Visible Light Communication using a Blue GaN µLED and Fluorescent Polymer Colour Converter

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Abstract—This letter presents a novel technique to achieve high-speed visible light communication (VLC) using white light generated by a blue GaN µLED and a yellow fluorescent copolymer. We generated white light suitable for room illumination by optimising the ratio between the blue electroluminescence of the µLED and yellow photoluminescence of the copolymer colour converter. Taking advantage of the components' high bandwidth, we demonstrated 1.68 Gb/s at a distances of 3 cm (at 240 lx illumination). To the best of our knowledge, This is the fastest white light VLC results using a single blue LED/colour converter combination.

Index Terms— VLC, micro LED, Super Yellow, organic semiconductors, colour converter, OFDM, illumination

I. Introduction

RECENT improvements in the efficiency of light emitting diodes (LEDs) have made them a strong candidate to replace existing lighting sources. Visible light communication (VLC) is attractive since any LED based lighting infrastructure provides the possibility of data communication and illumination.

A well-known bottle-neck in VLC, however, is the slow response of commercial white LEDs (WLED) [1]. In general, these are based on a blue LED chip with a phosphor that absorbs part of the blue LED emission and re-emits a broad yellow spectrum. However, the photoluminescence lifetime of conventional phosphors is too long (~µs) to support high rates of data transmission.

Typically, an optical short pass filter is used to reject the slow yellow component at the receiver, increasing the modulation bandwidth (B/W) from a few MHz to ~20 MHz. Despite

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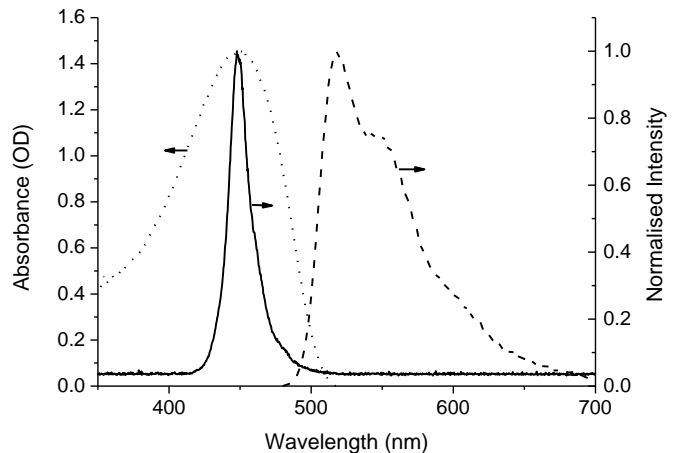
Fig. 1. EL spectrum of a GaN µLED (solid line). PL (dashed line) and absorption (dotted line) spectrum of S-Y.

the low bandwidth there is sufficient power to reach high data rates using higher order modulation, and a 1 Gb/s data rate has been achieved using a phosphor and blue chip WLED [2].

There is also effort to improve the LEDs themselves. Resonant cavity LEDs (RCLEDs) are an example. RCLEDs have enabled communication links of up to 3 Gb/s over a plastic optical fibre (POF) [3]. However, these are not easily adopted for white light illumination. In [4], GaN based blue µLEDs with small junction capacitance and higher current density were used to demonstrate 512 Mb/s wireless VLC. Using such devices, we have demonstrated the fastest wireless single-LED transmission of 3 Gb/s in a recent publication [5], but again these sources are not white.

In this letter, we investigate the feasibility of using a conjugated polymer to overcome the limitations of existing phosphors. Conjugated polymers are an important class of organic semiconductors that have high fluorescence quantum yields, short (~1 ns) radiative lifetimes and they are simple to process from solutions. Another advantage of using polymers is that they can be blended to obtain a higher quality white light than the conventional blue LED chip with a phosphor [6]. These properties make them attractive alternatives to current phosphors.

We propose a scheme to create white light suitable for both illumination and high speed VLC, by using the blue electroluminescence (EL) of a GaN µLED [4] and the yellow photo-

luminescence (PL) of a conjugated copolymer of poly para-phenylene vinylene, "Super Yellow" (S-Y; PDY132, Merck KGaA). The μLED - conjugated polymer design can not only generate white light but also provide higher modulation bandwidth than that of the blue chip and phosphor based commercial WLEDs.

In Section II, the process of generating white light is shown after introducing characteristics of the GaN μLED and S-Y colour converter we used. Section III details the communication performance of the generated white light by applying optical orthogonal frequency division multiplexing (OFDM). Section IV discusses practicality and on-going work, and section V concludes this letter by addressing the potential of the proposed method.

II. WHITE LIGHT GENERATION

A. Properties of the GaN μLED and Super Yellow

Fig 1 shows the EL emission spectrum of the GaN μLED and the PL emission and absorption spectrum of the S-Y. The GaN μLED used in this work has a diameter of 50 μm, Electrical-Optical-Electrical (EOE) B/W of 60 MHz and total radiant flux of 3.5 mW at 60 mA. Higher driving current can increase the B/W [4], but this value was selected to allow operation in linear region of its response.

S-Y has photoluminescence quantum yield (PLQY) of 60%. The measured bandwidth of S-Y in solution is > 200MHz, which can provide a ~50 fold higher B/W than a typical phosphor based colour converter, due to the short fluorescence lifetime (100s of ps) of the material. More details of the properties of S-Y can be found in [7].

B. Process to generate white-light

Fig 2 shows the experimental set up used to generate white light. Blue light from the GaN μLED was collimated and focused onto the S-Y colour converter via a series of high numerical aperture (NA) lenses as detailed in the figure. The high NA optics design was used because of the limited optical power from the μLED and its Lambertian emission profile (half divergence angle of 60°).

The S-Y colour converter consists of a 2 mm path length cuvette containing S-Y in chlorobenzene solution. This forms a
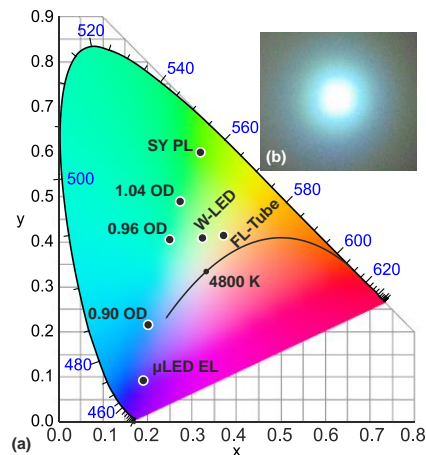
Fig. 3. (a) Representation of achieved colours on CIE chromaticity diagram and the black body locus (solid line). For comparison, the colours of a commercial WLED, and a fluorescent light tube are presented. (b) Photograph of the projected light of 0.96 OD solution.

Lambertian emitter and the mixture of emitted yellow and transmitted blue that is emitted from the cuvette holding the S-Y material is highly divergent. Another high NA optical system is used to collect and collimate this emission. To increase the emission efficiency in the forward direction a dichroic mirror, transparent for blue but reflecting yellow light, is placed just before the S-Y converter. This reflects part of the backward propagating yellow light into the forward direction, increasing the efficiency by approximately 20%.

The composition of the white light generated in this process can be altered by changing the concentration of the S-Y solution, which controls both the transmittance of the LED light and the intensity of yellow emission. It was found experimentally that the S-Y follows the Beer-Lambert law and the optical density (OD) is proportional to concentration of the solution: OD=5.2c, where c is the concentration in mg/ml.

Fig 3 (a) shows a CIE plot of the colour generated as the OD is varied. We experimentally verified that an OD of 0.96 leads to the smallest distance from the reference white point (0.33, 0.33). This results in a cool white-light as can be seen in Fig 3 (b). For comparison, we also measured the coordinates from a commercial WLED and a fluorescent light tube, and these are also shown in the figure.

III. COMMUNICATION PERFORMANCE

DC-biased optical OFDM (DCO-OFDM) [8] is used to transmit data as DCO-OFDM has the highest spectral efficiency among optical OFDM schemes, hence making it appropriate for a band-limited VLC system.

A. DCO-OFDM and signal conditioning

OFDM is a spectrally efficient multi carrier modulation scheme, using only half of the B/W that conventional frequency division multiplexing (FDM) scheme uses. In order to apply it to intensity modulation direct detection (IM-DD) based systems, the time domain sequence, $x(n)$, should be conditioned to have positive real values only. This condition is obtained by constraining the symbols $X(m)$ on the OFDM subcarriers to have Hermitian symmetry (1). This is followed by signal clipping (2) and DC addition (3).
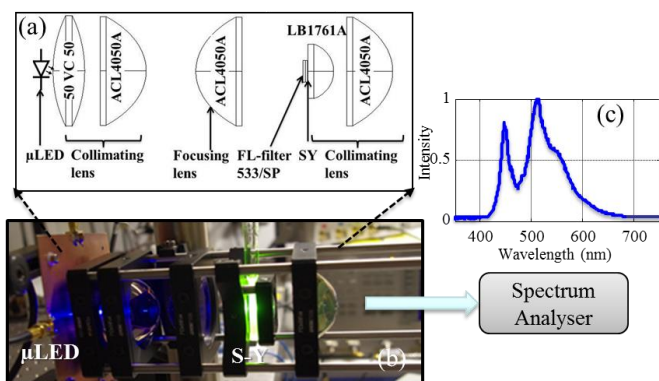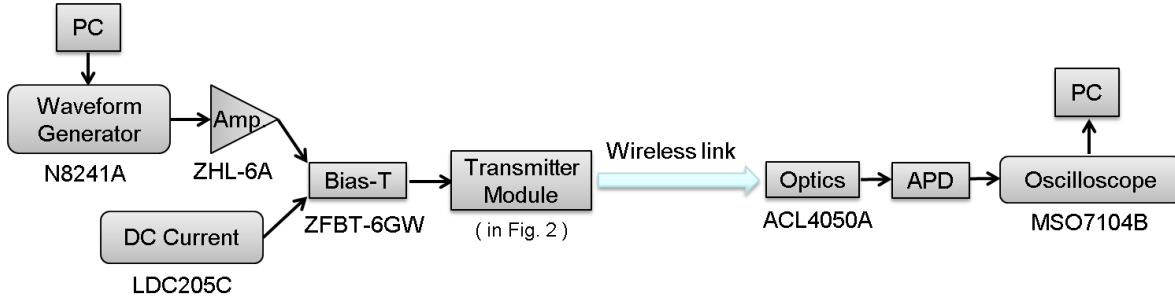

Fig. 2. Experimental set-up for white-light generation a) block diagram of the set-up, b) picture of the set-up and c) measured emission spectrum for GaN μLED illuminating a S-Y sample of optical density 0.96.

Fig. 4. Experimental set up for data communication

$$X(m) = X^*(N_{\text{fft}} - m) \qquad (1)$$

$$\tilde{x}(n) = \frac{1}{\sqrt{N_{\text{fft}}}} \sum_{0}^{N_{\text{fft}}-1} X(m) \exp\left(\frac{j2\pi mn}{N_{\text{fft}}}\right), \; C_{\text{low}} < x(n) < C_{\text{up}}$$

$$= C_{\text{low}} \quad , \tilde{x}(n) \leq C_{\text{low}} \qquad (2)$$

$$= C_{\text{up}} \quad , \tilde{x}(n) \geq C_{\text{up}}$$

$$x(n) = \tilde{x}(n) + DC \qquad (3)$$

where * denotes Hermitian operation. N_{fft}, C_{low}, and C_{up} means fast Fourier transform (FFT) size, lower and upper clipping level, respectively.

The clipping level, given a DC bias, is one of the most important factors which determine the overall performance of DCO-OFDM. In general, the clipping level is expressed in relation to the time domain signal standard deviation (σ). For a number of subcarriers greater than 64, clipping noise statistics follows a Gaussian distribution and hence one can predict the optimum clipping level [9]. In practice, optimum levels range between $\pm 2\sigma$ to $\pm 4\sigma$, chiefly depending on each system's dynamic range, frequency response, and non-linearity. We experimentally determined that $\pm 2.5\sigma$ clipping is optimum for the system we used.

B. Experimental set-up

Fig 4 shows experimental set-up for the data communication. The incoming bit stream is encoded and turned into a discrete time domain signal through an inverse fast Fourier transform (IFFT) operation and a cyclic prefix (CP) addition. This signal is clipped appropriately to guarantee a positive signal, and to avoid nonlinear distortion caused by transmitter and receiver components. MATLAB$^{®}$ was used for this signal conditioning.

The discrete signal is converted into an analogue signal using an arbitrary waveform generator (AWG), Agilent N8241A. Amplification by a wide band amplifier, Mini-Circuits ZHL-6A, follows. In conjunction with a direct current (DC) bias from a laser driver (LDC205C) via a bias-T, Mini-Circuits ZFBT-6GW, the modulated intensity is transmitted using the module described in Fig 2. The modulated white light generated from the module is focused onto an avalanche photo-detector (APD) based receiver, through a collecting lens.

A link distance of 3 cm was used, and an illumination level of 240 lx was measured at the receiver. This is a low level of illumination. (Normally 400 lux is considered to be well lit.)
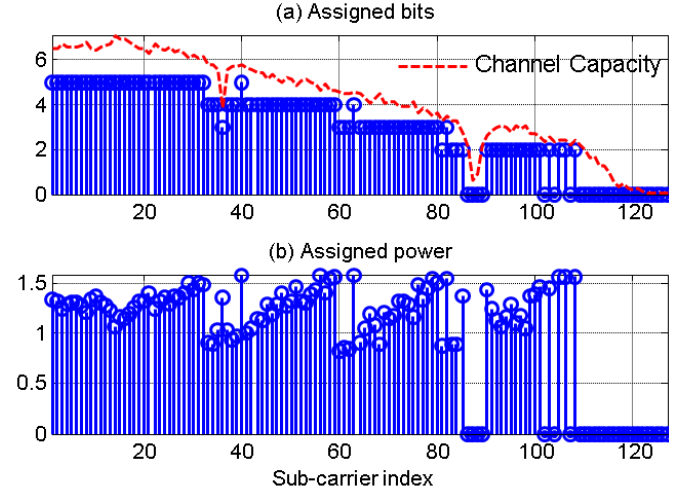

Fig. 5. (a) bit and (b) power loading scheme for 1.8 Gb/s at 3 cm link distance (240 lx) from OD 0.96
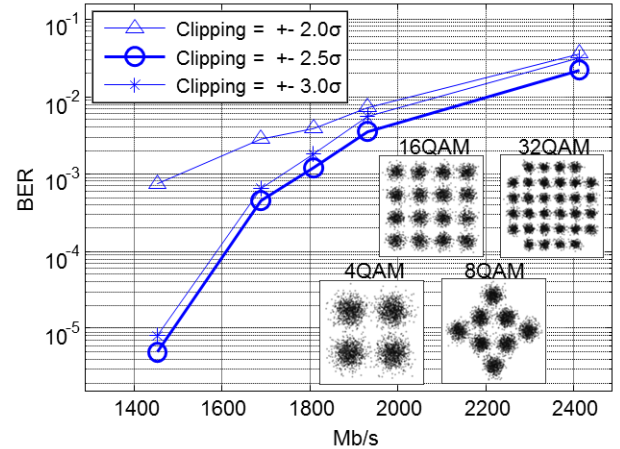

Fig. 6. BER results and a set of recovered constellations at 1.81 Gb/s and +- 2.5σ clipping, with 1.2×10^{-3} BER

The output signal is captured by a digital oscilloscope, Agilent MSO7104B. Finally, signal processing for recovery is executed in MATLAB$^{®}$ after synchronization.

C. Operating conditions

Considering the characteristics of the μLED, the optimal biasing point and AC voltage swing were found by comparing the SNR estimated from a training procedure. 200 known

BPSK symbols were transmitted on each subcarrier, and the noise variance and SNR were estimated from the received noise statistics. The optimum bias point was at 60 mA and the AC swing was 3.5 Vpp, leading to full modulation depth.

An FFT size (N_{fft}) of 256 and a cyclic prefix length (N_{cp}) of 3 were selected as there was no significant improvement for a greater CP (the CP overhead was ~ 1.2%). The sampling frequency (F_s) of the AWG is 1250 Ms/s which results in a maximum achievable single sided B/W of 625 MHz.

In this work, we used a bit and power loading scheme, since it is considered the optimum to reach channel capacity [10]. Fig. 5 shows the assigned bits and power on each subcarrier. Since the last 19 subcarriers were not used, the bandwidth that the OFDM signal occupied was 531 MHz. It can be clearly seen that the applied scheme enables to approach to the channel capacity derived from the estimated signal to noise ratio (SNR).

D. Result and discussion

Fig 6 summarises the measured bit error rate (BER) results. As shown, $\pm2.5\sigma$ clipping was found to be the optimum for the system we used. The BER curve using $\pm 3.0\sigma$ clipping follows that of the optimum one with a slightly higher BER. This is due to the fact that reduced clipping makes the useful signal variance smaller in a given dynamic-range, but the reduction of the clipping noise is smaller than background system noise. Clipping at $\pm2.0\sigma$ is shown to generate higher clipping noise, leading to a higher BER. Using the optimum clipping level, a data-rate of 1.81 Gb/s was achieved with a BER of 1.2×10^{-3}. Considering a forward error correction (FEC) overhead of 7% for an error-free-system [11], the data rate becomes 1.682 Gb/s.

IV. TOWARDS A PRACTICAL SYSTEM

Longer ranges can be achieved for this system, but at levels of illumination too low to be useful for lighting. (For instance a rate 0.84 Gbit/s at a range of 2 m at 14 lux was measured.) The major challenge for this approach is therefore to increase the power emitted from the white-light source, in order to provide greater range and/or coverage. In addition a more compact emitter is required.

Arrays of micro-LEDs can be used to increase the overall transmitted power, whilst maintaining the bandwidth of individual devices, and this approach is being pursued in UPVLC programme (of which this work is part). In a typical room there will be multiple LED lighting fixtures distributed over the ceiling in order to provide coverage, and in this case each fixture would consist of a micro-LED array. In order to create a simpler, more compact emitter, we are using grating and micro-optical structures on the LED to provide directional emission [12]. This will reduce the need for high NA collection optics. In addition, using a solid-state converter film attached, or close to the LED array is under investigation. A solid-film S-Y converter has been tested and shown promising results, despite some encapsulation issues limiting the life-span. Other conjugated polymers with higher PLQY (up to 90%) are being investigated as well. Together these approaches should lead to practical devices.

V. CONCLUSION

In this letter, we have demonstrated the feasibility of using a conjugated polymer for white light VLC. Our novel approach achieved white light with a high modulation bandwidth. A 1.68 Gb/s white light communication link was demonstrated at 3 cm distance, applying an adaptive DCO-OFDM technique.

However, limited power from the μLED and the significant insertion loss of the colour converter (due to its isotropic re-emission pattern) leads to illumination levels much lower (240 lx) than that obtained from a commercial white LED. However, table I shows that for a given illumination level the 'fast-white' LED described here can provide significant additional capacity. These are the fastest results so far reported for a single white source based VLC.

TABLE I.
DATA-RATE COMPARISON ON THE SAME ILLUMINATION LEVEL

Available Illumination level	Data-rate in [8]	Data-rate in [2]	Data-rate in this work
240 lx	~300 Mb/s	~1000 Mb/s	1682 Mb/s

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