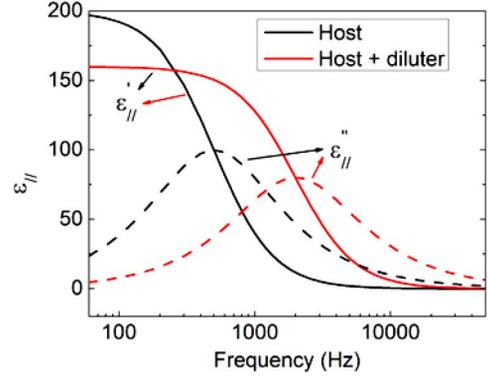


Fig. 2. Illustration of relaxation frequency shifting by doping a low viscosity diluter to a LC host.

[17]. For a low-viscosity nematic LC host, its f_r is usually over 50 kHz. For a BPLC host with a large $\Delta \varepsilon$, the molecules tend to be long and bulky because multiple dipole groups are employed. Therefore, its dielectric relaxation frequency is reduced significantly. For a positive $\Delta \varepsilon$ LC material, ε_\perp remains almost unchanged in the low frequency region due to its much higher f_r compared to $\varepsilon'_{//}$ (real part of the permittivity) [37]. The relaxation of $\Delta \varepsilon$ basically follows that of $\varepsilon'_{//}$. The frequency dependent $\varepsilon'_{//}$ was obtained by measuring the capacitance of a homeotropic LC cell (results are not shown here) and fitting the experimental data with Debye relaxation equation [38], [39]:

$$\varepsilon'_{//} = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (f/f_r)^2} \quad (7)$$

where ε_0 is the static permittivity along the long molecular axis at low frequency, and ε_∞ is the permittivity at the high frequency limit. The measured f_r at 25 °C for LC1 and LC2 is 12.6 kHz and 15.4 kHz, respectively. When we dope 6 wt% 5CP3 (structure shown in Table II) into LC1, f_r increases to 17.2 kHz. Diluters help to increase the relaxation frequency of the LC host due to the reduced viscosity and shortened average molecular length. This is particularly favorable for high frequency operation of the LC host and PS-BPLC. This effect becomes more critical for the LCs with low relaxation frequency, say $f_r \sim 1$ kHz. Let us illustrate this principle using following example.

As shown in Fig. 2, the LC host has a very large $\varepsilon'_{//}$ (190; black solid line) at 100 Hz, but it declines sharply as the frequency increases. At $f_r = 500$ Hz, $\varepsilon'_{//}$ drops by 2X, and at 1 kHz it further decreases to 40. By adding a diluter, the relaxation frequency shifts rightward to 2 kHz (red solid line). Although at 100 Hz, its real part is decreased from 190 to 160, at 1 kHz (the intended operation frequency for color sequential displays) its $\varepsilon'_{//}$ remains as large as 130 (cf., 40 for the host

TABLE II
PHYSICAL PROPERTIES OF PSBP SAMPLES CONTAINING 6% OF DIFFERENT DILUTERS. HERE, KERR CONSTANT AND DECAY TIME WERE MEASURED AT $\lambda = 633$ NM AND 25°C. (*THE *FoM* IS NORMALIZED TO THAT OF PSBP-1)

PSBP #	LC host	Diluter type	Diluter Structure	K (nm/V ²)	Decay time (τ , μ s)	FoM^* (K/τ)	T_{m_BP} (°C)	T_{c_BP} (°C)
1	LC1	No diluter		8.27	1700	1	5.6	82.3
2	LC2	5CC3		8.04	573	2.90	7.9	81
3	LC3	5CP3		8.83	740	2.46	-1	75.4
4	LC4	5CCV		7.48	1200.8	1.29	-4.5	79.5
5	LC5	5CP02		9.11	988	1.90	0	81
6	LC6	5PP3		9.44	737.3	2.64	4.5	76
7	LC7	4CC3		7.39	633.4	2.41	3	80.5
8	LC8	5CC2		7.4	678.7	2.25	1	79.3
9	LC9	5CAP02		7.36	738.2	2.06	-1.1	78.2
10	LC10	MLC-6686		7.36	1062.4	1.43	3.5	81.5
11	LC11	FPPF		6.37	638.4	2.06	-13	72.5
12	LC12	5CC3 & 4CC3 at 1:1 ratio		7.44	792	1.94	4.2	81.5

without diluter). Meanwhile, the dielectric absorption (imaginary part ϵ''_{ij}) peak also shifts to a higher frequency (red dashed lines), which helps to reduce dielectric heating effect.

IV. DILUTER EFFECT ON PS-BPLC

To investigate the diluter effect on a PS-BPLC without affecting its pitch length and monomer concentration, we keep the ratio of LC host to chiral dopant/monomer the same for the 12 PSBP samples studied. In Table II, the eleven LC hosts (LC2-12) all consist of 94 wt% of LC1 and 6 wt% of different diluters. We prepared BPLC mixtures with 4.5 wt% chiral dopant R5011 (HCCH) and 95.5 wt% LC host. Afterwards, 8 wt% of photocurable monomers (4.8 wt% RM257 (Merck)+3.2 wt% C12A, Sigma Aldrich) and 0.5 wt% of photoinitiator were blended with 91.5 wt% of the BPLC mixture to form the precursor. Next, we injected the LC/monomers mixture into an in-plane-switching (IPS) cell in an isotropic phase. The IPS electrode width and gap are 10 μ m and the cell gap is \sim 7.3 μ m. The cell was placed on a Linkam heating/freezing stage controlled by a temperature programmer (Linkam TMS94) and cooled to BP phase and then exposed to UV light ($\lambda = 365$ nm) with intensity of 8 mW/cm² for 10 min. After UV irradiation, the BPLC nano-composites were self-assembled and the blue phase to isotropic phase transition temperature (T_{c_BP}) for PSBP-1 was 82.3 °C. With diluters, the T_{c_BP} is few degrees lower, as listed in Table II, because of the relatively low clearing point of the diluter itself. The impact of 1°C–2 °C decrease in T_{c_BP} with some diluters is not significant. On the other hand, the chiral nematic to blue phase transition temperature (T_{m_BP}) could be lowered by adding a proper diluter, which helps to increase the low temperature stability. For PSBP-11, although 6% of FPPF lowers the T_{c_BP} by 10 °C, the T_{m_BP} is also lowered from 5.6 °C to –13 °C,

which is favorable for low temperature operation. The color of these PSPB samples looks almost the same, indicating the pitch length variation after adding diluter is negligible.

The IPS cell was mounted on the Linkam heating stage and sandwiched between two crossed polarizers. A linearly polarized He–Ne laser ($\lambda = 633$ nm) was used as probing beam. A 1-kHz square-wave AC signal was applied to the IPS cell. The light transmittance was measured by a photodiode detector (New Focus Model 2031) and recorded digitally by a LabVIEW data acquisition system (DAQ, PCI 6110). Fig. 3 depicts the measured voltage-dependent transmittance (VT) curves for PSBP-1, 2, 8, and 10. The first peak occurs at 61.6 V, 62.4 V, 66 V, and 66.6 V respectively. Through fitting with extended Kerr model [4], [40], we obtained the Kerr constant $K = 8.27$ nm/V² for sample PSBP-1. After adding 6% of diluters, the Kerr constant of PSBP-2, 8, and 10 decreases to 8.04, 7.40, and 7.36 nm/V², respectively. The variation is within 11%, since the effect of diluter on Δn and $\Delta \epsilon$ is small. On the contrary, the on-state voltage of PSBP-3, 5 and 6 decreases slightly to 61 V, 61 V, and 59.6 V. This is a pleasant surprise because the employed diluters are non-polar and low birefringence compounds. We expect they would decrease the mixture's Δn and $\Delta \epsilon$ significantly so that the on-state voltage would increase instead of decrease.

To understand this unexpected phenomenon, we have to examine what factors determine the Kerr constant. From (1), Kerr constant of a BPLC is primarily governed by the ratio of $\Delta n \cdot \Delta \epsilon/k$ (note here k is the average elastic constant of the PSBP, which is different from the k_{11} of the LC host), provided that the pitch length and wavelength remain the same. As discussed above, after doping a diluter both Δn , $\Delta \epsilon$, k_{11} and γ_{11} decrease but at different rates. Therefore, it is possible for $\Delta n \cdot \Delta \epsilon/k$ to either increase or decrease, depending on the relative change of

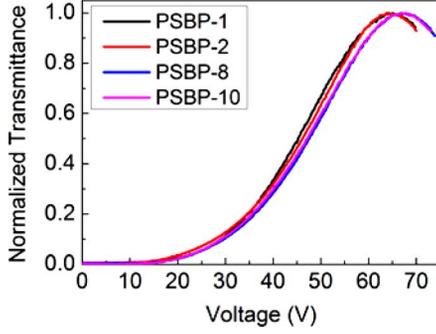


Fig. 3. Measured VT cures for PSBP-1, 2, 8, and 10. $\lambda = 633$ nm.

Δn , $\Delta \varepsilon$, and k induced by the diluter, which is related to the sophisticated inter-molecular interactions between the elongated, bulky host LC and the short, small-sized diluter molecules.

Fast response time is one of the major attractions of PS-BPLC devices. In experiment, we compared the decay time of those 12 PSBP samples because the rise time depends on the applied voltage, which is more complicated. The decay time was measured between 90% and 10% transmittance change at 25 °C. The measured decay time of PSBP-1 (without diluter) is 1700 μs . After adding diluters, the decay time is decreased by 2X–3X, as listed in Table II.

To explain this dramatic change in response time, we refer to Gerber's model [14]:

$$\tau = \frac{\gamma_1' p^2}{k(2\pi)^2}. \quad (8)$$

Here γ_1' represents the rotational viscosity of PSBP. In our samples with 6 wt% diluters, the variation of p is unnoticeable. The average elastic constant k of PS-BPLC becomes more complicated, since it involves the strong anchoring energy provided by the polymer network and also the interaction between LCs and the chiral dopant. When polymer network is involved, the elastic constant could be 1000X larger than that of the LC host [41]. The diluter effect on the elastic constant of the PSBP is not as significant as the polymer network effect. On the other hand, the viscosity tends to increase noticeably after adding the bulky chiral dopant to the LC host for a PS-BPLC. The small diluter molecules could break the rigid arrangement of the BPLC mixture, which in turn reduces the viscosity effectively and hence the response time.

To eliminate the effect of k , the FoM (defined as $K/\tau \propto \Delta n \cdot \Delta \varepsilon / \gamma_1'$) [29] of the 12 PSBP samples are calculated for comparing the performance of PS-BPLC materials. To see the difference more clearly, we normalized the FoM to that of PSBP-1. From Table II, the FoM can be improved by 1.3X–2.9X with different diluters. Specifically, our data show that the γ_1' of PSBP-2 is 3.4X lower than that of PSBP-1 (without any diluter). Plugging these values to (8), we find k is $\sim 15\%$ smaller after adding 5CC3, which proves that the dramatic decrease of response time results from the significant decrease in viscosity.

To investigate the activation energy, which is related to the viscosity of the PS-BPLC, we measured the temperature dependent decay time of PSBP-1 and PSBP-2. Results are shown in

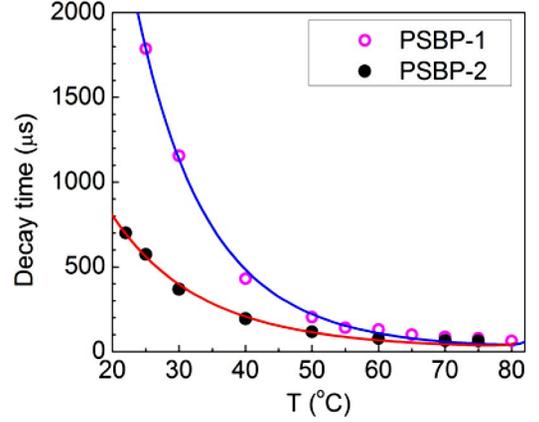


Fig. 4. Temperature dependent decay time of PSBP-1 and PSBP-2. Dots are measured data and lines are fitting with (8).

TABLE III
INFLUENCE OF DILUTER CONCENTRATION ON THE PS-BPLC PROPERTIES

5CC3 ratio	K (nm^2/V^2)	Decay time (τ , μs)	FoM (K/τ)	T_{m_BP} ($^\circ\text{C}$)	T_{c_BP} ($^\circ\text{C}$)
0	8.27	1700	1	5.6	82.3
6%	8.04	573	2.90	7.9	81
10%	7.50	516	3.00	10.4	80.7
15%	7.10	383	3.83	22	79.8

Fig. 4. The decay time decreases as the temperature increases, as described by following equation [42]:

$$\tau \approx B \cdot \frac{\exp(E_a/k_B T)}{(1 - T/T_{c_BP})^\beta} \quad (9)$$

where B is a proportionality constant, E_a is the activation energy of the PSBP, and T_{c_BP} is the clearing point of the PS-BPLC. The material constant β has been obtained from the LC host (listed in Table I). From fittings, we obtained $E_a = 738$ meV and $B = 4.0 \cdot 10^{-10}$ μs for PSBP-1, and $E_a = 573$ meV, $B = 7.8 \cdot 10^{-8}$ μs for PSBP-2. As expected, PSBP-2 has lower activation energy than PSBP-1, since the diluter in PSBP-2 helps to make the PS-BPLC less viscous. Moreover, PS-BPLC has a higher activation energy than the nematic LC host, indicating that the added chiral dopant indeed increases the viscosity.

V. CONCENTRATION EFFECT

Higher concentration of diluter helps to further reduce the viscosity, but it could have some side effects, such as poor solubility when the diluter has smectic phase, smaller Kerr constant and reduced T_{c_BP} . We prepared another two PSBP samples with 10 wt% and 15 wt% of 5CC3. The decay time decreases significantly with more diluters, as listed in Table III, however the Kerr constant also decreases noticeably. Moreover, T_{m_BP}

increases a lot with increased 5CC3 concentration, which is unfavorable for practical applications. Therefore, for a given diluter there exists an optimal concentration. Mixing diluters at a proper ratio is also a common practice for nematic LCs. We could do the same for BPLC in order to increase its solubility.

VI. CONCLUSION

We have investigated the effects of different diluters on PS-BPLC from various aspects. A small amount of diluter will slightly decrease the birefringence and dielectric anisotropy but dramatically reduce the viscosity of the LC host. By doping 6% of diluter, the decay time of the PS-BPLC could be reduced by $2\times-3\times$ while keeping the Kerr constant unchanged. We also studied the diluter effects on the relaxation frequency, melting point and clearing point. By increasing the concentration of a small molecular weight diluter (or a mixture among diluters), the response time of the BPLC can be further decreased, but some undesirable side effects (e.g., smaller Kerr constant) would become noticeable. Therefore, an optimal concentration of diluter should be considered for optimizing the overall performance of the BPLC composite.

ACKNOWLEDGMENT

The authors are indebted to J. Sun for helpful discussion.

REFERENCES

- H. Kikuchi, M. Yokota, Y. Hisakado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nat. Mater.*, vol. 1, pp. 64–68, 2002.
- Y. Hisakado, H. Kikuchi, T. Nagamura, and T. Kajiyama, "Large electro-optic Kerr effect in polymer-stabilized liquid-crystalline blue phases," *Adv. Mater.*, vol. 17, pp. 96–98, 2005.
- S. W. Choi, S. Yamamoto, Y. Haseba, H. Higuchi, and H. Kikuchi, "Optically isotropic-nanostructured liquid crystal composite with high Kerr constant," *Appl. Phys. Lett.*, vol. 92, p. 043119, 2008.
- Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 94, p. 101104, 2009.
- J. Yan, L. Rao, M. Jiao, Y. Li, H. C. Cheng, and S. T. Wu, "Polymer-stabilized optically isotropic liquid crystals for next-generation display and photonics applications," *J. Mater. Chem.*, vol. 21, pp. 7870–7877, 2011.
- L. Rao, Z. Ge, S. T. Wu, and S. H. Lee, "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 95, p. 231101, 2009.
- Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.*, vol. 96, p. 113505, 2010.
- J. Yan, Y. Li, and S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," *Opt. Lett.*, vol. 36, pp. 1404–1406, 2011.
- Y. Chen, J. Yan, J. Sun, S. T. Wu, X. Liang, S. H. Liu, P. J. Hsieh, K. L. Cheng, and J. W. Shiu, "A microsecond-response polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.*, vol. 99, p. 201105, 2011.
- K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, "Submillisecond gray-level response time of a polymer-stabilized blue-phase liquid crystal," *J. Disp. Technol.*, vol. 6, pp. 49–51, 2010.
- M. Kim, M. S. Kim, B. G. Kang, M. K. Kim, S. Yoon, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S. T. Wu, "Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays," *J. Phys. D: Appl. Phys.*, vol. 42, p. 235502, 2009.
- M. Jiao, Y. Li, and S. T. Wu, "Low voltage and high transmittance blue-phase liquid crystal displays with corrugated electrodes," *Appl. Phys. Lett.*, vol. 96, p. 011102, 2010.
- L. Rao, J. Yan, S. T. Wu, S. I. Yamamoto, and Y. Haseba, "A large Kerr constant polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.*, vol. 98, p. 081109, 2011.
- P. R. Gerber, "Electro-optical effects of a small-pitch blue-phase system," *Mol. Cryst. Liq. Cryst.*, vol. 116, pp. 197–206, 1985.
- M. Wittek, N. Tanaka, D. Wilkes, M. Bremer, D. Pauluth, J. Canisius, A. Yeh, R. Yan, K. Skjonnemand, and M. Klases-Memmer, "New materials for polymer-stabilized blue phase," in *SID Int. Symp. Dig. Tech. Papers*, 2012, vol. 43, pp. 25–28.
- C.-D. Tu, C.-L. Lin, J. Yan, Y. Chen, P.-C. Lai, and S.-T. Wu, "Driving scheme using bootstrapping method for blue-phase LCDs," *J. Display Technol.*, vol. 9, no. 1, pp. 3–6, Jan. 2013.
- Y. Li, Y. Chen, J. Sun, S. T. Wu, S. H. Liu, P. J. Hsieh, K. L. Cheng, and J. W. Shiu, "Dielectric dispersion on the Kerr constant of blue phase liquid crystals," *Appl. Phys. Lett.*, vol. 99, p. 181126, 2011.
- A. C. Metaxas and R. J. Meredith, *Industrial Microwave Heating*. London: IET, 1983.
- M. Schadt, "Dielectric heating and relaxations in nematic liquid-crystals," *Mol. Cryst. Liq. Cryst.*, vol. 66, pp. 639–656, 1981.
- C. H. Wen and S. T. Wu, "Dielectric heating effects of dual-frequency liquid crystal crystals," *Appl. Phys. Lett.*, vol. 86, p. 231104, 2005.
- M. Heckmeier and D. Pauluth, "Liquid-crystal medium having a low threshold voltage," U.S. Patent 7 033 651 B2, Apr. 25, 2006.
- M. Yanai, Y. Kubo, and E. Nakagawa, "Liquid crystal composition and liquid crystal display device," U.S. Patent 6 572 938 B2, June 3, 2003.
- N. Hattori, H. Yamamoto, and H. Fujita, "Liquid crystal composition and liquid crystal display device," U.S. Patent 7 608 310 B2, Oct. 27, 2009.
- M. Schadt, R. Buchecker, F. Leenhouts, A. Boller, A. Villiger, and M. Petrzilka, "New nematic liquid crystals: Influence of rigid cored, alkenyl side-chains and polarity on material and display properties," *Mol. Cryst. Liq. Cryst.*, vol. 139, pp. 1–25, 1986.
- M. Schadt, R. Buchecker, and K. Müller, "Invited lecture. Material properties, structural relations with molecular ensembles and electro-optical performance of new bicyclohexane liquid crystals in field-effect liquid crystal displays," *Liq. Cryst.*, vol. 5, pp. 293–312, 1989.
- J. Sun, H. Xianyu, S. Gauza, and S. T. Wu, "High birefringence phenyl tolane positive compounds for dual frequency liquid crystals," *Liq. Cryst.*, vol. 36, pp. 1401–1408, 2009.
- Q. Song, S. Gauza, J. Sun, S. T. Wu, and X. Liang, "Diluters' effects on high Δn and low-viscosity negative $\Delta\epsilon$ terphenyl liquid crystals," *Liq. Cryst.*, vol. 36, pp. 865–872, 2009.
- L. M. Blinov, *Electro-Optical and Magneto-Optical Properties of Liquid Crystals*. New York, NY, USA: Wiley, 1983.
- J. Yan, Y. Chen, S. T. Wu, and X. Song, "Figure of merit of polymer-stabilized blue phase liquid crystals," *J. Display Technol.*, vol. 9, no. 1, pp. 24–29, Jan. 2013.
- E. M. Averyanov and V. F. Shabanov, "Structural and optical anisotropy of liquid crystals," *Sov. Phys. Crystallogr.*, vol. 23, p. 177, 1978.
- S. T. Wu, "Birefringence dispersions of liquid crystals," *Phys. Rev. A*, vol. 33, pp. 1270–1274, 1986.
- V. V. Belyayev, S. A. Ivanov, and M. F. Grebenkin, "Temperature dependence of rotational viscosity of nematic liquid crystals," *Sov. Phys. Crystallogr.*, vol. 30, p. 674, 1985.
- A. Saupé, "Temperature-dependence and magnitudes of deformation constants in strained liquids," *Z. Nat. Teil A*, vol. 15, p. 810, 1960.
- S. T. Wu and C. S. Wu, "Experimental confirmation of the Osipov-Terentjev theory on the viscosity of nematic liquid-crystals," *Phys. Rev. A*, vol. 42, pp. 2219–2227, 1990.
- I. Haller, "Thermodynamic and static properties of liquid crystals," *Prog. Solid State Chem.*, vol. 10, pp. 103–118, 1975.
- S. T. Wu, "Infrared markers for determining the order parameters of uniaxial liquid-crystals," *Appl. Opt.*, vol. 26, pp. 3434–3440, 1987.
- T. K. Bose, B. Campbell, S. Yagihara, and J. Thoen, "Dielectric-relaxation study of alkylcyanobiphenyl liquid-crystals using time-domain spectroscopy," *Phys. Rev. A*, vol. 36, pp. 5767–5773, 1987.
- F. C. Frank, "I. Liquid crystals. On the theory of liquid crystals," *Discuss. Faraday Soc.*, vol. 25, pp. 19–28, 1958.
- H. Q. Xianyu, S. T. Wu, and C. L. Lin, "Dual frequency liquid crystals: A review," *Liq. Cryst.*, vol. 36, pp. 717–726, 2009.
- J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, and S. T. Wu, "Extended Kerr effect of polymer-stabilized blue-phase liquid crystals," *Appl. Phys. Lett.*, vol. 96, p. 071105, 2010.
- J. Sun, H. Q. Xianyu, Y. Chen, and S. T. Wu, "Submillisecond-response polymer network liquid crystal phase modulators at 1.06- μm wavelength," *Appl. Phys. Lett.*, vol. 99, p. 021106, 2011.
- L. Rao, J. Yan, and S. T. Wu, "Prospects of emerging polymer-stabilized blue-phase liquid-crystal displays," *J. Soc. Inf. Displays*, vol. 18, pp. 954–959, 2010.

Yuan Chen is currently working toward the Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando, FL, USA.

Her current research interests include novel organic materials and devices for advanced display and photonic applications, and low loss infrared liquid crystals. She has 17 journal publications.

Jin Yan is currently working toward the Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando, FL, USA,

Her research interests include device physics and materials of polymer-stabilized blue phase and isotropic phase liquid crystal displays. She has 24 journal publications.

Ms. Yan is a recipient of a 2012 SPIE scholarship and 2012 IEEE graduate student fellowship award.



Martin Schadt received the Ph.D. degree in physics from the University Basel, Switzerland. After the invention of the TN-LCD together with Wolfgang Helfrich, he headed the liquid crystal research division of F. Hoffmann–La Roche and was the first CEO of the spin-off company Rolic Ltd. Dr. Schadt holds more than 119 U.S. patents in the fields of liquid crystal devices and LC-materials.

Among others, Dr. Schadt is the recipient of the SID Karl Ferdinand Braun Award (1992), the Aachener und Münchener Preis für Technik und angewandte Naturwissenschaften (1994), the Robert-Wichard-Pohl Prize of the German Physical Society (1996), the IEEE Jun-ichi Nishizawa Medal (2008), the G.W. Gray Medal of the British Liquid Crystal Society (2010), the Blaise Pascal Medal for Material Sciences of the European Academy of Sciences (2010), the Frédérik Medal of the Russian Liquid Crystal Society (2011) and the Charles Stark Draper Prize of the US National Academy of Sciences (2012). He is a Fellow of the Society of Information Display (SID) and of the European Academy of Sciences.



Shih-Hsien Liu received the M.S. degree in chemistry from Fu Jen Catholic University, Taipei, Taiwan, in 1997, and is working toward the Ph.D. degree from the Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu, Taiwan.

He is currently a research supervisor of organic chemistry in the Division of Applied Chemistry, Material & Chemical Research Laboratories, Industrial Technology Research Institute (ITRI), Taiwan. His research interests include liquid crystals and polymer

dispersion technologies.



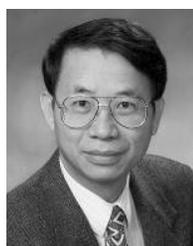
Kung-Lung Cheng received the M.S. degree from National Taiwan University in 1989, and the Ph.D. degree in chemistry from Michigan State University, East Lansing, MI, USA, in 1994.

He is currently a deputy division director in the Division of Applied Chemistry, Material & Chemical Research Laboratories, Industrial Technology Research Institute (ITRI), Taiwan. His current research interests are in organic chemistry, display materials, and nano-optical materials.



Jyh-Wen (Frank) Shiu received the M.S. degree in physics from National Tsing Hua University in 1993.

He joined ITRI since 2004 and is in charge of LCD research and department. Before that Frank worked at Toppoly and Hannstar for LCD cell process integration and yield improvement. He is now the deputy director at ITRI's Display Technology Center, leading the efforts of passive matrix flexible bi-stable display, thermal addressed cholesteric liquid crystal e-paper, electrowetting display, ink-jet printing technology and flexible cell/CF process development. The thermal rewritable e-paper received the R&D 100 award and WSJ TIA award in 2011.



Shin-Tson Wu (M'98–SM'99–F'04) received the B.S. degree in physics from National Taiwan University (Taipei), and the Ph.D. degree from the University of Southern California, Los Angeles.

He is a Pegasus professor at College of Optics and Photonics, University of Central Florida, Orlando.

Dr. Wu is the recipient of SID Slottow-Owaki prize (2011), OSA Joseph Fraunhofer award (2010), SPIE G. G. Stokes award (2008), and SID Jan Rajchman prize (2008). He was the founding Editor-in-Chief of IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY. He is a Charter Fellow of the National Academy of Inventors, a Fellow of the Society of Information Display (SID), Optical Society of America (OSA), and SPIE.