液晶的光电响应特性测量

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液晶简介

- 1. 液晶的结构特点:

液晶相中,分子的形状是使其具有一定的指向性而不容易自由转动的长棒状.

- 2. 液晶的宏观对称性:

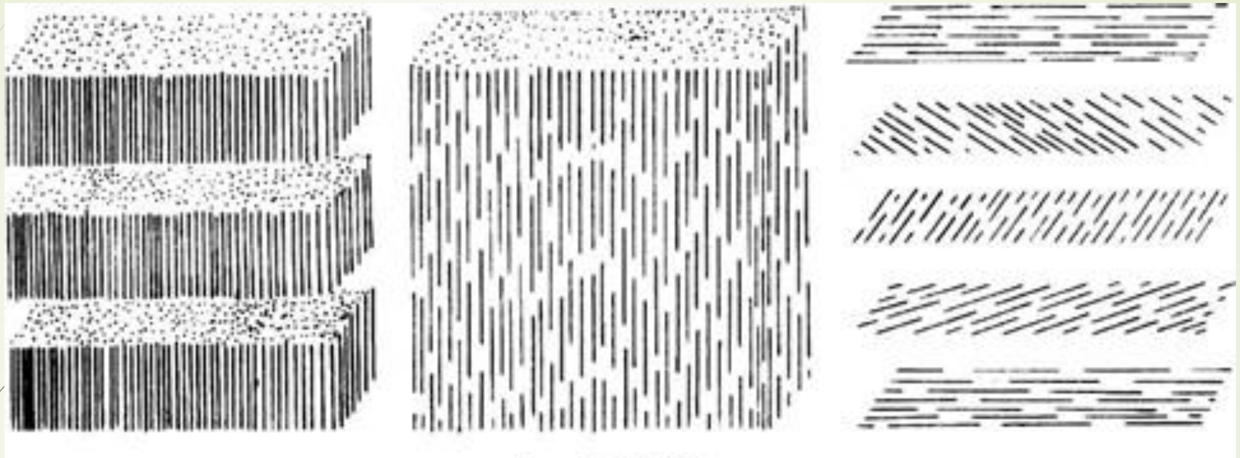
液晶分子的排列状态按其对称性可分成三大类: 向列型/胆甾型/近晶型.

- 3. 向列型液晶分子排列的特点:

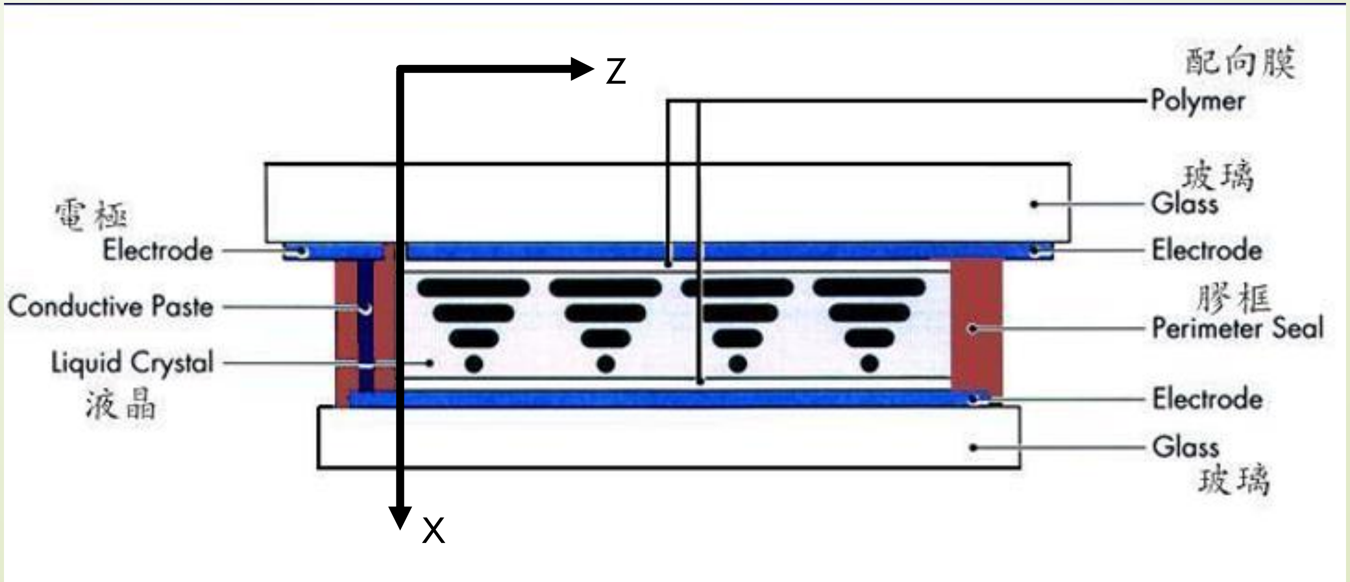
①分子的长程指向有序性,分子之间趋于彼此互相平行排列;

②向列相是流动的,即众多分子的中心排列是无序的或长程无序.

三种典型的液晶结构



(a) 近晶型结构 (b) 向列型结构 (c) 胆甾型结构



Chapter 1.
液晶分子在外场下的平衡态性质

理论部分: 5~7

实验部分: 8~10

对测量的分析与改进: 11~12

Friederieksz 转变电压(I)

- 自由能:

$$F = S\int_0^l \left\{\frac{1}{2}k\left[\frac{d\theta(x)}{dx}\right]^2 - \frac{1}{2}E^2\cdot\Delta\varepsilon\cos^2\theta(x)\right\}dx$$

- 利用Euler方程:

$$-\frac{k}{\Delta\varepsilon E^2}\frac{d^2\theta}{dx^2} + \sin\theta\cos\theta = 0$$

- 通解:

$$(\frac{d\theta}{dx})^2 = C - \left(\frac{\sin\theta}{l_e}\right)^2$$

$${l_e}^2 = -\frac{k}{\Delta\varepsilon E^2}$$

- 边界条件:

$$\begin{cases} \dfrac{d\theta}{dx}|_{x=0} = 0 \\ \theta|_{x=0} = \theta_m \end{cases}$$

Friederieksz 转变电压(II)

$\Longrightarrow$

$$\frac{d\theta}{dx} = \pm\frac{1}{l_e}\sqrt{\sin^2\theta_m - \sin^2\theta}$$

注: +号对应于$x < 0$的区域, -号对应于$x > 0$的区域.

$$\int_{-\frac{d}{2}}^{x}\frac{dx}{l_e} = \frac{1}{l_e}\left(\frac{d}{2} + x\right) = \int_{0}^{\theta(x)}\frac{d\theta'}{\sqrt{\sin^2\theta_m - \sin^2\theta'}}$$

由边界条件:

$$\frac{d}{2l_e} = \int_{0}^{\theta_m}\frac{d\theta'}{\sqrt{\sin^2\theta_m - \sin^2\theta'}} = \frac{\pi}{2}\left(1 + \frac{1}{4}\sin^2\theta_m + \cdots\right)$$

$\Longrightarrow$

$$E = \sqrt{-\frac{k}{\Delta\varepsilon}\cdot\frac{\pi}{d}\left(1 + \frac{1}{4}\sin^2\theta_m + \cdots\right)}$$

- 阈值电压:

$$V_{th} = \pi\sqrt{-\frac{k}{\Delta\varepsilon}}$$

外加电压大于阈值时的分子倾角

$$\frac{1}{l_e}\left(\frac{d}{2}+x\right)=\int_0^{\theta(x)}\frac{d\theta'}{\sqrt{\sin^2\theta_m-\sin^2\theta'}}$$

- 近似方法:

将$\sin^2\theta$展开至θ^4项, 注意到$E_{th}=\frac{\pi}{d}\sqrt{-\frac{k}{\Delta\varepsilon}}$

- 单位面积液晶盒的自由能:

$$\frac{F}{S}=\frac{1}{2}k\frac{\pi^2}{d}\left[\left(1-\frac{E^2}{{E_{th}}^2}\right){\theta_m}^2+\frac{E^2}{{E_{th}}^2}\frac{{\theta_m}^4}{4}\right]$$

$\delta F=0\Longrightarrow$

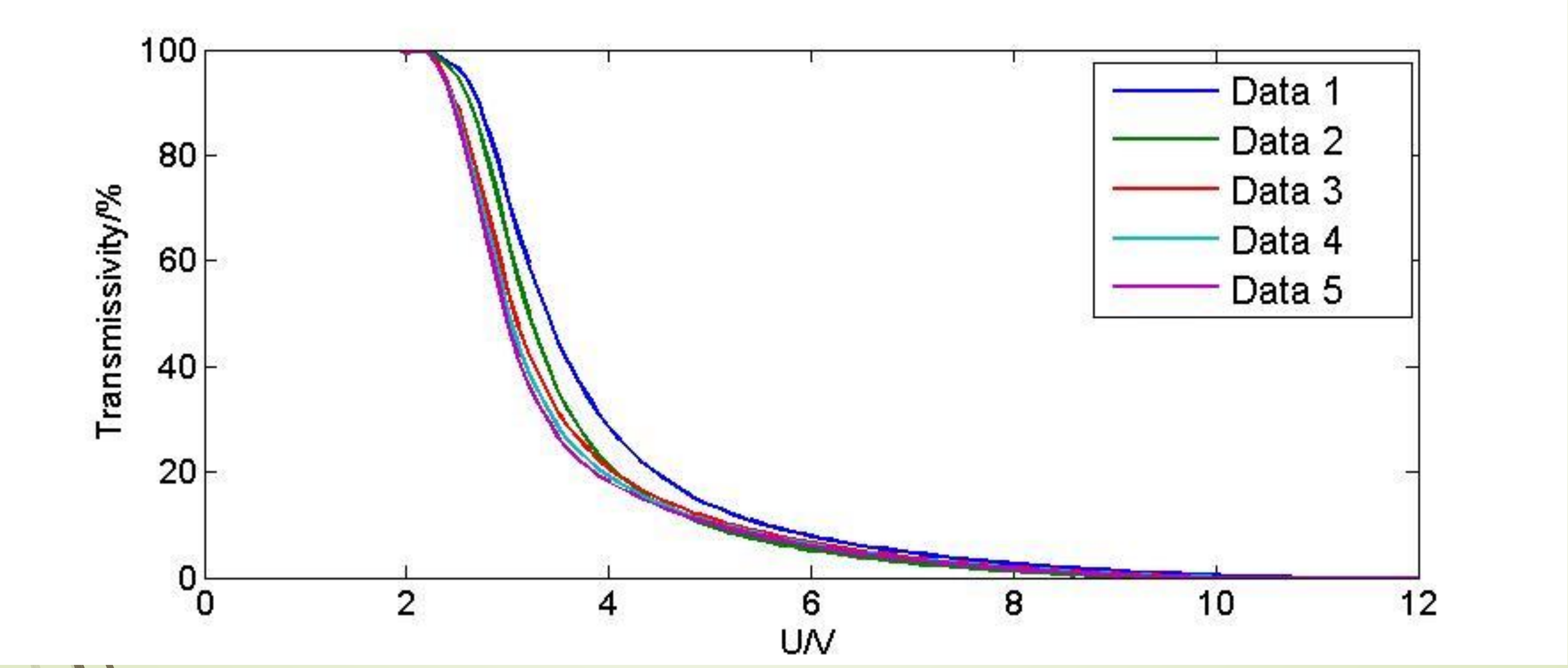
$$\left(1-\frac{E^2}{{E_{th}}^2}\right){\theta_m}^2+\frac{E^2}{{E_{th}}^2}\frac{{\theta_m}^4}{4}=0$$

$$\therefore\frac{{\theta_m}^2}{4}=\frac{E^2-{E_{th}}^2}{E^2}=\frac{V^2-{V_{th}}^2}{V^2}$$

$$\theta_m=2\sqrt{1-\frac{{V_{th}}^2}{V^2}}$$

Friederieksz 转变电压的测量

编号	1	2	3	4	5	均值
F转变电压(V)	2.2	2.2	1.8	1.8	1.8	1.96



验证分子倾角公式$\theta_m = 2\sqrt{1 - \frac{{V_{th}}^2}{V^2}}$(I)

$$\Delta n = n_e - n_o = (n_\parallel - n_\perp) sin^2\theta(x)$$

$$\theta(x) \approx \theta_m \cos\left(\frac{\pi}{d}x\right)$$

$$\Delta = \int_{-\frac{d}{2}}^{\frac{d}{2}} \Delta n dx = (n_\parallel - n_\perp){\theta_m}^2 \int_{-\frac{d}{2}}^{\frac{d}{2}} cos^2\left(\frac{\pi}{d}x\right) dx = (n_\parallel - n_\perp){\theta_m}^2 \frac{d}{2}$$

$\Longrightarrow$

$$\delta = \frac{2\pi}{\lambda_0}\Delta = \frac{\pi d}{\lambda_0}(n_\parallel - n_\perp){\theta_m}^2$$

$$T_{\text{absolute}} = \cos^2(\alpha - \beta) - \sin(2\alpha)\sin(2\beta)\cos^2(\frac{\delta}{2})$$

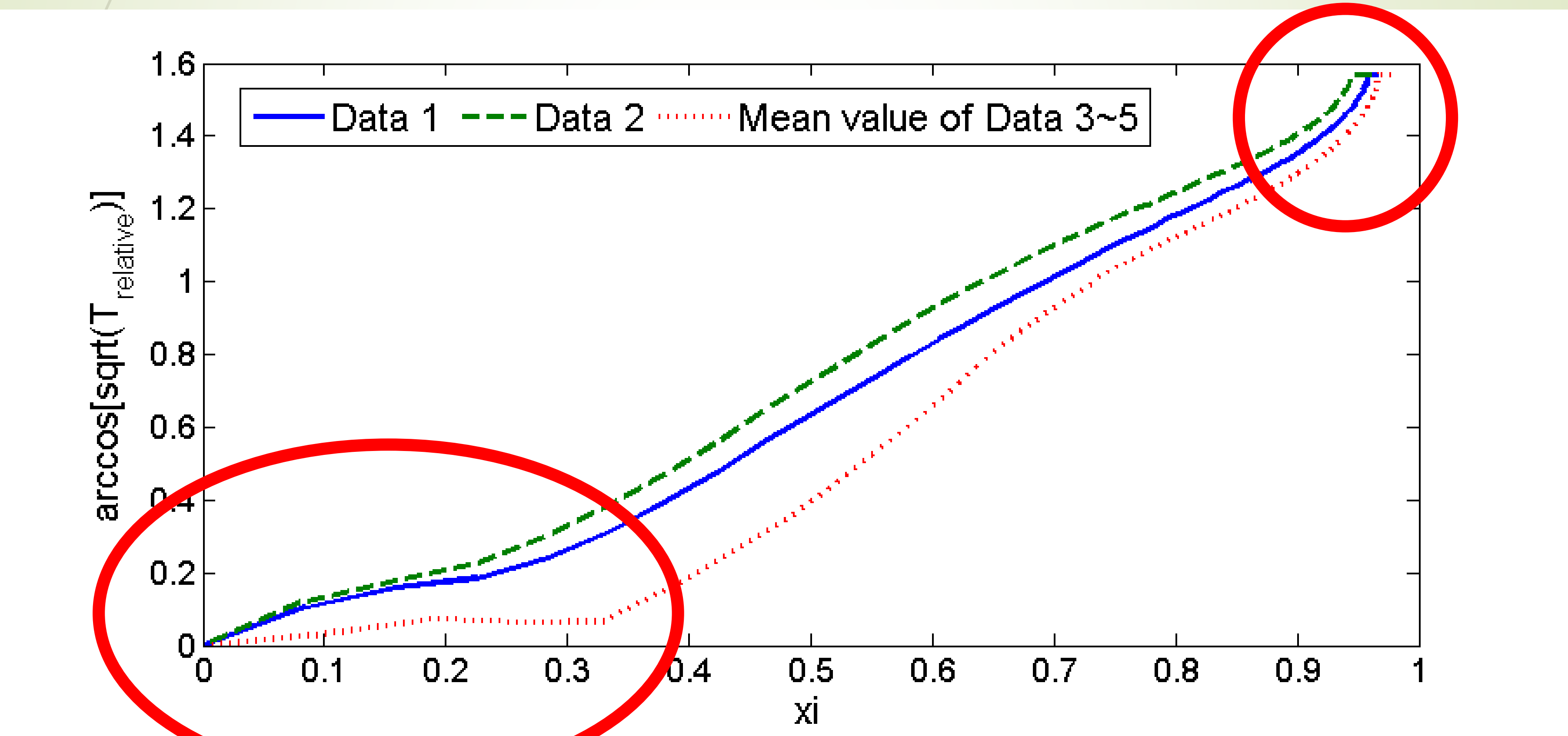
当两片偏振片垂直时:

$$T_{\text{relative}} = \cos^2(\frac{\delta}{2})$$

验证分子倾角公式$\theta_m = 2\sqrt{1-\frac{{V_{th}}^2}{V^2}}$(II)

$$T_{\mathrm{relative}} = \cos^2\left(\frac{\delta}{2}\right) = \cos^2\left(\frac{\pi d}{2\lambda_0}(n_\parallel - n_\perp){\theta_m}^2\right)$$

将 $\arccos\sqrt{T_{\mathrm{relative}}}$ 对 $\xi = 1-\frac{{V_{th}}^2}{V^2}$ 作图:



验证分子倾角公式$\theta_m = 2\sqrt{1-\frac{{V_{th}}^2}{V^2}}$(III)

Comments:

1. $\arccos\sqrt{T_{\mathrm{relative}}}$ 对 $\xi = 1-\frac{{V_{th}}^2}{V^2}$ 的线性度并不高:

编号	相关系数R^2
1	0.9831
2	0.9912
3~5	0.9596

由于T_{relative}的解析式对V_{th}非常敏感，很有可能是V_{th}测量的不准确导致 $\arccos\sqrt{T_{\mathrm{relative}}}$ 对 $\xi = 1-\frac{{V_{th}}^2}{V^2}$ 的线性度并不高.

2. 当$V > 3V_{th}$时，即$\xi > 0.89$时，$\theta(x) \approx \theta_m\, cos\left(\frac{\pi}{d}x\right)$ 的近似关系不再成立:

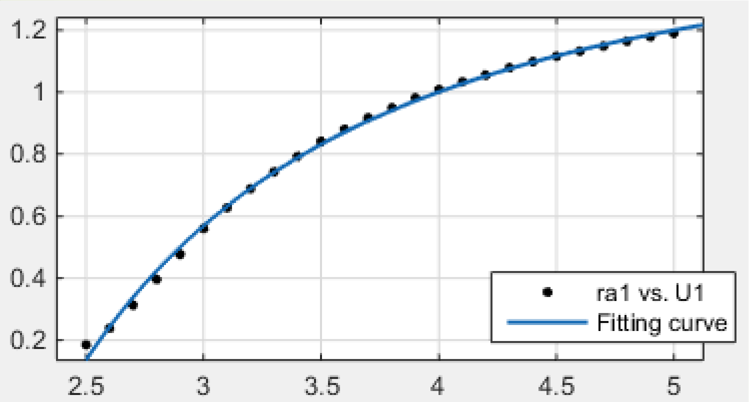
$$\delta = \eta\frac{\pi d}{\lambda_0}(n_{\parallel} - n_{\perp}){\theta_m}^2, 1 \le \eta < 2$$

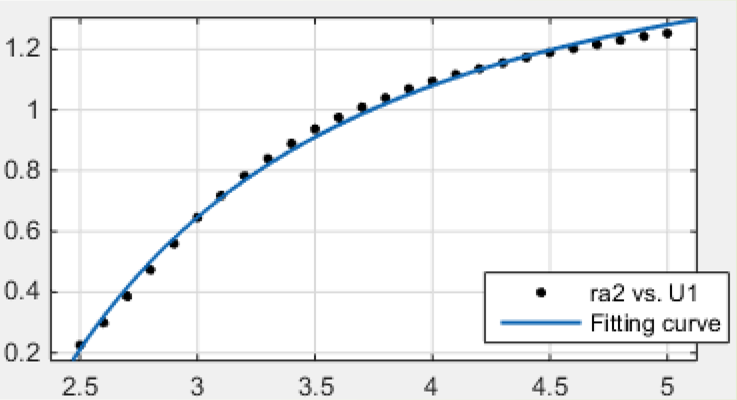
这是实验曲线在$\xi \approx 0.9$以后上翘的直接原因.

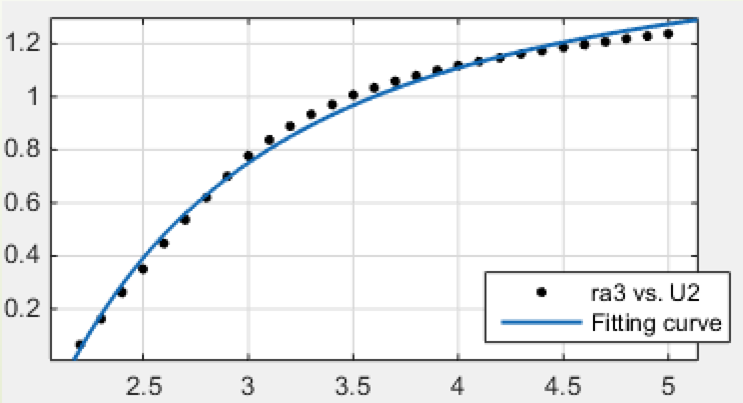
对于Comment. 1的回应

- 对$V \le 5V$的数据按$\arccos\sqrt{T_{relative}} = C \cdot \xi(V_{th})$拟合:

编号	1	2	3~5
V_{th}	2.388 V	2.333 V	2.165 V
R^2	0.9978	0.9964	0.9939

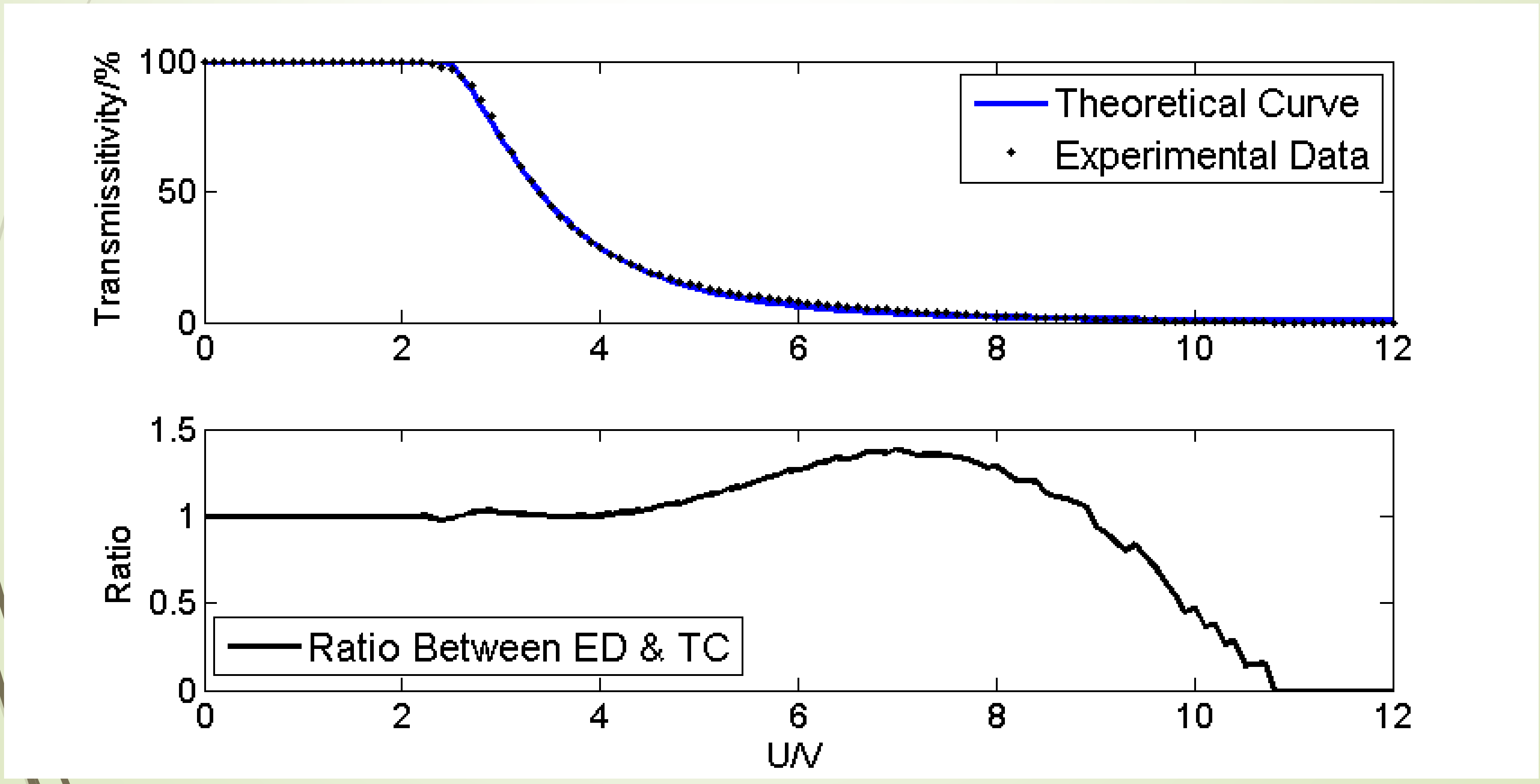






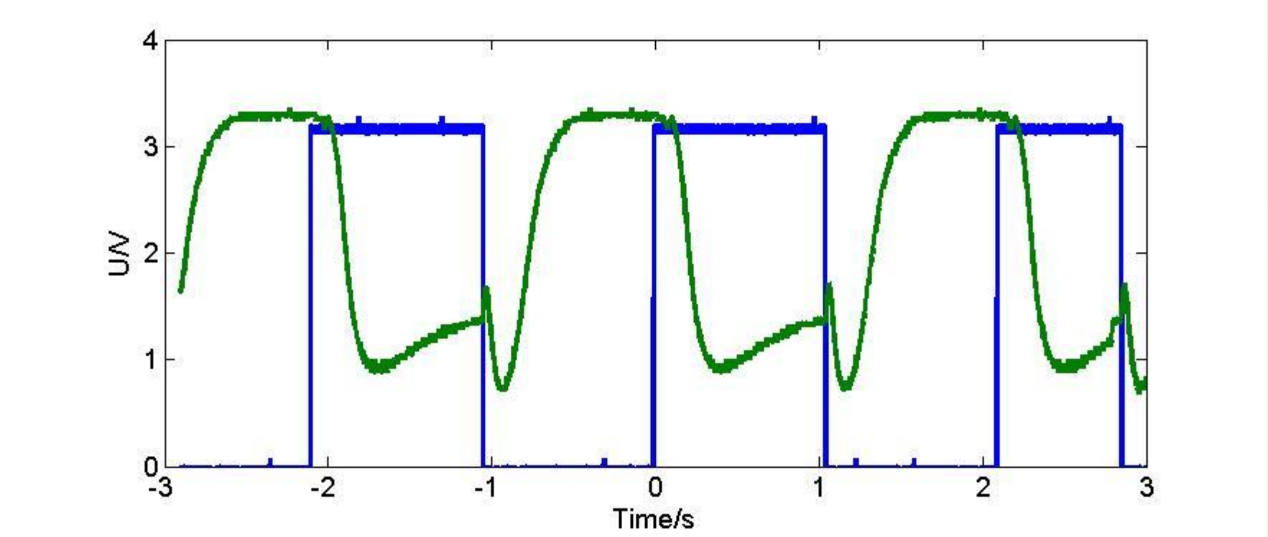
实验结论

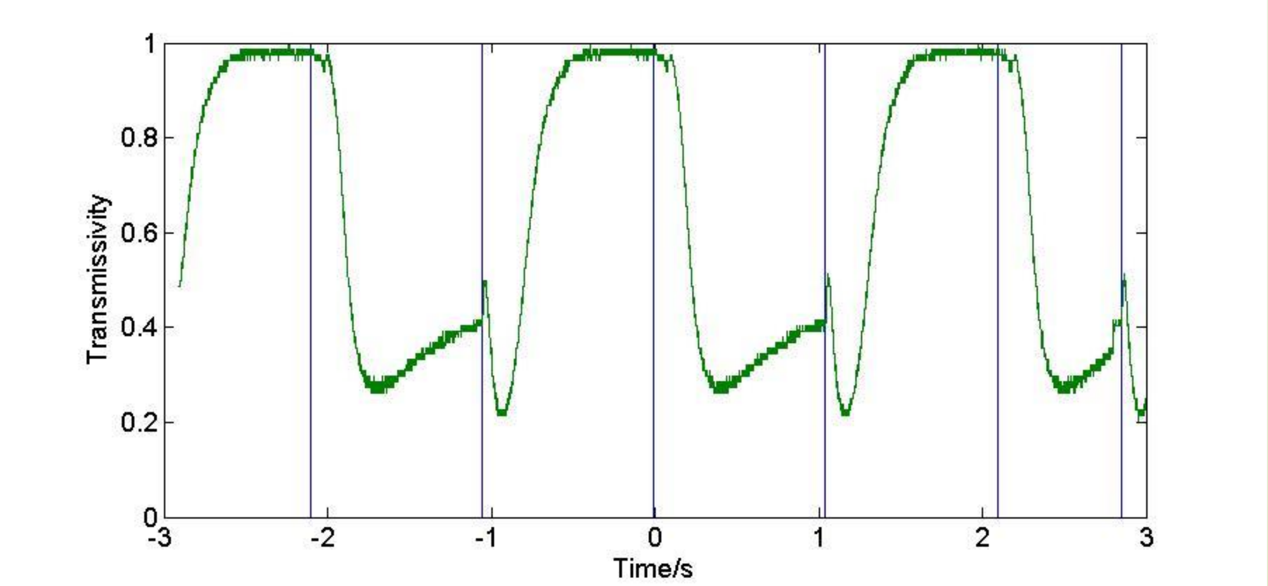
- 液晶体系的Friederieksz 转变电压在2.1V~2.4V之间;
- 分子倾角公式$\theta_m = 2\sqrt{1 - \frac{{V_{th}}^2}{V^2}}$得到验证.



Chapter 2.
液晶分子在外场下的转向弛豫

外场电压2.8V时的透射率图像





对瞬时分子反转的动力学解释(I)

液晶的自由能密度:

$$f=\frac{1}{2}k\left[\frac{\partial\theta(x,t)}{\partial x}\right]^2+\frac{1}{2}E^2\cdot\Delta\varepsilon\sin^2\theta(x,t)$$

动力学方程:

$$-\frac{\partial f}{\partial\theta}=\dot{p_\theta}=\mu\ddot{\theta}$$

将解分离变量并对t在零点邻域作Taylor展开:

$$\theta(x,t)=X(x)T(t)=X(x)(A_0+A_1t+A_2t^2+A_3t^3+\cdots)$$

$\Longrightarrow$

$$-kT(t)\frac{d^2X(x)}{dx^2}-\frac{1}{2}E^2\cdot\Delta\varepsilon\sin[2X(x)T(t)]=\mu X(t)\ddot{T}$$

考虑到$X(x)$的类cos函数的对称性, 可以认为:

$$\frac{d^2X}{dx^2}\sim-X.$$

对瞬时分子反转的动力学解释(II)

在取定点时，上述方程化为关于时间t的常微分方程：

$$C \cdot T(t) - Dsin[2XT(t)] = \ddot{T}$$

其中$C = \frac{k}{\mu} > 0 \,\&\, D = \frac{1}{2\mu X} E^2 \cdot \Delta\varepsilon.$

- 无外场时：$D = E = 0 \,\&\, A_0 > 0$

$$\Rightarrow \quad \begin{aligned} A_1 &< 0 \\ A_2 &= \frac{C}{2} A_0 > 0 \\ A_3 &= \frac{C}{6} A_1 < 0 \end{aligned}$$

偏转角减小→增大→减小，透射率增大→减小→增大

- 外加电场时：$A_0 = 0, D < 0$

$$\Rightarrow \quad \begin{aligned} A_1 &> 0 \\ A_2 &= A_4 = 0 \\ A_3 &= \frac{A_1}{6}(C - 2DX) > 0 \end{aligned}$$

偏转角将持续增大，透射率持续减小。(A_5的正负与C, D的比值有关)

- Hint：上述结论仅无阻尼时外场变动后的较短时间内有效。

实验结论

- 液晶的上升时间τ_u与下降时间τ_d:

$$\tau_u = 0.4483\ \mathrm{s}$$

$$\tau_d = 0.6046\ \mathrm{s}$$

THANKS!

Reference:

1. 世纪中科液晶电光效应综合试验仪说明书;
2. 黄子强.《液晶显示原理》，国防工业出版社, 2013.