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A Novel Approach to Visible Light Communication: Combining OFDM and $SrLa_2Al_2O_7:Er^{3+}$ LED

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Abstract: Visible Light Communication (VLC) presents a promising technology for future wireless communication systems, offering a high-speed and secure alternative to traditional radio frequency (RF) based wireless systems. To enhance VLC performance, the Orthogonal Frequency Division Multiplexing (OFDM) technique has been employed. OFDM's high spectral efficiency and robustness to multipath interference make it well-suited for mitigating inter-symbol interference (ISI) and maximizing spectral efficiency. This study explores the OFDM-VLC system under OptiSystem software, utilizing a high-efficiency Perovskite-based Light-Emitting Diode (LED). Specifically, the investigation emphasizes the $SrLa_2Al_2O_7:Er^{3+}$ LED, which exhibits high luminescence efficiency with a Quantum Efficiency (QE) of approximately 68.33%. The impact of the number of OFDM subcarriers and the $SrLa_2Al_2O_7:Er^{3+}$ LED's characteristics on system performance are thoroughly analyzed over various channel ranges and bit rates. To evaluate the system's efficacy, the performance of the proposed OFDM-VLC system was rigorously assessed using rigorous performance metrics, including Bit-Error Rate (BER) and constellation diagrams. The findings unequivocally demonstrate the substantial enhancement in communication reliability and efficiency achieved by the proposed OFDM-VLC system based on $SrLa_2Al_2O_7:Er^{3+}$ LED.

Keywords: Visible light communication (VLC), Orthogonal frequency division multiplexing (OFDM), $SrLa_2Al_2O_7:Er^{3+}$ LED, Quantum efficiency (QE), Bit-error rate (BER).

Introduction

Visible Light Communication (VLC) has emerged as a promising technology in the quest for high-speed, efficient wireless communication solutions. By modulating visible light emitted from LEDs, VLC serves a dual function, acting as both an energy-efficient lighting source and a high-bandwidth data transmission medium. This dual capability makes VLC particularly appealing for indoor wireless communication, where data transmission can seamlessly integrate into existing LED lighting infrastructure. However, despite these advantages, VLC faces challenges, particularly in maintaining signal quality over longer distances and managing high error rates under demanding conditions (Loureiro et al., 2023; Geng et al., 2022; He et al., 2023; Shi et al., 2022; Chi et al., 2018).

To overcome these limitations and make VLC more robust and capable of handling higher bit rates, researchers are exploring advanced LED materials that can better sustain signal integrity over extended distances. One of the key techniques for enhancing VLC systems is Orthogonal Frequency Division Multiplexing (OFDM), a modulation method known for its capacity to handle high data rates and its resilience to inter-symbol

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interference (ISI). By dividing a high-speed data stream into multiple lower-speed sub-streams, OFDM enables the VLC system to manage multipath distortion and interference more effectively, resulting in improved signal quality over various distances and bit rates (Shen et al., 2023; Fassi et al., 2022; Selvendran et al., 2019; Pradhan et al., 2021; Pradhan et al., 2023).

This study implements an OFDM-based VLC system to examine the performance of a standard LED compared with an LED that uses Strontium Lanthanum Aluminate doped with Erbium ions ($SrLa_2Al_2O_7$: Er^{3+}), a material noted for its enhanced optical characteristics and stability. $SrLa_2Al_2O_7$: Er^{3+}, a perovskite-type phosphor, is particularly promising for VLC applications due to its distinctive luminescence properties. With a structure similar to traditional perovskites (general formula ABX_3), its crystalline arrangement enhances luminescence efficiency, making it suitable for high-performance lighting and display applications. Doped with erbium ions, $SrLa_2Al_2O_7$: Er^{3+} emits a greenish light with a prominent peak at 548 nm. At an optimized Er^{3+} concentration of 2.0 mol%, it achieves a quantum efficiency of 68.33% and a radiative lifetime of 0.546 ms, making it a strong, stable light source capable of supporting high-bandwidth applications. Additionally, its nano phosphors display favorable color coordinates of (0.2657, 0.6031), supporting balanced white light generation. When paired with RGB phosphor chips, the $SrLa_2Al_2O_7$: Er^{3+} LED can emit warm white light with excellent color rendering, broadening its application potential for efficient VLC systems (Song et al., 2019a; Sehrawat et al., 2020; Zeng et al., 2022; Chen et al., 2023; Devi et al., 2019).

This study delves into the performance of an OFDM-VLC system, employing both a standard LED and an advanced $SrLa_2Al_2O_7$: Er^{3+} LED. To conduct a comprehensive analysis of the impact of varying transmission distances, bitrates ranging from 1 to 25 Gbps, and the number of subcarriers, OptiSystem software version 21.0.0 is used to simulate real-world indoor VLC scenarios. This paper is structured as follows: the *Methodology* section outlines the detailed simulation setup in OptiSystem used to evaluate VLC system performance. Subsequently, the *Results and Discussion* section presents an in-depth analysis, including a comparative examination of Bit Error Rate (BER), constellation diagrams, and Optical Signal-to-Noise Ratio (OSNR) between the two LED types. Finally, *Conclusion* section provides valuable findings on the potential benefits of utilizing $SrLa_2Al_2O_7$: Er^{3+} for advanced VLC applications and proposes directions for future research. This comparative analysis serves as a foundational step toward further exploration of advanced LED materials and their integration within VLC systems, ultimately contributing to the advancement of this innovative communication technology.

Methodology

This research rigorously evaluates the performance of a standard LED and a $SrLa_2Al_2O_7$: Er^{3+} enhanced LED within an OFDM-based VLC system, as illustrated in Figure 1. The simulation is configured to emulate indoor VLC conditions within a typical room of 5m x 5m x 3m, incorporating varying transmission distances from 1 to 5 meters and bit rates ranging from 1 to 25 Gbps to reflect realistic usage scenarios. Key performance indicators, including BER and OSNR, are assessed to evaluate the effectiveness of each LED type under identical conditions.

The data taransmission process begins with a Quadrature Amplitude Modulation (QAM) encoder, which converts binary data into a QAM signal at a symbol rate of 4 bits per symbol. This modulated data is then fed into an Orthogonal Frequency Division multiplexing OFDM Modulator. The OFDM modulator divides the signal into numerous orthogonal subcarriers, each carrying a portion of the modulated data. By employing a Fast Fourier Transform (FFT), the OFDM system transforms the time-domain signal into the frequency domain, enabling efficient transmission over wireless channels. This frequency-domain transmission significantly mitigates the effects of Inter-Symbol Interference (ISI), a common challenge in wireless communication, allowing for robust and high-speed data transmission (Selvendran et al., 2019).

The modulated signal undergoes amplification via an Electrical Amplifier, followed by filtration through a Low Pass Cosine Roll-Off Filter, which serves to restrict bandwidth and enhance signal integrity. The refined signal is then transmitted through one of the two light sources: either a standard LED operating at 550 nm with a quantum efficiency (QE) of 65% or a $SrLa_2Al_2O_7$: Er^{3+} LED emitting at 548 nm with an improved QE of 68.33%. The $SrLa_2Al_2O_7$: Er^{3+} LED is anticipated to demonstrate superior performance in comparison to the standard LED, owing to its optimized signal-emitting characteristics and advanced perovskite-based structure that enhances luminescence efficiency (Sehrawat et al., 2020).

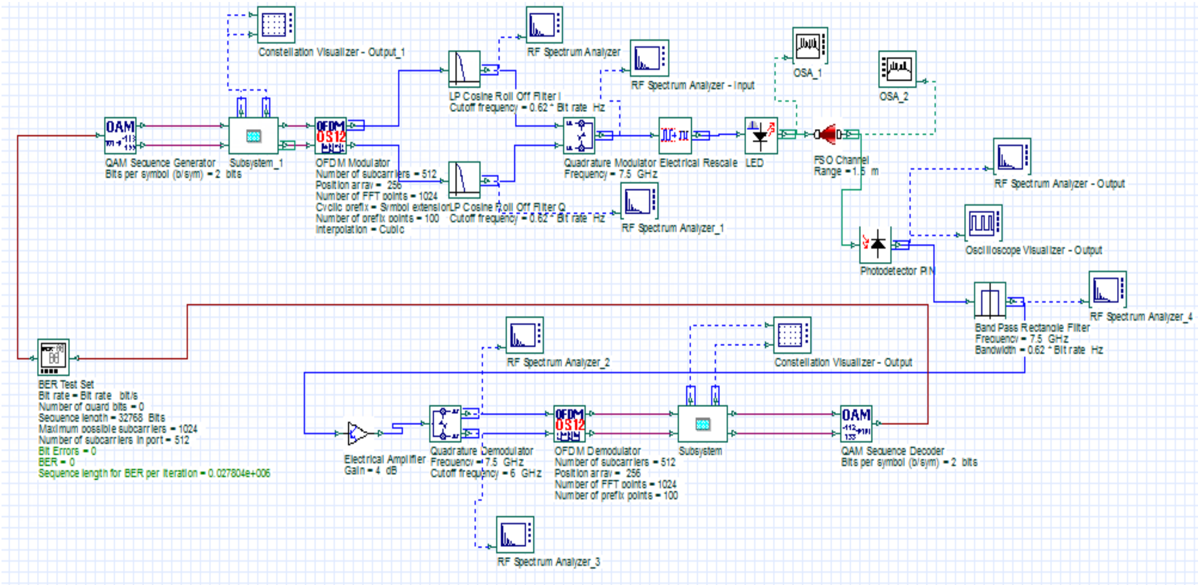


Figure 1. OFDM-VLC system model

The modulated light signal is transmitted through a Free Space Optical (FSO) Channel, set to a range of up to 5 meters, representing typical room-scale VLC applications. At the receiver end, a Photodetector PIN detects the transmitted light, which is then filtered and processed through a QAM Sequence Decoder to retrieve the original data. Various tools, such as RF Spectrum Analyzers, Constellation Visualizers, and an Oscilloscope Visualizer, are utilized to assess performance. The key metrics include BER, measured across different distances and bit rates using BER Test Set to gauge the reliability and accuracy of data transmission, and OSNR, calculated to assess the clarity of the transmitted signal, especially under high bit rate conditions.

Simulation Setup

To assess the performance of both the standard LED and $SrLa_2Al_2O_7$: Er^{3+}-enhanced LED in an OFDM-based VLC system, several simulation parameters were established to ensure accurate and comparable results. These parameters were configured to reflect typical indoor VLC conditions and are summarized in Table 1.

Table 1. Simulation parameters

LED parameters	Values
Frequency	550 nm (Standard LED); 548 nm ($SrLa_2Al_2O_7$: Er^{3+}LED)
Electron life Time	0.1 x10^{-9} s
RC constant	0.1 x10^{-9} s
Quantum Efficiency	65% (Standard LED), 68.33% ($SrLa_2Al_2O_7$: Er^{3+}LED)
OFDM parameters	Values
Numbers of Subcarriers	512 , 1024
Position array	256 , 512
Numbers of FFT points	1024 , 2048
PIN photodetector parameters	Values
Responsivity Type	Si
Dark current	10 nA
Shot noise distribution	Gaussian
FSO channel parameters	Values
Range	From 1m to 5m
Transmitter aperture diameter	7 cm
Receiver aperture diameter	1.5 cm
Layout parameters	Values
Bit Rate	From 1Gbps to 25 Gbps
Sequence Length	32768
Samples per bit	128
Number of samples	4194304

Results and Discussion

This analysis evaluates the performance of an OFDM-VLC system under two different configurations. The first configuration employs 512 subcarriers and a 1024-point FFT, while the second configuration utilizes 1024 subcarriers and a 2048-point FFT. This assessment employs the BER and OSNR as primary metrics to compare the performance of both the Standard LED and the $SrLa_2Al_2O_7$: Er^{3+} LED under varying conditions. Simulations were conducted over transmission distances ranging from 1 to 5 meters, with bit rates varying from 1 to 25 Gbps, allowing for an in-depth examination of the impact of subcarriers number on system performance (Selvendran et al., 2019).

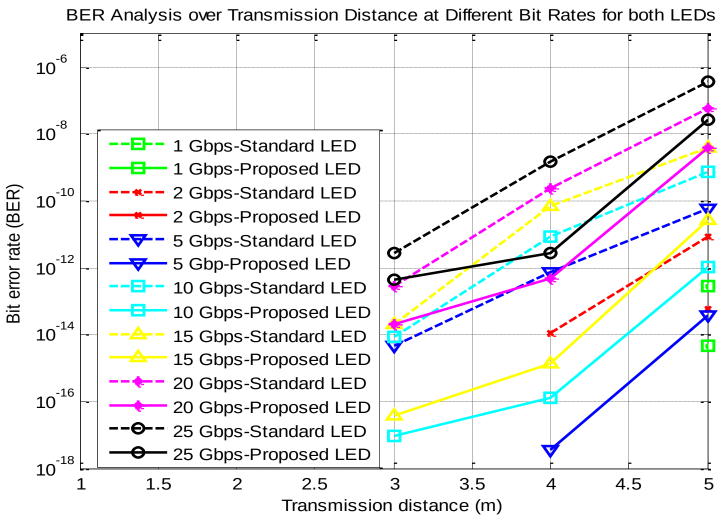


Figure 2. BER curves for both LEDs

*Analysis for 512 Subcarriers***:** The analysis of BER for the Standard LED and $SrLa_2Al_2O_7$: Er^{3+} LED across various data rates and different transmission distance with 512 subcarriers reveals significant performance differences. For the Standard LED, the minimum BER values exhibit a general increase with rising data rates and transmission distances, particularly evident at higher rates (10 to 25 Gbps), where the BER reaches values as high as $3.65132e^{-7}$ at transmission of 5 meters and 25 Gbps. This trend aligns with the observed decrease in OSNR, suggesting that as noise levels rise with increasing of transmission range and data rate, the likelihood of error in signal transmission increases, indicating poor noise resistance.

In stark contrast, the $SrLa_2Al_2O_7$: Er^{3+} LED demonstrates a markedly lower BER, achieving values down to $4.01889e^{-9}$ at 20 Gbps and transmission range up to 5 meters . The improved OSNR values for this LED type correlate with its superior performance, showing that it can maintain signal integrity even under higher bitrates conditions. Overall, the $SrLa_2Al_2O_7$: Er^{3+} LED clearly outperforms the Standard LED, evidencing its effectiveness for high-speed optical communication, as detailed in Table 2, 3, and 4. This enhanced performance highlights the $SrLa_2Al_2O_7$: Er^{3+} LED's suitability for applications requiring high data rates, as it better preserves data integrity under increased bit rate and distance conditions. Figure. 2 illustrates the BER performance curves for both the standard LED and the $SrLa_2Al_2O_7$: Er^{3+} LED across various bit rates and transmission distances. The BER curves for the $SrLa_2Al_2O_7$: Er^{3+} LED consistently lies below that of the standard LED, indicating superior performance with lower BER values. In the plotted graphs, the BER for the $SrLa_2Al_2O_7$: Er^{3+} LED approaches zero, particularly at shorter distances and lower bit rates, which underscores its enhanced ability to maintain data integrity compared to the standard LED. This trend highlights the $SrLa_2Al_2O_7$: Er^{3+} LED's robustness in high-speed VLC applications.

*Analysis for 1024 Subcarriers***:** For the 1024 subcarrier configuration, the differences in BER between the two LED types become even more pronounced. The Standard LED exhibits increasing BER values as the data rate escalates, with maximum values of $1.93751e^{-8}$ at 5 meters range and 25 Gbps, emphasizing its limitations in handling higher transmission ranges and data rates. This deterioration in performance aligns with the significant reduction in OSNR, which indicates a compromised signal-to-noise ratio detrimental to reliable data transmission. Conversely, the $SrLa_2Al_2O_7$: Er^{3+} LED continues to showcase minimal BER values, as low as $5.1556e^{-15}$ at 25 Gbps over a distance of 3 meters, and maintaining a BER of approximately $8.01504e^{-9}$ at a distance of 5 meters.

The consistently higher OSNR values indicate its robust performance against noise, allowing it to sustain a higher quality signal across a broader range of operating conditions. This stark contrast highlights the $SrLa_2Al_2O_7$: Er^{3+} LED as a superior choice for applications demanding high data rates, emphasizing its potential to enhance communication reliability and efficiency in demanding environments. as illustrated in Table 2 and 3. These results, coupled with higher OSNR values than the standard LED, illustrate the $SrLa_2Al_2O_7$: Er^{3+} LED's superior noise resistance and ability to maintain clear signal transmission over extended ranges and bit rates Table 5.

Table 2. Bit Error Rate (BER) values for Standard LED

	Min BER									
	512 Subcarriers					1024 Subcarriers				
Range / Bitrate	1	2	3	4	5	1	2	3	4	5
1	0	0	0	0	2.7536e^{-13}	0	0	0	0	3.27523e^{-17}
2	0	0	0	1.09591e-^{14}	8.32005e^{-12}	0	0	0	2.53843e^{-16}	2.7531e^{-14}
5	0	0	4.67661e^{-15}	7.24786e^{-13}	6.15734e^{-11}	0	0	2.34785e^{-18}	4.84125e^{-15}	1.32731e^{-13}
10	0	0	8.76182e^{-15}	8.78343e^{-12}	7.34375e^{-10}	0	0	4.57896e^{-17}	6.30251e^{-14}	5.78352e^{-12}
15	0	0	2.04984e-^{14}	6.98369e^{-11}	3.9465e^{-9}	0	0	8.94865e^{-17}	4.97035e^{-13}	1.2563e^{-11}
20	0	0	2.92168e^{-13}	2.51339e^{-10}	5.8137e^{-8}	0	0	1.23001e^{-16}	2.86695e^{-12}	4.97022e^{-10}
25	0	0	2.70977e^{-12}	1.52373e^{-9}	3.65132e^{-7}	0	0	7.61384e^{-14}	6.73365e^{-11}	1.93751e^{-8}

Table 3. Bit Error Rate (BER) values for SrLa2Al2O7:Er3+ LED

	Min BER									
	512 Subcarriers					1024 Subcarriers				
Range / Bitrate	1	2	3	4	5	1	2	3	4	5
1	0	0	0	0	4.72023e^{-15}	0	0	0	0	0
2	0	0	0	0	5.91018e^{-14}	0	0	0	0	0
5	0	0	0	3.713e^{-18}	3.9722e^{-14}	0	0	0	0	0
10	0	0	9.24549e^{-18}	1.27669e^{-16}	1.05681e^{-12}	0	0	0	0	0
15	0	0	3.72734e^{-17}	1.32878e^{-15}	2.603e^{-11}	0	0	2.674e-^{19}	3.51097e^{-17}	3.4062e^{-12}
20	0	0	2.08095e^{-14}	4.89778e^{-13}	4.01889e^{-9}	0	0	1.76282e^{-17}	8.16007e^{-14}	2.7346e^{-11}
25	0	0	4.56338e^{-13}	2.68356e^{-12}	2.6975e^{-8}	0	0	5.1556e^{-15}	7.3955e^{-13}	8.01504e^{-9}

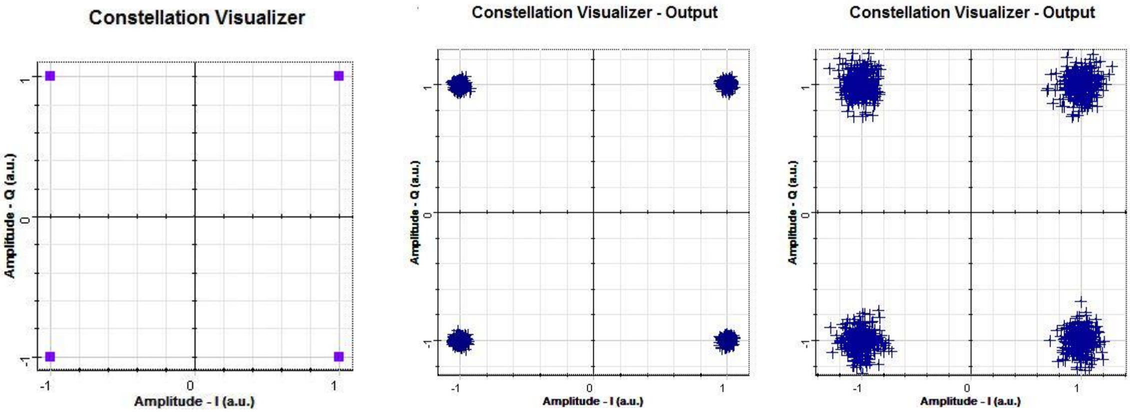
Table 4. OSNR for both LEDs for 512 subcarriers

	OSNR (dB) for 512 Subcarriers									
	Standard LED					$SrLa_2Al_2O_7$:Er^{3+} LED				
Range / Bitrate	1	2	3	4	5	1	2	3	4	5
1	85.823	74.452	69.527	63.453	59.678	93.302	83.594	69. 883	67.374	60.412
2	82.318	71.583	65.114	59.427	55.861	90.604	79.982	67. 654	63.525	58.258
5	78.974	64.632	62.612	57. 826	53. 718	87.837	77.734	66. 672	62.041	56.623
10	74.415	62.336	59.393	54.668	49.914	85.308	75.637	63. 297	58.116	51.092
15	72.479	60.025	57.713	52.926	47.981	82.582	73.392	62. 142	55.784	48.615
20	71.614	58.214	53.688	48.894	45.085	80.584	70.014	59.017	52.182	46.126
25	70.683	56.418	50.135	47.929	44.576	77.723	69.415	57.121	49.651	45.984

Table 5. OSNR for both LEDs for 1024 subcarriers

	OSNR (dB) for 1024 Subcarriers									
	Standard LED					$SrLa_2Al_2O_7$:Er^{3+} LED				
Range / Bitrate	1	2	3	4	5	1	2	3	4	5
20	78.245	70.135	60.679	51.866	48.963	84.149	79.349	68.330	60.425	49.764
25	74.385	66.714	56.226	48.507	46.387	80.762	75.173	65.915	52.682	47.118

In Table 5, the OSNR was specifically evaluated at 20 Gbps and 25 Gbps with 1024 subcarriers, as increasing the subcarrier count mainly benefits systems operating at higher data rates. With 1024 subcarriers instead of 512, the system can manage complex, high-throughput data transmissions more effectively, allowing bit rates up to 25 Gbps while maintaining acceptable BER levels. Lower bit rates, such as 10 Gbps, were likely not tested with 1024 subcarriers because these rates could be supported within the desired link range using just 512 subcarriers. Therefore, the use of 1024 subcarriers was focused on the higher, more demanding bit rates to assess the system's capacity at the upper limits of its throughput.

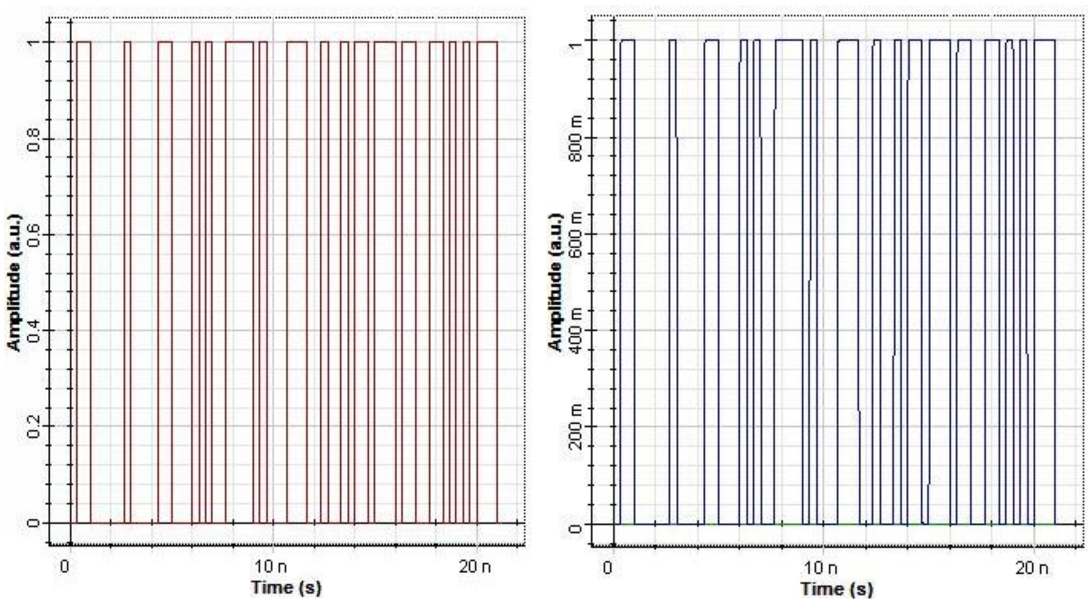


(a) (b) (c)

Figure 3. Constellation Diagrams. a. transmitted signal Constellation. b. Received signal Constellation for $SrLa_2Al_2O_7:Er^{3+}$ LED. c. received signal Constellation for standard LED

The constellation diagrams, shown in Figures 3a, 3b, and 3c, illustrate the constellation before and after transmission for both LEDs at 10 Gbps over a 3 meters range, revealing essential distinctions in performance. The $SrLa_2Al_2O_7$: Er^{3+} LED exhibits a well-organized and tightly clustered constellation with minimal distortion, indicating lower BER and enhanced signal integrity.

In comparison, the standard LED constellation displays a broader scatter in the data points, indicating a higher susceptibility to errors. This contrast in clustering suggests that the $SrLa_2Al_2O_7$: Er^{3+} LED provides superior stability and clarity in the transmitted signal, particularly at high bit rates and extended distances. Figure 4a and 4b displays the transmitted and received sequences when using the $SrLa_2Al_2O_7:Er^{3+}$ LED at 10 Gbps over 3 meters with configuration of 1024 subcarriers, showing an identical match. This close alignment indicates high signal integrity with minimal distortion, reflecting the LED's effectiveness in maintaining clear, stable transmission even at elevated data rates. The consistency suggests efficient ISI mitigation and noise suppression, underscoring the $SrLa_2Al_2O_7:Er^{3+}$ LED’s reliability for high-speed VLC applications.



(a) (b)

Figure 4. Transmitted and received Sequence

Conclusion

In conclusion, this study demonstrates that $SrLa_2Al_2O_7$: Er^{3+} LEDs are a promising advancement for VLC systems, outperforming standard LEDs in important performance metrics such as BER and OSNR at various transmission distances and bit rates. Simulations in OptiSystem revealed that these LEDs achieved lower BER and better signal integrity, particularly at data rates of up to 25 Gbps and longer ranges. Their capability to produce clear constellation diagrams and closely match transmitted and received sequences highlights their potential for high-throughput VLC applications, with minimized inter-symbol interference and effective noise reduction. The findings indicate that $SrLa_2Al_2O_7:Er^{3+}$ LEDs greatly improve signal quality and stability, making them suitable for advanced VLC systems for reliable, high-speed indoor communication. This research deepens the understanding of LED materials in VLC performance and sets the stage for integrating phosphor-based LEDs into high-speed optical networks. Future studies should optimize parameters, explore real-world applications, and investigate the role of new phosphor materials in VLC technology development.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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