Temperature-Dependent Optical Response of Phase-Only Nematic Liquid Crystal on Silicon Devices

Zichen Zhang（张紫辰）[1*], Huan Xu[2], Haining Yang（杨海宁）[2], Zheng You（尤政）[3], D.P. Chu（初大平）[2*]

[1] Institute of Microelectronics of Chinese Academy of Sciences,
[2] Electrical Engineering Division, Department of Engineering, University of Cambridge, 9JJ Thomson Ave, Cambridge CB3 0FA, UK
[3] State Key Laboratory of Precision Measurement Technology and Instruments, Collaborative Innovation Center for Micro/Nano Fabrication, Device and System; Department of Precision Instrument, Tsinghua University, Beijing 100029, China
**Corresponding author: zz241@ime.ac.cn ; ** corresponding author:dpc31@cam.ac.uk*

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Wavelength-dependent birefringence and dielectric anisotropy, two major optical properties of the nematic liquid crystal materials used in phase-only liquid crystal on silicon (LCOS) devices, are measured as a function of operating temperatures. The dynamic phase modulation depth and threshold voltage of these phase-only LCOS devices are also measured in the corresponding temperature range and compared with theoretical predictions. The results show that the dynamic response time can be reduced significantly by an appropriate increase of device operative temperature, while the necessary device performance such as phase modulation depth and threshold voltage can be maintained at the same time.
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Phase-only liquid crystal on silicon (LCOS) devices have been widely used as the key component in a wide range of applications, such as holographic projections [1], adaptive optics in medical sciences [2] and optical switching system [3-5]. Significant research effort has been made towards the LCOS device assembly technology, device applications and characterisation of their performance [6]. For assembly technology packaging process at wafer level was reviewed for manufacturing ferroelectric LCOS devices [7], which can be applied to nematic LCOS devices as well. At research level, phase-only LCOS devices are being assembled largely at die level at present [8], because of its flexibility and practicality [9]. Performance characterization of LCOS devices and their applications are mainly focused on the utilization and optimization of phase gratings [3, 10, 11], improvement of spatially varying phase responses [12, 13], multi-phase spatial compensation [14] or even optically phase compensation [15, 16], as well as crosstalk mitigation in LCOS based optical switches by constructing asymmetrical output positions in space [10, 17].

One of the most important features for a phase-only LCOS device is its use of optically non-linear liquid crystal (LC) materials, which are sensitive to the working temperature. Some of the theoretical and experimental research works have been carried out to analysis optical properties of LCs when temperature changes. Wu et al. derived a four-parameters model [18] for describing the temperature effect on the refractive indices of LCs based on Vuks equation [19]. Lin et al. also examined optical properties of twist nematic LCs in different temperature ranges [20].

All the studies show that temperature is an essential parameter in determining the optical properties of LCs. However, there is a lack of systematic research of the LC's temperature dependence on the overall performance of phase-only LCOS devices. This is partly because the main application interest of LCOS devices in the past was on optical intensity modulation rather than phase modulation, and the former is less or little affected by temperature variation in particular when the binary mode is used. As a result, temperature sensing and performance compensation are not always considered for those devices in practice. For phase-only LCOS devices, optical phase modulation of the incident light is an essential performance parameter and it can easily be affected by a small change of working temperature, resulting a significant and sometimes dramatic change in the outcome of corresponding optical diffractions. For instance, Fig. 1(a) shows the simulated spatial distribution of a diffracted optical intensity at a replay plane in far field when a phase-only blazed grating pattern displayed on an LCOS device at a constant temperature. The pixel pitch is assumed to be 8μm and the grating period is 160μm. In this situation, the optical intensity of the background is less than -70dB in comparison to the normalized intended diffraction peak at position zero. Fig. 1 (b) shows the changed spatial optical intensity when there is only 1% phase error caused by temperature variation. In this case the background optical intensity at some positions can increase by 20 to even 40dB, leading to an unacceptable level of the crosstalk in telecommunication switches or wavelength selective switches.

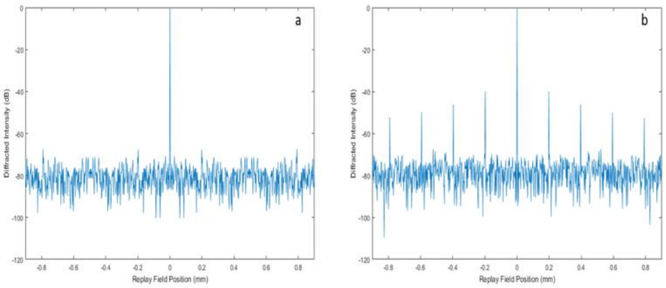

Fig. 1: Temperature effect on the spatial distribution of diffracted optical intensity at a far field replay plane, where (a) is recorded at a constant working temperature while (b) with 1% phase error caused by temperature variations.

In this paper, temperature effect on the performance of phase-only LCOS devices using the nematic LC BLO37 is investigated systematically, including the material birefringence and dielectric anisotropy as well as the device dynamic phase modulation depth and threshold voltage.

A phase-only LCOS device was assembled in-house using a die-level process [9] with a 5μm thick LC layer of BLO37. It has 1280×720 pixels with a pixel pitch of 15μm, and it can achieve a 2π phase modulation at the light wavelength 1550nm for telecommunication applications. In this study, the wavelength used was 633nm. This was for a better understanding of the effect of unbalanced optical response over a wide phase modulation range of 2π and more. This would also allow us to explore the effect of lower phase modulation depths (still >2π) at higher temperatures, since the device was assembled to achieve minimum 2π phase modulation depth for infrared (IR) which could be 5-6π or more in the visible range. In addition, using visible light can be a convenient way to characterise phase-only LCOS devices assembled for IR applications if it is done properly [12]. Fig.2 shows a basic setup for characterizing the temperature effect of phase-only LCOS devices. A light beam emits from a He-Ne laser into the system through a collimated beam expander. It then passes through the polariser 1, which is aligned to ensure that the light is polarized in parallel to the alignment direction of the LC materials in the LCOS device. After passing through a beam splitter (BS) and encountering the blazed grating uploaded on the phase-only LCOS device, the light beam is diffracted back and its spatial intensity profile is measured by the photodiode for measurement (PDM). In this setup, a heating stage is put next to the LCOS device for the adjustment of the device working temperatures in a range of 15°C to 55°C, as the birefringence of most of the LC materials will reduce significantly when the temperature goes higher. The temporal changes of the diffracted optical intensity are recorded using a data acquisition (DAQ) card. The voltage applied across the LC layer is up to ±5 volts with a DC balanced square waveform generated by the CMOS circuitry on the silicon backplane. The actual voltage can be set at any of the 256 individual levels between zero and the maximum voltage.

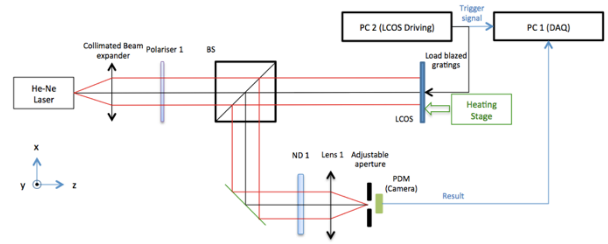

Fig. 2: Optical setup for the temperature effect of phase-only nematic LCOS device. BS: beam splitter; ND: neutral density filter (adjustment of diffracted intensity); PDM: photodiode for measurement; DAQ: data acquisition card.

Birefringence is probably the most important property of LC materials for phase modulations, as it determines the speed of light propagation depending on the direction and polarization of the light wave travelling through LC materials. For phase-only nematic LCOS devices with a positive electrically controlled birefringence (ECB), the director of the LC molecules normally switches from almost "planar" to "homeotropic" when a voltage is applied. In the experiment setup shown in Fig. 2, the incident polarization direction is aligned with the initial direction of the LC molecules and the electro-optic switching has the access to almost the complete range of refractive index changes from the extraordinary refractive index (ne) to ordinary refractive index (no), i.e. the magnitude of birefringence. For the validity of studying the temperature effect in LCOS devices, it is only meaningful to operate in a temperature range before the LC material reaches its clearing point [21].

Birefringence depends not only on the working temperature but also on the wavelength of the light. A quantitative equation was proposed [22] to describe the birefringence dispersion as a function of wavelength in the visible and infrared spectral regions. It showed a good agreement with the measured results for the LC material BLO37 at several wavelengths, demonstrating its relatively high value birefringence especially in the near IR region (0.224 @1550nm) [23].

In Fig. 3(a), the birefringence of the LC material BLO37 in our LCOS device was measured as a function of temperature for three different wavelengths, 445, 532 and 633 nm, respectively. It confirms that the birefringence reduces the temperature [22] and the wavelength spectrum increase. In Fig. 3(b), it shows the phase modulation depth as a function of the applied voltage at different temperatures. It is well known that the phase modulation depth is proportional to the magnitude of birefringence as the device thickness is fixed as shown in Eq. (1):

$$\boldsymbol{\delta} = \frac{\boldsymbol{2\pi \cdot 2d \cdot \Delta n}}{\boldsymbol{\lambda}} \qquad (1)$$

where δ is the phase modulation depth, d the thickness of the LC layer in an LCOS device, Δn the magnitude of the LC birefringence and λ the light wavelength. The empirical fitting for the dependence of the phase modulation depth on the applied voltage is shown in Eq. (2):

$$\boldsymbol{\delta} = \boldsymbol{\delta_{max}}(\mathbf{1} - \mathbf{10}^{-k(V-V_{th})}) \quad (2)$$

where δmax is the maximum capability of the phase modulation for a given wavelength (about 7π for our LCOS device at wavelength of 633 nm), k a fitting parameter (from 1.42 to 1.84 at different temperatures for our device), V the external voltage across the LC layer and Vth the threshold voltage. It is clear as shown in Fig. 3(b), the fitting using Eq. (2) has a good agreement with the experimental data with the phase modulation depth decreases as the temperature increases. Note that, due a series of raw data has been extracted and processed through the empirical fitting equations, the real-time measurement might be diversified because of the operating temperature is not constant for most of time. Also, for the temperature above 50°C, the phase modulation depth seems to be higher than that of lower temperatures, which is an artefact due to the enhanced phase flicker - an indispensable phenomenon of temporal phase variation in an LCOS device. As the result, unbalanced phase modulations happen due to the instability of the LC materials under driven. This leads to a subjectively temporal instability of the diffracted intensity detected by a fast response photodiode. Garcia-Marquez et al. [24] commented that the phase flicker could be reduced only if the LC material is kept at a low temperature range for a certain level of the material viscosity.

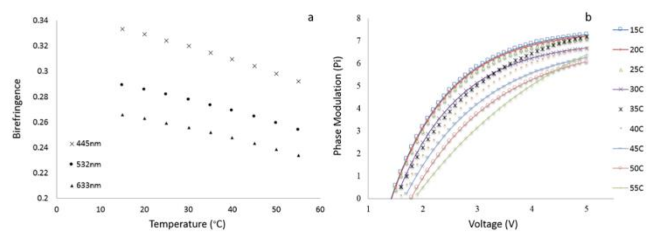

Fig. 3: The optical performance of the nematic LC BLO37 in the phase-only LCOS device in use when the working temperature varies from 15°C to 55°C. (a): Birefringence vs temperature for different wavelengths; (b): Phase modulation depth vs applied voltages with an empirical fitting using Eq. (2) at the wavelength of 633nm.

The dielectric anisotropy of a nematic LC material under an external electric field can be described by the Maier theory [25]. The dielectric anisotropy is defined as the difference of the dielectric constant in directions parallel and perpendicular to the long molecular axis, which is given by Eq. (3):

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} \quad (3)$$

where Δε is the dielectric anisotropy, $\varepsilon_{\parallel}$ is the dielectric constant parallel to the LC director (optical axis) and $\varepsilon_{\perp}$ is the dielectric constant normal to the LC director (optical axis). The measured dielectric permittivity and dielectric anisotropy at 1 kHz as a function of temperature for BLO37 are shown in Fig.4. Both the dielectric permittivity normal to the long axis and the dielectric anisotropy decrease as the temperature increases. In addition, the LC material has a reasonably high positive dielectric anisotropy and its threshold voltage can be described by Eq.4 [26]:

$$V_{th} = \sqrt{\frac{4\pi K_{ii}}{\Delta\varepsilon}} \quad (4)$$

where Vth is the threshold voltage, Kii the elastic constant of the LC material (it is set to be equal to the splay elastic constant K1 since the ECB mode is used for phase-only LCOS devices in this experiment) and Δε the dielectric anisotropy. The threshold voltage represents the onset voltage for the movement of the LC director in the middle of the LC layer. Here, the threshold voltage is only related to the dielectric anisotropy and the elastic constant. The magnitude of Δε, which usually follows the magnitude of Δn, should be as high as possible for a low Vth.

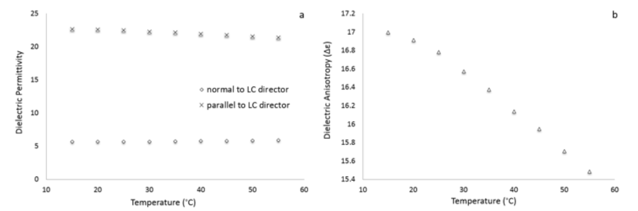

Fig. 4: Temperature-dependent dielectric permittivity (a) and anisotropy (b) for BLO37.

Fig. 5 shows the change of the threshold voltage as a function of temperature measured in our BLO37 layer It shows an increase of the Vth with temperature, which is in a good agreement with Eq. (4) where Δε decreases with temperature. It is good to see that in our temperature range from 15 to 50°C the Vth only increases by 0.3 V and the magnitude of dielectric anisotropy does not decrease excessively, which allows to drive the LC molecules effectively with a sufficient phase modulation depth for desired applications. For instance, the test device with the LC Δn=0.282 at room temperature is designed for achieving 7π of phase modulation depth at 633 nm, which is equal to 2.4π at 1550 nm. If the working temperature is set to be 50°C, the phase modulation can still reach 2.2π at 1550 nm [23], which is sufficient for most applications.

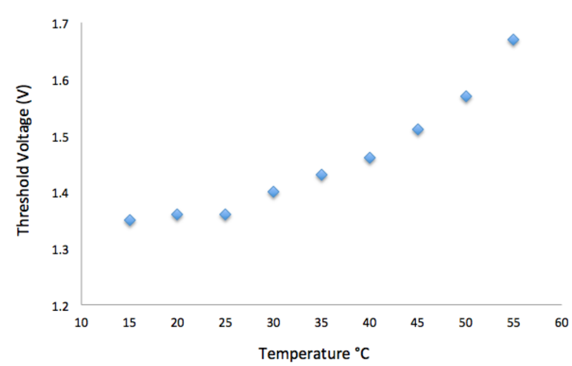

Fig. 5: Threshold voltage of the BLO37 layer as a function of temperature.

Many high dielectric anisotropic LC materials, such as BLO37, have a fairly high viscosity, hence a slow response time. The response time described in Eq. (5) (either the rising time or the decay time) is a function of the birefringence, dielectric anisotropy and temperature:

$$t = f(\Delta n, \Delta\varepsilon, T) \tag{5}$$

While both the wavelength-dependent birefringence and dielectric anisotropy are affected by temperature as well:

$$\Delta n = u(T, \lambda) \tag{6}$$

$$\Delta\varepsilon = \nu(T) \tag{7}$$

Therefore the response time can be shown as

$$t = f(u(T, \lambda), \nu(T), T) \tag{8}$$

Thus, it is clear that temperature is a vital parameter here and the response time of phase-only LCOS devices can be hugely improved by working at a high temperature.

Fig. 6 shows that the tremendous reduction of the response times, both the rising time and the decay time, in the test LCOS device with BLO37 when the working temperature increases. It also shows that the rising time can be reduced considerably if a large electric field is applied [27]. For instance, the rising time is about 280 ms when 2 V is applied and less than 50ms when 5V is applied. For the decay time, the increase of the applied electric field can also have some effect of improvement. Considering the impact of the phase flickers when the working temperature is above 50°C, it is considered 50°C as the optimized working condition for the improvement of the response time.

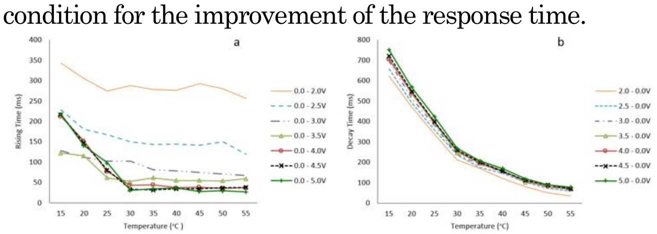

Fig. 6: The response times, (a) rising time and (b) decay time in the phase-only LCOS device with BLO37 as a function of temperature.

In conclusion, the temperature-dependent properties of the non-linear nematic LC materials BLO37 have been investigated systematically in relation to the optical performance and operational conditions for phase-only LCOS devices. Real-time performance of a test phase-only LCOS device as a function of working temperatures has been studied on three aspects: the phase modulation depth as defined by the birefringence, the threshold voltage as affected by the dielectric anisotropy and the response time. The results in Fig.3 and Fig. 5 show that the working temperature could be practically as high as 50°C for significantly fast response times (both rising time and decay time), without compromising the required phase modulation depth for practical applications and the threshold voltage to be driven by the LCOS device.

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