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Flexible photoluminescent waveguide amplifiers to improve visible light communication platforms

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Abstract: Commercial light-emitting diodes are a low-cost and energy-efficient solution for the implementation of optical wireless communication, known as visible light communication (VLC). This technology has a huge growing interest, being recently a research spotlight in the scientific community, especially due to the increasing popularity and rapid development of self-sustainable smart houses and the Internet of Things. As the VLC link is free space, big challenges arise in its implementation. To improve the VLC performance, this work proposes an enhanced system solution integrating an optical amplifier. In this context, organic–inorganic hybrids incorporating a blue-emitting conjugated polymer with high quantum yield (>50%) were synthesised and processed as planar waveguides. The waveguides were tested in a testbed scenario, showing a signal amplitude improvement of 2.5 dB, establishing the proposed approach as a promising cost-effective solution for optical amplification in VLCs.

1 Introduction

Commercial light-emitting diodes (LEDs) are a low-cost and energy-efficient solution for illumination [1]. Unlike older lighting technologies, LEDs are capable of modulating the emitted light intensity at a very fast rate (gigabits per second) [2], allowing them to be used as a light source and a wireless transmitter in visible light communication (VLC), simultaneously. These attributes will enable the facile repurposing of existing lighting infrastructure, leading to the easier and lower-cost deployment of VLC [3]. Nonetheless, this technology presents some drawbacks related to signal attenuation and the existence of multiple optical paths due to reflections in physical barriers present in a free space connection [4]. To date, there is still an open question on how to optically improve the VLC performance using already installed LEDs and photodetectors, and, in parallel, taking into account the requirements for cost effectiveness, sustainability and low carbon footprint associated with deployment, manufacturing and recycling issues, which are relevant to meet UN sustainable development goals. To cope with these challenges, optical pre-amplifiers have been suggested to improve the VLC performance [5–7].

Herein, we study an optical pre-amplifier based on a conjugated polymer (CP) in an organic–inorganic hybrid matrix (di-ureasil) integrated into a VLC system. This material was selected, because it combines the relevant optical features (optical gain, refractive index and absorption coefficient), reduced production cost and power consumption, and has recently been successfully implemented as an optical amplifier with high photoluminescence quantum yields ($\Phi_{PL} > 50\%$), and sub-nanosecond emission lifetimes [5, 8]. It was also shown recently that the incorporation of CPs into a di-ureasil organic–inorganic hybrid minimised interchain interactions leading to highly emissive solid-state materials with high optical gain [5, 9, 10]. Additionally, di-ureasils themselves emit in the purple-blue spectral region with a lifetime of nano–microseconds [11], and present mechanical flexibility, thermal stability and low insertion losses [12].

In this context, the blue-emitting CP (poly[9,9-bis(4-sulfonylbutoxy phenyl) fluorene-2,7-diyl-alt-1,4-phenylene], PBS-PFP) was incorporated into a di-ureasil organic–inorganic hybrid and processed as monoliths (planar waveguides). The resultant material presented a high photoluminescence quantum yield (>50%) and exhibited a large optical gain efficiency (0.73 ± 0.01 cm/ μJ) [5]. Inspired by these results and as a proof of concept, the planar waveguides were tested in a VLC test-in-bed as a pre-amplifier, showing an improvement in the communication performance. The optical gain was estimated as a function of the input power and the CP concentration, yielding a maximum value of 2.5 dB for the sample with higher CP concentration for an input power of 0.20 ± 0.01 mW.

2 Experimental details

2.1 Synthesis and processing

The CP PBS-PFP was dispersed in a di-ureasil organic–inorganic hybrid via the direct insertion method as previously reported [7]. In this method a fixed volume of a stock solution of PBS-PFP was mixed in 1,4-dioxane: water (25/75 v/v%) with a di-ureapropyltriethoxysilane (d-UPTES) precursor solution, before inducing acid-catalysed hydrolysis and condensation of the siliceous backbone to obtain the final PBS-PFP-di-ureasil. The synthesis details are described elsewhere [5]. The final material was processed into free-standing monoliths. The solution containing the PBS-PFP-di-ureasil was transferred into a polypropylene mould and covered with Parafilm M (Fig. 1*a*). After 24 h, the Parafilm M was pierced to promote slow evaporation of the solvent, after which it was placed in an oven at 40°C for 48 h to complete the drying process, producing a free-standing monolith with a thickness of around 3 mm, and length × width of 23×16 mm^2. The gain in dB/cm is a property of the material, and thus is independent of the device length. In this work, the dimensions were chosen to simplify the waveguide–photodiode coupling, and as a compromise between the device gain and miniaturisation to be applied in VLC.

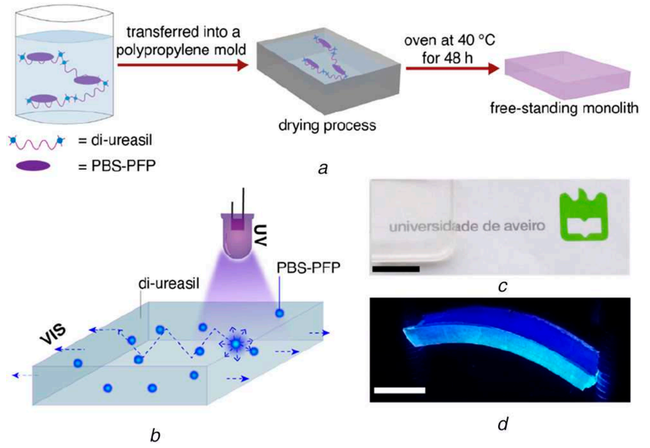

Fig. 1 *Synthesis, mode of operation and appearance of CP-di-ureasil optical amplifiers*
(a) Schematic representation of PBS-PFP-di-ureasil processing into planar monoliths, ***(b)*** Representative scheme of the PBS-PFP-di-ureasil planar waveguide. The arrows inside the waveguide indicate the total internal reflection of the emitted light, ***(c)*** Photographs of the flexible PBS2 under daylight, ***(d)*** Photographs of the flexible PBS2 under UV illumination
The scale bars represent 1 cm

Table 1 Sample composition and Φ_{PL} for PBS-PFP-di-ureasil composites. The weight percent of polymer incorporated was estimated from the PBS-PFP concentration in the stock solution and the resultant mass of the dry PBS-PFP-di-ureasil

Sample	PBS-PFP, wt%	Thickness, mm	Φ_{PL}[a]
dU(600)	0	2.9	0.18
PBS1	1.2×10^{-3}	2.7	0.41
PBS2	1.3×10^{-3}	3.1	0.49
PBS3	1.2×10^{-2}	3.2	0.76

[a] The error is estimated to be $\Delta\Phi_{PL}/\Phi_{PL} = 0.10$ (see [5] for details).

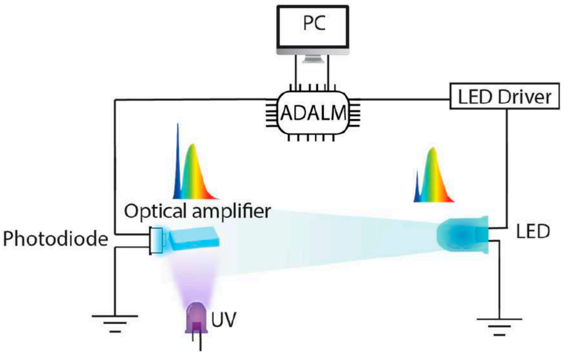

Fig. 2 *Scheme of the experimental set-up used for the transmission measurements in the VLC scenario*

The monoliths will function as planar waveguides, guiding and concentrating the radiation in the lateral faces, see Fig. 1*b*. The PBS-PFP-di-ureasil-based waveguides showed flexibility, transparency under daylight (absorption coefficient <0.1 cm^{-1} for wavelengths above 400 nm [5]), and exhibited an intense blue emission under UV radiation (365 nm), as shown in Figs. 1*c* and *d*.

Hereafter the samples are designated as dU(600) for the undoped di-ureasil, and as PBS1–3, where PBS1 has the lowest PBS-PFP concentrations. The weight percent (wt%) of PBS-PFP incorporated in each sample and the respective photoluminescence quantum yield, Φ_{PL}, are indicated in Table 1. The chosen maximum PBS-PFP concentration has a compromise between the photoluminescence quantum yield required for this application (>50%), the transparency and the minimum amount of polymer needed.

2.2 Optical gain measurements in VLC scenario

The experimental setup for transmission measurements in the VLC testbed is shown in Fig. 2. This system is based on a commercial LED Lamp (Codex-E Lamp Lightening), operating as a light source and a wireless transmitter, simultaneously. These lamps were used because they are easily available at a low cost, which make them appealing for sustainable implementation. As the LED lamp is a combination of a long lifetime yellow emission combined with the faster response time of a blue-emitting LED (peaking at ∼450 nm), the signal detection and amplification should focus on the blue component. To quantify the input power, the spectral radiant flux of the LED lamp (or spectral radiant power, W/nm) was measured through an integrating sphere (ISP 150L-131, Instrument Systems) with a $BaSO_4$ coating and an internal diameter of 150 mm coupled to an array spectrometer (MAS-40, Instrument Systems). Before the measurements, a self-absorption correction was implemented using a reference lamp (ISP 150L-131, Instrument Systems).

The data sequence transmitted by the LED lamp was a binary message, generated in MATLAB®, with a word length of 2^{12} bits, a bit rate of 500 bits/s, and a sample rate of 10^5 samples/s. The digital message was then uploaded to a DAC board (Analogue Devices ADALM1000) and seeded a current controller (T-Cube LED Driver, Thorlabs), connected to the LED lamp. At the receiver, the planar waveguides were coupled directly to the photodiode active area (DET10A, Thorlabs) with a refractive index matching gel to reduce insertion losses. The waveguides were optically pumped with a UV-emitting diode (MCLS LED 365, Ocean Optics) acting as an excitation source. The transmission tests were performed with a distance between the transmitter and the receiver of 20.00 ± 0.05 and 30.00 ± 0.05 cm. The photocurrent generated in the photodiode was also acquired with the ADALM1000 and processed in MATLAB®, allowing estimation of the signal amplitude and signal-to-noise ratio (SNR) values.

3 Results and discussion

To assess the performance of the PBS-PFP-di-ureasil planar waveguides as optical amplifiers in a VLC scenario, the received signal amplitude and SNR were obtained with and without UV excitation for different input powers ($0.04 \le P_{in} \le 0.20$ mW). The optical on/off gain values were calculated from the ratio between the peak-to-peak voltages of the received signal, with and without the optical pump signal. As an illustrative example, a temporal sample of the received signal is represented in Fig. 3*a*, which was obtained with a signal optical power, at the waveguide input, of 0.20 ± 0.01 mW. An improvement in the intensity was observed when the waveguides were coupled to the photodiode active area, yielding an optical gain of 0.84, 0.86 and 2.49 dB for PBS1, PBS2 and PBS3, respectively. The similar values between PBS1 and PBS2 are due to the analogous PBS-PFP concentration, which is responsible for the blue emission and, consequently, the optical gain. For comparison purposes, this experiment was repeated for the undoped dU(600) as a control sample, yielding a null optical gain for the input power range studied. This confirms that the optical gain is entirely due to the PBS-PFP CP. Therefore, it is important to quantify the optical gain as a function of the input power for the PBS1, PBS2 and PBS3 samples.

An increase in the optical gain was observed with the input power, with a rate of 5.0, 5.4 and 12 dB/mW for PBS1, PBS2 and PBS3, respectively, as shown in Fig. 3*b*. The waveguides containing a higher PBS-PFP concentration showed an increase of gain with the input power, with a maximum optical gain of 2.49 dB, as observed by the other optical gain measurements [5]. In contrast, PBS1 and PBS2 which have a low PBS-PFP concentration, and consequently less optical centres available for excitation, presented a lower gain for similar input powers.

As an illustrative example, in Fig. 3*c* the eye diagrams of the best scenario using the most concentrated sample (PBS3) are shown, which yielded an optical gain of 2.5 dB for an input power of 0.20 ± 0.01 mW. In this configuration, the estimated SNR was

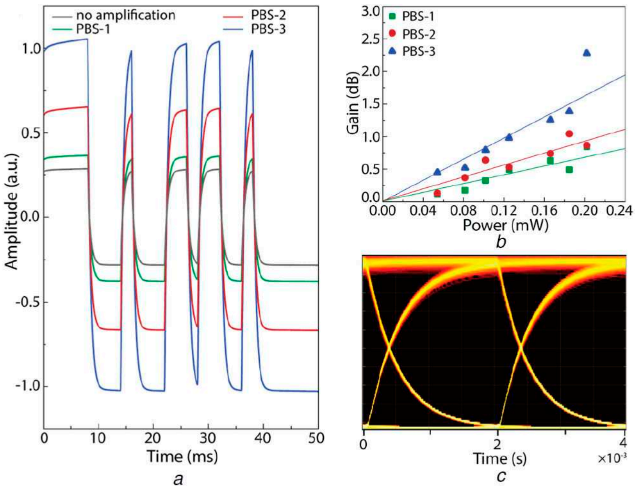

Fig. 3 *Performance of PBS-PFP-di-ureasil waveguides as optical amplifiers in a VLC test in bed*

(a) Sample of the received binary sequences with and without the planar waveguide as pre-amplifiers, obtained with a signal input power of 0.20 ± 0.01 mW. The photodiode operates with an output capacitor, removing the DC component, ***(b)*** Calculated optical gain as a function of the input power for the scenario where the planar waveguide functions as a pre-amplifier, ***(c)*** Eye diagram of the 500 bits/s signal at the planar waveguide PBS3 output (input power density of 0.20 ± 0.01 mW)

The colour intensity has no significant meaning

13 dB, and the corresponding bit error rate for a non-return-to-zero signal is estimated to be 10^{-7}.

4 Conclusion

Planar waveguides based on PBS-PFP-doped di-ureasils were prepared, showing a high blue emission which overlaps with that of the InGaN-based LED used to produce the commercial solid-state LEDs. Additionally, this material presented a high photoluminescence quantum yield (>50%) and high optical gain efficiency (0.73 ± 0.01 cm/μJ). Taking advantage of these features, the waveguides were implemented as optical amplifiers in a VLC test-in-bed system, yielding a maximum optical gain of 2.5 dB in the most concentrated sample for an input power of 0.20 ± 0.01 mW, showing the potential of these materials for optical amplification in the visible spectral range. Since this material has shown a high optical gain, other monolithic architectures (e.g. fibres) can be designed to optimise the amplifier–photodiode coupling. As far as we know, there are no solutions based on optical amplification to improve the VLC reliability, showing the huge potential of this work to solve this technological gap.

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