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Analysis of Quantum Dot LEDs for Enhancing Efficiency and Stability in Visible Light Communication

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Abstract: From the late 19th and the early 20th, people have focused a lot on the application of radio waves ranging from 3 kHz to 300 GHz. Different frequency bands are distributed to various applications. However, the limited range of radio frequency (RF) caused the insufficiency of communication resources across various areas of daily life, including military, medical, and other sectors. Engineers have developed numerous methods for managing and efficiently utilizing radio frequencies. Using Visible light Communication (VLC) is a solution to the RF crisis. This passage mainly researches the improvements that Quantum Dot LED(QLED) can do to increase the capability and stability of VLC compared to traditional LEDs. The purpose of this research is to leverage the advantages of QLED over traditional LEDs to address issues encountered in conventional VLC, such as signal quality degradation due to interference between signals and reduced transmission efficiency caused by indoor obstacles. Through a literature review, this paper finds that the various advantages of QLED make it perfectly suited for VLC and enhance its transmission capability.

Keywords: VLC, QLEDs, stability, efficiency.

1. Introduction

Visible light Communication (VLC) is a signal-transferring method using visible light as a medium. The frequency range of visible light, from 430 THz to 770 THz, gives it sufficient capability to replace radio waves in transmitting information within certain limits[1].

Quantum Dot LED(QLED) is a new type of LED that uses quantum dots to realize photoelectric conversion. The photoelectric conversion devices currently used in VLC are LED and OLED. The current OLEDs have low cost and flexible sizes, which allow them to adapt and partially address the stringent spatial requirements of VLC [1]. Phosphor-based LEDs have a relatively wide bandwidth [2]. However, both of these two kinds of LEDs' photoelectric conversion speed and signal quality are also limited. QLEDs can enhance the signal quality and transmission speed in VLC because of the unique properties of quantum dots. This passage discusses the working principle and advantages of QLED and how these advantages can benefit the function and efficiency of VLC. This paper uses the literature analysis method to study the character and function of QLEDs. The research describes the specific advantages of QLEDs and how these advantages enhance VLC performance. It proposes feasible research directions to address the limitations of indoor VLC coverage and the interference caused by indoor lighting. Researchers in related fields can refer to this paper to gain a general understanding of QLEDs and identify clear research directions.

2. Principle of QLEDs

2.1. Principle of Quantum Dots

Quantum Dots are nanocrystals with a size from 1 to 10 nanometers. Quantum dots are typically composed of semiconductor materials such as CdSe and CdS. At the nanoscale close to or smaller than the de Broglie wavelength of the electron, the movement space of electrons is restricted, which enhances the quantum confinement effect of the semiconductor materials [3]. The quantum confinement effect brought by quantum dots causes the energy levels of electrons to become discrete, allowing quantum dots to emit light of a certain wavelength since the energy level is fixed [3].

With the decreasing of size in the range of quantum dots, the quantum dots will show stronger quantum confinement effect band increase the band gap energy of emitting a photon.

2.2. Principle of QLEDs

The principle of QLEDs to realize photoelectric conversion, same as other LEDs, is through forming electron-hole pairs(exciton) by applying electric fields or emitting photons to the quantum dots as the electrons will The electron will transition from the valence band to the conduction band. When the exciton recombines, the energy decreases, and a photon is released [3]. QLEDs can realize the tuning through the whole visible light range by changing the size of quantum dots since the band gap energy changes with the size. The material will also affect the band gap energy of quantum dots as the structure of the materials is different.

The high-speed photoelectric conversion rate provides QLEDs with a modulation bandwidth greater than 800 MHz, which is higher than other traditional LEDs. Such a modulation bandwidth allows QLEDs to change their light intensity more than 800 million times per second, which means that QLEDs can transmit "0" or "1" information at least 800 million times per second under the primary OOK modulation and will have higher bandwidth in other modulation methods [4]. Thus, the fast reaction of quantum dots will enhance the transferring speed of VLC. In the study by Zhang et al., the authors proposed a fabrication method for QLED devices. Experimental results showed that the peak EQE(External Quantum Efficiency) of the green QLED device reached 17.40%, the red QLED device achieved a peak EQE of 18.96%, and the blue QLED device had a peak EQE of 6.20% [5]. This not only improved the current efficiency of the devices but also demonstrated the high transmission efficiency of QLEDs.

3. Advantages of QLED Compared to Traditional LED and Its Applications in VLC

3.1. The High Photoelectric Conversion Efficiency of QLED

Due to the discrete energy levels, QLED does not use phonons for non-radiative photoelectric conversion like traditional LEDs, as a single phonon is insufficient to provide the energy needed to excite an electron transition [4]. Therefore, QLED more commonly utilizes radiative recombination and prevents phonons (the transmitting form where energy is emitted through lattice vibrations instead of photons) from generating. The quantum confinement effect gives QLEDs faster speed for photoelectric conversion because they finish the radiating process through the Columbus force, which is a force strong enough to accelerate the energy-transmitting process and transfer the electrical energy to photons in single combustion instead of releasing multi-phonons [4].

3.2. Narrow Bandwidth and High Color Purity of QLEDs

The discrete energy levels of quantum dots give them a narrow bandwidth characteristic because, once the energy levels are discrete, the electron transitions and electron-hole pair recombination will

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only absorb and emit fixed amounts of energy. As a result, the wavelength range of the emitted visible light is relatively fixed. The emitted light with extremely similar wavelengths will have enhanced color purity, which greatly helps improve VLC performance and facilitates the application of various communication methods in the VLC field. The emission bandwidth of quantum dot LEDs can reach below 25 nanometers, which represents a significant improvement compared to the 20-50 nanometer range of previous LEDs [6].

3.3. QLED's Tunable Spectrum

The wavelength of QLED depends on the size of the quantum dots. The frequency of the emitted light will increase, which corresponds to a decrease in the size of quantum dots. When the size of quantum dots decreases, there will be a larger quantum confinement effect and causing the energy levels to become more discrete and resulting in photons with higher energy [4]. Therefore, QLED can control the output wavelength by adjusting the size of the quantum dots instead of relying on the inherent bandgap of the semiconductor material, which will offer QLED the ability to cover a broader spectrum.

4. The Improvement of QLEDs on VLC Performance

4.1. QLEDs’ Improvement for OFDM in VLC

4.1.1. QLEDs’ Improvements on OFDM Signal Quality

OFDM is a signal-transmitting method that separates the wave into several subcarriers. Through Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT), OFDM enables the transmitted subcarriers to convert the frequency domain signal into a time domain signal [7]. The subcarriers can avoid interfering with each other by being orthogonal to each other, which means the inner products between the two subcarriers are zero [7]. However, the light emitted by LEDs made by semiconductors or OLEDs has a range that will cause mutual interference between the light, which leads to energy loss and signal distortion. QLED has a narrower emission bandwidth, which can make the transmitting of information more controllable in OFDM since it will be easier for the subcarriers to maintain orthogonal when the range of error is smaller. In this condition, the signal transmitted in the VLC system using OFDM will be more likely to produce pure and accurate signals with a low signal-to-noise ratio (SNR).

4.1.2. Solving the high Peak-to-Average Power Ratio (PAPR) in Orthogonal Frequency Division Multiplexing(OFDM)

PAPR is the ratio of peak power to average power. High peak power causes the LED to enter the nonlinear operating region [7]. In this case, the input current and the output optical signal are nonlinear, which can result in reduced signal amplitude, affecting precision, or cause the signal to be clipped, leading to information loss [7]. Quantum dot LEDs have unique advantages in addressing information loss and transmission rate limitations caused by nonlinear distortion. The previously mentioned dispersed energy level structure makes quantum dots less likely to transfer energy in the form of heat (i.e., phonons) under high power conditions, reducing the degree of nonlinearity in the device. At the same time, the faster exciton recombination speed means that QLEDs can transmit more information at the same power. Conversely, this also implies that QLEDs use less power to transmit the same amount of information, reducing the likelihood of the device entering a nonlinear operating mode. A narrow emission bandwidth can let more light emitted by QLED fit with the expected wavelength, which can reduce the energy used in the modulation process and produce

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photons with unfitting frequency. This improvement will increase the efficiency of the power to the work that can be done by the QLED, which decreases the PAPR and decreases the possibility of nonlinear distortion.

4.2. QLEDs' Improvement on Wavelength Division Multiplexing(WDM)

4.2.1. QLEDs' Improvement on WDM Efficiency

Narrow emission bandwidth can also contribute to WDM and improve the utility of the spectrum. WDM is a signal-transmitting method that transfers multi-signals in one channel by using waves with different wavelengths so they do not interfere with others [8]. However, maintaining the interval between the frequency of sub-channels will cause the wasting of the spectrum sources.

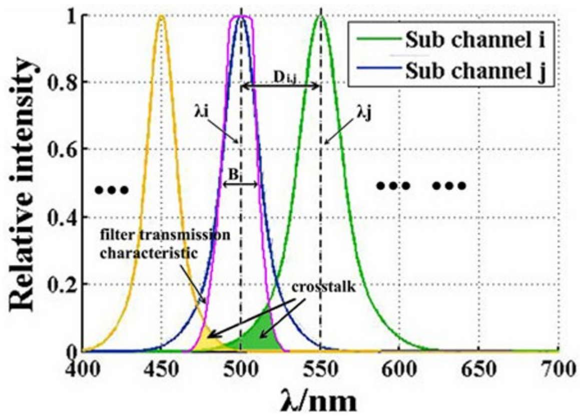

Figure 1: The spectrum of RGB LED emitting the light of violet, blue and cyan [8]

The yellow band is the emitting band for violet light, the purple band is for blue light, and the green band is for cyan (see Figure 1). Each of these lights has a range of about 100 nanometers from the peak and can interfere very easily with other waves. The full width at half maximum (FWHM) of LED is in the range of tens of nanometers. A type of InGaN-based blue LED chip has an FWHM of 23nm to 30.8nm. Red LEDs and green LEDs commonly have larger FWHM than blue LEDs [4].

QLED has a narrower emission bandwidth which can reduce the interval exist between different sub-channels without affecting each other since the overlap part of the waves decreases. Zhang et al designed a type of QLED which has the FWHM in the range of 12nm to 14nm [6]. By compacting the wavelengths, WDM can have more sun channels in the same channel and thus increase the transmitting efficiency.

4.2.2. QLEDs' Improvement on WDM Stability and Controllability

QLEDs have the ability to control their emitting wavelength accurately because of the controllability of the size of the quantum dots [3]. Compared to previous LEDs, QLEDs show less problem on the deviation of wavelength due to modulation and other factors since the QLED does not need modulate and can directly change its emitting wavelength. This accuracy can enhance the utility of WDM. By using QLEDs, people can control the emitting wavelength of LEDS to be in the expected range. Therefore, the spectrum resource that was originally wasted due to modulation's inaccuracy can be reduced.

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5. Conclusion

This passage mainly discusses the principle and special properties of QLEDs and how these properties can improve the function of VLC. The special properties of quantum dots, like the quantum confinement effect, offer QLEDs special properties that contribute to their outstanding performance in VLC. QLEDs have fast photoelectric conversion speed, which can enable a higher speed of signal transformation to support more VLC devices working at the same time and working faster. Moreover, the narrow emission bandwidth gives QLEDs more stability in the process of signal transmitting compared to previous LEDs because the interference between the waves will be smaller since the possible area of the wavelength will appear smaller. The narrow emission bandwidth can also give QLEDs the ability to make the signal transmitting in the same channel more compact, thus saving the spectrum resource. Therefore, QLEDs are a valuable method to improve the behavior of VLC in order to release the pressure on the RF spectrum crisis. This passage does not mention how the properties of QLEDs can be applied to more complex modulation methods, such as Quadrature Amplitude Modulation and Quadrature Phase Shift Keying. Future research on QLEDs can focus on how the properties of quantum dots overcome the interference from natural light and the effect of other light-emitting devices.

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