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Towards a 100 Gb/s visible light wireless access network

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Abstract: Potential visible light communication (VLC) data rates at over 10 Gb/s have been recently demonstrated using light emitting diodes (LEDs). The disadvantage is, LEDs have an inherent trade-off between optical efficiency and bandwidth. Consequently, laser diodes (LDs) can be considered as a very promising alternative for better utilization of the visible light spectrum for communication purposes. This work investigates the communication capabilities of off-the-shelf LDs in a number of scenarios with illumination constraints. The results indicate that optical wireless access data rates in the excess of 100 Gb/s are possible at standard indoor illumination levels.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks; (140.2020) Diode lasers; (140.7300) Visible lasers.

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1. Introduction

Multimedia applications and video streaming are now extensively used in everyday life. At the same time, the number of mobile devices has greatly increased, and both have lead to an exponential growth in wireless data throughput [1]. As the electromagnetic spectrum with favourable communication properties, below 10 GHz, is almost completely expended, it is expected that the future demand for mobile data traffic will not be met. As a result, research has been directed towards utilizing alternative spectrum regions such as millimetre waves, terahertz waves and optical waves [2]. High-speed wireless communication has been demonstrated using the 60 GHz band [3]. Communication at such high frequencies, however, requires new high-speed components, such as amplifiers and mixers, which are not yet readily available for commercial use. High-speed data rates have also been demonstrated in the field of optical wireless communication (OWC) [4–6]. A major advantage of OWC is the wide availability of incoherent front-end components which allow intensity modulation and direct detection (IM/DD) to be realized relatively straightforwardly. As an IM/DD approach, OWC is based on baseband modulation techniques for which a large variety of off-the-shelf high-bandwidth components are already available. Further advantages of OWC over the other spectrum regions include: 1) a large amount of unregulated bandwidth; 2) no interference with sensitive electronic equipment and other communication networks; 3) simple, efficient and cost-effective beamforming realised with passive optical components; 4) reduced interference between individual access nodes; and 5) the possibility for integration into the existing lighting infrastructure, which promises significant energy savings and seamless network deployment.

Solid-state lighting components such as light emitting diodes (LEDs) are now in common use, in part due to their unmatched energy efficiency in lighting applications. There are two main concepts for generating white light using LEDs. The first one constitutes a blue chip covered with a yellow phosphor [4]. The chip emits blue light, part of which is absorbed by the phosphor and re-emitted with a wide spectrum. The second concept employs a red-green-blue (RGB) triplet, where the emission of the three colour LEDs is mixed in order to generate white light. The phosphor-coated LEDs are popular in lighting applications as they are relatively cheaper and easier to manufacture. The relatively slow re-emission time of the yellow phosphor, however, limits the modulation bandwidth of the device to approximately 2 MHz. In some applications, a blue bandpass filter is used at the receiver in order to filter the slow component, thus increasing the modulation bandwidth to up to 20 MHz for commercially available LEDs [4, 7]. This, however, reduces the light intensity reaching the photodetector. For communication purposes, RGB LEDs have two main advantages over phosphor-coated LEDs: 1) there is no bandwidth limiting colour converter coating; and 2) the three LEDs can be modulated separately, thus, allowing for wavelength division multiplexing (WDM) and the transmission of three parallel independent information streams. Despite the limited modulation bandwidth of LEDs, a rate of 1 Gb/s has been demonstrated for phosphor-coated LEDs, and a rate of over 3 Gb/s has been demonstrated for a RGB LED using advanced signal processing techniques such as signal equalization and adaptive bit and energy loading in combination with orthogonal frequency division multiplexing (OFDM) [4, 5].

Research has been taken towards increasing the modulation bandwidth of LEDs. As a result, resonant-cavity light emitting diodes (RCLEDs) have been introduced capable of achieving high data rates ($\sim$ 3 Gb/s) over a plastic optical fiber (POF) [8]. Recently, a wireless link at over 3 Gb/s was demonstrated using a 50 μm-in-diameter micro light emitting diode (μLED)

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operating at blue wavelengths around 450 nm [6]. The use of a RGB triplet of such devices could potentially deliver data rates in the order of 10 Gb/s. The small diameter of the μLED decreases the innate junction capacitance of the device and also allows very high current densities – in excess of 10 kA/cm^2 – to be achieved. This decreases the carrier life time and increases the modulation bandwidth [6]. High current density, however, leads to the so-called "efficiency droop" in LEDs [9]. In fact, the highest luminous efficacies have been demonstrated for current densities approximately four orders of magnitude smaller (~ 2.5 A/m^2) than the current densities in μLEDs [9]. The LED design for communication purposes is likely to face an inevitable trade-off between modulation speeds and output power levels.

The requirement for high optical efficiency at high current densities suggests the use of laser diodes (LDs) which at high current densities (~ 10 kA/cm^2) are the most efficient converters of electrical power to optical power [9]. Blue lasers with efficiency of $> 24\%$ have already been demonstrated [9]. The experience in the design of infrared (IR) lasers for optical fibre communication suggests that efficiencies in excess of 75% can be achieved at modulation bandwidths in the GHz range. These figures put LDs forward as the most prominent optical transmitter front-end elements for communication and possibly even as the most "economical" light sources for illumination purposes [9]. Laser diodes, however, have one more important and unique advantage over LEDs. Their wavelength profile is very narrow. The emission profile of a typical off-the-shelf LD is in the order of $2-3$ nm. For comparison, a typical RGB triplet of LEDs already occupies most of the visible light spectrum. This suggests that, while only a few LED transmitters are likely to be used in WDM, the number of LDs transmitting data in parallel could be in the hundreds when the entire visible light spectrum is utilized.

The concept of using LDs for free-space communication has been employed in fixed-link scenarios for many years. High data rates (1.25 Gb/s) have been demonstrated for mobile access using dispersed light from IR LDs in the OMEGA project [10]. Designs have been proposed for combining visible light lasers with LEDs for improving data rate and lighting quality [11]. In general, however, LDs are not very popular in optical wireless access implementations due to potential health hazards, cost, colour mixing complexity and the questionable quality of laser light for illumination purposes. A recent study, however, has demonstrated that diffused laser light does not compromise the user experience compared with conventional light luminaires [9]. The current work provides an investigation of the communication capabilities of commercially available off-the-shelf laser diodes while simultaneous illumination restrictions are imposed on the light output. Different approaches towards utilizing the available visible light spectrum for communication purposes are studied. The results indicate that off-the-shelf components can provide Gigabit-class wireless connectivity with substantial coverage at practical distances even for single LDs. A full utilization of the visible light spectrum with such off-the-shelf LDs could allow for wireless access in the excess of 100 Gb/s at standard illumination levels. These results could have great implications in future wireless networks and the future Internet of Things considering that, along with high-speed connectivity, the use of laser diodes also enables accurate control over the radiation patterns of the transmitter front-end which facilitates precise coverage adjustment, interference management and possibilities for very high data rate densities.

The rest of this paper is organized as follows. The experimental set-up and the communication parameters used for the investigation are described in Section 2. The results of three performance studies conducted under three different scenarios are presented in Section 3. Finally, concluding remarks are given in Section 4.

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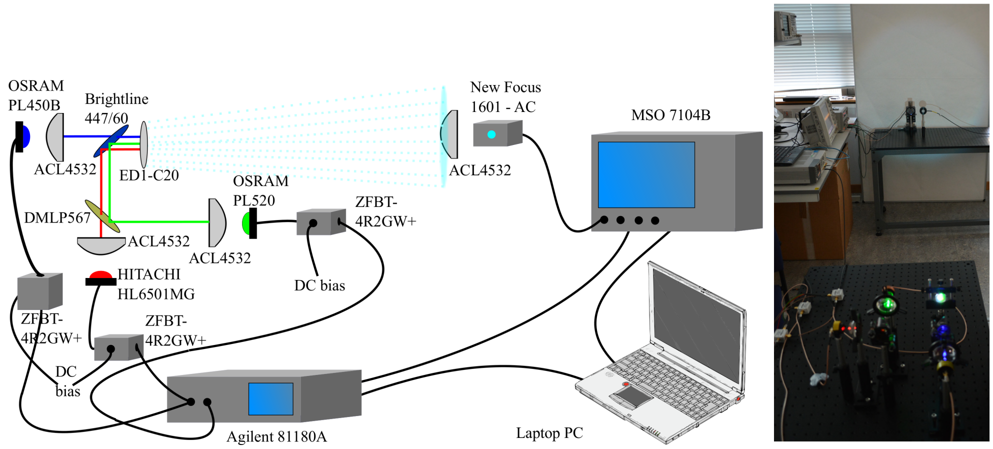

(a) Set-up diagram. (b) Set-up.

Fig. 1. Experimental set-up.

2. Experiment description

2.1. Experimental set-up

Figure 1 presents a diagram of the experimental set-up. The output of three colour LDs is used to generate white light. The employed devices are: 1) a red LD, HL6501MG by HITACHI, with a nominal emission spectrum width of 2 nm centered around 658 nm; 2) a green LD, PL520 by OSRAM, with a nominal emission width of 2 nm centered around 520 nm; and 3) a blue LD, PL450B by OSRAM, with a nominal emission width of 2 nm centered around 450 nm. The output of each device is collimated with a pair of lenses: a Thorlabs A110TM-A aspheric lens followed by a Thorlabs ACL4532 aspheric lens. The output of the green LD and the output of the red LD are aligned assisted by a dichroic mirror, Thorlabs DMLP567. The mirror passes the red beam and reflects the green light, as illustrated in Fig. 1. The output of the blue LD is also added in parallel to the other two beams with the help of an optical bandpass filter, Brightline Fluorescence Filter 447/60. The filter passes the blue light and reflects the other two beams, as illustrated in Fig. 1. Finally, all three parallel beams are incident on a holographic diffuser, Thorlabs ED1-C20 with a 20° full divergence angle. The diffuser mixes the three beams and outputs diffused white light.

The communication part of the experimental set-up is described as follows. First, a pseudo-random bit stream is generated and encoded into M-ary quadrature amplitude modulation (M-QAM) symbols. The M-QAM symbols are modulated on different frequency subcarriers and rescaled according to the assigned energy for each subcarrier. The subcarrier modulation procedure is achieved with an inverse fast Fourier transform (IFFT) operation applied on a block of M-QAM symbols, which produces a discrete time-domain signal. The time-domain signal is conditioned for transmission by root-raised cosine (RRC) pulse shaping and by clipping of any signal values outside a pre-determined range set by the electrical properties of the LDs. All digital signal generation steps are performed in MATLAB®. The conditioned discrete time-domain signal is supplied to an arbitrary waveform generator (AWG), Agilent N81180A, which interpolates it and outputs an analog signal. The analog output of the generator is used to directly modulate the voltage over a LD. The operational point of the diode is set with a bias-T, Mini-Circuits ZFBT-4R2GW+, according to the illumination requirement for the specific investigation scenario. The light output of the LD is mixed with the outputs from the other LDs as described previously. At the receiver site, the white-light output of the diffuser is collected with an aspheric lens, Thorlabs ACL4532, and focused on a p-intrinsic-n (PIN) photodetector, New Focus 1601FS-AC. The electrical output of the photodetector is digitized with a digital oscilloscope, Agilent MSO7104B. The captured signal is passed on to the computer and processed in MATLAB® using a series of demodulation steps which include: synchronization, channel estimation, fast Fourier transform (FFT), equalization, and M-QAM demodulation.

In a practical implementation of WDM, a separate photodetector would be used to detect the communication signal at every wavelength. An optical filter is required in front of each detector in order to separate the signals at the different wavelengths. Such optical filters with very high efficiency ($>90\%$) and a very steep wavelength response profile are already commercially available. In this study, the AWG is capable of modulating only one LD at a time. Therefore, while all three diodes are switched on during the experiments, they are being modulated one by one. Hence, the use of an optical filter at the receiver is not required. The optical filter is expected to further improve the operation of the receiver as it would reduce shot noise by filtering out undesired light components and would ensure that the linear operation of the photodetector cannot be compromised by strong ambient light.

2.2. Modulation parameters

Incoherent visible light communication (VLC) can only be realized using IM/DD. As a result, an information signal has to be both real and non-negative. Conventionally, the OFDM signal is both complex and bipolar. Therefore, it has to be modified before it is suitable for VLC.

A real OFDM signal can be generated with the IFFT operation by imposing Hermitian symmetry on the block of M-QAM symbols [4, 6]. As part of the Hermitian symmetry, the direct current (DC) subcarrier and the 180° subcarrier should be set to zero. In addition, half of the subcarriers, corresponding to the negative frequencies, are set to be complex conjugates of the other half, corresponding to the positive frequencies. In an OFDM signal, a total of $N_{\rm fft}$ subcarriers are equally spaced in the frequency range $[-1/2T_{\rm s}; 1/2T_{\rm s}]$, where $T_{\rm s}$ is the time-domain signal sampling period which corresponds to the Nyquist rate. Certain subcarriers can be left unmodulated in order to avoid frequency-dependent distortion effects such as interference stemming from ambient light sources, low-frequency attenuation due to the DC-wander effect or signal attenuation due to the frequency response of the front-end elements and the communication channel. The spectral efficiency of OFDM can be expressed as:

$$\eta = \frac{\sum\limits_{\substack{k=0\\ M_k>0}}^{\frac{N_{\rm fft}}{2}-1} \log_2 M_k}{N_{\rm fft} + N_{\rm cp}(1+\beta)} \text{ bits/s/Hz}, \tag{1}$$

where $N_{\rm fft}$ is the FFT size; M_k is the constellation size modulated on the subcarrier with index k; $N_{\rm cp}$ is the OFDM cyclic prefix length; and β is the roll-off factor of the employed RRC filter (for the ideal sinc pulse, $\beta = 0$). The single-sided bandwidth of the system can be calculated as:

$$B = \frac{1}{2T_{\rm s}}(1+\beta) \text{ Hz}. \tag{2}$$

The data rate of the system can be calculated as:

$$D = 2B\eta \text{ bits/s}. \tag{3}$$

The FFT size used in this study is $N_{\rm fft}$=1024. The cyclic prefix length is set to $N_{\rm cp}$=5 after exhaustive experiments have shown that it is sufficient to remove any significant intersymbol interference (ISI) effects between the OFDM frames.

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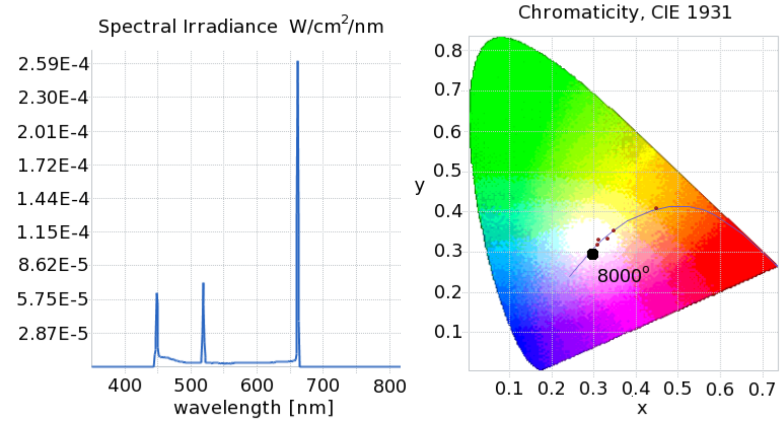

Fig. 2. Characteristics of the generated white light. Measurements have been taken with a Labsphere spectral irradiance receiver head (E1000) at a distance of 30 cm for a light spot radius of 6 cm. The achieved colour temperature is approximately 8000° K as indicated by the black spot on the chromaticity diagram.

A bipolar OFDM signal can be used to modulate an LD if a suitable positive operating point is set for the LD around which the bipolar signal can be realized [4, 6]. This scheme is referred to as DC-biased optical OFDM (DCO-OFDM). A typical time-domain OFDM signal is characterized by high peak-to-average power ratio (PAPR), which increases with the employed IFFT size. The active range of the LD is limited, and so clipping on both sides of the signal distribution is practically unavoidable. Monte Carlo simulations have determined that clipping levels at -3.2σ and 3.2σ, where σ is the standard deviation of the time-domain signal:

$$\sigma^2 = \frac{2 \sum_{k=0}^{\frac{N_{\text{fft}}}{2}-1} E_{\text{b}k} \log_2 M_k}{N_{\text{fft}}}, \tag{4}$$

are sufficient to make the non-linear distortion insignificant for the signal-to-noise ratio (SNR) levels that are achievable in the presented communication scenarios. In (4), $E_{\text{b}k}$ is defined as the energy per bit on the subcarrier with index k.

The bias levels for the red, the green and the blue LD are set to $V_{\text{bias,r}}$=2.6 V ($I_{\text{bias,r}}$=85 mA), $V_{\text{bias,g}}$=5.7 V ($I_{\text{bias,g}}$=80 mA) and $V_{\text{bias,b}}$=4.5 V ($I_{\text{bias,b}}$=36 mA), respectively, which correspond to output radiation flux levels of approximately 48.7 mW, 15.89 mW, and 12.79 mW. The spectral characteristic of the generated white light corresponding to the presented light intensity ratios between red, green and blue has been measured with a Labsphere spectral irradiance receiver head (E1000) and is presented in Fig. 2. The colour temperature is approximately 8000° K. Warmer colours could be achieved by increasing the red and the green component. In this study, the limiting factor for the colour temperature adjustment is the optical output power of the red device. A more powerful red LD or the addition of a yellow LD can be used for the generation of a warmer and more aesthetically pleasing white light [9, 11]. Note that due to their smaller packages, good contact between the optical mount and the LD package is harder to achieve for the green LD and the blue LD. As a result, the behaviour of the two devices indicates that in the current set-up they operate at temperatures higher than the ambient room temperature. The measured voltage-to-current (V-I) and current-to-light (I-L) characteristics

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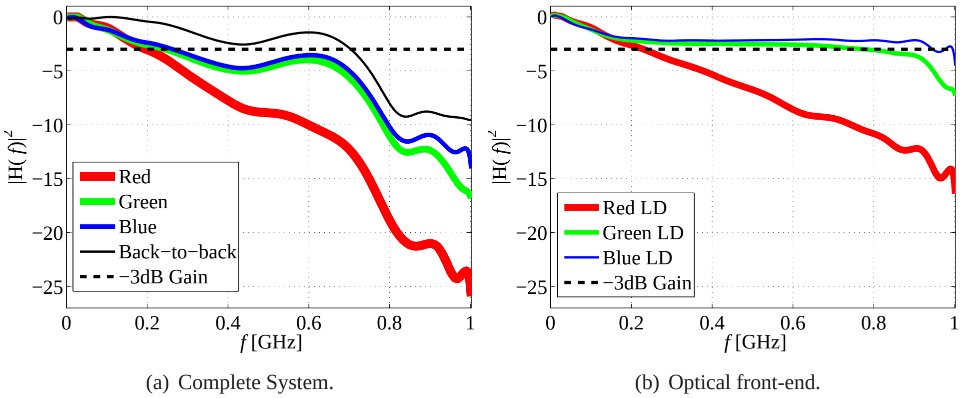

Fig. 3. Frequency response of the proposed system.

of the two devices appear to be consistent with operation at temperatures between 40° C and 60° C according to the respective device data sheets. The modulation depth is adjusted according to the respective scenario under investigation. In general, a larger modulation depth leads to a higher swing in the optical intensity signal, which increases the SNR at the receiver. However, a higher modulation depth also introduces more non-linearity distortion, which reduces the achievable SNR at the receiver. In each of the presented cases, the modulation depth is adjusted empirically in order to maximize the achievable data rate. The sampling frequency of the AWG is fixed at F_s=4 Gs/s, which results in a maximum achievable single-sided bandwidth of B=1GHz after taking into account the Nyquist sampling criterion and the oversampling factor of 2 used in the pulse shaping procedure. The pulse shaping filter used in the signal generation step is an RRC filter with a roll-off factor of 0.1. Note that 1 GHz is the analog bandwidth of the Agilent MSO7104B oscilloscope and the New Focus photodetector. Hence, it is taken as the absolute modulation bandwidth limit in this investigation.

The frequency response of the three LDs is consistent in all scenarios investigated in this study and is presented in Fig. 3. The frequency response of the overall system (including the generator, the LD, the photodetector, and the oscilloscope) is presented in Fig. 3(a). The 3 dB attenuation for the red link occurs around 198 MHz; for the green link it occurs around 245 MHz; and for the blue link the 3 dB attenuation occurs around 263 MHz. The frequency response of the back-to-back link (generator and oscilloscope only) is also presented in Fig. 3(a). It appears that the frequency response of the generator amplifier is the limiting factor for the modulation bandwidth. The frequency responses of the front-end elements only (after accounting for the response of the back-to-back link) are presented in Fig. 3(b). The red device exhibits a 3 dB bandwidth of 230 MHz; the green device exhibits a 3 dB bandwidth of 780 MHz; and the blue device has a 3 dB bandwidth of approximately 1 GHz. Compared with off-the-shelf LEDs [4,7] and μLEDs [6], the laser diodes exhibit modulation bandwidths which are at least an order of magnitude higher. For communication purposes, the LDs clearly appear to be superior to LEDs.

In order to achieve better utilization of the non-flat communication channel, an adaptive bit and energy loading algorithm has been employed in the OFDM generation procedure. The algorithm is based on the work of Levin [12] and performs bit and energy allocation based on the achievable SNR for each communication link. The same bit and energy loading algorithm has been used to achieve the results in [6].

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3. Results and discussion

Three cases for LD deployment are described and investigated in this study. For each case a description of the envisioned deployment scenario is given including: illumination constraints, scenario-specific operational parameters, achievable data rate and achievable system coverage. All communication results have been achieved at bit error rate (BER) levels for which a number of forward error correction (FEC) codes can provide reliable communication with an overhead of approximately 7%. [13].

3.1. Scenario I - RGB illumination

In the first scenario, an investigation is performed on the possibility for using arrays of the presented three RGB LDs for the purpose of providing complete indoor illumination and simultaneous high-speed data access. The data rate is estimated at a distance of 30 cm from the transmitter, where the light spot has a radius of 6 cm. The irradiance levels provided by the red, green and blue LDs at this distance are measured to be $4.303 \times 10^{-4}\,\mathrm{W/cm^2}$, $1.405 \times 10^{-4}\,\mathrm{W/cm^2}$ and $1.131 \times 10^{-4}\,\mathrm{W/cm^2}$, respectively, which correspond to illuminance levels of $171.2\,\mathrm{lx}$, $645.4\,\mathrm{lx}$ and $27.09\,\mathrm{lx}$. The combined illuminance levels achieved by the three LDs is $843.69\,\mathrm{lx}$ which is close to the upper limit for expected average illuminance ($\sim 1000\,\mathrm{lx}$) in an indoor environment [14]. The optimal modulation depth in this scenario has been determined empirically for the three devices and it corresponds to a peak-to-peak modulation voltage of $0.8\,\mathrm{V}$. Increasing the modulation depth any further is shown to introduce a marginal effect on the achievable data rate. In this scenario, the red LD achieves a data rate of $4.882\,\mathrm{Gb/s}$ at a BER of 2.23×10^{-4}. The green LD achieves a data rate of $4.632\,\mathrm{Gb/s}$ at a BER of 7.89×10^{-4}. The blue device achieves a data rate of $4.465\,\mathrm{Gb/s}$ at a BER of 8.37×10^{-4}. Measurements with the irradiance receiver show that the light distribution within the specified light spot radius is uniform, *i.e.*, the achievable irradiance levels are the same for an arbitrary spot within the coverage area. Hence, the LEDs can deliver the presented data rates at a coverage of approximately $113\,\mathrm{cm^2}$ ($\pi 6^2\,\mathrm{cm^2}$). This means that approximately 89 such RGB triplets would be required for every square meter of illuminated area. With this approach, the overall communication rate achievable in the illuminated area is approximately $14\,\mathrm{Gb/s}$.

3.2. Scenario II - full utilization of the visible light spectrum

In the second scenario, it is assumed that the entire visible light spectrum is utilized by employing multiple LD transmitters operating at different wavelengths. The LDs presented in this work are specified to have a spectral emission width of $\approx 2\,\mathrm{nm}$. The spectral analysis, presented in Fig. 2, reveals that the spectral width of the green and the blue devices is close to $4\,\mathrm{nm}$. In addition, the center emission wavelength for the different devices deviates by up to $3\,\mathrm{nm}$ from the specification. Therefore, after accounting for a possible center wavelength shift of $\pm 3\,\mathrm{nm}$, it is assumed that approximately $10\,\mathrm{nm}$ should be allocated per information stream. Hence, the visible light spectrum between $390\,\mathrm{nm}$ and $750\,\mathrm{nm}$ can fit 36 parallel information streams realized at different wavelengths. This means that the equivalent of at least 12 RGB triplets as the one used in this study can fit within the visible light spectrum. Note that this is a general assumption because no actual information has been gathered regarding the communication properties of all LDs operating in the different wavelength bands, and because in a practical scenario, the emission at different wavelengths could be subject to specific illumination constraints. Due to the complexity of such an exhaustive study and because the aim of the current work is to focus on the potential of the proposed communication/illumination approach, it is assumed that the results for the presented RGB triplet can be extrapolated to an arbitrary LD triplet. Also note that optical bandpass filters capable of completely separating the narrow wavelength emissions

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over the entire visible spectrum are already commercially available. One such example is the TECHSPEC® Hard Coated OD4 10 nm Bandpass Filter line by Edmund Optics.

In this scenario, it is assumed that the equivalent of 12 RGB triplets (36 individual wavelengths) can fit within the visible light spectrum. As a result, the communication capabilities of the presented RGB triplet are investigated at a distance of 93 cm from the transmitter where the spot radius is 19 cm. The irradiance levels provided by the red, green and blue LDs are measured to be $4.306 \times 10^{-5}\,\mathrm{W/cm^2}$, $1.376 \times 10^{-5}\,\mathrm{W/cm^2}$ and $9.886 \times 10^{-6}\,\mathrm{W/cm^2}$, respectively, which correspond to illuminance levels of 17.43 lx, 60.61 lx and 2.899 lx. The overall illumination level provided by the three devices is 80.94 lx. This is approximately 1/12 of the 1000 lx upper limit for average light illuminance in an indoor environment [14]. Hence, if the entire visible light spectrum is utilized with a total of 12 LD triplets operating at different wavelengths and delivering illumination levels comparable to the ones presented in this work, the overall illumination requirements for a well-lit environment can be satisfied.

In this experiment, the optimal modulation depth has been determined empirically as a voltage of 1 V for the red device and a voltage of 1.5 V for both the green and the blue devices. In this scenario, the red LD achieves a data rate of 3.156 Gb/s at a BER of 7.27×10^{-4}. The green LD achieves a data rate of 3.049 Gb/s at a BER of 1.912×10^{-3}. The blue device achieves a data rate of 2.579 Gb/s at a BER of 3.78×10^{-3}. Uniform light distribution is measured within the generated light spot. Hence, the LDs can deliver the presented data rates within the entire coverage area of approximately $1134\,\mathrm{cm^2}$ ($\pi 19^2\,\mathrm{cm^2}$). This means that approximately 9 such RGB triplets (or 9 devices per employed wavelength) would be required for every square meter of illuminated area. With this approach, the overall communication rate achievable by the investigated RGB triplet within the illuminated area is 8.784 Gb/s. If the equivalent of 12 such triplets (36 streams in total) are used, delivering an illumination level of approximately 971.28 lx, then the estimate for the achievable data rate becomes 105.41 Gb/s. If a less conservative estimation is used for the number of wavelengths that can be employed for parallel data transmission, then data rate estimates much greater than 100 Gb/s can be reached.

3.3. *Scenario III - wireless access without illumination*

The third study presents a scenario where the output of the presented RGB triplet is used for communication without simultaneous illumination. The aim of the study is to establish the data rates which can be expected in a configuration where a single RGB triplet is used as a transmitter front-end, providing coverage of approximately $1\,\mathrm{m^2}$. This is in the order of the expected coverage in a typical optical attocell network configuration [15]. The transmission distance in this scenario is 2.88 m, which is consistent with a transmitter mounted on the ceiling in a typical indoor environment. Because illumination is not intended in this scenario, the outputs of the LDs are readjusted to optimize the achievable data rates. The biasing levels for the red, green and blue devices are set to $V_{\mathrm{bias,r}}$=2.6 V ($I_{\mathrm{bias,r}}$=85 mA), $V_{\mathrm{bias,g}}$=6 V ($I_{\mathrm{bias,g}}$=112 mA) and $V_{\mathrm{bias,b}}$=4.75 V ($I_{\mathrm{bias,b}}$=52 mA). The modulation depth for all three devices has been set to 2 V, which is the maximum output swing of the AWG. The irradiance levels provided by the red, green and blue LDs are measured to be $5.205 \times 10^{-6}\,\mathrm{W/cm^2}$, $4.179 \times 10^{-6}\,\mathrm{W/cm^2}$ and $3.158 \times 10^{-6}\,\mathrm{W/cm^2}$, respectively, which correspond to illuminance levels of 2.529 lx, 17.39 lx and 1.327 lx. At such illumination levels, the light spot generated by the three LDs is barely visible in a well-lit environment. As a result, the colder appearance of the generated white light is unlikely to have any effect on the user experience. Furthermore, an additional yellow light source can be introduced to the RGB triplet in order to improve the light quality.

In this scenario, the maximum possible modulation depth of the AWG is used to convey the information signal due to the relatively weak optical intensity levels reaching the receiver. In order to further optimize the system, the digital clipping levels are also optimised in order to

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Table 1. Summary of Results.

Scenario	Data Rate [Gb/s]	Average BER	Number of devices for 1-m^2 coverage	Illumination [lx]
I	14	6.07×10^{-4}	89×3	843.69
II	105.41	2.04×10^{-3}	9×36	971.28
III	3.43	2.33×10^{-3}	3	21.25

improve the achievable received SNR but with the drawback of increased non-linear distortion. The red LD achieves a data rate of $1.713\,\text{Gb/s}$ at BER of 2.48×10^{-3}. The optimal clipping levels for the red LD are determined empirically to be $[-1.75\sigma; 1.75\sigma]$. The green device achieves a rate of $950.34\,\text{Mb/s}$ at a BER of 2.05×10^{-3}. The optimal clipping levels for this device are determined empirically to be $[-1.3\sigma; 1.3\sigma]$. The blue device achieves a data rate of $767\,\text{Mb/s}$ at a BER of 2.34×10^{-3}. The optimal clipping levels are determined at $[-1.2\sigma; 1.2\sigma]$. The overall data rate achieved in the system is $3.43\,\text{Gb/s}$. Measurements with the irradiance receiver show that the light distribution over the entire coverage area of $1\,\text{m}^2$ is uniform. Hence, the presented data rates can be delivered over the entire coverage area. It is clear that VLC using even a single triplet of off-the-shelf RGB LDs can deliver Gigabit-class communication over a practical coverage area at a practical transmission distance for indoor wireless access.

4. Conclusion

The communication properties of off-the-shelf visible light LDs have been studied. The investigated devices exhibit very high modulation bandwidth properties with 3 dB signal attenuation occurring at 230 MHz for the red LD, at 780 MHz for the green device and at approximately 1 GHz for the blue LD. Compared with off-the-shelf LEDs and even compared with the fast μLEDs, laser diodes exhibit modulation speeds which are at least an order of magnitude higher. At the same time, the output efficiency of LDs is high enough to support a coverage of $1\,\text{m}^2$ at a distance of $2.88\,\text{m}$ and at an achievable data rate of $3.43\,\text{Gb/s}$ for a single RGB triplet of LDs. When simultaneous wireless connectivity and illumination are realized with such RGB LDs, the achievable data rate in well-illuminated areas is approximately $14\,\text{Gb/s}$. One unique advantage of LDs over LEDs is the narrow emission profile which can be achieved. This allows for better utilization of the available visible light spectrum. Using WDM with 36 parallel streams, for example, is expected to deliver data rates of over $100\,\text{Gb/s}$ at standard illumination levels. All results have been summarized in Table 1. In this study, the modulation bandwidth on each data stream is limited by the frequency response of the signal generator. The use of a faster digital-to-analog converter and a faster amplifier could allow for the achievement of higher data rates than presented in this work.

In addition to very high data rates, LDs enable precise control over the emission profile of the transmitter front-end. This is achieved with passive optical components. Such precise control of the emission profile cannot be matched by any alternative technology for wireless connectivity such as radio frequency (RF) waves, millimetre waves or terahertz waves. This feature is expected to have an important part in future wireless networks where beamforming is envisioned as a necessary technique for improving link directionality, coverage uniformity and interference management. With their superior beamforming properties, laser diodes can enable extremely high data rate densities, which are anticipated in the future Internet of Things.

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