Macro–modeling of Liquid Crystal Cell with VerilogA

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1. Background
Background

Liquid Crystal Displays (LCDs) pervade in our daily life

TV
Portable DVD Player
Digital Video Camera (DVC)
Personal Digital Assistance (PDA)
Portable Game
Digital Still Camera (DSC)
Portable Music Player
Mobile Phone (MBL)
Personal Computer (PC)
Background

**High Image quality**
- High Contrast
- Fast Response
- Low Power Consumption
- Image Uniformity (Low noise), etc.

**Compact Design**
- Narrow Frame
- Thinner Profile, etc.

**Higher expectation from customers**

**Inexpensive Price**

**No room and no time to waste in LCD design**

**Necessity of more accurate and fast simulation**
**Basic operation of general LCDs**

1. Signal pulses for driving LCD are generated in the peripheral circuit.

2. Thin Film transistor (TFT) acts as a switch transferring electrical charges from a signal line to a liquid crystal capacitor (Clc).

3. The charges in Clc generate the electric field $E$ in LC cell.

4. The electric field $E$ tries to align liquid crystal (LC) parallel to $E$.

5. The transmittance of incident light changes as the orientation of LC.
Background

**Issues in conventional LCDs’ design**

In typical circuit simulators.....

- **Non-linear and time-dependent capacitor** is NOT prepared.
- The influence of electrical behaviors on **optical properties** can NOT be estimated.

**Assumption**

LC capacitor is the simple static capacitor

**Issues**

- Designers tend to have excessive design margin.
- Optical properties of LCDs may not meet the customers’ requests.
The direct method to improve this situation is … to integrate LC simulator into a circuit simulator.

Liquid Crystal simulation

- **Poisson equation**
  \[ \nabla \cdot \mathbf{E} = \rho / \varepsilon \]
  
- **Iteration until convergence**

- **Torque balancing equation**
  \[
  \gamma \frac{\partial \psi}{\partial t} = K \frac{\partial^2 \psi}{\partial z^2} + \Delta \varepsilon \cdot \sin \psi \cdot \cos \psi \cdot E^2
  \]
  
- **After convergence…**

- **Optical equation**
  Berreman 4x4 matrix method

However ..... this way costs huge amount of simulation time due to its heavy iterative algorithm.

Macro-model for LC cell is strongly demanded.
2. Proposed Model
**Smet’s macro-model**

(Liquid Crystal, 31(5):705-711, May 2004)

- Three kinds of torque affects a liquid crystal molecule
  
  Elastic: \( F_{elas} = Kx \)
  
  Electrical: \( F_{elec} = cE^2 \)
  
  Viscosity: \( F_{vis} = \gamma \frac{dx}{dt} \)

  \( (K, c, \gamma : \text{constant}) \)

- The equilibrium of torques:

\[
cE^2 = Kx + \gamma \frac{dx}{dt}
\]

**Well-known first-order system**

- Time constant: \( \tau = \gamma / K \)

- Steady state: \( x(t) \to \frac{c}{K} \left[ \frac{V_{ext}}{d} \right]^2 \quad (t \to \infty) \)
Proposed model

Smet’s macro-model (Cont.)

Well-known first-order system

- Time constant : \( \tau = \gamma / K \)
- Steady state : \( x(t) \rightarrow \frac{c}{K} \left[ \frac{V_{\text{ext}}}{d} \right]^2 \) \((t \rightarrow \infty)\)

The orientation of liquid crystal molecule \( x(t) \) is given as a node voltage of low pass filter circuit.

Equivalent expression
Proposed model

Smet’s macro-model (Cont.)

\[ cE^2 = Kx(t) \] : Equilibrium equation in steady state

\[ V_i = \sqrt{\frac{Kd^2}{c}} x(t) \] : Effective voltage

\[ C(V_i) = C_\perp + \frac{2}{\pi} (C_{||} - C_\perp) \arctan \left[ \frac{\alpha + (\alpha^2 + \delta^2)^{\frac{1}{2}}}{2} \right] \]

\[ \alpha = \frac{V_i - V_{tc}}{V_{mc}} \]

\[ T(V_i) = T_{min} + (1 - T_{min}) \tanh \left[ \frac{\beta + (\beta^2 + \eta^2)^{\frac{1}{2}}}{2} \right] \]

\[ \beta = \frac{V_i - V_{to}}{V_{mo}} \]
**Issues in Smet’s model**

Following trends are not supported.

1. **External applied voltage dependency**
2. **Individuality of rise/fall process**

**Response time dependencies on the external applied voltage (Measured)**

*Response time is defined as the time constant*
Proposed model

Model enhancements to improve accuracy by authors

(1) External applied voltage dependency

\[ \tau = R_d \cdot C_d = \frac{1}{a_1 + a_2 V_{ext}^m} \]

(a1, a2, m : model parameters)

(2) Individuality of rise/fall process

If

\[ \frac{c}{K} \left( \frac{V_{ext}}{d} \right)^2 \geq x(t) \]

then

\[ a_1 = a_{1 \text{r}}, \ a_2 = a_{2 \text{r}} \] (for rise process)

else

\[ a_1 = a_{1 \text{f}}, \ a_2 = a_{2 \text{f}} \] (for fall process)
3. Implementation
Why with VerilogA?

- **Flexibility**
  - High potential in mixed technology modeling

- **Simple implementation**
  - Many commercial simulators support VerilogA interface.

- **Availability of ADMS** (To get much higher performance)
  - Easier implementation compared with that of C-Code
  - Superiority in keeping the confidentiality of models
Implementation

VerilogA Code

~ Electrical property block (Excerpt) ~

```verbatim
// Verilog for Liquid Crystal Capacitor
include "discipline.h"

module lccap(a,b);
inout a,b; //Interface ports
electrical a,b;
electrical nvc; //Internal node
...

analog
begin
@ (initial_step)
begin
...
//Initial voltage for internal node
vi_c = vini * vini;
end
...
begin //Probing terminal voltage
vin = V(a,b);
vv = vin * vin;
...
//Detection of rising or falling
if (vv >= vi_c)
begin //rising
alc = alc_r;
...
end
else
begin //falling
alc = alc_f;
...
end
end
...
endmodule
```

vin = V(a,b)

qlc = cap * vin
l(a,b) <+ ddt(qlc)

Interface with a circuit simulator
This circuit is only used for the evaluation of the liquid crystal orientation and should not behave as the load of the actual external circuit.

Judge whether it’s rise or fall process

\[
\text{cap} = f(\sqrt{nvc})
\]
ADMS has been used to attain much higher performance.

**Procedure**

- **Step 1.** Prepare a “Source code” in VerilogA and XML Scripts provided by Cadence.

- **Step 2.** ADMS translates VerilogA code into some C-codes.

- **Step 3.** C-codes is compiled by gcc with Spectre-CMI library.

Model module running on Spectre
Implementation

Parameters Extraction

Rough fitting with spread sheet

Accurate fitting with Genetic Algorithm (GA) tool

* Neocircuit ® (Cadence)
4. Evaluation
Model Validity

- Static electrical /optical behavior

(a) Capacitance
(b) Transmittance

Good agreement with the experimental data

- Static electrical behavior:
  - Capacitance
  - Transmittance

- Parameters:
  - $(c_v=2.0, c_p=18.2, v_{to}=1.4, v_{mo}=0.2, \delta=3.3)$
  - $(t_{min}=0.0004, v_{to}=0.990, v_{mo}=0.450, \eta=0.200)$
**Model Validity**

*Method to measure the dynamic capacitance of LC cell has not been established.*

- **Dynamic optical Behavior**

  - (a) Rise process
    - \( a_{1t_r} = 0.070, a_{2t_r} = 0.030, m_{t_r} = 2.40 \)
  - (b) Fall Process
    - \( a_{1t_f} = 0.070, a_{2t_f} = 0.030, m_{t_f} = 2.05 \)

**Good agreement with the experimental data**
Performance

- "ADMS+CMI" is …
  - 10 times faster than “Native VerilogA”
  - 500 times faster than “Physical Model”

- All bench mark tests are performed on Spectre®.

- Physical model is implemented by Spectre CMI®.

500 times faster than the conventional physical model

Simulation Condition
- 720 liquid crystal cells array
- transient time : 200msec
- CPU : 3.2GHz Intel® Xeon™
- Memory : 4GB
5. Application to LCD Design
Application to LCD design

1st Example: Storage Capacitor (Csc) optimization

Insufficient Csc causes...

A) Low-speed response time
B) Inadequate transmittance

Csc > 200fF is necessary.

Designers can estimate the optimum size of Csc.
2nd Example: Common voltage (Vcom) optimization

Failure to optimize Vcom induces flicker image.

Flicker image terribly degrades the display quality.

Vcom should be set to 3.3 ~ 3.5 v

Designers can estimate the optimum Vcom
3rd Example : Signal voltage optimization for each gray level

Generally, the relationship between the gray level and the transmittance is given by customers.

Designers can optimize the signal voltages for each gray level.
6. Conclusion
Conclusion

- Developed an accurate macro-model for a LC cell
  - Included some enhancements to the model based on Smet’s
  - Verified its validity by fitting it to measurement data

- Integrated into Spectre® with VerilogA and ADMS
  VerilogA : suitable for multi-technology modeling (electrical / optical)
  ADMS : realize much higher performance
  (x500 faster than physical model)

- Provides useful information for optimum LCD design
  We took following property of LC cells into account
    - Non-linear time-dependent capacitor
    - Optical device varied with the applied voltage
We are grateful to Dr. Laurent Lemaitre and Cadence Design Systems for helpful advice and discussion in implementing our model into Spectre® on Cadence Virtuoso® platform.
Thanks to your attention
In this appendix, we derive the form of the voltage dependent time constant shown in equation (4). 
\( \mathbf{n}(|\mathbf{n}| = 1) \) is director vector of liquid crystal. The director vector \( \mathbf{n} \) roughly denotes the averaged orientation of the liquid crystal molecules. \( \mathbf{E} \) is the electric field in the cell. As easily derived, the projection of \( \mathbf{E} \) parallel to \( \mathbf{n} \) is \( (\mathbf{E}, \mathbf{n})\mathbf{n} \) and perpendicular to \( \mathbf{n} \) is \( \mathbf{E} - (\mathbf{E}, \mathbf{n})\mathbf{n} \) respectively. Therefore the displacement field vector \( \mathbf{D} \) can be written as in equation (5). Note that the dielectric constants of liquid crystal differs in value along the parallel to the axis(\( \epsilon_{||} \)) and perpendicular to the axis(\( \epsilon_{\perp} \)).

\[
\mathbf{D} = \varepsilon_0[\epsilon_{||}(\mathbf{E}, \mathbf{n})\mathbf{n} + \epsilon_{\perp}(\mathbf{E} - (\mathbf{E}, \mathbf{n})\mathbf{n})]
\]

In this case, the electromagnetic energy density \( U \) can be written in equation (7).

\[
U = -\frac{1}{2}\varepsilon_0(\mathbf{E}, \mathbf{D}) = -\frac{1}{2}\varepsilon_0[(\epsilon_{||} - \epsilon_{\perp})(\mathbf{E}, \mathbf{n})^2 + \epsilon_{\perp}|\mathbf{E}|^2]
\]

Here \( z \)-axis is parallel to \( \mathbf{E} \), \( \theta \) is the angle between \( \mathbf{n} \) and \( z \)-axis, and \( \phi \) is the angle between the projection vector of \( \mathbf{n} \) into \( x-y \) plane and \( x \)-axis. \( \mathbf{E} \) and \( \mathbf{n} \) are expressed as \( \mathbf{E} = (0, 0, E_z), \mathbf{n} = (\cos \theta \cos \phi, \cos \theta \sin \phi, \sin \theta) \), then equation (8) can be derived from equation (7).

\[
U = -\varepsilon_0(\epsilon_{||} - \epsilon_{\perp})E^2(\epsilon_{||} \sin^2 \theta + \epsilon_{\perp} \cos^2 \theta) + \epsilon_{\perp}E_z^2
\]

Applied torque to director by the electric field is shown in equation (10).

\[
f = -\frac{\partial U}{\partial \theta} = \frac{1}{2}\varepsilon_0(\epsilon_{||} - \epsilon_{\perp})E^2 \sin(2\theta)
\]

Under the assumption that \( \sin \theta \approx \theta \) when \( \theta \) is very small,

\[
f = \varepsilon_0(\epsilon_{||} - \epsilon_{\perp})E^2 \theta
\]

For the convenience, the dielectric anisotropy \( \Delta \varepsilon \) is defined as \( \Delta \varepsilon = \epsilon_{||} - \epsilon_{\perp} \). Then,

\[
f = \varepsilon_0\Delta \varepsilon E^2 \theta
\]

When equation (12) replaces the electrical term in equation (1), torque balance equation (1) can be rewritten by equation (13).

\[
\varepsilon_0\Delta \varepsilon E^2 \theta = K \theta + \gamma \frac{d\theta}{dt}
\]

\[
\frac{d\theta}{dt} = \left( \frac{\varepsilon_0\Delta \varepsilon E^2 - K}{\gamma} \right) \theta
\]

Therefore the time constant for equation (14) can be expressed as follows.

\[
\tau = \frac{\gamma}{\varepsilon_0\Delta \varepsilon E^2 - K}
\]

\[
= \frac{1}{\left( \frac{\varepsilon_0\Delta \varepsilon}{\gamma} \right) \left( \frac{V}{a} \right)^2 - \left( \frac{K}{\gamma} \right)}
\]

\[
= \frac{1}{a_1 + a_2V^2}
\]
**Model Validity**

- Dynamic electrical Behavior

![Graphs showing rise and fall processes with model parameters:]

\[a_{1c_r}=0.070, \quad a_{2c_r}=0.030, \quad m_{t_c}=2.40\]

(a) Rise process

\[a_{1c_f}=0.070, \quad a_{2c_f}=0.030, \quad m_{t_c}=2.05\]

(b) Fall Process