Why Optical Wireless Communications is ready for 6G

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Abstract *Mobility, security, energy efficiency, data density and peak user data rates of 100 Gbps are key performance indicators (KPIs) of 6G. We show that the OWC can address these KPIs. Specifically, we report experimental results of a light fidelity (LiFi) system achieving 105.36 Gbps.*

Introduction

Worldwide there are many research programs on the way aimed at defining the sixth generation (6G) cellular systems. Key requirements include peak user data rate of up to 100 Gbps[1]. In order to achieve these data rates it is important to explore new spectrum. The optical spectrum is an excellent candidate as the overall spectrum is 2600 times greater than the entire radio radio frequency (RF) spectrum, and there exist optical transmitter and receiver devices that are able to provide sufficient power for mobile applications.

In the past decades, laser diodes (LDs) with visible light emission using Gallium nitride (GaN) material have been developed and enabled several useful applications such as blue ray disc and high quality projection display systems[2],[3]. Recently, GaN-based LDs have been developed for solid state lighting (SSL) applications[4]. This makes these devices very good candidates for optical wireless communication (OWC).

One key advantage of OWC is that the directionality of lightwaves can be controlled in a more efficient way compared to computationally complex beamforming in millimeter-wave (mmWave) and sub-THz systems. Furthermore, in the case of light fidelity (LiFi)[5], the infrastructure can provide both illumination and wireless communication functionalities simultaneously. Most of the existing LiFi studies are based on light-emitting diode (LED) light sources, which exhibit limited modulation bandwidth of a few to tens of MHz[6]. This significantly limits the achievable data rates. Therefore, laser-based sources have been proposed for LiFi transmission[7]. These devices offer a modulation bandwidth of 1 GHz and higher. This property as well as the higher brightness, and directionality enable the development of high-density LiFi systems that provide both ultra-high transmission speeds and high brightness illumination purposes.

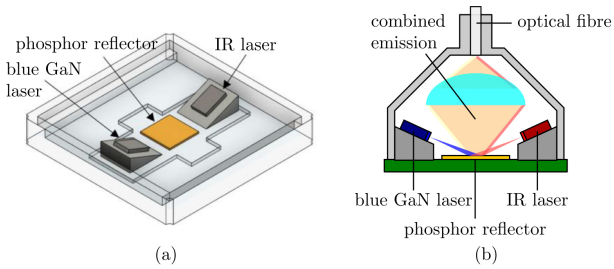

Fig. 1: (a) Schematic of the SMD light source with a blue and an IR laser for illumination, communication and sensing. (b) Cross-section schematic of the SMD package.

There are a number of studies on the performance of laser light sources for high speed LiFi systems[8]–[13]. In our previous work we have demonstrated a data rate of 26 Gbps using a dual wavelength (blue/white and infrared (IR)) surface mount device (SMD) exploiting wavelength division multiplexing (WDM)[14]. The combination of a blue LD and an IR LD in a single device enables wireless data transmission when illumination is not required, and provides an additional data channel when illumination is needed. In this paper, we extend the work in[14] by developing a large-scale WDM system based on multiple dual wavelength laser light devices. By combining the data rates achieved by ten wavelengths and by applying a non-linear Volterra equaliser, an aggregate data rate of over 100 Gbps is demonstrated.

Dual Wavelength Laser Device

Two LDs are placed on the two wedges mounted on the edges of the package and a phosphor reflector is deployed in the centre of the package, as shown in Fig. 1 (a). The orientations of the LDs are configured so that the emitted collimated light incident to the phosphor reflector and the reflected light is coupled into an optical fibre,

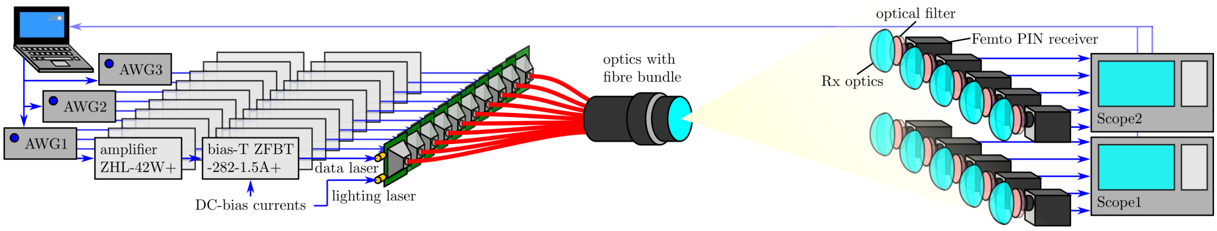

Fig. 2: Block diagram of LiFi transmission system with multiple parallel channels.

as shown in Fig. 1 (b). One of the LDs emitting blue light (450 nm) is designed for illumination purpose. The phosphor reflector converts the blue laser light into white light. It also creates an eye-safe Lambertian beam profile[6]. The second LD emits IR light so that effective WDM channels can be formed. In this work, ten devices with ten wavelengths have been developed which include three blue LDs (405 nm, 450 nm, 455 nm) and seven infrared LDs (850 nm, 900 nm, 905 nm, 940 nm, 955 nm, 980 nm, 1064 nm). In order to avoid electrical coupling within a device we only use one wavelength per device to encode data. However, when the IR channel is used for data transmission we simultaneously drive the blue wavelength with a direct current (DC) signal for illumination.

Experimental Demonstration Setup

The block diagram of the WDM LiFi system is depicted in Fig. 2. Each WDM channel is driven by a high-speed arbitary waveform generator (AWG) (Keysight M8195A) to convert the digital orthogonal frequency division multiplexing (OFDM) waveform into an analogue waveform. A power amplifier (Mini-Circuit ZHL-42W+) is used to amplify the modulated alternating current (AC) signal followed by a bias-T (Mini-Circuit ZFBT-282-1.5A+) to combine the DC-bias and AC signal. This is followed by a SMD laser device to convert the electrical signal to an optical signal. The output of the ten SMD laser sources are coupled into a fibre bundle, which combines the optical signals and guides the light to a single launch optic. On the receiver side, a 2 $\times$ 5 array of receivers units are deployed, as shown in Fig. 2. Each receiver unit is composed of a collimating lens to focus the detected light; an optical filter with 10 nm passband to remove crosstalk; a positive-intrinsic-negative (PIN) detector (Femto receiver HSA-X-S-1G4-SI) to convert the optical signal to a photocurrent signal and a high-speed oscilloscope (Keysight MXR608A) to convert the analogue waveform into a digital signal. The implemented system is depicted in Fig. 3.

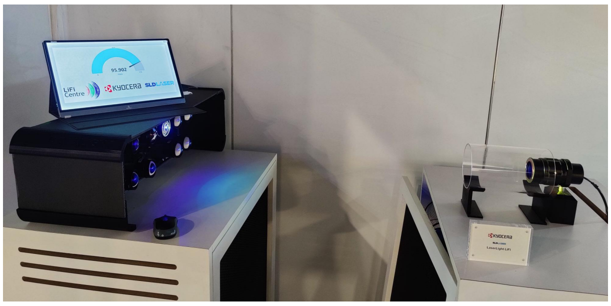

Fig. 3: Implemented demonstrator of the LiFi transmission system with ten parallel channels.

OFDM modulation, pulse shaping, channel estimation and single-tap channel equalisation are implemented in Matlab. Spectrum efficient DC-biased optical (DCO)-OFDM in conjunction with quadrature amplitude modulation (QAM) modulations are used. Root-raised cosine pulse shaping with roll-off factor of 0.1, a fast Fourier transform (FFT) size of 1024 and a cyclic prefix (CP) length of 20 is implemented. Measurements show significant nonlinear behaviour of the overall system. Therefore, a Volterra based nonlinear equaliser is implemented to mitigate the nonlinear effects. In the modulation and demodulation process, the variance of the QAM symbols and the constellation order are adaptively selected according to the channel estimate so that the available modulation bandwidth can be fully utilized. In this work, the Hughes-Hartogs (HH) adaptive bit and energy loading algorithm is applied. The HH algorithm has been widely used in many multi-carrier transmission systems[15].

Results

The main parameters for the different channels are listed in Table 1. These parameters have been carefully selected to maximise the aggregate data rate. It can be observed that generally the blue LD requires a high peak-to-peak voltage to overcome the stronger background noise at the blue spectrum region. As expected, compared to blue LDs, infrared LDs generally can be driven with a higher bias current and demonstrate larger modulation bandwidths.

Tab. 1: System setting for LiFi transmission with parallel channels

Wavelengths [nm]	405	450	455	850	900	905	940	955	980	1064
Peak-to-peak voltage [mV]	280	450	320	200	100	140	140	140	130	175
DC-bias current [A]	0.93	1	1.05	1	1.1	1.171	1.45	1.45	1.3	1.05
Used bandwidth [GHz]	1.33	1.6	1.6	2.67	3	2.67	2.67	2.67	2.67	3
Clipping level	3.4	3.2	3.3	3.2	3.9	3.2	3.2	3.2	3.2	3.4

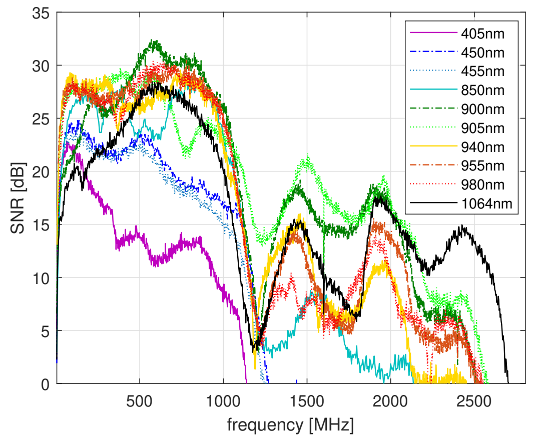

Fig. 4: signal-to-noise ratio (SNR) against frequency of LiFi transmission with multiple parallel channels.

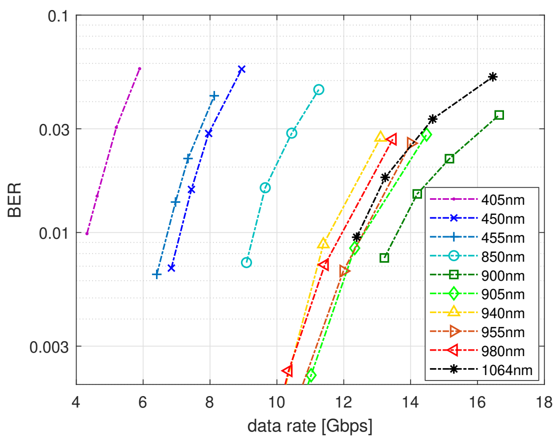

Fig. 5: bit error rate (BER) against achievable data rate of LiFi transmission with multiple parallel channels.

Tab. 2

Wavelength [nm]	Data rate [Gbps]	BER
405	4.62	0.015
450	7.44	0.016
455	6.97	0.014
850	9.65	0.016
900	14.2	0.015
905	14.48	0.028
940	11.4	0.009
955	12	0.007
980	11.4	0.007
1064	13.2	0.018
Overall	105.36	0.0148

The SNR and BER results of all channels are shown in Fig. 4 and Fig. 5, respectively. Fig. 4 shows that the achievable SNR at frequencies below 1 GHz are above 20 dB for all of the IR WDM channels, but it drops significantly at higher frequencies. This is due to a number of factors: 1. The used PIN receiver has a 3-dB bandwidth of 1.4 GHz; 2. the system nonlinearity limits the achievable SNRs at high frequencies; 3. the SNR is affected by the interference caused by signal reflections due to impedance mismatch. The three blue channels achieve slightly worse link quality. The usable bandwidth for the blue LDs is below 1.5 GHz, and the SNRs ranges between 10 dB and 25 dB. As a result, the data rates are below 10 Gbps for the three blue wavelengths. In contrast, the performance of the IR LDs is considerably superior, which generally exhibit a usable modulation bandwidth of at least 2 GHz. In the case of the 1064 nm laser a different PIN photodiode (PD) receiver is used, e.g., (HSA-X-S-2G-IN), which has larger 3-dB bandwidth of 2 GHz. This boosts the total usable bandwidth to about 2.7 GHz. The extended useable bandwidth and the high SNR which in some cases exceeds 30 dB lead to data rates above 10 Gbps. The aggregate data rate of all the ten WDM channels is summarized in Table 2. It can be seen that the sum data rate is 105.36 Gbps, and that the 905 nm channel achieves the highest single data rate of 14.48 Gbps. The peak responsivity of the receiver PIN diode is around 770 nm. This means that other factors in the end-to-end transmission also contribute to the peak data rate. Note that in this study, a BER threshold of 5.6×10^{-2} is considered. This BER threshold is used in long-term evolution (LTE), and it can be shown that with soft decision decoding and 3% to 5% forward error correction (FEC) coding overhead, the final BER can be driven below 1×10^{-6}[16].

Conclusions

In this paper, we have demonstrated for the first time to the best of our knowledge a LiFi WDM system based on ten SMD laser sources achieving over 100 Gbps and providing white light illumination simultaneously.

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