Third-order Nonlinear Dynamic Model for Electrical Characterization of Organic Light-emitting Diodes

Mun Chae Yoon*, Gyu-Tae Kim* and Tae-Woong Yoon[†]

Abstract – A third-order nonlinear model for organic light emitting diodes (OLEDs) is presented. The model can consistently describe dynamic and static characteristics of OLEDs. The model can also be used to estimate the physical characteristics of specific layers of an OLED. The parameters of the proposed model are estimated using a trust-region algorithm and a particle swarm optimization algorithm. Several of the resulting parameters relate to the electrical and light emission characteristics of OLEDs. Using only one set of experiments on an OLED device, a nonlinear model including all parameters, can be obtained; this method is highly advantageous for the fast quality control of OLEDs.

Keywords: Organic light-emitting diodes, System identification, Nondestructive testing

1. Introduction

Organic light emitting diodes (OLEDs) are widely used in the displays of electrical devices including TV displays, mobile devices, and lighting. Moreover, OLEDs have received attention as next-generation displays because of their merits including low production costs, high durability, high efficiency, high flexibility, a lack of mercury, and emission without UV rays [1].

Therefore, research is actively being conducted into OLED light emission mechanisms. The main issues of light emission from an OLED include carrier injection, recombination, and transport processes [2]. These processes are closely related to the electrical characteristics of OLEDs. For this reason, electrical behavior prediction and analysis of electrical characteristics for OLEDs are important while studying the light emission mechanisms of OLEDs.

To understand the electrical characteristics of an OLED, Roy et al. analyzed the organic layer using a parallel RC circuit and evaluated the electrical properties employed in layer-by-layer self-assembled thin films [3]. Liao et al. reported the PN junction effects in an OLED [4]. Pitarch analyzed the SCLC (space charge limited conduction) effects occurring in an OLED [5]. Therefore, the extraction of parameters related to PN junctions and SCLC is a key process in the analysis of OLEDs.

To extract parameters, low-frequency impedance spectroscopy, steady-state I-V measurements, photo-detectors, and impedance meters are used [6]. However, each method only estimates a small number of parameters. Therefore, employing existing methods for estimating the important OLED parameters is costly and laborious, requiring separate sets of experiments and measurements. Moreover,

as some measurements use linearization techniques, the measurement results can vary because of the DC biases.

To reduce the required effort and inaccuracy of existing estimation methods, we suggested the second-order nonlinear model for an OLED [7]. This model can be used for OLED's electrical behavior prediction and parameter estimation based on the PN junction using a single data set. However, this model cannot be used to independently inspect each layer of an OLED because this model does not consider the electrical characteristics of an OLED's layers (except for the emission layer).

This paper proposes a third-order nonlinear model, which considers the layer structure of an OLED and contains parameters related to the PN junction and SCLC. Trust-region (TR) algorithms and particle swarm optimization (PSO) algorithms are employed to estimate these parameters using a single set of measurement data. As a consequence, this nonlinear model efficiently provides in-situ characterization of the OLED parameters. All of the parameters related to the PN junction and SCLC are simultaneously estimated, which is demonstrated in our experimental results. Moreover, model parameters are used to estimate the physical characteristics of the layers of the OLED.

2. Structure of an OLED and Model

In this section, the structure of the OLED under test is explained. The third-order model suggested in this paper is also explained and is compared to the second-order model for OLEDs presented in our previous works. [7]

2.1 Structure of an OLED

An OLED consists of several thin layers of film: the cathode, electron injection layer (EIL), electron transport layer (ETL), emission layer (EML), buffer layer, hole

[†] Corresponding Author: School of Electrical Engineering, Korea University, Korea. (twy@korea.ac.kr)

* School of Electrical Engineering, Korea University, Korea. ({gkst41x, gtkim}@korea.ac.kr)

Received: January 2, 2016; Accepted: April 25, 2016

Fig. 1. Structure of an OLED

transport layer (HTL), and p-type doped hole transport layer (p-HTL). The capping layer (CPL) surrounds the thin layers as depicted in Fig. 1.

Among the layers, ETL, HTL, and EML play important roles in the electrical and light emission mechanisms of an OLED. These layers are made of organic materials.

2.2 Structure of the third-order Model for OLEDs

The second-order nonlinear model suggested in [7] considers two electrical characteristics of an OLED, the PN junction and parasitic elements. In the second-order model, it is assumed that only the EML affects the parameters related to the PN junction since the EML has a similar structure to that of a PN diode. It is also assumed that the other layers only affect the parasitic elements. Therefore, the second-order model can be used to find only the electrical parameters related to the EML. Therefore, the second-order model cannot be used to find electrical parameters related to HTL or ETL, which is a drawback, because the HTL and ETL also play an important role in the light emission mechanism of OLEDs.

To evaluate the electrical mechanisms occurring in the ETL and HTL, the third-order model for OLEDs is developed. The third-order model is created by adding a parallel RC circuit that reflects the parameters related to the SCLC mechanism to the second-order nonlinear model. Since a parallel RC circuit is added, the structure of the third-order nonlinear model changes, as shown in Fig. 2

In Fig. 2, V_{OLED} and I_{OLED} denote the voltage across the OLED and current flow through the OLED, respectively.

Fig. 2. Equivalent circuit of an OLED

The parallel RC circuit, consisting of C_{PN} and R_{PN} , is an equivalent circuit for the PN junction. C_{PN} and R_{PN} are given by [8]

$$R_{PN} = R_{PN0} V_{PN} / \exp\left(\frac{V_{PN}}{nkT}\right) \quad (1)$$

$$C_{PN} = C_{PN0} \exp(V_{PN}/nkT) \quad (2)$$

where V_{PN} is the voltage drop due to the PN junction. n , k , and T are the ideality factor, Boltzmann constant, and absolute temperature, respectively. R_{PN0} and C_{PN0} are coefficients.

The parallel RC circuit consisting of C_{SC} and R_{SC} is an SCLC-equivalent circuit. C_{SC} and R_{SC} are given by [9]

$$R_{SC} = R_{SC0} V_{SC}^l \quad (3)$$

$$C_{SC} = C_{SC0} V_{SC}^l \quad (4)$$

where V_{SC} is the voltage drop due to SCLC. l is a parameter that is determined by impurity concentration. R_{SC0} and C_{SC0} are coefficients. R_P and C_P are parameters representing parasitic resistance and capacitance, respectively.

Combining the equivalent circuits of the mechanisms occurring in the OLED, the differential equations of the model are as follows:

$$\dot{V}_{OLED} = [I_{OLED} - (V_{OLED} - V_{PN} - V_{SC})/R_P]/C_P \quad (5)$$

$$\dot{V}_{PN} = nkT/[C_{PN0} \exp(V_{PN}/nkT)] \times [(V_{OLED} - V_{PN} - V_{SC})/R_P - \exp(V_{PN}/nkT)/R_{PN0}] \quad (6)$$

$$\dot{V}_{SC} = 1/[(l+1)C_{SC0} V_{SC}^{l-1}] \times [(V_{OLED} - V_{PN} - V_{SC})/R_P - V_{SC}^{l+1}/R_{SC0}] \quad (7)$$

3. Parameter Estimation using the Model

The OLED analyzed in the paper is made by Samsung Display Co., Ltd.; it is a bottom-emitting device, i.e., light generated in EML radiates through HTL. However, the data sheet parameters are unknown. For measurement purposes, a resistor R_L is connected in series with the OLED as shown in Fig. 3. The room temperature is 298K.

To create the overall circuit, V_{IN} is applied, and V_{OLED} is measured as the output. I_{OLED} is given by

Fig. 3. Measurement circuit for the OLED

$$I_{OLED} = (V_{IN} - V_{OLED})/R_L \quad (8)$$

To estimate the parameters of the model, a two-stage estimation strategy is introduced. In this strategy, the parameters are divided into θ_1 and θ_2 which are given by

$$\theta_1 = [R_{PN0} \ R_{SC0} \ R_P \ n \ l]^T \quad (9)$$

$$\theta_2 = [C_{PN0} \ C_{SC0} \ C_P]^T \quad (10)$$

In the first stage, θ_1 is estimated using the TR algorithm provided by Fontes et al. [10]. In the second stage, θ_2 is estimated using the PSO algorithm provided by Schwaab et al. [11].

To allow estimation using only one data set, V_{IN} is split into two parts. One part is a stepwise signal for measuring the static response of the OLED. The other is a pseudorandom binary sequence (PRBS) signal for measuring the dynamic response of the OLED. The PRBS signal is a sequence of pulse-width-modulated rectangular pulses, which has more frequency components than simple square waves [12]. The resulting V_{IN} values are shown in Fig. 4.

In Fig. 4, (a) shows the entire sequence of V_{IN} ; (b) shows the first part (stepwise increase) of V_{IN} , which is used for the estimation of θ_1 ; and (c) shows the second part (PRBS) of V_{IN} , which is used for the estimation of θ_2 .

3.1 Estimation of θ_1

In the first stage of model parameter estimation, θ_1 is estimated using the TR algorithm, which minimizes (11).

$$f(\hat{\theta}_1) = \sum_r \|\bar{V}_{OLED}(r) - \hat{V}_{OLED}(\hat{\theta}_1, r)\|^2 \quad (11)$$

Fig. 4. Input (V_{in}) used for model estimation

where $\bar{V}_{OLED}(r)$ is the steady state value of V_{OLED} when the input V_{IN} takes the r th value of the stepwise part, which is given by

$$\bar{V}_{OLED}(r) = R_P \bar{I}_{OLED}(r) + nkT \log(R_{PN0} \bar{I}_{OLED}(r)) + (R_{SC0} \bar{I}_{OLED}(r))^{1/(l+1)} \quad (12)$$

with $\bar{I}_{OLED}(r)$ computed by (8); $\hat{V}_{OLED}(\hat{\theta}_1, r)$ is the estimated value of $\bar{V}_{OLED}(r)$ with the parameter vector θ_1 replaced by its estimate $\hat{\theta}_1$. Note that equation (12) results from setting the left-hand sides of (5)-(7) to zero.

Let θ_1^j denote the candidate estimate at the j th iteration for θ_1 . Then the improvement direction denoted by $\Delta\theta_1^j$ is given as follows:

$$\Delta\theta_1^j = \arg \min_{\|Ds\| < \Delta} \{s^T Hs + s^T g\} \quad (13)$$

where H and g are the Hessian matrix and the gradient of $f(\theta_1^{j-1})$, respectively; D and Δ are the scaling matrix and a positive integer, respectively. If the constraint in (14) is satisfied, θ_1^j is updated using (15).

$$f(\theta_1^{j-1} + \Delta\theta_1^j) < f(\theta_1^{j-1}) \quad (14)$$

$$\theta_1^j = \theta_1^{j-1} + \Delta\theta_1^j \quad (15)$$

If the constraint in (14) is not satisfied, reduce Δ and recalculate (13) until (14) is satisfied. This iteration procedure is repeated until $\Delta\theta_1^j = 0$ or j reaches a given maximum iteration number. The estimation results for θ_1 are shown in Table 1.

3.2 Estimation of θ_2

In the second stage of model parameter estimation, θ_2 is estimated by the PSO algorithm using $\hat{\theta}_1$ obtained in TABLE I. Let $\theta_2^{j,i}$ denote the i th candidate estimate for θ_2 at the j th iteration, for $1 \leq i \leq M$, where M is the number of candidate estimates at each iteration; the best estimate $\theta_2^{*,i}$ of the i th candidate is given by

$$\theta_2^{*,i} = \arg \max_{\theta_2 \in \{\theta_2^{j-1,i}, \theta_2^{j,i}\}} h(\hat{\theta}_2) \quad (16)$$

where $h(\hat{\theta}_2)$ is the objective function defined as

$$h(\hat{\theta}_2) = -\sum_t \|V_{OLED}(t) - \hat{V}_{OLED}(\hat{\theta}_2, t|\hat{\theta}_1)\| \quad (17)$$

and $\hat{V}_{OLED}(\hat{\theta}_2, t|\hat{\theta}_1)$ is the estimated value of $V_{OLED}(t)$

Table 1. Estimation results for θ_1

Parameters in $\hat{\theta}_1$	
$R_{PN0} (\Omega)$	1.33×10^{25}
$R_{SC0} (\Omega)$	1.04×10^3
$R_P (\Omega)$	10.0
n	2.33
l	1.00

using (5)-(7) with θ_2 replaced by its estimate $\hat{\theta}_2$ while the value of θ_1 is fixed to $\hat{\theta}_1$ in Table 1. Then, the best estimate $\theta_2^{k,*}$ at the k th iteration is calculated using

$$\theta_2^{k,*} = \arg \max_{1 \leq i \leq M} h(\theta_2^{i,*}) \quad (18)$$

Having obtained the estimate $\theta_2^{k,*}$ from $\theta_2^{j,i}$ for $1 \leq j \leq k$ at the k th iteration, $\theta_2^{k+1,i}$ is updated for the next iteration as follows:

$$\theta_2^{k+1,i} = \theta_2^{k,i} + c_1^i(\theta_2^{*,i} - \theta_2^{k,i}) + c_2^i(\theta_2^{k,*} - \theta_2^{k,i}) \quad (19)$$

where c_1^i is a random number between 0 and c_1^m , and c_2^i is a random number between 0 and c_2^m . c_1^m and c_2^m are pre-determined constants; in the estimation, c_1^m and c_2^m are 1.5. The value of $\theta_2^{k+1,i}$ resulting from (19) is further constrained to satisfy the following inequalities:

$$\begin{aligned} 10^{-15} &\leq C_P \leq 10^{-8} \\ 10^{-35} &\leq C_{PN0} \leq 10^{-27} \\ 10^{-23} &\leq C_{SC0} \leq 10^{-11} \end{aligned} \quad (20)$$

These constraints are given on the basis of the known physical characteristics such as the turn-on time of the device.

The best estimate $\theta_2^{*,k+1}$ at the $(k+1)$ th iteration is obtained using the same procedure as given above. This iteration procedure is repeated until the objective function $h(\theta_2^{*,k})$ converges. In this paper, the algorithm is stopped at the 16th iteration. Thus, the estimation result $\theta_2^{16,*}$ of the iteration procedure becomes the final estimate of θ_2 . The final estimate of θ_2 is given in Table 2.

Table 2. Estimation results for θ_2

Parameters in $\hat{\theta}_2$		
C_{PN0} (F)	C_{SC0} (F)	C_P (F)
2.82×10^{-34}	1.55×10^{-15}	2.79×10^{-9}

4. Model Verification with Experimental Check

In this section, the validity of the model estimated in the previous section is demonstrated. The validity is confirmed using two methods. One method compares the dynamic and static characteristics of the OLED and the resulting model. The other method identifies whether the resulting model parameters accurately reflect the OLED's physical characteristics.

4.1 Model verification with input-output data

The validity obtained by comparing the input-output relationship between the OLED and the resulting model identified in the previous section, is demonstrated here; both

dynamic and static characteristics of the OLED are shown, to be consistent with the corresponding experimental data.

Static characteristics of the model are verified by comparing the I-V relationships of the OLED and the resulting model. I-V curve of the resulting model can be obtained analytically by solving the steady-state equations as shown in (12). These results are compared to the experimental data in Fig. 5, in which two curves are seen to be very close to each other.

Note that the current is shown in log scale in the smaller figure and in linear scale in the larger figure. The maximum value of the residual is less than 7% of the current flowing into the OLED. Since the turn-on voltage of the OLED is roughly 3 V, the I-V relationship is compared when V_{OLED} is larger than 2.5 V.

To verify the dynamic performance of the third-order model, the output of the resulting model is compared to that of the OLED. The comparison results obtained are shown in Fig. 6, in which the model outputs are seen to match the real-world data. Note that the PRBS signal applied in this experiment is different from the third-order model in Fig. 4, which is used in the parameter estimation. The maximum value of the residual is less than 5 % of the output of the OLED.

4.2 Model verification via analyses of the model parameters

OLEDs, which have the same materials but with

Fig. 5. Static characteristics comparison result for the OLED (solid line) and the model (dotted line)

Fig. 6. Dynamic characteristics comparison result for the OLED (solid line) and the model (dotted line)

Table 3. Thickness/brightness comparison for the OLEDs

	Layer Thickness(nm)			Brightness(W)
	ETL	EML	HTL	
Std	36	20	135	24.9×10^{-7}
M-ETL	60	20	135	18.7×10^{-7}
M-EML	36	40	135	0.93×10^{-7}
M-HTL	36	20	180	3.30×10^{-7}

Table 4. Parameters comparison for the OLEDs

	Parameters to be compared		
	R_p	n	l
Std	10.0	2.53	1.00
M-ETL	10.0	2.13	1.01
M-EML	3.00×10^2	3.11	4.43
M-HTL	16.7	2.56	1.00

thickness of layers being different, are modelled in this section for the purpose of verifying the relation between the physical characteristics of OLEDs and the model parameters. Table 3 lists detailed thickness and brightness information for the OLEDs used in the experiment.

Brightness indicates the lighting power measured by the photodetector placed 5 cm away from the OLEDs when the voltage applied to the OLEDs is 4 V. Note that the OLED named Std is the one verified in the previous section; it has the highest lighting efficiency among the other OLEDs.

Low light emission efficiency of the OLED named M-HTL is caused by degradation of the thick HTL. Estimation results for several important model parameters of the OLEDs are shown in Table 4.

Comparing Std to M-HTL and M-ETL, we see that the thickness modification of HTL has little effect on the parameters of the estimated models. Whereas, thickness modification of the ETL affects the value of n of the model. Based on these results, we estimate that the sheet resistivity for holes in the HTL will be significantly smaller than the sheet resistivity for electrons in the ETL. This implies that the hole mobility of HTL is much larger than the electron mobility of ETL, which is confirmed by the well-known results of Park [13].

Comparing Std to M-EML, the value of R_p of the model for M-EML is larger than that of Std. Based on this result, we estimate that the power consumption ratio, not generating excitons but instead generates heat, will increase. Moreover, the sharp increase means that the ratio of traps, which does not affect the light emission mechanism, increases in the EML. These results match the lowest light emission efficiency of the M-ETL among the other OLEDs used in the experiments.

Based on these analyses, we have confirmed that several of the model parameters are useful to reveal the physical characteristics of an OLED. Specifically, the results of in Section IV. B confirm that the model can be used to determine the optimal thickness of the layers of the OLED using a simple experiment.

5. Conclusion

A novel third-order nonlinear model for an OLED was suggested; its parameters were estimated using the TR algorithm and the PSO algorithm. Experiments showed that the proposed nonlinear modeling method is effective when describing the dynamic and static behavior and estimating some of the physical characteristics of the OLED, which means that this model can be used to determine the optimal structure for an OLED in terms of light emission efficiency. Using a single set of experiments, it was possible to estimate all of the important parameters and characteristics of the OLED; this was in sharp contrast with conventional cases in which different experiments are carried out for the different characteristics of the device.

Further investigation will be conducted to reveal more closely the correlation between the model parameters and the device performance, such as determining the relationship between aging effects and the model parameters. It will also be necessary to develop a more efficient estimation scheme because the PSO algorithm employed in this paper is relatively slow.

Acknowledgements

This work was supported by Samsung Display Co., Ltd. Tae-Woong Yoon is also grateful to Korea University for sabbatical leave at Jeju National University when this work was performed.

References

- [1] T. Komoda, N. Ide, and J. Kido, "High efficient OLEDs and their application to lighting", *Journal of Light & Visual Environment*, vol. 32, pp. 75-78, 2008
- [2] J. Ahn, D. Chung, and J. Lee, "Equivalent-circuit analysis of organic light-emitting diodes by using the frequency-dependent response of an ITO/Alq3/Al device", *Journal of the Korean Physical Society*, vol. 46, pp. 546-550, 2005
- [3] S. Roy, S. Kundu, S.K. Roy, and A.J. Pal, "Impedance characteristics of layer-by-layer electro-static self-assembled films of evans blue.", *Materials Chemistry and Physics*, vol. 77, pp. 784-790, 2003
- [4] L. S. Liao, K. P. Klubek, and C. W. Tang, "High-efficiency tandem organic light-emitting diodes", *Applied Physics Letters*, vol. 84, pp. 167-169, 2004
- [5] T. Mori, T. Ogawa, D. C. Cho, and T. Mizutani, "A discussion of conduction in organic light-emitting diodes", *Applied surface science*, vol. 212, pp. 458-463, 2003
- [6] R. K. Ahrenkiel, "Measurement of minority-carrier lifetime by time-resolved photoluminescence", *Solid-*

- state electronics, vol. 35, pp. 239-250, 1992
- [7] M. C. Yoon, S. H. Choi, Y.-J. Kim, G.-T. Kim, and T.-W. Yoon, "Note: In-situ parameter extraction from a nonlinear dynamic model for electrical characterization of OLEDs", *Review of Scientific Instruments*, vol. 85, pp. 116102, 2014
- [8] S. O. Kasap, *Principles of Electronic Materials and Devices*, McGraw-Hill, Columbus, OH, 2006
- [9] A. Rose, "Space-charge-limited currents in solids", *Physical Review*, vol. 97, pp. 1538, 1955
- [10] J.J. Moré and D.C. Sorensen, "Computing a trust region step", *SIAM Journal on Scientific and Statistical Computing*, vol. 4, pp. 553-572, 1983.
- [11] M. Schwaab, E. C. Biscia Jr, J. L. Monteiro, and J. C. Pinto, "Nonlinear parameter estimation through particle swarm optimization", *Chemical Engineering Science*, vol. 63, pp. 1542-1552, 2008
- [12] W. D. T. Davies, *System Identification for Self-adaptive Control*, Wiley-Interscience, Hoboken, NY, 1970
- [13] J. Park, "Speedup of dynamic response of organic light-emitting diodes", *Journal of Lightwave Technology*, vol. 28, pp. 2873-2880, 2010

Tae-Woong Yoon He received his B.S. and M.S. degrees in Control Engineering from Seoul National University in 1984 and 1986, and his D.Phil degree in Engineering Science from Oxford University. During 1986-1994, he worked as a researcher at the Korea Institute of Science and Technology (KIST). In 1995, he joined the faculty of Electrical Engineering, Korea University where he is now a Professor. His research interests include control/systems theory, e.g. on adaptive systems and model predictive control (MPC). As an educator, he emphasizes to his students the importance of mathematical/critical thinking and logical/clear technical writing.

Mun Chae Yoon He received B.S degree in electrical engineering from Korea University in 2008. His research interests include nondestructive testing, system identification and organic electronic devices.

Gyu-Tae Kim He received B.S, M.S and PhD degree in Physics from Seoul National University in 1992, 1996 and 2000. During 2000-2002, he worked as a Humboldt Fellow at the Max-Planck Institute for Solid State Physics in Stuttgart. In 2002, he joined the faculty of Electrical Engineering, Korea University. His research interests include emerging electronic devices such as low-dimensional nanoscale electronic devices, and organic electronic devices.