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Advanced LiFi technology: Laser light

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ABSTRACT

We demonstrate high-speed LiFi data communication of over 20 Gbit/s using visible light from a laser-based white light emitting surface mount device (SMD) product platform that offers 10-100X the brightness of conventional LED sources. Equipped with high power blue laser diodes that offer over 3.5 GHz of 3 dB bandwidth, the laser-based white light SMD modules exhibited a signal-to-noise ratio (SNR) above 15 dB up to 1 GHz. The high SNR was combined with high order quadrature amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM) to maximize the bandwidth efficiency. In this work, we present a laser based white light SMD module configured with a single 3W blue laser diode mounted on heat-sink, optically coupled to a collimating optic, achieving a LiFi data rate of up to 10 Gbit/s. Moreover, we demonstrate wavelength division multiplexing (WDM), from a white light SMD module configured with two blue laser diodes separated in peak wavelength to serve as separate communication channels. Using WDM, the dual laser SMD module enabled LiFi data rates of over 20 Gbit/s by simultaneously transmitting data over both channels.

Keywords: Li-Fi, GaN, Laser diodes, visible light communication, VLC, Solid state lighting, OFDM, WDM

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1. INTRODUCTION

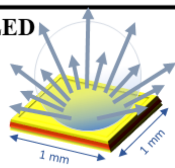
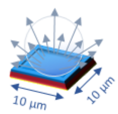
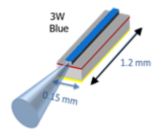
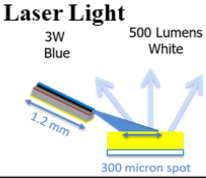
Solid-state lighting based on light emitting diodes (LEDs) has been widely used by replacing incandescent light bulbs in last decade. LEDs have satisfied existing demands with the advantages of low power consumption, low cost, long life time, and compact form factor [1], [2]. However, as the technologies rapidly grow, more functions are required to be added on solid-state lighting. GaN based laser diodes (LDs) are emerging as an advanced solid-state lighting technology by its unique but powerful characteristics: extremely high luminance from a single chip, small spot size, and temporal and spatial coherence while maintaining the merits of existing LEDs and other light sources [3]–[5]. This allows GaN-based LDs to be utilized in various high-value application spaces such as automotive, AR/VR display, medical devices, 3D sensing and specialty lighting [6]. More recently, data transmission capability of GaN-based LDs has gained high momentum for next generation communication technology. High speed data transmission for LDs is well-known properties because LDs operating in the near- and mid-infrared spectrum have long been used for telecommunication and optical fiber technologies. However, visible LDs have not been typically used for wireless communication, an application which has not been well-researched yet. As the spectral capacity in conventional radio frequency (RF) is getting fully saturated in 4G to 5G technology, LiFi using visible light is considered as a solution to mitigate RF spectrum crunch [7]. LiFi technology is not only a source for alternative spectrum, but also offers advantages such as no electromagnetic interference (EMI), high security with line-of sight communication, and multi-functionality of the light source [8]. LiFi is also cost-efficient by using the relatively cheap light bulbs as transmitters while conventional RF technology needs extra antennas for its small coverages of 5G.

Most reported LiFi studies have used LEDs as transmitters in the communication systems. Even though conventional LEDs have limited carrier lifetime and high RC parasitic effects limiting the bandwidth in a few MHz, micro-LEDs or super-luminescent light emitting diode (SLED) as a transmitter enabled increasing bandwidth [9]–[11]. High 1.5 GHz bandwidth was reported with micro-LED for the transmitter, which is limited by intrinsic carrier lifetime [12]. By utilizing fast color-converting materials and high order modulation scheme, low bandwidth can be overcome up to 1.8 Gbit/s [13]–[15]. SLED based LiFi was also demonstrated with relatively high bandwidth between LED and LD [16].

More recently, laser-based LiFi has been studied to maximize the data rate beyond existing 5G and LED-based LiFi limitations. 4 Gbit/s of data transmission with commercial high-power laser diode was demonstrated by using simple on-off keying modulation and even higher data rate can be achieved by higher order modulation scheme [17], [18]. The combination of LD and phosphor was also demonstrated for actual LiFi system sustaining Gbit/s data rate, with the data rate not highly limited by phosphor response [19]–[21]. In addition to phosphor based white lighting, wavelength division multiplexing (WDM) of red, green, blue lasers can triple the data rate as well as emitting white light. In this way, multiple lasers in visible spectrum can potentially offer up to 100 Gbit/s [22]. Even though laser-LiFi showed high potential as the candidate of next generation communication by overcoming the limitation of LEDs as well as 5G, most of studies in laser-LiFi were performed in lab-scale systems or with low power LDs. In this paper, a practical laser-LiFi system is demonstrated using a commercially available laser-based white light source. Also, a multi-wavelength transmitter chip and module is introduced to maximize both data rate and luminosity.

2. LASER LIGHT TRANSMITTER

Table 1. Types of LiFi transmitter

	LED 	µLED 	Laser diode 	Laser Light 
Area	0.1~1mm^2	<0.01mm^2	<0.2mm^2	~0.01mm^2
Limiting factor	τ_{RC}(~1 ns)	$\tau_{carrier}$(~0.1 ns)	τ_{Photon}(~ 1ps)	τ_{Photon}(~ 1ps)
Bandwidth	~10 MHz	<1.5 GHz	10~20 GHz	10~20 GHz
Power$_{out}$	>1 W	~ µW	>1 W	>1 W
Eye safe	Yes	Yes	No	Yes

Different type of light emitting devices can be used as LiFi transmitters. Conventional LEDs has been widely used for many studies because full white LED packages are readily available. As shown in Table 1., LEDs has relatively large area, which enables high optical power but causes a significant RC parasitic effect [23]. In this case, the modulation bandwidth is limited on the order of MHz by the RC constant rather than carrier lifetime. Micro-sized LEDs (µLEDs) have at least 1 to 2 order of magnitude lower area compared to conventional LEDs [24]. Even though light output is proportionally reduced to smaller area, the RC parasitic effect is dramatically reduced. Thus, the modulation bandwidth is limited by carrier lifetime, which can be the theoretical limit of carrier recombination in the active region. The highest record bandwidth of µLEDs was reported as more than 1 GHz in both GaN and GaAs material system [25], [26]. µLEDs arrays have been suggested as a means to recover the output power achievable in LEDs. LDs are a more fascinating transmitter in terms of both light output and high-speed performance. The device area is not as small as µLEDs, however, the modulation bandwidth is at least one order higher than µLEDs because the limiting factor is photon lifetime in the laser cavity. This is because carrier density in the active region clamps once it reaches the lasing threshold. Thus, the modulation is dominated by stimulated fast photons in the cavity rather than the carriers in the active region. As a result, the modulation bandwidth of LDs can be much higher than LEDs; up to around 20 GHz [27].

However, LD chips are typically single wavelength but need to generate white light for a LiFi transmitter if they are to be also used for lighting applications. The key requirement of white laser light technology is to maintain same high-speed performance as an isolated laser source while also generating white light. The laser-pumped phosphor material creates an eye safe white light emission, which provides significant advantage compared to the non-eye safe beam from single wavelength coherent emitting high-power LD chip [3], [6]. Figure 1. shows an integrated surface mount device (SMD) package for laser lighting applications. The laser beam hits the phosphor and the combination of the photons from LD and phosphor-converted photons generate a white light spectrum. These laser light SMDs can generate directional beams with 400~500 lumens from a 300~400 micron spot, to generate luminance levels well in excess of 1,000 cd/mm2 and beyond

[28]. In short, the generated laser light results in a Lambertian white emission similar to LEDs, but with drastically higher luminosity. This higher luminance enables more efficient collimation of the emitted white light to deliver more photons to a target at distance. This is significantly beneficial for long distance communication without losing signal intensity through the wireless channel. Also, the bandwidth of laser light is not degraded from that inherent to LDs.

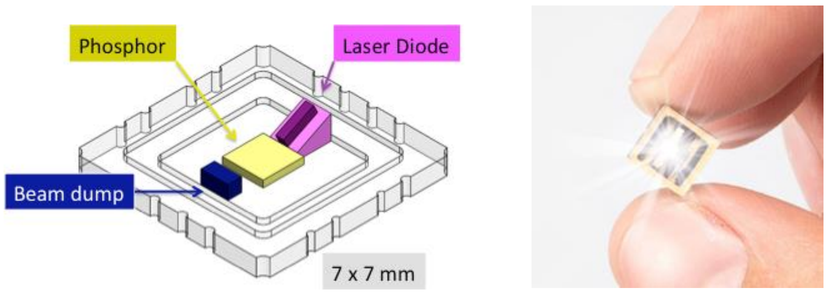


Figure 1. Schematic (left) and top view (right) of laser SMD package including LD chip and phosphor material.

3. EXPERIMENTAL SETUP

The free-space communication setup comprised the arbitrary waveform generator (AWG, Keysight M8195A), high-speed oscilloscope (DSA 90804A), various transmitters including SMD and integrated modules, high-speed photodetector (PD), bias-T (ZFBT-282-1.5A+), and amplifier (SHF-S126A). Signal waveforms were loaded by MATLAB from the laptop to the AWG to generate analogue bipolar waveforms. The signals were amplified by the amplifier with a gain of 25 dB and then biased by the bias-T to sit on the linear DC range of laser output. Different optics and filter setup were used to maximize the performance. The received signals at the PD were shown in high-speed oscilloscope and processed by MATLAB. Transmitter (Tx) side was installed with laser diode in TO-can, laser SMD, micro-spot module, or fiber-coupled module for different experiment.

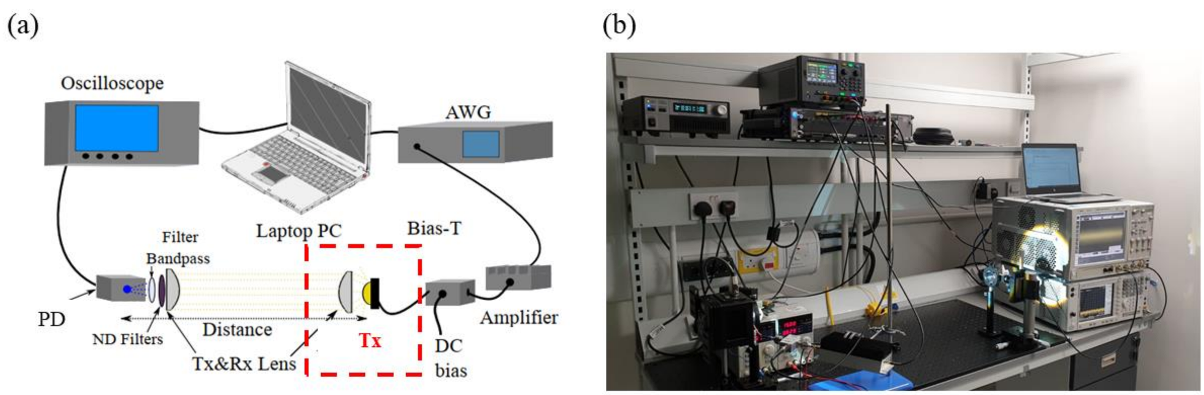


Figure 2. (a) Schematic of LiFi experimental setup (red Tx box can be different transmitter source) and (b) a photograph of experimental setup with laser light.

Orthogonal Frequency Division Multiplexing (OFDM) was used as the modulation scheme. OFDM that uses adaptive bit and energy loading is suitable to maximize information capacity of channel utilization for incoherent light source [29]. A random bit stream was generated and modulated using quadrature amplitude modulation (QAM). The QAM symbols were loaded into orthogonal sub-carriers. The OFDM frame size was set up to N_{FFT} = 1024 subcarriers but depends on the experimental system.

4. SINGLE LASER SMD

Prior to performing LiFi data transmission, a blue LD packaged in a TO-can was first tested to characterize the modulation bandwidth. The packaged blue LD design is rated for long lifetime at 3W of optical output power in the 445nm to 455nm range. A -3 dB bandwidth of 3.5 GHz was measured at 1 A~ 1.2 A of drive current and started to saturate above 1.2 A. It should be noted that the 3.5 GHz bandwidth was limited by the bandwidth of the PD, not limited by the LD itself [27]. Thus, the inherent LD bandwidth is likely higher than 3 dB. The kink at 1 GHz is due to the impedance mismatch from un-optimized RF connections and system.

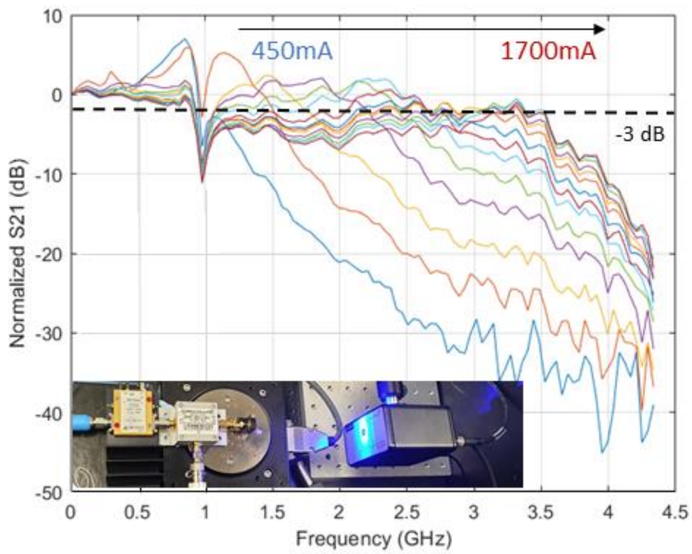


Figure 3. Normalized frequency response of blue LD in TO-can (subset: a photograph of measurement setup including an amplifier, a bias-T, LD in TO-can, and PD)

The high power blue LDs characterized with >3.5 GHz 3dB bandwidth served as the light engine within the white light SMD package as shown in Figure 1. This white light emitting SMD was installed in a Tx with a collimating optical lens and tested for signal-to-noise ratio (SNR) and bit-error-rate with QAM-OFDM modulation. The bit loading can be up to 128-QAM at the sub-frequencies of high SNR. SNR below 600 MHz was almost flat above 20 dB except 450 MHz of 17 dB. SNR was above 5 dB until 1.2 GHz where the PD limit as shown in Figure 3(a). For SMD experiment, 1.4 GHz PD was used rather than higher-speed PD because the active area of PD is larger receiving more photons and signals even though it is trade-off between the bandwidth and SNR. Highest data rate from this single laser SMD was obtained up to 6.8 Gbit/s with BER of 2.98×10^{-3}, which is right below forward error correction (FEC) limit as shown in Figure 3(b).

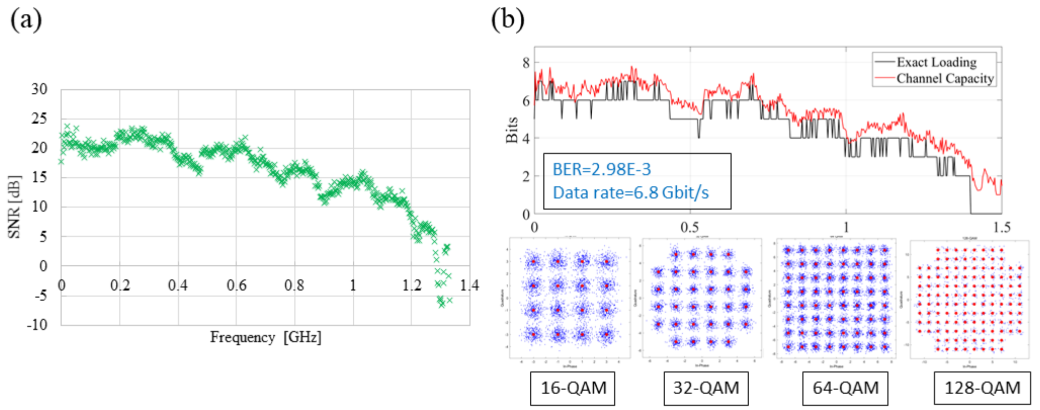


Figure 4. (a) Signal-to-Noise ratio (SNR) of single laser SMD and (b) Bit loading of QAM signals representing 6.8 Gbit/s of data rate with BER of 2.98× 10^{-3} and different constellations in 16-, 32-, and 64-QAM

Due to their drastic brightness advantage, laser light sources can transmit the data at much longer distance than LED light when coupled through similar size optics as mentioned in section 2. The distance measurement from 5 m to 50 m was performed with same modulation scheme. The laser-based white light SMD was integrated into a compact lighting module including a Tx lens, which allows to achieve high data rate at long distance link. For long distance, the drive condition was adjusted to achieve highest optical power at the receiver. Also, the bandwidth was reduced at longer distance to maximize the SNR. Figure. 5(a) shows data rate in different distance in terms of BER. Under FEC limit, the data rate of 7 Gbit/s in 5 m reduced to around 1 Gbit/s in 50 m. For practical performance, FEC target was considered to be too stringent for wireless link with 7 % overhead [30]. Thus, less a stringent target with staircase code was introduced and a higher overhead up to 33% was acceptable for new BER target for LiFi, which is typically accepted in 4G/LTE [31], [32]. Under this error correction target, a data rate was achieved up to 11 Gbit/s at 5 m and 1.7 Gbit/s at 50 m with integrated transmitter. Sustaining Gbit/s data rate in long distance makes laser light LiFi system more practical in various applications. 50 m range with Gbit/s data rate can cover most of indoor circumstances as well as typical concert or stadium.

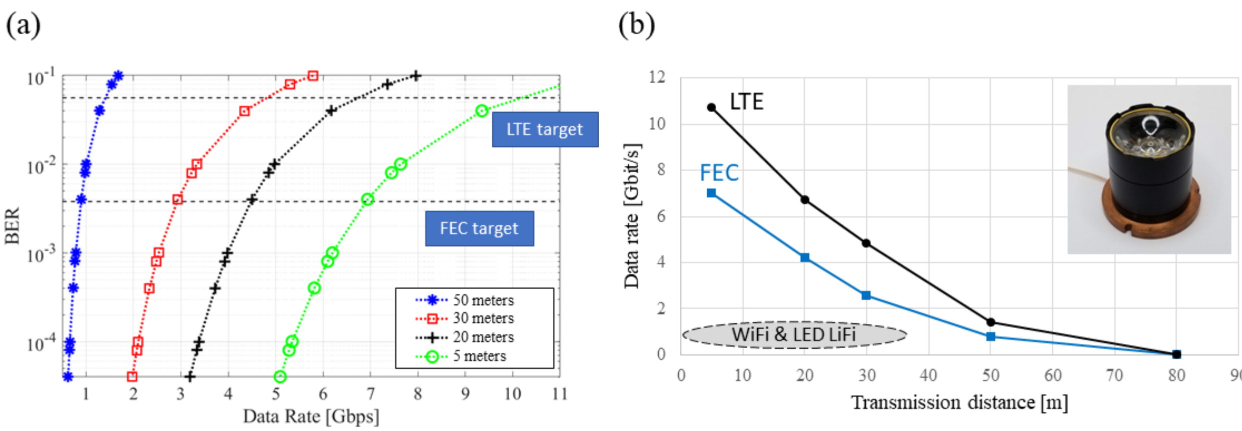


Figure 5. (a) BER vs. Data rate in different distances with two targets: FEC and LTE. (b) Data rate vs. Transmission distance for two targets: FEC and LTE. The subset is a photograph of micro-spot module used in this experiment

5. DUAL LASER SMD

A key advantage of the laser-based white light SMD package is the ability to integrate more than one LD in a single package. By including multiple LDs in the white light source, the total LD output power can be increased to generate higher levels of white light emission and the data rate can be dramatically increased over single LD based devices by using wavelength division multiplexing (WDM). Here we integrate two blue LDs separated in peak wavelength by 5-10 nm within a single white light emitting SMD package. The two LDs were connected in parallel to be driven individually and transmit data on two separate channels. This dual laser SMD chip was integrated into an integrated lighting module wherein the white light emission from the SMD is coupled to the Tx collimating lens via an optical fiber as shown in Figure. 6(a). The two distinct blue wavelengths from the LDs were received at two separate PDs within the single white light beam overlapping both PDs at the distance of 3 m. The PDs were configured with appropriate filters such that one PD received the signal from the first blue wavelength and the second PD received the signal from the second blue wavelength to achieve a WDM LiFi system. The experimental set-up is shown in Figure 6(a) and the spectrum of the white light device with two distinct blue wavelengths is shown in Figure. 6(b).

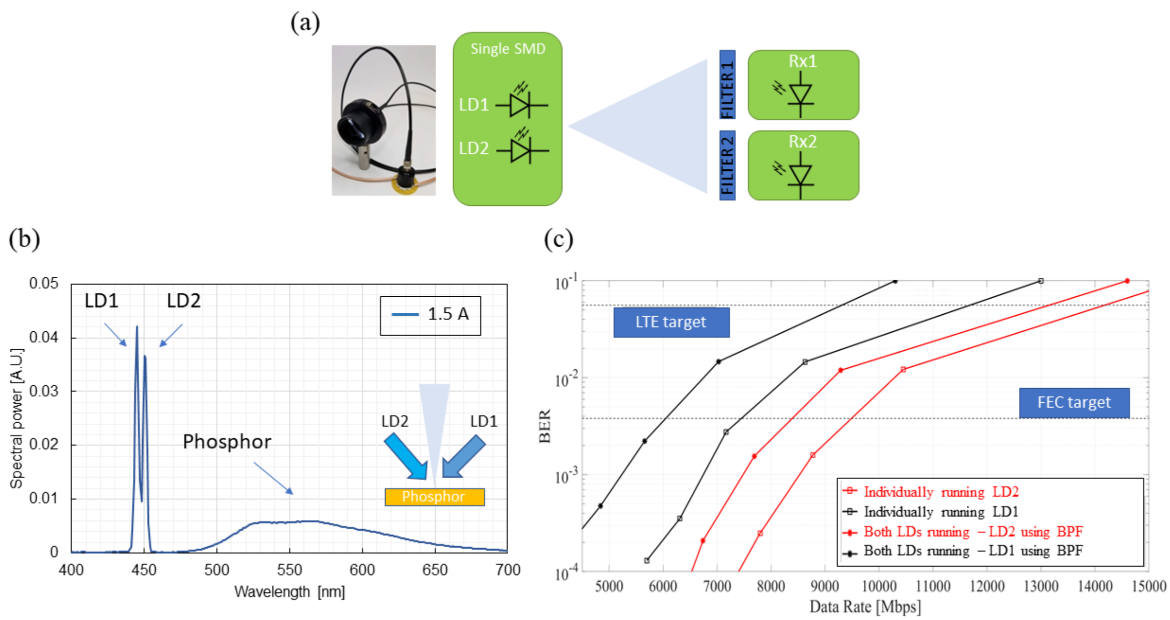


Figure 6. (a) A photograph of fiber-coupled module and the schematic of dual laser SMD-based WDM LiFi system. (b) Spectra of dual laser SMD with two peaks near at 450 nm and phosphor peak. (c) BER vs. Data rate for fiber-coupled module of dual laser SMD in LiFi system

Each blue LD in the dual laser SMD was modulated using the same QAM-OFDM scheme performed in the single laser SMD experiment described above. Since the lasing peaks are separated by less than 10 nm, the optical interference affected the SNR by filtering out unwanted photons to each PDs. Targeting the BER limit of LTE, when individually operating the two LDs (LD1 and LD2) the data rates of LD1 and LD2 were 11.65 Gbit/s and 14.15 Gbit/s, respectively. This data rate represents the maximum data rate from each LDs without optical interference, but still including potential electrical interference. When both LDs were simultaneously operated for data transmission, the data rate of 9.3 Gbit/s and 13.15 Gbit/s for LD1 and LD2 were achieved at each PDs, respectively. Thus, the total data rate of 22.45 Gbit/s was achieved when both LDs were simultaneously transmitting data in the white light SMD, representing only about 10% degradation from total date rate of 25.8 Gbit/s of individual LDs.

Testing was performed in broad daylight and highly artificially illuminated environments for nearly 100 hours across several days without failure or malfunction. Moreover, very bright white light from a ~500 lumen laser-based flashlight was intentionally subjected to the photodiodes without causing issues to operating the LiFi system performance. This result proves the viability of WDM LiFi schemes operating in the visible spectral range using closely spaced peak wavelength separation in practical environments while preserving the photometric qualities of the white light source. By scaling this approach to an increased number of WDM channels, more than 100 Gbit/s can be achieved with 10 or fewer high power blue LDs.

6. CONCLUSION

In summary, a practical laser light-based LiFi system was demonstrated with high data rates above 20 Gbit/s. The integrated white light SMD source comprising blue LDs and phosphors for bright white light emission was used as the high-speed transmitter. QAM-OFDM was used as modulation technique to maximize channel capacity. The LiFi system with a single laser white light SMD integrated in micro-spot module performed at 11 Gbit/s at 5 m distance and 1.7 Gbit/s at 50 m distance above the LTE criteria of BER. Dual laser SMD integrated in fiber-coupled module performed 22.45 Gbit/s with two channel WDM without significant interference between two wavelengths. These results show the great potential of laser light-based LiFi systems for very high-speed data transmission in practical real-world environments.

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