Micro-LED-based Guided-Wave Optical Links for Visible Light Communications

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ABSTRACT

Visible light communications (VLC) have attracted considerable research interest in recent years for use in both free-space and guided-wave optical links. In this paper, we review recent work on the development of guided-wave VLC links over plastic optical fibres (POF) and multimode polymer waveguides utilising micro-pixelated light-emitting diodes (µLEDs) and pulse amplitude modulation (PAM) schemes. Record 6.25 Gb/s single-directional and 10 Gb/s bi-directional data transmission have been achieved over 10 m of POF using this low-cost technology, while low-cost waveguide-based VLC systems achieving 4 Gb/s per channel have been developed.

Keywords: visible light communications, micro-pixelated LEDs, plastic optical fibres, multimode polymer waveguides, advanced modulation formats, pulse amplitude modulation

1. INTRODUCTION

Visible light communications (VLC) have attracted considerable research interest in recent years for use in both free-space (e.g. Li-Fi) and guided-wave optical links. This increasing interest has been fuelled by the recent development of low-cost light-emitting diodes (LEDs) that are suitable for both lighting and data transmission [1, 2], and advanced modulation formats that enable the transmission of relatively high data rates (> 1 Gb/s) over channels with limited bandwidth using optical and electrical components with lower specifications [3, 4]. In particular, micro-pixelated LEDs (µLEDs) operating in the visible range appear to be favourable sources for VLC links as they exhibit larger bandwidth than conventional LEDs and can be formed in large array configurations [5]. Their use in conjunction with the deployment of advanced modulation formats, such as pulse amplitude modulation (PAM) and orthogonal frequency division multiplexing (OFDM), can enable transmission of data rates (>1 Gb/s) far greater than those obtained with conventional LEDs and on-off keying (OOK) [6, 7]. In this paper, we review recent work on the development of guided-wave VLC links over plastic optical fibres (POF) and multimode polymer waveguides utilising µLEDs and PAM modulation schemes.

POF links have attracted interest for use in home networks and automotive applications owing to their low-cost, ease of installation and mechanical robustness, while multimode polymer waveguides are promising candidates for use in short-reach board-level links with lengths up to 1 m. POF links are promoted as do-it-yourself optical connections which can provide high-speed interconnection in future home and work environments [6, 8, 9], while polymer multimode waveguides can readily integrated in common printed circuit boards (PCBs) and provide interconnection capacities beyond the limits of conventional copper-based wiring [10-12]. These low-cost technologies match very well with the characteristics of µLEDs, namely their small dimension (typically < 50 µm), wavelength range and potential to be formed in large arrays, enabling the implementation of cost-efficient high-speed VLC optical links. However, to overcome the inherent limited bandwidth of LEDs and POFs and achieve interconnection data rates above 1 Gb/s, advanced modulation formats are deployed. Record 6.25 Gb/s single-directional and 10 Gb/s bi-directional transmission have been achieved over 10 m of POF using µLEDs and PAM schemes. Multimode polymer waveguides have been considered for use for short-reach board-level optical links with lengths <1 m. The use of large waveguide arrays with matching µLED arrays and in conjunction with advanced modulation formats can enable the achievement of high data densities (~1 Tb/s/mm^2) at the board edge using very low-cost optical and electrical components. Examples of such low-cost waveguide-based VLC systems achieving 4 Gb/s per channel are presented.

2. MICRO-PIXELATED LEDs AND GUIDED-WAVE VLC LINKS

2.1 µLEDs

The work presented herein is based on the use of GaN-based micro-pixelated LEDs. These devices have typical dimensions of the order of 20 to 100 µm and have been shown to exhibit relatively large modulation bandwidths (> 100 MHz) and output powers (>1 mW per pixel) [5]. Their improved bandwidth characteristics over conventional LEDs can be attributed to the reduction in device self-heating and current crowding owing to their small area [5]. As a result, larger current densities can be sustained through the device and therefore, shorter carrier lifetimes and larger modulation bandwidths are obtained. Moreover, such devices can be readily formed in large arrays and directly interfaced with CMOS technology, enabling easy-controllable on-chip multi-channel optical transmitters [1, 2]. This LED technology has currently attracted wide interest for wireless optical communications (LiFi) as it can provide relatively high-speed data transmission as well as high-quality illumination. Recent examples of such LiFi systems include [13-15]. The small dimensions of the µLEDs make them also suitable for use in guided-wave optical links, as they can be directly interfaced with large core optical fibres or waveguides. In particular, POFs and polymer-based multimode waveguides match the low-cost character of LED-based technologies and can be efficiently used in the visible wavelength range. In this particular work, blue-emitting (peak wavelength ~450 nm) µLEDs 20 or 40 µm in diameter are employed. Output power ≥1 mW is obtained for a bias current of ~20 mA with a modulation bandwidth of ~150 MHz.

2.2 POF technology and multimode polymer waveguides

POFs are an attractive technology for use in in-home and automobile networks owing to their very low cost, ease of handling and connectorisation, mechanical robustness and small bending radius. Typical dimensions of the POF diameter are in the range 0.4 to 1 mm, while typical loss values are of the order of 0.2 dB/m at the visible wavelength range. Due to their large core size, their bandwidth is limited by multimode dispersion, with typical bandwidth-length product values in the range of 200 MHz×50 m. Nevertheless, they appear to be the most suitable candidate for short-reach, yet low-cost optical interconnections, such as for the aforementioned applications, where link lengths of up to 50 m are required. Various types of POFs have been developed based on different materials and exhibiting different refractive index profiles and geometries in order to match the specific requirements of each application. The work presented here is based on the use of a standard low-cost commercially-available 1 mm-diameter step-index POF (Eska-Mega).

Optical technologies constitute a promising alternative to conventional metal-based interconnections inside electronics systems such as data storage systems, data centres and supercomputers [16]. Optics offer larger interconnection bandwidth, immunity to electromagnetic interference, reduced power consumption, increased density and relaxed thermal management requirements. Multimode polymer waveguides have recently attracted particular interest for use in board-level interconnections for link lengths up to 1 m [11]. This technology leverages new cost-efficient polymer materials which exhibit excellent thermal, mechanical and optical properties as well as the required environmental stability and lifetimes to be directly integrated onto standard PCBs, and multimode waveguides that offer relaxed alignment tolerances in the system assembly [17]. Moreover, the waveguides can be formed in one- or two-dimensional arrays enabling large aggregate interconnection capacities [18, 19]. Typical waveguide dimensions and pitches employed range from 20 to 70 µm and 40 to 250 µm respectively, matching very well the dimensions of µLEDs and µLED arrays. As a result, the combination of these two technologies can form very low-cost optical waveguide systems that can find application in short-reach communication links, such as optical USBs, low-cost backplanes and optical sensors. Large aggregate data capacities can be achieved by deploying large number of parallel links, spectrally-efficient modulation schemes and implementing wavelength multiplexing techniques. In the work presented herein, siloxane-based multimode waveguides are employed which have been already demonstrated for use in VCSEL-based optical interconnects [20, 21].

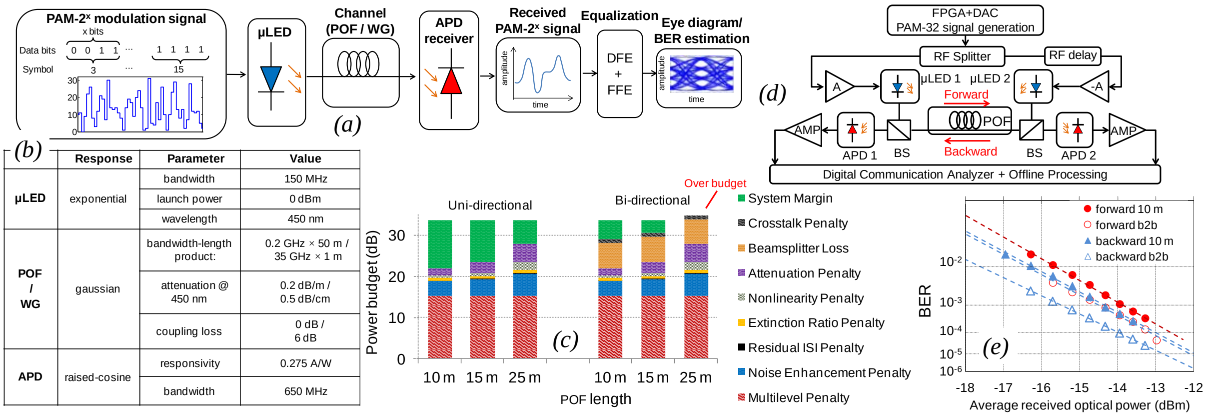
2.3 VLC guided-wave links

In order to overcome the bandwidth limitation of µLEDs and POFs, advanced modulation formats are employed. In particular, PAM schemes can enable higher data transmission rates than conventional OOK schemes and over link components of lower bandwidth [3, 22]. In a PAM-2^x scheme, x bits of information are combined to form one symbol (2^x symbols possible) which is then transmitted over the link. At the receiver end, 2^x-1 thresholds are employed to identify each transmitted symbol and therefore the corresponding bits of information. Such schemes are relatively straightforward to implement in CMOS electronics and don't require cumbersome digital signal processing techniques. Moreover, the proposed VLC guided-wave links are based on the use of avalanche photodiodes (APDs) at the receiver end as they offer a larger power budget over conventional PIN receivers. The benefits of their use have been theoretically and experimentally demonstrated [23, 24]. The basic link model for VLC guided-wave links is shown in Fig. 1(a) with the important component parameters noted in Fig. 1(b). The link model is used to assess the feasibility of achieving data transmission with a particular bit-error-rate (BER) performance. A BER of 10^{-3} is employed in the calculations as it constitutes a standard threshold for efficient implementation of forward-error-correction (FEC) schemes. Finally, feed-forward (FFE) and decision-feedback (DFE) equalization schemes are also assumed at the receiver to overcome the limited bandwidth of such links.

3. SIMULATION RESULTS AND EXPERIMENTAL DEMONSTRATIONS

3.1 POF-based VLC links

The feasibility of 5 Gb/s data transmission over POF using PAM-32 modulation scheme and an APD receiver has been investigated [24]. The simulation results indicate the 5 Gb/s data transmission is possible over 25 m of POF with a power margin of 5.84 dB [Fig. 1(c)]. In order to further increase the data capacity of the link, a bi-directional scheme is considered, effectively doubling the aggregate data rate over the link [25]. The simulation results indicate that such a link can successfully operate over 15 m of POF [Fig. 1(c)]. The link is setup and tested using two 450 nm µLEDs 20 µm in diameter, two Si APDs 800 µm in diameter, and beamsplitters (BS) enabling bi-directional transmission at each POF end [Fig. 1(d)]. Record aggregate 10 Gb/s data transmission with a BER<10^{-3} is achieved over 10 m of POF using this scheme [Fig. 1(e)][25]. A small power penalty of 0.7 dB is observed in the link operation due to optical crosstalk induced by the simultaneous two-channel operation.



	Response	Parameter	Value
µLED	exponential	bandwidth	150 MHz
		launch power	0 dBm
		wavelength	450 nm
POF / WG	gaussian	bandwidth-length product:	0.2 GHz × 50 m / 35 GHz × 1 m
		attenuation @ 450 nm	0.2 dB/m / 0.5 dB/cm
		coupling loss	0 dB / 6 dB
APD	raised-cosine	responsivity	0.275 A/W
		bandwidth	650 MHz

Figure 1. (a) Basic link model and (b) component parameters, (c) power budget for 5 Gb/s PAM-32 data transmission over a uni- and bi- directional µLED-POF-APD link for different POF lengths, (d) experimental setup for the bi-directional µLED-POF link and (e) obtained BER curves for both link directions.

In the aforementioned demonstration, the PAM signals are electrically generated. Optically-generated PAM schemes have also been studied and implemented with µLED arrays. Each µLED is driven using OOK but multiple µLEDs are turned on during each symbol period with appropriate optical power ratios so as to generate the multi-level optical PAM symbol [Fig. 2(a)]. Simulation studies have been carried out on the implementation of PAM-16 schemes using 4 µLEDs [26]. The obtained results indicate that an improved link performance can be achieved over the equivalent electrically-generated PAM schemes owing to the larger link power budget (larger launch power from the µLED array) [Fig. 2(b)]. The scheme is implemented [Fig. 2(c)] and a record uni-directional 6.25 Gb/s data transmission with a BER<10^{-3} is demonstrated over 10 m of POF [Fig. 3(d)][26].

PAM-16 symbol

(a)

µLED (P_{out})	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 (×1)		On		On		On		On		On		On		On		On
2 (×2)			On	On			On	On			On	On			On	On
3 (×4)					On	On	On	On					On	On	On	On
4 (×8)									On	On	On	On	On	On	On	On

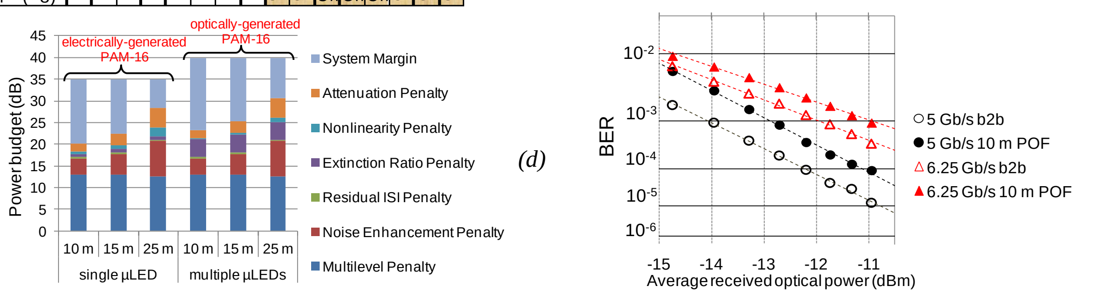


Figure 2.(a) Optically-generated PAM-16 symbols using 4 µLEDs, (b) comparison of the power budgets for 6.25 Gb/s data transmission using an electrically-generated PAM-16 signal and a single µLED and an optically-generated PAM-16 signal using 4 µLEDs, (c) experimental setup of the optically-generated PAM-16 scheme and (d) BER curves at 5 Gb/s and 6.25 Gb/s using 4 µLEDs for the back-to-back (b2b) and 10 m POF link.

3.2 Polymer waveguide-based VLC links

A similar link model is employed to assess the feasibility of high-speed µLED-based VLC links over multimode polymer waveguides. The simulation parameters are adjusted so that the channel matches the waveguide characteristics [Fig. 1(b)]. The simulation results indicate that the transmission of 4 Gb/s PAM-16 data is feasible over 20 cm of polymer multimode waveguides [Fig. 3(a)]. As a proof-of-principle experiment, a VLC link is setup over 2 cm-long multimode polymer waveguide and tested using PAM schemes [Fig. 3(b)]. 4 Gb/s (PAM-16) and 5 Gb/s (PAM-32) data transmission are achieved with a BER of 10^{-12} and 10^{-5} respectively [Fig. 3(c)]. The link currently suffers from high coupling loss at the waveguide input due to the Lambertian profile of the µLED output beam. Various coupling schemes are currently considered in order to improve the coupling efficiency and hence enable successful data transmission demonstration over of longer waveguide lengths.

Finally, the potential to achieve very high interconnection densities at the board/connection edge is assessed using µLEDs and multimode polymer waveguides. A simple two-dimensional square geometry is assumed for the waveguide and matching µLED array as shown in Fig. 3(d). The required data rate over each waveguide channel to achieve a particular target aggregate data density is calculated as a function of the waveguide pitch. Fig. 3(e) shows the obtained curves for a target data capacity of 1 Tb/s/mm^2 and 2 Tb/s/mm^2. It can be observed that for a waveguide pitch of 62.5 µm, a 3.5 Gb/s data rate per waveguide provides a 1.01 Tb/s/mm^2 board edge data density. The demonstrated 4 Gb/s data transmission indicates therefore that data densities > 1 Tb/s/mm^2 can be achieved with this technology. Coupling efficiency and crosstalk issues for such closely-spaced waveguides are currently studied and different layouts with improved crosstalk performance are considered. Multi-layered waveguide structures and matching µLEDs are currently under development and we hope to be able to demonstrate these in the near future.

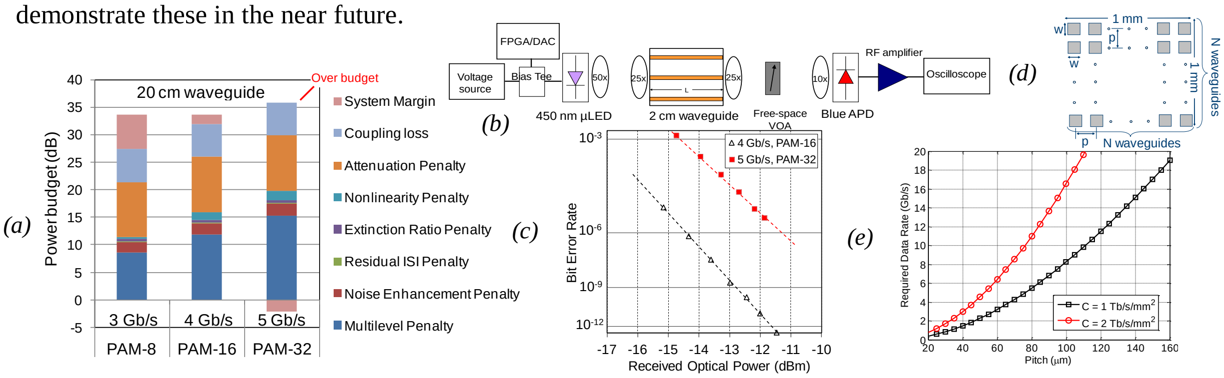


Figure 3. (a) Simulation results on µLED-based VLC link over a 20 cm multimode polymer waveguide, (b) experimental setup over a 2 cm long waveguide, (b) BER curves for 4 Gb/s (PAM-16) and 5 Gb/s (PAM-32) data transmission, (c) two-dimensional waveguide geometry and (d) required data rata per waveguide channel to achieve target on-board data density C as a function of the pitch p.

4. CONCLUSIONS

VLC guided-wave links based on the use of µLEDs and PAM schemes can offer high-speed (>1 Gb/s) optical interconnection in short-reach low-cost communication links. Recent work on POF and polymer multimode waveguide technologies demonstrate that data rates ≥ 4 Gb/s per channel are feasible in these technologies, highlighting their potential in real-world low-cost interconnection applications.

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