Modeling and Implementation of Micro-LEDs for High-Speed Visible Light Communication Circuits

Xinyi Liu, Li Wang*, Chongyun Zhang*, Zhaojun Liu**, and C. Patrick Yue**

***State Key Laboratory of Advanced Displays and Optoelectronics Technologies and the Integrated Circuit Design Center, Hong Kong University of Science and Technology**

****Department of Electrical and Electronic Engineering, Southern University of Science and Technology**

In recent years, with the rapid development of information technology, high-speed data transmission plays an increasingly important role in people's daily life. The booming wireless communication business has continuously expanded the demand for internet bandwidth. However, the traditional radio frequency (RF) spectrum resources used now are very limited, and most of them have been allocated. Even now, through spectrum resource management and dynamic spectrum access, people have alleviated the shortage of RF spectrum resources to a certain extent. But in the foreseeable future, the lack of spectrum resources will still limit the development of RF technology, people need to develop more effective wireless communication technologies. Visible light communication (VLC) technology emerges at the historic moment. Compared with traditional wireless communication technology, VLC technology does not occupy wireless spectrum resources and does not require spectrum licenses. Since the wavelength range of visible light is 380-750 nm, as shown in Fig. 1, the spectrum of visible light is even tens of thousands of times that of the traditional RF spectrum, so there is no need to worry about the exhaustion of spectrum resources. In addition, VLC technology also has the advantages of integrated communication and display, communication and lighting, green environmental protection, safety and confidentiality, no electromagnetic interference, no electromagnetic radiation, small size, and easy establishment. It can be used in special demand areas such as hospitals, airplanes, nuclear power plants, and mines, and can also be used in indoor homes as a supplement to 5G/6G mobile communications. VLC technology has great development prospects.

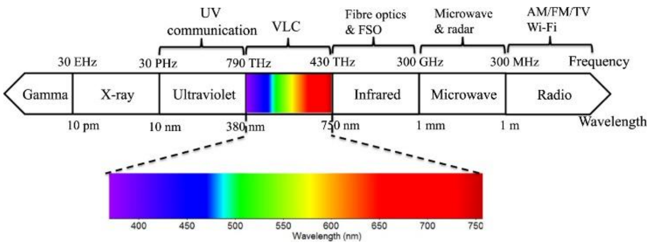


Fig. 1. The electromagnetic spectrum.

The choice of light source is an important part of designing a VLC system. The VLC system bandwidth is fundamentally limited to the electrical to optical bandwidth of light source. The light sources that can be used for VLC are mainly focus on light-emitting diode (LED), laser diode (LD) and Micro-LED [1]. Due to low cost and long lifetime, most of the light sources commonly used in VLC systems are commercial phosphorescent LEDs. However, because of the low response speed of phosphors, the bandwidth of conventional LED is limited to a dozen or even a few MHz [2-3], which cannot meet the requirements of high modulation bandwidth and high transmission data rate. It severely restricts the development of VLC technology. Micro-LED is a new generation of display and lighting technology, its size is smaller than the general LED, usually in the micron level, as shown in Fig. 2. Ga-based Micro-LED has shorter carrier lifetime, better current diffusion effect and better thermal diffusion effect. Affected by this, Micro-LED also has larger bias current density as LD, and the modulation bandwidth of Micro-LED can also reach almost GHz level by applying specific epitaxial structure [4]. Because of the small size of Micro-LED, its parasitic capacitance is relatively small, resulting in a higher frequency of response to electrical signals, allowing faster signal transmission and reducing data delay.

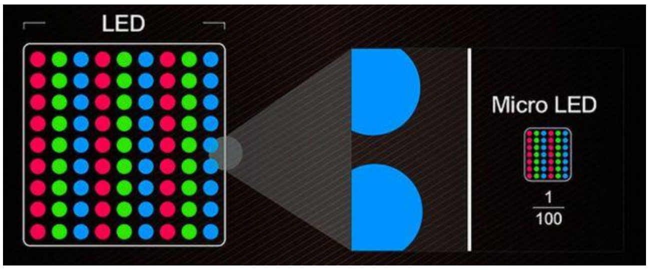


Fig. 2. Comparison diagram of Micro-LED and commercial LED.

There is no doubt that Micro-LED is a very competitive VLC light source candidate. However, only improve the quality of light source itself still cannot meet the high-speed communication needs. In the existing research, the advantages of most light sources have not been fully utilized. Therefore, the compact equivalent circuit model of Micro-LED is of practical importance for designing efficient driver and modulation circuits as well as equalizers to extend modulation bandwidth. Without compact equivalent model of Micro-LED, it is impossible to customize the drive circuit and modulation circuit design of the Micro-LED according to the properties of the device, so that the circuit in the design stage cannot predict the performance of the actual VLC system, which increases the risk of circuit design failure.

The compact equivalent model of VLC light source is usually divided into two parts: electrical extrinsic model and optical intrinsic model [5]. The electrical extrinsic model is mainly composed of parasitic passive components: resistor, inductor and capacitor. The optical intrinsic model takes into account the diffusion and recombination of carriers in the device, which can be fitted as a first-order RC response function, it can be analyzed by Matlab. For the electrical extrinsic model, it must be based on the physical properties of the device itself. As shown in Fig. 3, the parasitic components that will affect the performance of VLC system are the series resistor R_s of intrinsic Micro-LED from p-pad to n-pad, junction resistor R_j of active region, and junction capacitor C_j of active region which are inside the device. For the parasitic components outside the device, they are parasitic resistor R_b of bonding wire, parasitic capacitor L_b of bonding wire and parasitic parallel capacitor C_b between the bonding wires. The impedance of the Micro-LED can be obtained from the vector network analyzer (VNA) by testing the S-parameters. Import the S-parameter into Advance Design System (ADS), build a compact equivalent circuit in the ADS, and use the built-in tunning and optimize functions of ADS to fit the parasitic parameter of the Micro-LED. The model can be fitted at the circuit level to facilitate the further circuit design.

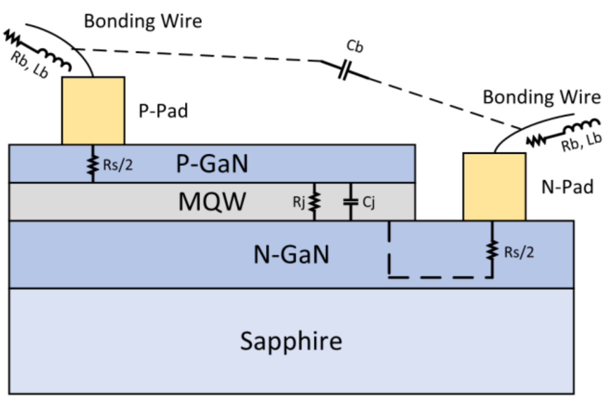


Fig. 3. The general device structure of Micro-LED.

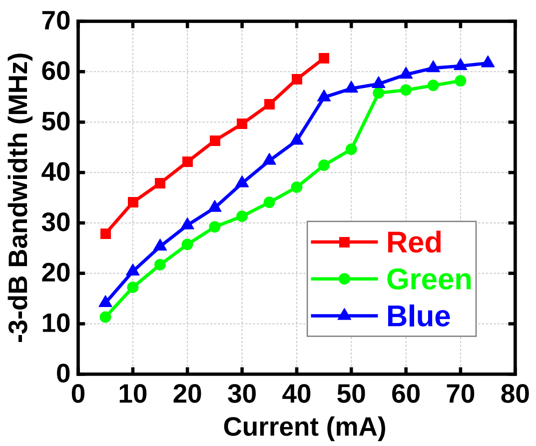


Fig. 4. Measured VLC system bandwidth under different current bias.

In this paper, an all-in-one Micro-LED pixel technology that integrate red-green-blue (RGB) sub-pixels in a single unit cell is presented. According to the measurement results, this Micro-LED pixel technology delivers excellent electrical, optical and communication link characteristics, including wide color gamut (109% NTSC), wide correlated color temperature range (2831.7~10016.8 K), and high modulation system bandwidth (58~62 MHz), which has great potential for application in lighting, display and high-speed communication. The measured system bandwidth of RGB sub-pixel is shown in Fig. 4. The bandwidth of VLC system increases with the diode bias current. When the RGB sub-pixels are bias at 45 mA, 70 mA and 75 mA, the system bandwidth reach 62 MHz, 58 MHz, and 61 MHz, respectively.

Using the aforementioned modeling method, a compact equivalent circuit model of Micro-LED pixel is developed based on each RGB sub-pixel to help evaluate the overall VLC link performance under different circuit architecture and signaling schemes. The values of each component in the equivalent circuit model are extracted and curve-fitted from the measured S-parameters under different bias conditions. The measured and modeled small-signal frequency responses of the green super-pixel are in excellent agreement as demonstrated in Fig. 5, under 20 mA and 70 mA current bias.

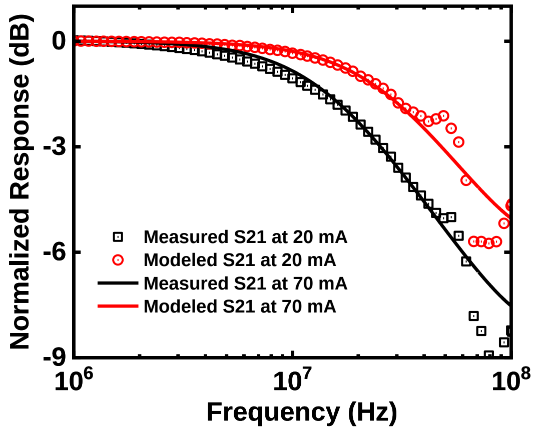


Fig. 5. Measured vs. modeled S_{21} of green super-pixel under bias of 20 mA and 70 mA.

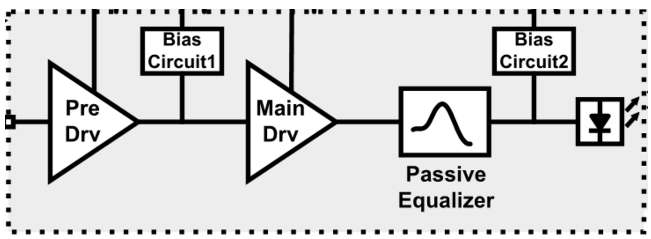
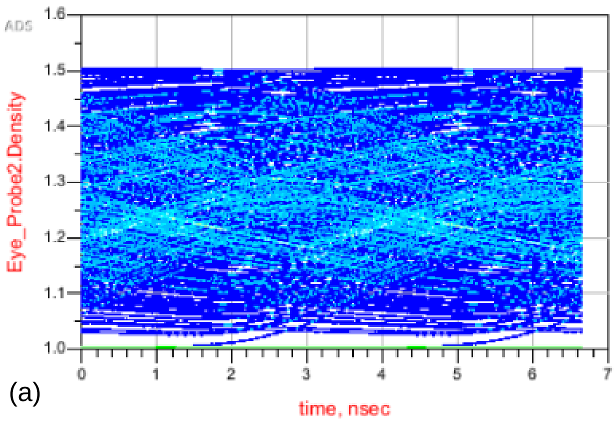


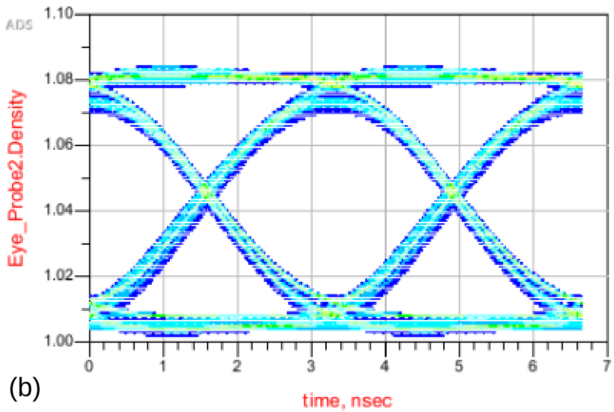
Fig. 6. The detailed block diagram of NRZ VLC transmitter.

To implement this Micro-LED pixels in high-speed VLC circuits, a NRZ and a PAM-4 VLC system is designed using ADS using the compact models described above. In the NRZ VLC system, the RGB Micro-LEDs are driven individually and used as three data transmission channels. RGB optical signals are separated using color filters on the receiver side. In the PAM-4 VLC system, the PAM-4 driving current is producing from three NRZ transmitters controlled by 3-bit thermometer codes. The NRZ transmitter consists of a pre-driver (Pre-Drv), a main driver, and a passive current-mode equalizer (CMEQ), as shown in Fig. 6.

Under the fine parameter design, passive CMEQ can play a great role in bandwidth expansion. As shown in Fig. 7-8, in the case of passive equalizer and without passive equalizer, the simulation eye diagram of the NRZ and PAM-4 VLC system at 300-Mb/s shows different performance. With the equalizer, the bandwidth has been extended obviously which is reflected in wider open eyes.

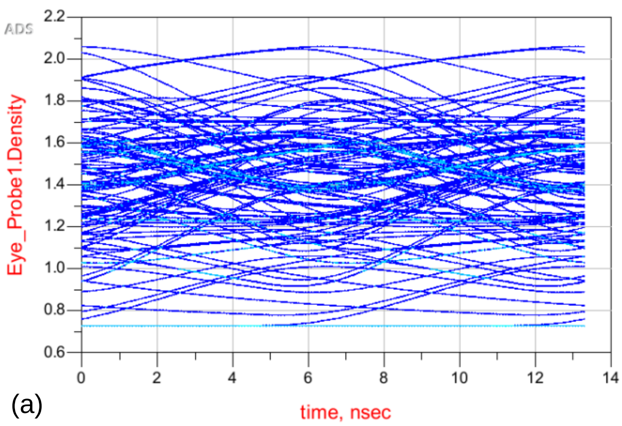


(a)

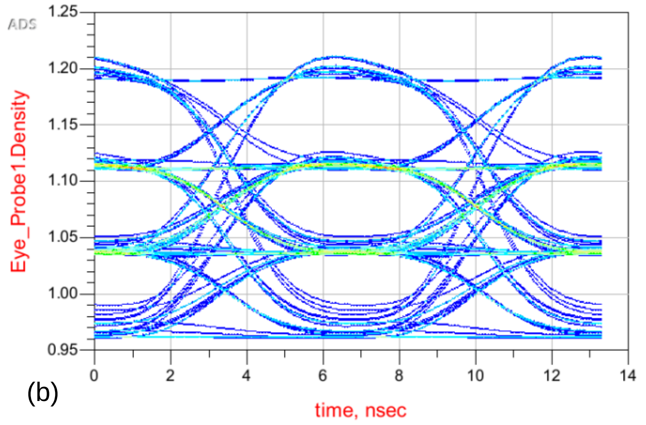


(b)

Fig. 7. The eye diagram of NRZ VLC system at 300-Mb/s: (a) without and (b) with the passive equalizer, using the green super-pixel.



(a)



(b)

Fig. 8. The eye diagram of PAM-4 VLC system at 300-Mb/s: (a) without and (b) with the passive equalizer, using the green super-pixel.

The promising results confirm that the Micro-LED pixel has the possibility of simultaneously realizing display/lighting and VLC and can achieve excellent performance such as wide color gamut, wide correlated color temperature range, and high data transmission rate. Together with the establishment of the equivalent circuit model, it will help the faster practical application of high-speed VLC system.

References

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