Optical Wireless Transmission at Rates Beyond 100 Mbit/s Using LED both as Transmitter and Receiver

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***Abstract*—In the paper, experimental operation of a wireless transmission link employing identical LEDs both as transmitter and receiver is demonstrated. The transmitted signal is a simple, two-level pulse amplitude modulation. Digital equalization at the receiver is applied to overcome the bandwidth limitation of the link. Transmission throughput exceeding 100 Mbit/s is reported, even if the receiving red LED operates in the photovoltaic mode.**

***Index Terms*—LED, visible light communications**

I. Introduction

THE size of a cell in wireless mobile communications has been constantly shrinking over the last decades and currently transmission within pico- or femto-cells is being proposed for the new mobile radio standards. In such small cells, optical wireless communications becomes an attractive alternative to radio links [1]. A lot of research is taking place in the area of visible light communications (VLC), where the transmitters use commercial lighting LEDs as light sources. The detectors in such links usually employ avalanche or p-i-n photodiodes [2]. While these solution allow for transmission in excess of 1 Gbit/s [3], to compete with the radio, low-cost optical solutions are needed.

It is well known that LED can be used as a light detector [4], however so far it was generally believed that it is suitable only for the low-cost and simple applications, which do not require high data rates. In most of the demonstrations of such a transmission the bit rate was considerably lower than 1 Mbit/s [5]. In this paper we experimentally prove that transmission with bitrates exceeding 150 Mbit/s are possible with LED used both as a transmitter and receiver. However, several restrictions to LED-LED transmission at this data rates apply. Firstly, not all LED have responsivities high enough to provide a power budget sufficient for such a transmission. Secondly, a transimpedance amplifier has to be applied to reduce the time constant formed by the p-n junction, which is high, especially if it is not reversely polarized. Although we demonstrate that transmission is feasible without reverse biasing, the bandwidth of the link and responsivity is higher with reverse voltage. Thirdly, to overcome the inter-symbol interference (ISI), digital equalization or ISI-resistant modulation format (e.g. discrete multitone - DMT) has to be applied.

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Our results confirm the outcomes of a very recent paper [6], where a bi-directional LED-LED link was demonstrated with the aggregate capacity of 110 Mbit/s. This was achieved by properly selecting LEDs with large transmit areas and employment of efficient but rather complex discrete multitone (DMT) modulation format [6].

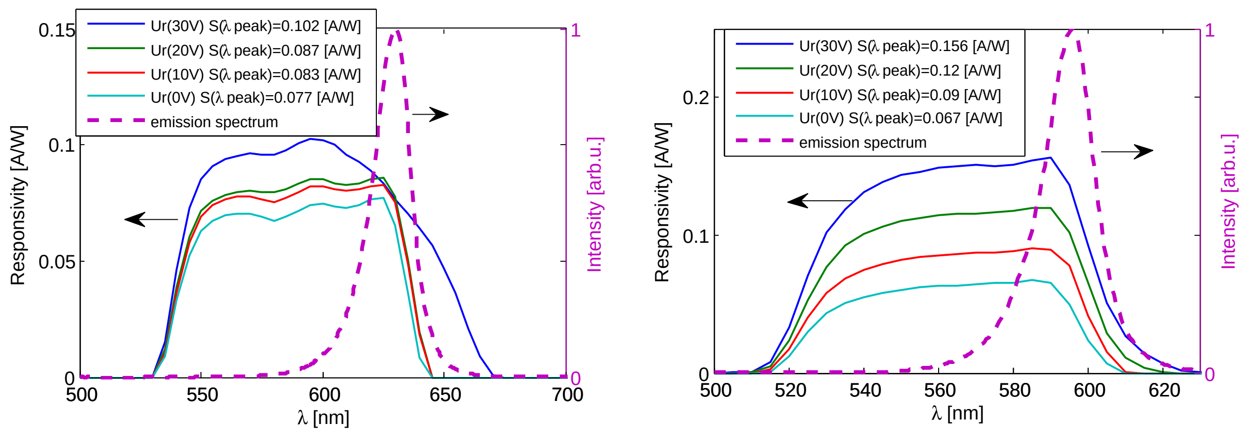
II. Characterization of the LEDs used in the experiment

From our previous study of bandwidth and responsivity of LED used as receivers [7] it follows that not all LED can efficiently serve as light detectors. We have measured several LED responsivities and, as a rule of thumb, the longer the emission wavelength of the LED, the higher its responsivity was [7]. This is probably caused by a well known dependence of the responsivity on wavelength. The highest responsivity was observed for red and amber LED and these were selected for the transmission experiment in this paper. Their most significant parameters are shown in Fig. 1 - 3.

It is interesting to note that the responsivity curve (Fig. 1) is shifted towards lower wavelengths (or higher energy photons) with reference to the peak of LED emission spectra. Obviously, this is because LED cannot detect photons of lower energy than its bandgap. In Fig. 1 the impact of LED reverse voltage is also shown. As mentioned previously, by increasing the bias level, higher sensitivity can be achieved most probably due to the avalanche multiplication effect (Fig. 3). Apart from higher sensitivity, a reversely polarized LED exhibits also a lower junction capacitance, which in turn causes its higher bandwidth. This is illustrated in Fig. 2, where the measured frequency responses for the red and amber diodes are shown. The LD-LED curves should be treated as the frequency responses of the LED when used in receiving mode. These were measured using a laser diode (LD) having much higher modulation bandwidth than LED as a transmitter. As seen in Fig. 2 even without applying the reverse voltage, the bandwidth of the link is limited by the transmitter rather than the detector.

III. The experimental setup

The LEDs used for the experiment were C503B-RAN (red) and C503B-AAN (amber), both manufactured by CREE. Both of them were equipped (by the manufacturer) with the standard, polyethylene lens. Despite that, the divergence angle of the beam was high (approx. 15 deg.) and, as we did not use any additional optics, it resulted in a very rapid loss of the received power with the increasing transmission distance. Of



(a) (b)

Fig. 1. Responsivity with emission spectrum (a) red (b), amber

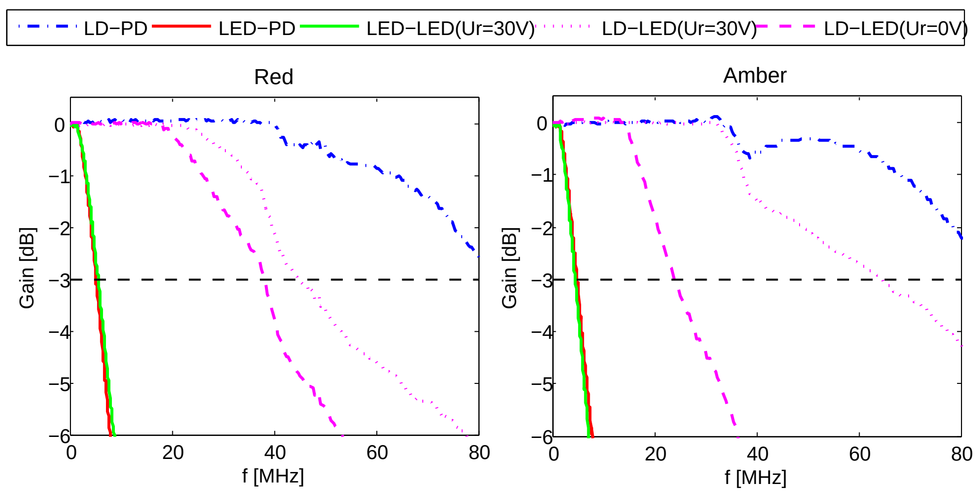


Fig. 2. Frequency responses of the LED-LED link measured for different transmitter receiver combinations (LD- laser diode, PD- photo-diode, Ur-reverse voltage

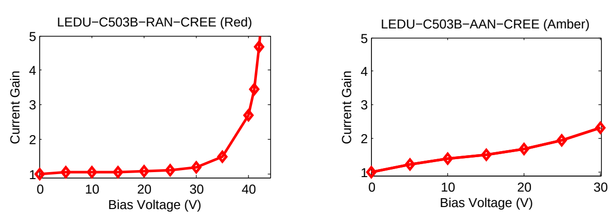


Fig. 3. Current multiplication gain: (a) red, (b) amber

course, this would not take place if the beam was collimated (like in [6]). The diagram of the experimental setup and its photo are shown in Fig. 4 and Fig. 5, respectively. The receiving LED was mounted on a moving stage to see the results as a function of a variable distance (or received power). A trans-impedance amplifier (TIA) was applied at the receiver.

In the experiment, we have changed the bias current of the transmitter LED as well as the reverse voltage of the receiving LED. A greater bias current increases the modulation bandwidth of the LED [8], but a bias too high may result in nonlinear behavior and increased energy consumption. In both LEDs (red and amber) the bias currents were 7.5 mA, 15 mA, 22.5 mA, and the modulation index (MI) was 15 %, calculated according to the definition

$$IM = \frac{I_{\Delta}}{I_{th2} - I_{th1}}, \tag{1}$$

where I_{Δ} is the current swing and I_{th2}, I_{th1} are the higher and lower thresholds of the modulation currents. The receiving LED was operated in two modes: photovoltaic and with reverse polarization of 30 V.

The transmitted signal was 2-level pulse amplitude modulation (PAM-2). Higher modulation orders (eg. PAM-4) did not lead to the throughput increase. The data symbols were generated in Matlab, mapped to PAM symbols, filtered with a root raised cosine (RRC) filter with a roll-off factor of 0.2 and fed to the memory of an arbitrary waveform generator (AWG Tektronix 71122). Upon transmission in free space, a

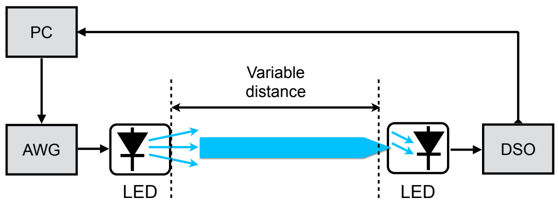


Fig. 4. The experimental setup

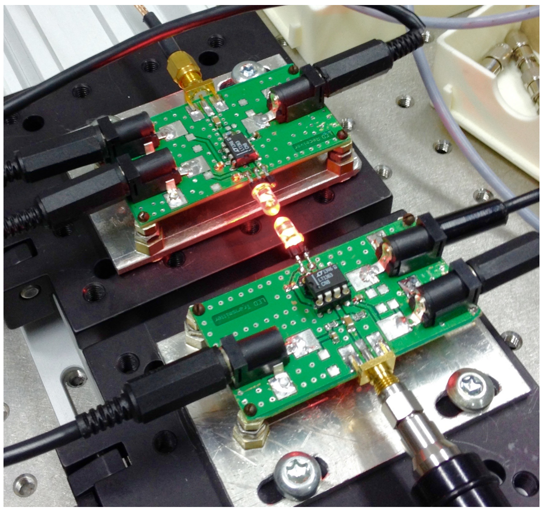


Fig. 5. Photograph showing the transmitter and receiver

digital scope (LeCroy 204MXi) served as an analog to digital converter. The digital signal was further processed in Matlab, i.e. resampled, synchronized and passed to an equalizer. Two equalizers were considered: the feed forward equalizer (FFE) and decision feedback equalizer (DFE). Of course, a better transmission quality was observed with the use of DFE. However, the results obtained for FFE can serve as an estimate of the system capabilities in case a cheap and low-power consuming analog equalizer was used [9]. The equalizers had 40 (40+10) symbol-spaced taps for FFE (DFE), and recursive least squares (RLS) algorithm was used for the convergence.

IV. Transmission results

To fully verify system capabilities, i.e. the possible transmission distance and data rate, the transmission experiment was performed for 3 bitrates: 50, 100 and 150 Mbit/s and for a varying distance between the transmitter and the receiver. We also consider two reverse biasing scenarios for the receiving LED: photovoltaic mode (0 V) and 30 V, as for this value the best experimental results were obtained. Although a higher reverse voltage increases the bandwidth and responsivity (Fig. 1 and 2), above a certain level it causes breakdown. The transmission results are shown in Fig. 6 for the amber and in Fig. 7 for the red LED. On the Y axis, the estimated SNR is shown, which was calculated from the received x_n and transmitted d_n symbols according to [10]

$$SNR_{est} = \frac{< |d_n|^2 >}{< |x_n - d_n|^2 >}, \qquad (2)$$

where $< \cdot >$ denotes ensemble average. The bit error rate (BER) before forward error correction (FEC) for PAM-2 can be estimated using the formula

$$\text{BER} = \frac{1}{2}\text{erfc}(\frac{SNR_{est}}{\sqrt{2}}). \qquad (3)$$

The transmission quality drops rapidly as the distance between the transmitter and receiver is increased, mostly due to a smaller received power. The red LED performed better than the amber one, especially in the preferable, photovoltaic mode (no reverse voltage). Assuming the 10^{-3} pre-FEC BER threshold (approx. 9.8 dB for PAM-2 [11]), gross data rate of 50 Mbit/s was achieved for transmission distances of up to 4-5 cm and also 100 Mbit/s was possible, although up to approx. 1 cm only. The amber LED, when in photovoltaic mode, allowed for transmission up to 1 cm at the lowest data rate of 50 Mbit/s only. Obviously, the better performance of the red LED is easily explained by its slightly higher responsivity in photovoltaic mode and slightly higher bandwidth when used as a transmitter (Fig. 1 and 2). Interestingly, when the reverse voltage of 30 V is applied to both LEDs, the performance of the amber one is as good as of the red one. Although transmission up to 100 Mbit/s was possible even with FFE, DFE provided an additional gain of 5-7 dB, which could be exchanged for increasing the transmission distance or the bit rate. Changing the transmitting LED bias voltage resulted in up to 2 dB transmission quality improvement and reverse polarizing the receiving LED improved the performance by about 5-6 dB for the red and up to 10 dB for the amber LED.

We have also measured BER directly for 100 Mbit/s transmission. The results (Fig. 8) confirm the previously shown SNRs. It is noted that BER was measured by a direct comparison of 50k transmitted and received bits and the confidence level for the BER values below 10^{-4} is low. Clearly, the operation below FEC threshold was possible for the red LED with DFE in photovoltaic mode. In all the other cases a reverse voltage needs to be applied.

V. Conclusion

In the paper, we have experimentally demonstrated that low-cost data transmission at rates exceeding 100 Mbit/s is possible using the same LED as transmitter and receiver. In addition, in red LED, such a transmission is possible even without reverse polarization, which highly simplifies the receiver circuit and lowers the cost. Furthermore, such transmission is possible using a simple, 2-level PAM modulation and equalization at the receiver. The transmission distance could be increased if additional, external optics were used [6], or by using LEDs having higher output powers than the ones used in the experiment (2-3 mW).The modulation index (approx. 15 %) in the experiment was also rather low due to the current limit of the TIA, and it certainly leaves some room for improvement of the transmission distance or bit rate.

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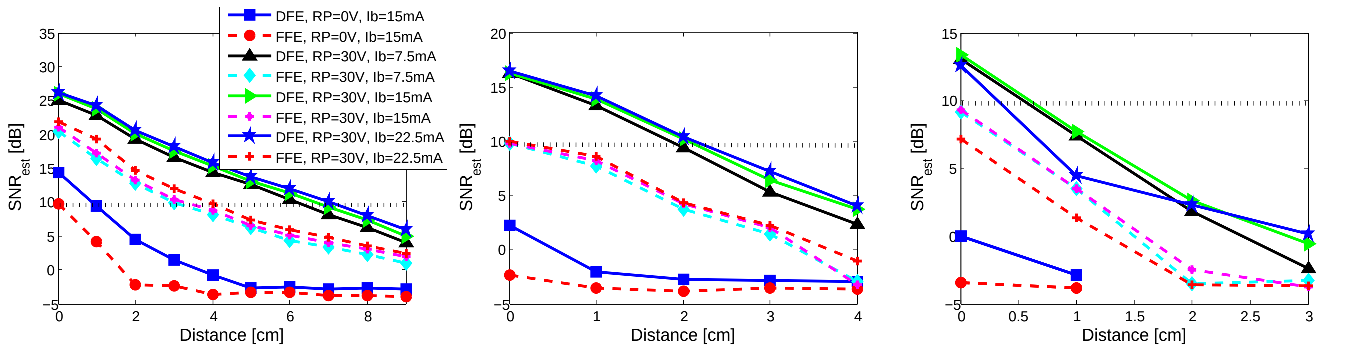


Fig. 6. Performance of the amber LED transmission link for 50, 100 and 150 Mbit/s (left to right). RP - reverse polarization, Ib - bias current. Threshold corresponding to 10^{-3} pre-FEC BER shown for reference

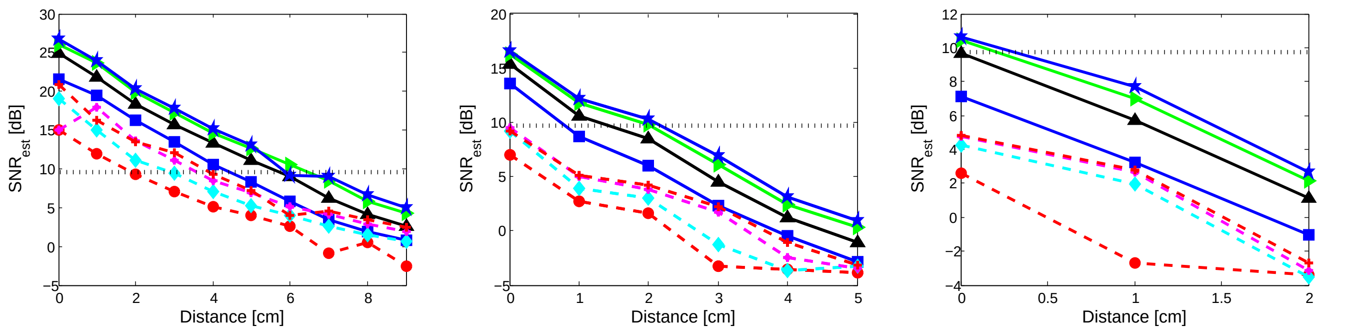
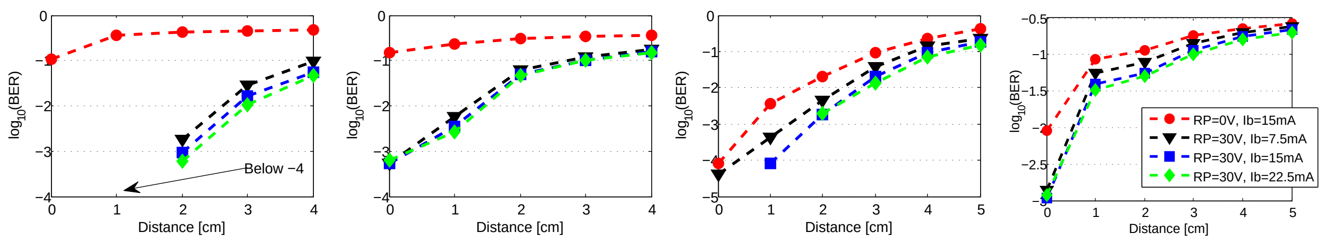


Fig. 7. Performance of the red LED transmission link for 50, 100 and 150 Mbit/s (left to right). Legend is the same as in Fig. 6



(a) (b) (c) (d)

Fig. 8. BER measured for transmission at 100 Mbit/s. Amber (a,b) and red (c,d) LEDs with DFE (a,c) and FFE (b,d).

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