Dynamic Non-linear Model for High Luminous Flux Blue LED

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Introduction

In recent years, Light Emitting Diodes (LEDs) have undergone remarkable advancements, solidifying their place as integral components across myriad applications, ranging from lighting and displays to communication systems. With their applications becoming increasingly diverse, there arises a need for accurate and sophisticated models capable of capturing the complex behavior of these devices.

To achieve high data rates in Visible Light Communication (VLC), signal modulation beyond the LED linear zone is required. Different models like the Volterra, memory polynomial, Wiener, and Hammerstein have been proposed to characterize the static non-linearities [1]. The first two combine memory effects and non-linear responses, while the latter two separate linear and non-linear responses into distinct blocks [2]. The Volterra model offers superior performance at the cost of more complex parameter extraction [3].

[4] shows that when OFDM signals are modulated beyond the 3-dB cut frequency of the LED, the modulated signal is affected not only by the frequency response of the LED, but also by dynamic non-linearities such as memory effects and non-white distortion noise. [4] proposes a dynamic non-linear model inspired by the physical behavior of LEDs, whose validity is tested experimentally with a mid-power infrared LED.

On the other hand, a linear system model for high luminous flux LED is proposed in [5]. It shows that the well-known 1st-order model of the intrinsic LED is no longer suitable when the LED is mounted in a lighting fixture, and a 2nd-order model is required. This is because some parasitic effects appear (e.g., the inductance and resistance of the wires and lighting fixture).

This paper extends the system linear model of [5] to add the dynamic non-linear model of [4] and shows that the model is suitable to emulate wide-band OFDM transmission with high luminous flux blue LED.

Proposed model

A dynamic LED model is proposed in [4], which is particularly suited for LEDs with a homogeneous distribution of charge carriers in the Quantum Well (QW). This model defines the photon output power ($X_{\phi}(f)$) as the addition of a linear term $H_1(f)X_{IN}(f)$ and a non-linear distortion term $H_3(f)X_D(f)$:

$$X_{\phi}(f) = H_1(f)X_{IN}(f) + H_3(f)X_D(f) \qquad (1)$$

$H_1(f)$ is the intrinsic LED's linear response, $X_{IN}(f)$ is the input signal, $H_3(f)$ is a high-pass filter for the non-linear distortion, and $X_D(f)$ is the self-convolution of $H_1(f)X_{IN}(f)$.

The intrinsic LED's linear response ($H_1(f)$) is a 1st-order low-pass filter with the 3-dB bandwidth of the LED (f_{LED}).

$$H_1(f) = \frac{E_p}{q}\frac{2\pi f_0}{2\pi f_{LED} + 2\pi jf} \quad , \qquad (2)$$

where f_0 is the radiative recombination rate ($2\pi f_0 = 2BN_{QW}$) and is lower than f_{LED}, E_p is the photon energy, N_{QW} is the carrier concentration, B is the radiative coefficient of the generally accepted ABC-model ([6]), and q is the elementary charge of $q = 1.6 \times 10^{-19}$ coulomb.

$H_3(f)$ constitutes a high-pass filter characterized by the quasi-stationary cut-off frequency (f_x) and the 3-dB bandwidth of the LED (f_{LED}). f_x represents the frequency below which static non-linearities accurately describe the LED's response, whereas at frequencies below $|f_x|$, dynamic non-linearity supersedes static distortion.

$$H_3(f) = A_{\phi}BN_{QW}^2\frac{2\pi f_x + 2\pi jf}{2\pi f_{LED} + 2\pi jf} \quad , \qquad (3)$$

where $A_{\phi} = E_pA_wt_w$, and A_w and t_w are the active area and thickness of the LEDs with a QW, respectively.

The blue LED is modeled in [5] as a 2nd-order system (Eq. (4)) with real poles $-p_{b1}$, $-p_{b2}$, and $k_b = H_b(0)$.

$$H_b(s) = \frac{k_b}{\left(\frac{s}{p_{b1}} + 1\right)\left(\frac{s}{p_{b2}} + 1\right)} \qquad (4)$$

Next, the integration of both models ([4] and [5]) is detailed. Although the model in [4] involves parameters that can be intricate to obtain, the proposed integration maintains the simplicity and ease of modeling of [5]. Fig. 1 shows the model proposed for the blue LED, where $H_b(s)$ is the transfer function of the blue LED from [5] (Eq. (4)) and $H_d(s)$ is the high-pass filter of the non-linear distortion branch.

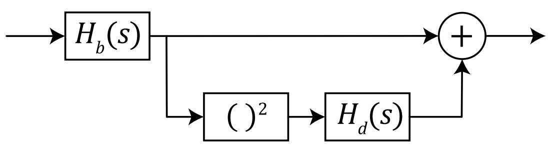

Fig. 1. Non-linear Blue LED model.

Even though $H_b(s)$ is a 2nd-order low-pass filter, $H_d(s)$ retains its 1st-order characteristic from [4] because the nonlinearity only depends on the intrinsic LED properties (without the influence of parasitic effects). With all this, $H_d(s)$ is a 1st-order high pass filter (Eq. (5)), with one pole $(-p)$ and one zero $(-z)$ and $p > z$.

$$H_d(s) = K\frac{s+z}{s+p} \tag{5}$$

Measurement Setup and Model Calibration

The experiments were carried out with the OSRAM LZ4-40CW08-0065, a phosphor-coated white LED composed of 4 LEDs connected in series, biased at 650 mA. The modulation used in the experiments was OFDM with 4-QAM, a cyclic prefix of 32 samples, a sampling frequency of 100 MHz, and a 256-point FFT, which corresponds to a bandwidth of 25 MHz.

The experimental setup in [7], whose block diagram is in Fig. 2, was used to perform the measurement.

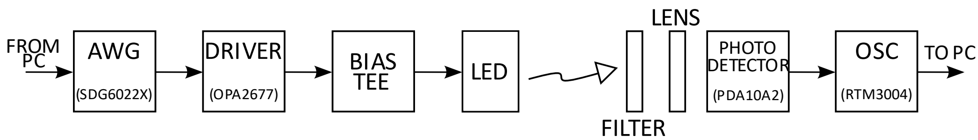

Fig. 2. Scheme of the LED setup.

The use of a blue filter was required to detect only the blue component of the light transmitted by the white LED. The measurements were done at 40 cm, and the noise level measured in the setup was used in the simulations.

The parameters of the non-linear blue LED model were extracted as follows. On the one hand, $H_b(s)$ was obtained from [5] as the same LED model was used. On the other hand, the estimation of the pole, zero, and gain, K, of $H_d(s)$ was performed by inspecting the EVM (Error Vector Magnitude) curve, which was measured during the transmission of a wideband OFDM signal using the maximum achievable voltage (9 Vpp) with the aim of inducing significant nonlinear behavior. First, K was set so the simulated EVM equaled the measured EVM at high frequencies. Then, p and z were set so both EVMs matched at low frequencies. As a result, the values obtained for K, p, and z were $K = 0.17$, $p = 9.42 \times 10^7 s^{-1}$, and $z = 8.79 \times 10^6 s^{-1}$.

Once the values of K, p, and z were determined, the model performance was evaluated through transmissions with different amplitudes as shown in the Results section.

Results

This section compares the measurements performed with the setup of Fig. 2 and simulations to validate the proposed model.

Fig. 3 shows (a) the transmitted power spectrum, the measured power spectrum of the received OFDM signal after photodetection and its estimation, and (b) the estimated throughput of the measured and simulated signal using bit loading as in [7]. As can be seen, the VLC link frequency response and its dynamic non-linearity are accurately modeled.

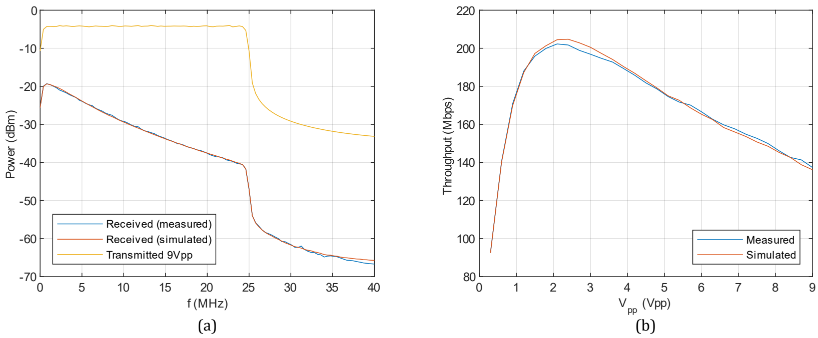

Fig. 3. (a) Transmitted and received (measured and simulated) power spectrum for 9Vpp OFDM signal; (b) Estimated throughput of the measured and simulated signal.

Conclusions

The models introduced in [4] and [5] offer insightful frameworks for comprehending the LEDs with quantum wells and the varied behaviors of LEDs in Visible Light Communication, respectively. Integrating these models and refining their parameters facilitated to capture and predict the complex dynamics of LED performance effectively. Through a blend of empirical measurements and simulations, the robustness and effectiveness of the proposed model are showcased. This enhanced understanding paves the way for more precise design and optimization of LED-based systems.

Funding: This research was funded by MCIN/AEI/10.13039/501100011033; by the European Union's “ERDF A way of making Europe” grant numbers PID2021-126514OB-I00 and RTI2018-101296-B-I00; and by the Ministerio de Ciencia, Innovación y Universidades para la Formación de Profesorado Universitario, grant number FPU19/04648.

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