10 Mb/s visible light transmission system using a polymer light-emitting diode with orthogonal frequency division multiplexing

Son T. Le,[1,*] T. Kanesan,[2,9] F. Bausi,[6,7,11] P. A. Haigh,[3,4,10] S. Rajbhandari,[5] Z. Ghassemlooy,[3] I. Papakonstantinou,[4,7] W. O. Popoola,[8] A. Burton,[3] H. Le Minh,[3] F. Cacialli,[6,7] and A. D. Ellis[1]

[1]Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK

[2]Telekom Research & Development (TM R&D), TM Innovation Centre, 63000 Cyberjaya, Selangor, Malaysia

[3]Optical Communications Research Group, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, UK

[4]Department of Electronic and Electrical Engineering, University College London, WC1E 6BT, UK

[5]Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

[6]Department of Physics and Astronomy, University College London, WC1E 6BT, UK

[7]London Centre for Nanotechnology, University College London, WC1E 6BT, UK

[8]School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow G4 0BA, UK

[9]e-mail: thavamaran.kanesan@ieee.org

[10]e-mail: paul.haigh@northumbria.ac.uk

[11]e-mail: f.bausi@ucl.ac.uk

*Corresponding author: let1@aston.ac.uk

Received April 16, 2014; revised May 27, 2014; accepted May 27, 2014; posted May 28, 2014 (Doc. ID 210276); published June 24, 2014

We present a newly designed polymer light-emitting diode with a bandwidth of ~350 kHz for high-speed visible light communications. Using this new polymer light-emitting diode as a transmitter, we have achieved a record transmission speed of 10 Mb/s for a polymer light-emitting diode-based optical communication system with an orthogonal frequency division multiplexing technique, matching the performance of single carrier formats using multitap equalization. For achieving such a high data-rate, a power pre-emphasis technique was adopted.

OCIS codes: (060.4510) Optical communications; (250.3680) Light-emitting polymers.

http://dx.doi.org/10.1364/OL.39.003876

With the exponentially increasing demand for data caused by the limited (and therefore expensive) radio frequency bandwidth available, researchers are increasingly turning to optical domain technologies such as visible light communications (VLC). The optical transmitters in VLC links are generally accepted as phosphor-converted gallium nitride (GaN) light-emitting diodes (LEDs) due to their high optical power and simplicity of implementation. Thus the vast majority of experimental research reported in the field has utilized just a solitary LED to achieve high throughputs [1–3]. GaN LEDs are produced using epitaxial methods that result in brittle crystals; as such it is not trivial to produce devices with large photoactive areas. To provide illumination in a home/office environment would therefore require a matrix of LEDs, which has its own associated problems such as resonance in the circuitry and increasing system complexity. A simpler approach would be to use a single panel with a large photoactive area.

As an alternative to inorganic LEDs, we consider here organic, polymeric LEDs (PLEDs) as the transmitter. Organic electronics is a technology that allows solution-based fabrication of semiconductor devices to concurrently have the properties of plastics (i.e., mechanical flexibility and arbitrary shape) and the conduction properties of metals as well as bandgap tuning by selection of polymer to control the emission wavelength. These advantages are very important for VLC systems, especially considering that large panel illumination devices can be produced with unrestricted shapes and sizes. As VLC becomes more prevalent in modern technologies, as is reflected in the increasing number of VLC start-up companies, we predict that new PLED-based screens, monitors, and devices will begin to arrive packaged with VLC capability. Therefore it is imperative to investigate the suitability of a range of PLED-based VLC systems across a wide gamut of modulation formats and signal-processing techniques.

However, the major challenge when adopting PLEDs for VLC systems is the relatively small raw bandwidth. The polymers used as semiconductors in PLEDs are characterized by the charge transport mobilities that are orders of magnitude lower than those available in crystalline inorganic semiconductors. In turn this causes a restricted PLED bandwidth that is also orders of magnitude lower than that obtainable from inorganic LEDs. As a result, achieving high-capacity data communications with PLEDs is a substantial challenge that needs addressing.

Several reports of high throughput polymer VLC (PVLC) links are available in the literature. In [4] a 9.3 Mb/s link is experimentally demonstrated using the on–off-keying (OOK) modulation format and a 270 kHz bandwidth PLED in real time with an FPGA. This transmission data rate was achieved using a least mean squares equalizer with 25 tapped weight coefficients. In [5] a transmission speed of 2.7 Mb/s was reported for a system that only utilized ~90 kHz bandwidth with an artificial neural network equalizer. However, these digital signal processing (DSP) based equalization techniques are highly computationally complex. Therefore, in order to bring PVLC systems closer to real-world applications, more DSP-efficient modulation formats and transmission schemes should be considered and explored.

It has been demonstrated that discrete multitone modulation schemes such as orthogonal frequency division multiplexing (OFDM) considerably outperform unequalized time-domain modulation schemes such as OOK in VLC systems due to their high spectral efficiency, meaning that multiple bits per symbol can be transmitted to achieve a much higher bit rate [6]. In addition, OFDM is extremely robust against frequency-selective and multipath fading channels, resulting in inherent protection against intersymbol interference (ISI), thus making OFDM the dominant modulation format in current RF wireless communications. As a result, OFDM has been considered a strong candidate for future VLC applications due to its inherent resilience to ISI [3,7]. However, there is a lack of reported research on the performance of OFDM in PVLC-based systems. To the best of our knowledge, the only demonstration of an organic VLC link with OFDM was reported in [8], at a bit rate of 1.4 Mb/s using a bandwidth of 93 kHz.

In this Letter, we present a 10 Mb/s PVLC link using custom-designed PLEDs with an increased device bandwidth of ~350 kHz, which is a noteworthy improvement of around four times over [8]. The increase in bandwidth is achieved by using thermal annealing above the glass transition temperature of the polymer during the PLED manufacturing process. This results in a lower turn-on voltage and higher currents for a certain voltage, compared with that in our previous reports. Thermal annealing is expected to facilitate packing of the different polymer chains and therefore favor higher charge mobilities. By using such a PLED with OFDM as the transmission scheme and a power pre-emphasis technique to increase the bandwidth efficiency, we have successfully transmitted a 10 Mb/s data stream without the use of any complex multitap equalization schemes. In comparison with the previous PVLC OFDM transmission systems [8], this represents significant improvements both in the achievable data rate (10 Mb/s in comparison to 1.4 Mb/s) and also in the net data-rate/bandwidth gain (30 times here in comparison to 14 times in [8]). For the purpose of comparison, we also present here the performance of an unequalized OOK system using the same PLED.

One of the main limits of organic-based photonic devices is the degradation mechanisms of the polymers due to contact with oxygen/water from air, which drastically limits performance and lifetime. For this reason, PLEDs are usually prepared under nitrogen atmosphere. In this work, encapsulated PLEDs were prepared that allowed safe utilization in air without any apparent degradation with time. A schematic and photograph of the PLED used in this work is shown in Fig. 1.

For the preparation of the devices, a glass substrate is used with pre-patterned indium-tin oxide (ITO) as a transparent anode (Ossila Ltd). The ITO was cleaned with sonication in acetone and isopropanol and treated with oxygen plasma [9] to increase work function and reduce surface roughness. Immediately following this, we spin-coated (5000 rpm for 30 s in air) a water dispersion of PEDOT:PSS (Heraeus Clevios P VP AI 4083) to produce a hole-injection layer of approximately 40 nm thickness. The polymeric layer was annealed at 180°C for 600 s in nitrogen atmosphere to remove water residue. Then the active layer of poly [2-methoxy-5-(3′, 7′-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) with a Mn of ~23,000 g/mol (Sigma-Aldrich) was deposited via spin coating (2000 rpm for 60 s) from a 1% w/w (8.76 g/mL) solution in toluene. We then annealed the samples for 10 min at 150°C, i.e., above the glass transition temperature. The annealing is expected to induce a reorganization of the polymer chains, thus favoring the interchain interaction and hence determining a better charge transport [10], resulting in a higher bandwidth compared with that in the previous work [4] while causing a partial but acceptable decrease in the luminance from 17,000 to 12,000 cd/m^2 at 10 mA operation (Fig. 2).

The ~30 nm metallic calcium cathode is evaporated in high vacuum, followed by evaporation of a ~150 nm protective aluminum layer. The devices were then encapsulated using epoxy glue (Ossila Ltd) to apply a protective glass slide on top of the layers. The glue was cured with UV light (4–5 mW/cm^2) for 15 min in nitrogen atmosphere to form a solid thin film that protects the device from the infiltration of oxygen and water. Contact legs

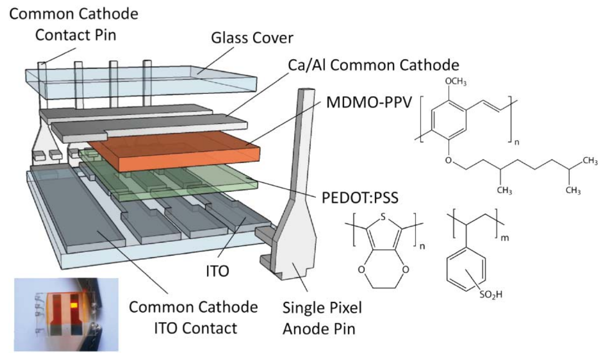

Fig. 1. Exploded schematic of the PLED used in this work; inset is a top-view photograph of a single 3.5 mm^2 photoactive area PLED at 8 V (DC bias). To prevent air exposure of the cathode and the polymer layers, the device is covered with a film of epoxy glue and a glass slide. The glass cover is smaller than the glass substrate to leave enough space to attach the pins. The external contact is made through an ITO stripe (left in the image above).

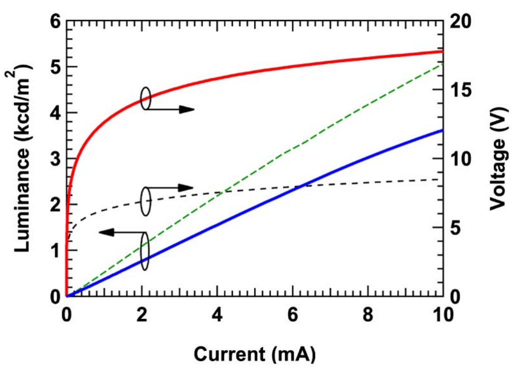

Fig. 2. L-I-V curve of the PLED under test, shown in dashed lines are the plots for diodes used in [4].

were applied to the devices (Ossila Ltd). The L-I-V curves, shown in Fig. 2, were measured for the PLED under test between 0 to 10 mA (solid lines) in comparison to [4] (dashed lines). As shown in Fig. 1, the metallic calcium cathode is connected to the contact pin through an ITO stripe to prevent air exposure. This ITO contact forms a resistance of about 100 Ω in series to the diode; this explains why, for any voltage, the current is lower in the encapsulated devices compared with that in the nonencapsulated one [4]. However, even with a higher series resistance, the encapsulated devices show wider bandwidth than the nonencapsulated devices because the degradation due to air exposure is prevented. This suggests that even higher bandwidth could be reached through a better design of encapsulated devices so as to achieve a lower series resistance. The PLEDs electroluminescence spectra feature a 600 nm peak with a similar emission profile as in [4]. The frequency response curve of the PLED under test is shown in Fig. 3.

The block diagram of the OFDM transmission test setup implemented is illustrated in Fig. 4. The OFDM time-domain signal at a predetermined data rate was generated offline in MATLAB using an IFFT size of 256, which is a good compromise between the performance and the DSP complexity [3]. To ensure that the OFDM time-domain signal is real-valued, the Hermitian symmetry condition was satisfied in the frequency domain. In order to accomplish link synchronization, a training sequence with two identical formats was inserted after every 100 OFDM symbol. A known training symbol was also inserted after every 100 OFDM symbol for the channel estimation at the receiver using a single-tap equalizer, as is standard in OFDM systems. The generated signal is clipped at 10 dB peak-to-average power to keep the signal within the PLED's *s* dynamic range. The OFDM time-domain signal is then loaded into a Rohde and Schwarz SMBV100A vector signal generator (VSG), which is controlled by a custom LabVIEW script. The generated signal from the VSG is first amplified using a voltage amplifier and is then fed into a current-converting driver to intensity modulate the PLED while biasing the device in the linear operating region (8 mA_{DC} bias, 6 mA_{AC}). The output of the PLED is transmitted over the channel, which is represented by a less-than-unity DC gain [11]. The transmission link distance is 0.05 m, which is very short in comparison to a full room scale. With such a short distance, the insertion of cyclic

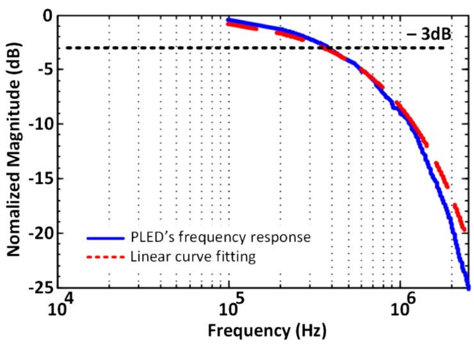

Fig. 3. Frequency response curves of the PLED under test. The dashed line in red is the linear curve fitting (in logarithmic scale).

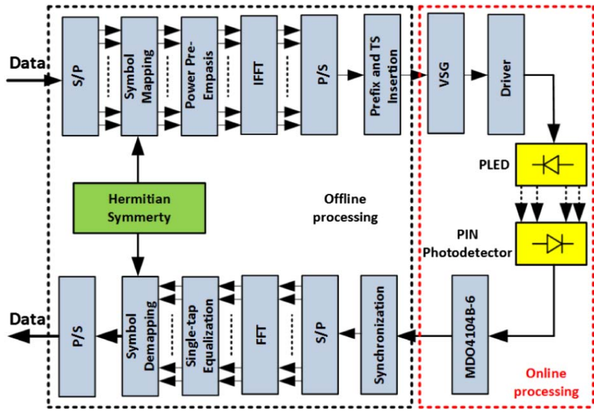

Fig. 4. Schematic block diagram for the system under test: S/P, serial/parallel conversion; P/S, parallel/serial conversion; TS, training symbol; VSG, vector signal generator.

prefix was not required. It should be noted that the experiment was performed using a 3.5 mm^2 photoactive area pixel; hence the distance could be increased by increasing the photoactive area. Furthermore, the devices were encapsulated allowing transmission outside of a pumped vacuum environment for the first time. The received signal is sampled and digitized by a Tektronix MDO4104B-6 oscilloscope. 10^7 samples per acquisition were recorded with a sampling frequency that was varied according to the transmitter's symbol rate to give a maximum of 10 Sa/sym. The data is then captured in MATLAB for further off-line processing with a standard OFDM receiver, including resampling, synchronization, single-tap equalization, and symbol de-mapping.

In our experiment, the achievable SNR limited the constellation to 4 bits/subcarrier (e.g., 16 QAM). The data rate was varied by selecting the OFDM symbol duration appropriately, which in turn varies the signal's bandwidth. As shown in Fig. 3, the PLED can be modeled as a low-pass filter with a cut-off frequency $f_c = (2\pi RC)^{-1}$ where R is the series resistance and $C = \epsilon_0 \epsilon_r A/d$ is the plate capacitance, where ϵ_0 and ϵ_r are the relative permittivity of a vacuum and the dielectric constant of the organic layer, respectively. As a result, the system performance deteriorates when the signal bandwidth is increased due to attenuation of the high-frequency components, thus causing low SNR for the subcarriers allocated outside the modulation bandwidth. To overcome this problem power, pre-emphasis can be applied by transmitting subcarriers with higher indices (higher frequencies) with relatively higher powers. In OFDM systems, this can be implemented directly in the frequency domain before the IFFT block (Fig. 4). In order to obtain the best performance, the power pre-emphasis function can be chosen as the invert function of the PLED's frequency response function (see Fig. 3). By using a linear curve fitting (see Fig. 3), the power pre-emphasis function (in dB) can be approximately expressed as

$$[P(k)]_{\mathrm{dB}} = \frac{3}{B} \cdot f_k,$$

where B is the 3 dB bandwidth (~350 kHz) of the PLED, and f_k is the frequency of the kth subcarrier. By applying this power pre-emphasis technique, the modulation index

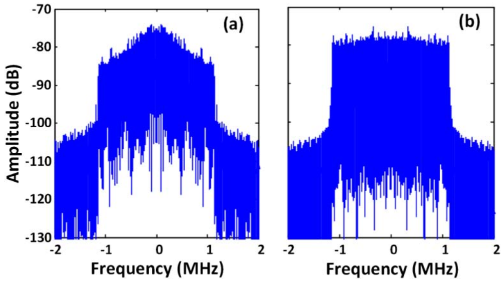

Fig. 5. Frequency spectra of the received OFDM signals (both with 1 MHz bandwidth) without (a) and with (b) power pre-emphasis.

of the transmitter will be nearly independent of the frequency (Fig. 5), thus allowing the transmission of a signal with a much larger bandwidth in comparison to the PLEDs bandwidth, meaning a relatively high net data-rate/bandwidth gain.

The received constellation diagrams at 4.5 Mb/s without power pre-emphasis before and after single-tap equalization are shown in Figs. 6(a) and 6(b), respectively. A 16 QAM modulation format was adopted. It is clear that the PLED and the system front end not only introduce amplitude distortion (acting as a low-pass filter) but also phase distortion (introducing a frequency-dependent positive phase shift). As a result, with the increase of subcarrier index (frequency), these amplitude and phase distortion perturbations rescale and rotate the received constellation points simultaneously. However, both the amplitude and phase distortions introduced by the PLED are frequency-dependent and thus can be effectively corrected by transmitting a known symbol and performing single-tap equalization with the zero-forcing method. At a bit rate of 4.5 Mb/s, the data can be recovered with a bit error rate (BER) of $\sim 5.6 \times 10^{-3}$.

The BER performance of the investigated OFDM system with and without power pre-emphasis and unequalized OOK transmission schemes is shown in Fig. 7. At a transmission speed of 1 Mb/s or above, error-free transmission was not achieved due to the noise level at the receiver, which is responsible for a BER floor of $\sim 3 \times 10^{-4}$. As a result, for real-world applications it is necessary to introduce a BER limit for forward error correction (FEC) at 3.8×10^{-3}, at the cost of 7% overhead [3], as is a common practice in high-speed VLC systems [3]. The 7% FEC limit is indicated by the dashed line in the Fig. 7. When power pre-emphasis is not employed, the system BER increases drastically with the transmission data rate (or signal's bandwidth) due to the low level of SNR for subcarriers with higher frequencies. At 7% FEC

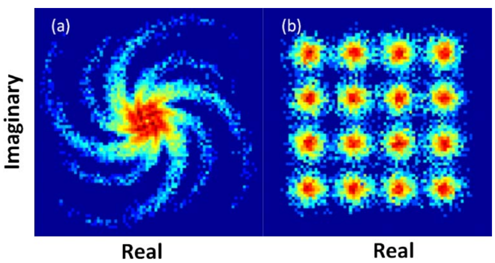

Fig. 6. Received constellation diagrams at 4.5° Mb/s without power pre-emphasis, before (a) and after (b) single-tap equalization.

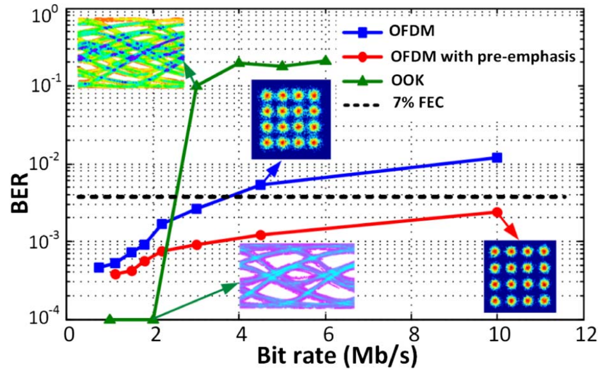

Fig. 7. BER versus transmission data rate for OFDM systems with and without power pre-emphasis and OOK.

threshold level, the achievable data rate is around 4 Mb/s, demonstrating the advantage of OFDM over unequalized OOK, where a transmission speed above 2.5 Mb/s cannot be supported. Finally, when the above-mentioned power pre-emphasis technique is applied, a transmission speed up to 10 Mb/s can be achieved, which is 2.5 and four times faster than the standard OFDM and unequalized OOK schemes, respectively.

In conclusion, we have discussed a 10 Mb/s OFDM VLC link using a newly designed PLED with a bandwidth of ~350 kHz. A net data rate/bandwidth of around 30 was achieved by applying a relatively simple but efficient power pre-emphasis technique. Taking into account the robustness of OFDM signal against the frequency-selective and multipath fading channels, this work presents a significant step for the future of PLED-VLC systems as the achieved data rate is sufficient for an indoor Ethernet connection.

The authors gratefully acknowledge Aston University for financial support, Dr. Chin-Pang Liu, Prof. Izzat Darwazeh, and Dr. Haymen Shams, all of University College London, for providing the test and measurement equipment.

References

1. P. A. Haigh, Z. Ghassemlooy, S. Rajbhandari, I. Papakonstantinou, and W. Popoola, J. Lightwave Technol. **32**, 1807 (2014).
2. W. Fang-Ming, L. Chun-Ting, W. Chia-Chien, C. Cheng-Wei, H. Hou-Tzu, and H. Chun-Hung, IEEE Photon. Technol. Lett. **24**, 1730 (2012).
3. G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, Opt. Express **20**, B501 (2012).
4. P. A. Haigh, F. Bausi, Z. Ghassemlooy, I. Papakonstantinou, H. Le Minh, C. Flechon, and F. Cacialli, Opt. Express **22**, 2830 (2014).
5. P. A. Haigh, Z. Ghassemlooy, I. Papakonstantinou, and M. Hoa Le, IEEE Photon. Technol. Lett. **25**, 1687 (2013).
6. A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, IEEE Photon. J. **4**, 1465 (2012).
7. J. Vucic, C. Kottke, S. Nerreter, K. D. Langer, and J. W. Walewski, J. Lightwave Technol. **28**, 3512 (2010).
8. P. A. Haigh, Z. Ghassemlooy, and I. Papakonstantinou, IEEE Photon. Technol. Lett. **25**, 615 (2013).
9. T. M. Brown and F. Cacialli, J. Polym. Sci., Part B **41**, 2649 (2003).
10. Z. E. Lampert, S. E. Lappi, J. M. Papanikolas, C. L. R. Jr, and M. O. Aboelfotoh, J. Appl. Phys. **113**, 233509 (2013).
11. J. M. Kahn and J. R. Barry, Proc. IEEE **85**, 265 (1997).