26 Gbit/s LiFi System With Laser-Based White Light Transmitter

Changmin Lee, Mohamed Sufyan Islim, *Member, IEEE*, Sovan Das, Adrian Spark, Stefan Videv, Paul Rudy, Binith Shah, Melvin McLaurin, Harald Haas, *Fellow, IEEE*, and James Raring

(Invited Paper)

***Abstract*—We demonstrate a high-speed light fidelity (LiFi) communication system deploying ultra-high brightness laser-based white light illumination sources in a surface mount device (SMD) packaging platform. The LiFi transmitter SMD source provides 450 lumens of white light output with a brightness of 1000 cd/mm^2 in a dual wavelength configuration comprising blue and infrared (IR) emitting laser diodes within the SMD. First, we present high-speed data transmission beyond 25 Gbit/s over a 3 meter channel distance with the combined data rates from the blue and IR lasers in the single SMD. Next, we present a 2.8 Gbit/s data rate with the dual wavelength laser SMD light source using a side-emissive fiber as the transmitter. This work proves the viability of LiFi systems deploying laser-based white light sources operating at very high data rates with the visible light and communication signal delivered in conventional free-space transmission architectures along with novel configurations using side-emitting fibers.**

***Index Terms*—Emissive fiber, laser diode, light fidelity (LiFi), modulation, optical communication, optoelectronics, solid-state lighting, surface mounting device (SMD), visible light communication, wireless communication (VLC).**

I. Introduction

LASER based technologies have been widely developed for different markets over recent decades. Traditionally, laser diodes (LDs) emitting in the infrared (IR) have been in high demand for optical telecommunication applications as transmitters sources [1], [2]. The inherent high-speed characteristics such as the high modulation bandwidth as well as narrow linewidth to minimize dispersion in optical fibers for dense wavelength division multiplexing (WDM) make LDs ideal transmitter sources in communication systems. More recently, IR LDs have experienced a new surge in demand for the rapidly growing sensor market where they provide the sensor signals in a wide range of sensors such as time-of-flight (ToF) distance sensors and coherent detection distance sensors to enable full 3-dimensional (3D) imaging in LiDAR systems due to their, high speed, long coherence length, low noise, and high pulse repetition capability [3], [4].

Gallium nitride (GaN) based LDs emitting in the visible wavelength spectrum have been emerging over the past two decades in blu-ray optical disc data storage, direct laser diode based projection displays, phosphor converted projection display systems, and most recently in advanced solid state lighting technology [5]–[9]. The unique properties of LD-based solid state lighting include higher luminance white light emission for increased range and directionality, smaller light emission areas for more compact sources, and drastically higher modulation bandwidth than traditional LED based solid state lighting [10], [11]. By offering 10X to 100X the brightness of LEDs, 10X the range of LEDs, and optics that are 1/10 the size of those required for LEDs, LD-based lighting systems offer unique value propositions in many lighting applications. Moreover, the inherent inclusion of the LD in the light source enables LD-based solid state lighting to expand to more advanced markets such as automotive and all mobility applications, smart infrastructure, depth sensing, full 3D sensing, augmented reality and virtual reality display systems, and medical applications wherein LEDs offer limited performance [12]. In addition, these LD-based white light sources can function as high-speed transmitters for data links in communication systems, similar to infrared LDs found in traditional optical communication systems, but within a multi-function light source for both lighting and data transmission.

Laser-based light fidelity (LiFi) technology has been considered as a strong candidate for next generation communication systems complimenting 5G technology and beyond. Radio frequency (RF) based communication is facing growing congestion and interference challenges associated with the limited available spectral bandwidth of 300 GHz wherein only a small portion is allocated for wireless communication [13]. The channel congestion in multi-use RF allocations leads to significant reliability and interruption issues. Moreover, the expected demand for wireless bandwidth is supposed to increase by 12000 times over the next 20 years. This is based on 60 percent compound

Manuscript received August 1, 2021; revised October 5, 2021; accepted October 27, 2021. Date of publication November 4, 2021; date of current version March 2, 2022. *(Corresponding author: Changmin Lee.)*

Changmin Lee, Paul Rudy, Binith Shah, Melvin McLaurin, and James Raring are with Kyocera SLD Laser, Inc., Goleta, CA 93117 USA (e-mail: clee@kyocera-sldlaser.com; prudy@kyocera-sldlaser.com; bshah@kyocera-sldlaser.com; mmclaurin@kyocera-sldlaser.com; jraring@kyocera-sldlaser.com).

Mohamed Sufyan Islim, Sovan Das, Adrian Spark, Stefan Videv, and Harald Haas are with the LiFi Research and Development Center, University of Strathclyde, G1 1RD Glasgow, U.K. (e-mail: m.islim@strath.ac.uk; sovan.das@strath.ac.uk; adrian.sparks@strath.ac.uk; stefan.videv@strath.ac.uk; harald.haas@strath.ac.uk).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2021.3124942.

TABLE I
RECENT DEMONSTRATIONS OF LASER-BASED LIFI

Ref. Year	Tx configuration	Applied scheme	Data rate
[18] 2015	B LD + remote phosphor	OOK	2 Gb/s
[19] 2015	B LD + phosphor diffuser	QAM-OFDM	5.2 Gb/s
[20] 2015	B LD + remote phosphor	QAM-OFDM	6.52 Gb/s
[22] 2015	R + G + B LDs	QAM-OFDM	12.4 Gb/s
[23] 2020	Violet LD + fast R&G phosphors	QAM-OFDM	12.8 Gb/s
[24] 2020	Dual blue LDs in single SMD package	QAM-OFDM+WDM	22.45 Gb/s

*Tx: transmitter, LD: laser diode, R: red, G: green, B: blue, OOK: on-off keying, Gb/s: Giga bit per second, QAM: quadratic amplitude modulation, OFDM: orthogonal-frequency division multiplexing, SMD: surface mount device, WDM: wavelength division multiplexing

annual growth rate of mobile data traffic [14], [15]. A convenient solution to this looming spectral crunch is to utilize the IR and visible spectrums which offer 800 THz of unregulated and uncongested spectrum. Further, the narrow spectral linewidth of LDs can maximize spectral usage efficiency. Such communications systems based on visible and IR wavelengths provide high security since the signal of light is contained to the area it is transmitted within, without leaking through walls where the signal can be intercepted by unknown entities with a malicious intent. Although confined to the area or room the transmission originates, it should be noted that the transmission link may not require a strict line of sight (LOS) condition because LiFi systems have been shown to enable signal detection and a secure link even with reflections from walls and other surfaces [16]. It is also important emphasize that LiFi systems such as those described here are proven to work in direct sunlight with negligible impact to the system performance [17].

The performance of initial LiFi studies were significantly limited by low 3 dB bandwidth of conventional LEDs in 10$\sim$100 MHz range. When micro-LEDs and superluminescent diodes (SLEDs) are utilized as transmitters for visible light communication, the 3 dB bandwidth can be increased up to 1$\sim$2 GHz, enabling higher data rates, but these solutions come with drawbacks or lower light output and/or lower efficiency [18]–[21]. Increased data rates for a given 3 dB bandwidth is maximized by implementing high order modulation scheme such as quadratic amplitude modulation (QAM) Orthogonal Frequency Division Multiplexing (OFDM), adopting technology from conventional wireless communication platform and combining with optical communication in LiFi systems. With inherently better frequency response, LD-based LiFi enables much higher 3 dB bandwidth of up to several GHz using high power LDs that can efficiently generate many hundred lumens of white light [22]–[24]. More than 2 Gbit/s and 10 Gbit/s were achieved by simple on-off keying (OOK) and QAM modulation, respectively, from a laser-based LiFi system in [25]–[30]. Table I summarizes recent reports of laser-based LiFi systems.

Recently, we demonstrated a more advanced LiFi system using a laser-based white light source that integrated two blue LDs with slightly shifted lasing wavelengths into single surface mount device (SMD) package as a transmitter. This laser-based white light SMD source offers high design flexibility in the LiFi system while providing the capability for extremely high data rates of over 20 Gbit/s by utilizing both OFDM and WDM [31]. Unlike LEDs with broad emission spectra, the narrow spectral width of LDs allows for efficient WDM and low optical interference with the two blue LDs operating at peak wavelengths spaced by only a few nanometers. This result showed the capability of high density WDM with the laser-based SMD platform.

In this work, we present a laser-based white light source that integrates an IR LD and a blue LD into a single SMD package to utilize the dual wavelengths and form communication links with the blue wavelength and the IR wavelength. Due to the very wide wavelength spacing, the optical interference of the two channels is expected to be negligible in this LiFi system. The SMD based transmitter technology integrating multiple LDs allows for straightforward scaling of the data rate through WDM without adding excessive complexity to the Tx design of communication system. Specifically, it is possible to utilize WDM with N communication channels covering the visible and IR spectrum by integrating multiple LDs within a single SMD package, enabling a novel transmitter and white light source architecture for LiFi applications.

In the first section of this work, we demonstrate a 26 Gbit/s LiFi communication system using a laser-based SMD with its white light emitted through a launch optic connected for free space transmission from the Tx module. In this first system, the data link was established over free space from the output of the launch optic of the transmitter module to the receiver positioned 3 meters away (launch optic system). In the second section of this paper, 2 Gbit/s data transmission is demonstrated using fully packaged transmitter and receiver units. In this second system, the data link is established from the transmitter unit emitting white light along the length of a side emissive fiber to the receiver unit (emissive fiber system). It is noted that data transmission using side-emissive fiber is a totally new concept for LiFi systems that could find use in many communication applications.

II. DUAL LASER BLUE + INFRARED INTEGRATED SURFACE MOUNTING DEVICE

Fig. 1(a) shows the 7 mm $\times$ 7 mm sized SMD package integrating a blue LD emitting at about 450 nm, an IR LD emitting at about 850 nm, and a phosphor element. The SMD package includes wedges to support the LDs with the wedges designed such that both laser beams are incident on the phosphor element at an angle optimizing the excitation spot position, size, and angular distribution of the Lambertian emitted white light. As shown in Fig. 1(b), the light emitted from the two LDs is incident on the center of the phosphor surface, wherein some of the blue light emitted from the blue LD is converted to yellow light. As a result, a bright white light comprising unconverted blue light from the blue LD and a broad, longer-wavelength yellow light derived from the conversion of the blue laser light by the phosphor element is emitted. The 850 nm emission from the IR LD is reflected off the phosphor surface in the same spot location that the white light is emitted from to create an overlapping white light and IR light Lambertian emission from the phosphor. This

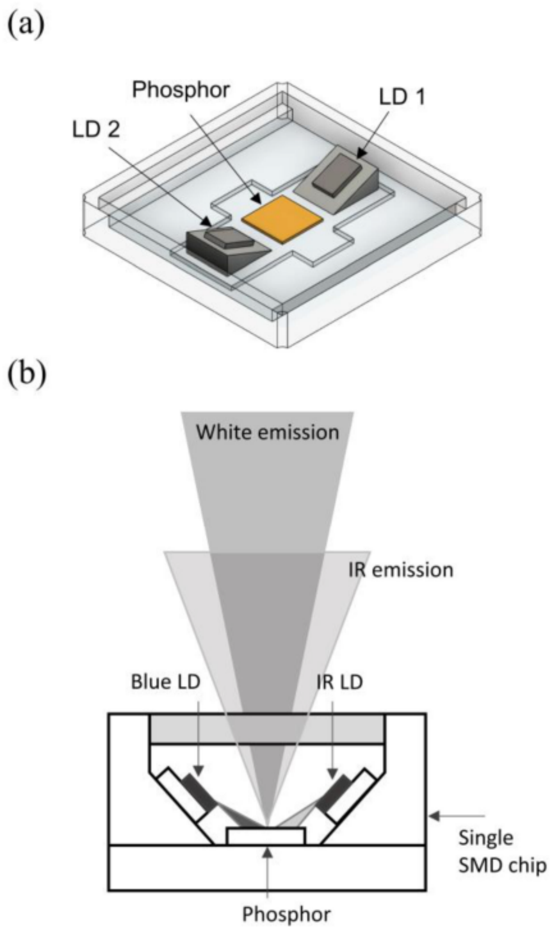

Fig. 1. (a) Schematic of the SMD light source with two LDs operating with blue and IR wavelengths. (b) Cross-section schematic for dual wavelength emission from blue and IR LDs in the SMD.

combined Lambertian emission is collimated using conventional optics to create colinear propagating beams of IR and white light. Since the white light and scattered/reflected IR light are emitted from the SMD in a Lambertian pattern and are incoherent, the laser-based SMD light source is eye-safe and certified by IEC standards [32].

The widely separated blue and IR spectra from the two lasers in the SMD light source are expected to fully avoid optical interference. A unique feature of the SMD light source platform is that it allows the integration of multiple LDs from different material systems emitting at significantly different wavelengths to be combined and emitted from the same spatial location on the phosphor. Since the data is transmitted with the directly emitted blue laser emission and IR laser emission rather than with the phosphor converted yellow emission, the data rates are not limited by the long lifetimes associated with the phosphor conversion process. The SMD platform can scale to 4 or more laser emitters with varying wavelengths. In this work, the blue + IR SMDs generate 450-500 lumens of white light from an emission spot of 300~400 μm diameter using a single blue LD along with the IR emission at 850 nm. The white light luminous flux can be increased to 1000 lumens with two blue LDs, while enabling dual channel WDM communication links if the lasing wavelengths are sufficiently separated [31]. Luminance levels of the laser-based sources can well exceed 1000 cd/mm^2 resulting in a Lambertian white emission similar to LEDs, but with 10X to 100X higher luminance [33]. Based on the first principal law of etendue, the higher brightness enables drastically improved collimation of the emitted white light to increase the white light range and deliver more photons to a target at distance relative to larger area LED source with similar luminous flux output. This is significantly beneficial for free-space communication over long distance wherein the increased illumination range also results in increased communication link distance by maintaining high signal-to-noise ratio (SNR) through the wireless channel.

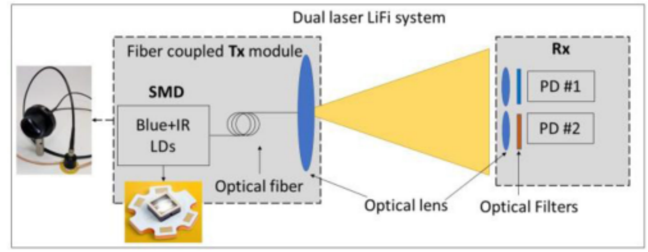

Fig. 2. Experimental system of dual laser LiFi system.

In summary, the laser-based white light SMD can offer superior illumination compared to LEDs along with increased data rates from higher bandwidth, higher spectral usage efficiency with the narrower linewidth providing WDM capability, and increased transmission range due the higher brightness versus LED in LiFi systems. Moreover, outside the scope of this work, the inclusion of IR LDs in the white light source can also enable further functionality including IR illumination, depth sensing, and full 3-dimensional LiDAR imaging.

III. High Speed Performance of Launch Optic LiFi System for IR/White Laser SMD

The experimental setup for the launch optic LiFi system is shown in Fig. 2. An arbitrary waveform generator (AWG, Keysight M8195A) was connected to the Tx module to generate data signal of high order modulation schemes. The data signals are combined through a bias-T(ZFBT-282-1.5A+) and amplified by an amplifier (SHF-S216A). The Tx module is designed for the white light and IR emission to be coupled through a fiber for delivery to a remotely positioned launch optic. The fiber coupling efficiency is highly dependent on the fiber core diameter, the numerical aperture of the fiber, and coupling optics, but it should be noted that the drastically higher brightness of the laser-based white light source enables improved (~10X) fiber coupling efficiency. A high-speed oscilloscope (DSA 90804A) is used to read out the signals received from two high speed photodetectors (PDs, HSA-X-S-1G4-SI). The free space link is set at a distance of 3 m from Tx to Rx. Two WDM channels are established on the two different wavelengths with the blue and the IR links separately received and signal-processed at the Rx by using bandpass filters at each PD.

Each communication channel is modulated with Direct Current (DC) biased Orthogonal Frequency Division Multiplexing (DCO-OFDM). OFDM utilizes adaptive bit and energy loading over the bandwidth to maximize the channel usage based on the

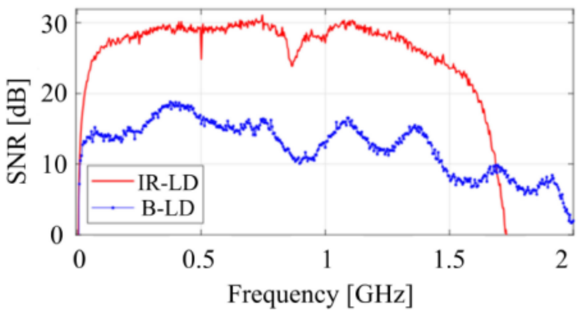

Fig. 3. Signal-to-noise ratio (SNR) over the bandwidth for LDs of blue (BLD) and IR (IR-LD).

available channel capacity [20]. Compared to a single carrier modulation, OFDM is computationally effective due to the use of single-tap equalizer [34]. A random bit stream of quadrature amplitude modulation (QAM) is generated as data signal. The QAM symbols were loaded into orthogonal narrow-band sub-carriers. The OFDM frame size is set up to $N_{FFT} = 1024$ subcarriers and a cyclic prefix of $N_{FFT} = 5$ was found experimentally sufficient to mitigate any inter-symbol-interference.

The SNR performance is first characterized to estimate the channel condition and obtain the channel state information (CSI), which is required to equalize the frequency response of the complete system. This is also required to perform the adaptive data loading on each channel of the two wavelengths, as shown in Fig. 3. The IR LD shows an almost flat channel and an SNR of around 30 dB up to 1 GHz, and an SNR of more than 20 dB up to 1.5 GHz. The high roll-off above 1.5 GHz is primarily due to the bandwidth of PD and package. The SNR of the blue LD is measured at 10∼20 dB with more ripples over the bandwidth than the IR LD. The lower SNR of the blue LD link could largely be due to the Si-based PD having about half of the responsivity at 450 nm compared to 850 nm as a dominant reason, with other possible contributing factors such as thermal noise contribution from two different laser chips and electrical noise contribution to the amplifier by different bias and signal intensity of two LDs.

The ripples in the blue LD SNR curve are believed to result from the impedance mismatch including the wire-bonding variation and RC parasitic from different chip dimensions. When compared with the IR LD, the blue LD has a higher driving current and lower resistance, which leads to a greater impedance mismatch. Further RF optimization of the SMD package is required to improve the SNR over broadband frequencies up to 2 GHz to enable higher data rates.

The blue LD and IR LD were individually driven at different bias current with separate bit loading of *M*-ary QAM for subcarriers over the bandwidth. The IR LD is able to achieve bit loading up to 512-QAM at the bit-error-rate (BER) passed the error correction target of 5.6×10^{-2}, which we define here as LTE target for soft decision with higher overheads than forward error correction limit (FEC). Adaptively load more power and bits over the bandwidth depending on SNR at a given frequency as shown in Fig. 4(a). In adaptive power loading, the sub-carriers with lower channel gain are loaded with a higher power to compensate for the loss. In adaptive bit loading, the

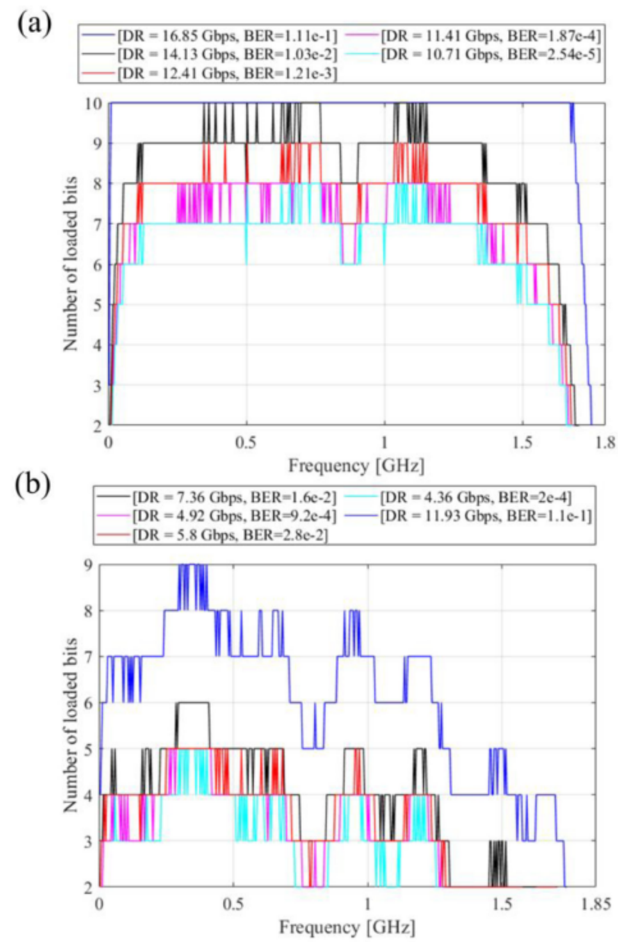

Fig. 4. Bit-loadings with data rate (DR) at different bit-error-rate (BER) for (a) IR LD and (b) blue LD. .

appropriate modulation index is selected for each subcarrier based on its SNR estimated and independent of SNR of the other sub-carriers. The blue LD achieved maximum modulation level of only 64-QAM due to lower SNR as shown in Fig. 4(b). In real world, advanced error correction techniques have higher overheads rather than FEC limit of 3.8×10^{-3} for wireless links [35]. For example, with a staircase code, we can handle a higher initial BER which after error correction can be reduced. The maximum overhead of such a code is 33.3% but it can also be as low as 6.25%, which would be capable of reducing the input BER on the order of $0.7{\sim}2 \times 10^{-2}$ down to 10^{-15} [36]–[36]. In LTE systems, the block error rate (BLER) target is generally defined as 10% giving 3.5×10^{-6} of the error corrected BER. Therefore, a peak data rate of between 93.75% and 85% of the over the air transmission rate can be achieved with a uncorrected BER of roughly 5% even though it can vary depending on channel condition. Based on this, 5.6×10^{-2} limit with 3∼5% overheads can be acceptable target with higher overheads to reduce the input BER down to 10^{-6} than typical FEC limit. The fast Fourier transformation (FFT) is used at the Rx to process the received OFDM signal followed by a single-tap equalizer and QAM. The recovered *M*-QAM constellations for the highest three *M*-ary levels of each channel are shown in Fig. 5.

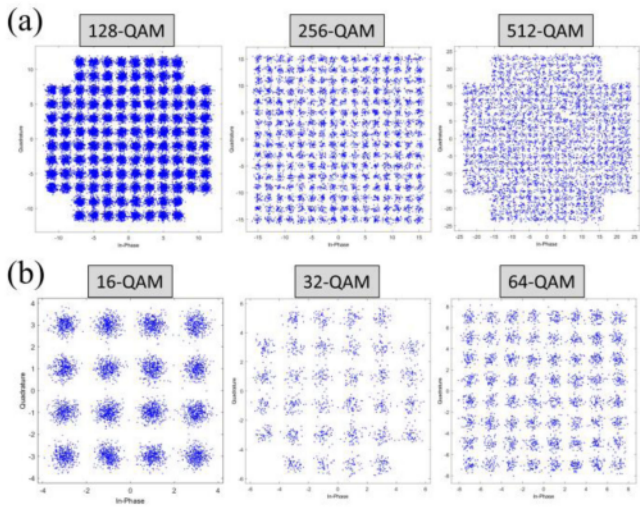

Fig. 5. M-QAM constellation symbols for (a) IR LD and (b) blue LD individually driven from the SMD.

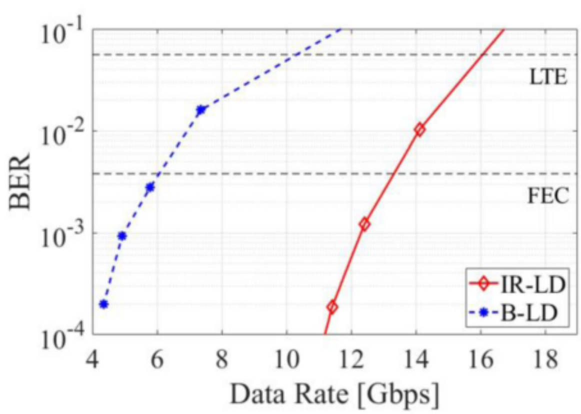

Fig. 6. BER versus data rate achieved in IR (IR-LD) and blue (BLD) LDs.

The BER versus achieved data rate for the blue LD and IR LD communication links is plotted in Fig. 6. The maximum data rate at FEC floor was 6.1 Gbit/s and 12.33 Gbit/s for the blue and the IR LD, respectively, resulting in 18.33 Gbit/s as a combined data rate. With LTE error correction limit, the combined maximum data rate reaches up to 26 Gbit/s with 10 Gbit/s and 16 Gbit/s for the blue and the IR LD, respectively. The measurement is performed by driving the two LDs individually because of the Tx driver board configuration used in this work, which can easily be configured for simultaneous operation as was already proven in our previous report [31]. However, we believe it is fair to directly combine the two data rates to accurately calculate the aggregate data rate if the LDs operate simultaneously since there should be no appreciable optical or electrical interference as reported in [31]. This result along with the previous report demonstrates the viability of utilizing WDM in laser-based LiFi systems. This result expands into the IR spectrum by combing visible and IR emitting wavelengths LDs into a single SMD. In this way, the number of LDs emitting across the visible and IR spectrums can be increased to N to scale the data rate by N using WDM without substantial increase in the system complexity.

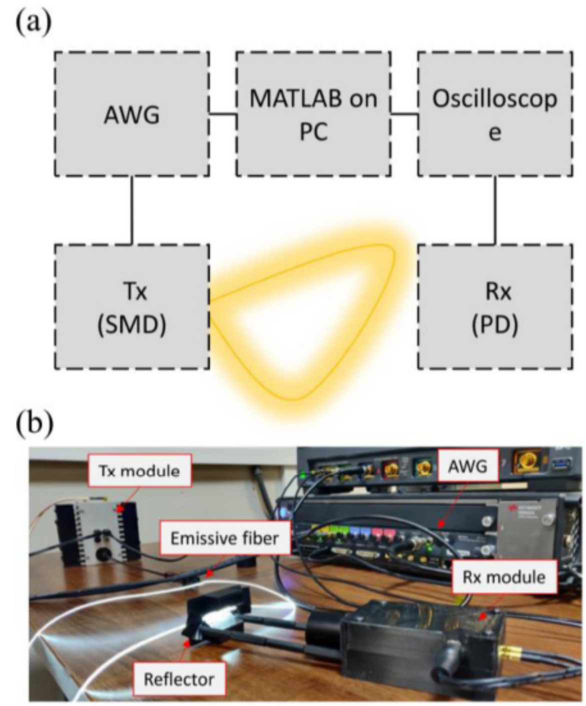

Fig. 7. (a) Schematic of LiFi system transmitting data over side-emissive fiber from dual laser SMD. (b) Photo of LiFi system setup with complete Tx and Rx units.

IV. Demonstration of Side-Emissive Fiber LiFi System

The laser-based white light SMD source offers unique design flexibility for innovative LiFi systems. In this section we present a novel LiFi system architecture designed to both emit white light and transmit data along the length of a side-emissive fiber optic as shown in Fig. 7(a). This side-emissive fiber system is ideal for dual function applications by both providing an ambient 1-dimensional white light source with illumination along the length of the fiber as well as the transmitter emission source in the LiFi data link. The very high brightness of the white light emitted from the SMD enables efficient collimation with small optics to provide high optical coupling efficiency into fiber optic cables with relatively small core diameters of $\sim$1 mm or less to enable a brilliant looking line source of white light. Using LEDs, the coupling efficiency into the same size fiber would be an order of magnitude lower.

This side-emissive fiber LiFi system consists of fully packaged Tx and Rx modules. The Tx module of this system utilizes the same dual laser SMD design with a blue LD emitting at about 450 nm and IR LD emitting at about 850 nm, and a phosphor for white light generation. The two lasers in the SMDs are independently driven to create two WDM channels in the data link. The emitted light from the SMD package is coupled into the side-emissive optical fiber as a data link. The total length and diameter of looped fiber is 1.8 m and 1.2×10^{-3} m, respectively. Therefore, considering the fiber as a long cylinder, the total surface area of the fiber which emits light is calculated to be 6.78×10^{-3} m^2. The center of the looped side-emissive fiber is placed at the focal point of a parabolic reflector unit at the Rx to maximize the photon reception at the PD, and the PD has a one-inch collimating optic as shown in Fig. 7(b). The reflector enveloping around the side-emissive fiber has a length of 3×10^{-1} m. The fiber is contained within a reflective trench, which exposes only part of the fiber to the receiver and can be considered as a longitudinal-half cylinder with length equal to the parabolic reflector and diameter equal to the width of fiber. Hence, only a part of the light emitted by the exposed surface area inside the reflector is captured by the receiver. The surface area of the fiber exposed to the receiver is calculated to be 5.65×10^{-5} m^2. The side-emissive fiber with the reflector unit is placed at 6.2 cm from the Rx optics to achieve the optimal performance.

The transmitter data signals are generated by an AWG at a sampling rate of 16 GSa/s with 25 symbols/sample. The effective communication bandwidth for this system is 320 MHz. The communication bandwidth is lower than previous system using the launch optic transmission due to the limited bandwidth of the drive circuit in the Tx module, impedance mismatch between the LD and drive circuit, and the type of PD used in the Rx module. In this configuration an avalanche PD (APD, SAR1500H4) with a 1.5 mm diameter of active area is used to achieve higher sensitivity instead of the positive-intrinsic-negative (PIN) PD used in the experiment described in section III. The APD is used because the optical power incident on the photo-receiving device is much lower compared to that in the launch optic transmission system. With a PIN PD a large bandwidth can be achieved at the cost of reduced sensitivity. Whereas, with a large active area APD, extremely high sensitivity can be achieved at the cost of bandwidth and noise performance. However, the degradation in noise performance is compensated up to certain extent by using some digital filtering and sample averaging at the oscilloscope.

A high-speed oscilloscope (MXR608A) with extended digital signal processing capabilities is used to capture the received signal from Rx module. The sampling frequency of the oscilloscope is set to 1.6 GSa/s to avoid aliasing the received signal with the high frequency noise and harmonics. The analog-to-digital converters' (ADC) resolution is set to 13-bit to achieve better precision while sampling the received analog signal. This enables the high-resolution mode of the oscilloscope (HRO) which averages the digital samples at 2.6 times, further reducing the measurement noise floor down to 81 μV_{rms} at 50 Ω input. Lastly, a brick wall filter with cut-off frequency at 320 MHz is enabled on the oscilloscope to reject any residual high frequency noise. The rest of the signal processing algorithms are implemented in MATLAB.

Fig. 8(a) shows the estimated SNR for the two laser channels. As discussed in previous section, the IR LD has a higher SNR of 20 dB with a flat band compared to that of the blue LD with a SNR of 10 dB, which largely results from the lower PD responsivity in the blue wavelength region. The overall SNR of two LDs is lower than launch optic system because the side-emissive fiber Rx module captures only 0.83% of the total optical power irradiated by the surface of the fiber. The DCO-OFDM modulation scheme is applied by using adaptive bit and power loading for dynamic channel condition based on SNR as shown in Fig. 8(b). Fig. 9. shows the achieved data rate along with the BER performance for both the blue LD and the IR LD. For qualitative comparison, the constellation diagrams for the highest achieved modulation index for both the blue LD and the IR LD are provided as insets of Fig. 9. For FEC target, the highest modulation index achieved in the IR LD and the blue LD is 64-QAM and 16-QAM, respectively. For the IR LD, the peak data rate measured at 1.3 Gbit/s with a BER of 1.19×10^{-3}. Similarly, for the blue LD the peak data rate is measured at 758.9 Mbit/s with a BER of 2.6×10^{-3}. For LTE target with higher overhead, the same 64-QAM is achieved with the IR LD and 32-QAM is achieved from the blue LD as the highest modulation index. The highest data rates are measured in the IR LD and the blue LD were 1.8 Gbit/s with a BER of 1.37×10^{-2} and 1.0 Gbit/s with a BER of 1.68×10^{-2}, respectively, which is well within more practical limit of optical wireless communication. This results in a combined data rate of 2.8 Gbit/s.

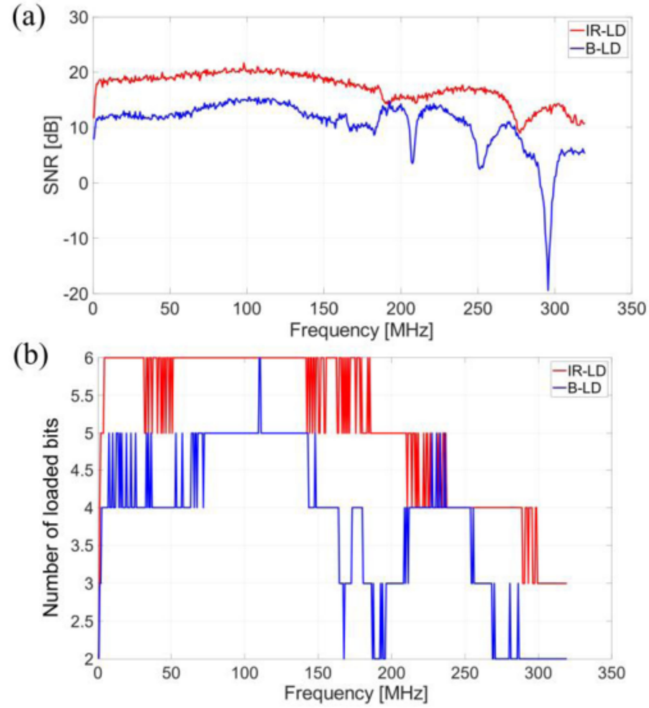

Fig. 8. (a) SNR and (b) Adaptive bit-loading over the bandwidth for blue and IR channels measured from side-emissive fiber.

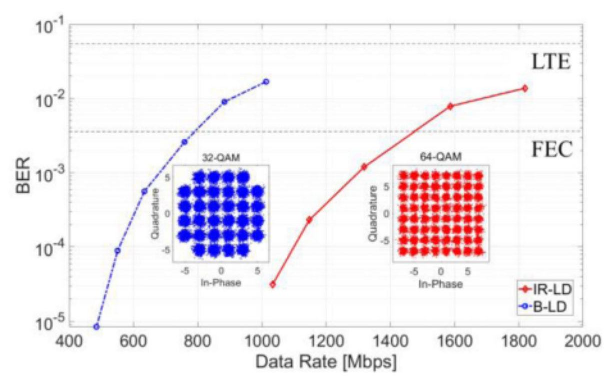

Fig. 9. BER versus data rate including highest QAM constellation symbols achieved in IR (IR-LD) and blue (B-LD) LDs for side-emissive fiber LiFi system.

V. Conclusion

We have demonstrated high speed advanced LiFi systems using a dual wavelength laser-based SMD white light source. A blue LD with a peak wavelength of about 450 nm and an IR LD with a peak wavelength of about 850 nm were integrated into single SMD packaged light source within the Tx. The blue and IR LDs provided 10 Gbit/s and 16 Gbit/s transmission, respectively, below the LTE target, for a combined data rate of 26 Gbit/s over a distance of 3 m. The lower data rate of the blue LD resulted from the lower SNR due to impedance mismatch and from the lower responsivity of Si-based PD in the blue wavelength range.

We reported the first compact laser-based LiFi system using side-emissive fiber as the transmitter, achieving a combined data rate of 2.8 Gbit/s below the LTE limit. This novel LiFi system with the side-emissive fiber is expected to meet the demand of dual function applications including decorative ambient lighting with highly flexible design as well as a high-speed transmitter in a communication link.

References

[1] D. Liang and J. E. Bowers, "Recent progress in lasers on silicon," *Nature Photon.*, vol. 4, no. 8, pp. 511–517, Aug. 2010, doi: 10.1038/nphoton.2010.167.

[2] A. Liu, D. Bimberg, J. A. Lott, and P. Wolf, "Vertical-cavity surface-emitting lasers for data communication and sensing," *Photon. Res.*, vol. 7, no. 2, pp. 121–136, Feb. 2019, doi: 10.1364/PRJ.7.000121.

[3] F. Blais, "Review of 20 years of range sensor development," *J. Electron. Imag.*, vol. 13, no. 1, pp. 231–243, Jan. 2004, doi: 10.1117/1.1631921.

[4] H. Moench *et al.*, "VCSELs in short-pulse operation for time-of-flight applications," vol. 10552, Feb. 2018, Art. no. 105520G, doi: 10.1117/12.2288172.

[5] I. Ichimura, F. Maeda, K. Osato, K. Yamamoto, and Y. Kasami, "Optical disk recording using a GaN blue-violet laser diode," *Jpn. J. Appl. Phys.*, vol. 39, no. 2B, pp. 937–942, Feb. 2000, doi: 10.1143/JJAP.39.937.

[6] L. Y. Kuritzky and J. S. Speck, "Lighting for the 21st century with laser diodes based on non-basal plane orientations of GaN," *MRS Commun*, vol. 5, no. 3, pp. 1–11, 2015, doi: 10.1557/mrc.2015.53.

[7] S.-Y. Tu, H. Y. Lin, and T.-X. Lee, "vol. 62.3: Invited paper: Speckle contrast reduction in a Blue-LD pumped micro-vibrated-reflective phosphor paper for lighting source applications," *SID Symp. Dig. Tech. Pap.*, vol. 46, no. 1, pp. 923–926, Jun. 2015, doi: 10.1002/SDTP.10404.

[8] H.-A. Chen, J.-W. Pan, and Z.-P. Yang, "Speckle reduction using deformable mirrors with diffusers in a laser pico-projector," *Opt. Exp.*, vol. 25, no. 15, pp. 18140–18151, Jul. 2017, doi: 10.1364/OE.25.018140.

[9] M. Cantore, N. Pfaff, R. M. Farrell, J. S. Speck, S. Nakamura, and S. P. DenBaars, "High luminous flux from single crystal phosphor-converted laser-based white lighting system," *Opt. Exp.*, vol. 24, no. 2, Jan. 2016, Art. no. A215, doi: 10.1364/OE.24.00A215.

[10] J. J. Wierer, J. Y. Tsao, and D. S. Sizov, "Comparison between blue lasers and light-emitting diodes for future solid-state lighting," *Laser Photon. Rev.*, vol. 7, no. 6, pp. 963–993, Nov. 2013, doi: 10.1002/lpor.201300048.

[11] J. J. Wierer and J. Y. Tsao, "Advantages of III-nitride laser diodes in Solid-State lighting," *Phys. status solidi*, vol. 212, no. 5, pp. 980–985, May 2015, doi: 10.1002/PSSA.201431700.

[12] J. Y. Tsao *et al.*, "Toward smart and ultra-efficient solid-state lighting," *Adv. Opt. Mater.*, vol. 2, no. 9, pp. 809–836, Sep. 2014, doi: 10.1002/adom.201400131.

[13] H. Haas, "LiFi is a paradigm-shifting 5G technology," *Rev. Phys.*, vol. 3, pp. 26–31, Nov. 2018, doi: 10.1016/j.revip.2017.10.001.

[14] P. J. Winzer and D. T. Neilson, "From scaling disparities to integrated parallelism: A decathlon for a decade," *J. Lightw. Technol.*, vol. 35, no. 5, pp. 1099–1115, Mar. 2017, doi: 10.1109/JLT.2017.2662082.

[15] T. Cogalan and H. Haas, "Why would 5G need optical wireless communications?" in *Proc. IEEE Int. Symp. Pers. Indoor Mob. Radio Commun.*, Montreal, QC, Canada, 2018, pp. 1–6, doi: 10.1109/PIMRC.2017.8292749.

[16] H. Haas, "LiFi: Conceptions, misconceptions and opportunities," in *Proc. IEEE Photon. Conf.*, Waikoloa, HI, USA, 2016, pp. 680–681, doi: 10.1109/IPCon.2016.7831279.

[17] M. S. Islim *et al.*, "The impact of solar irradiance on visible light communications," *J. Lightw. Technol.*, vol. 36, no. 12, pp. 1–1, 2018, doi: 10.1109/JLT.2018.2813396.

[18] R. X. G. Ferreira *et al.*, "High bandwidth gan-Based Micro-leds for Multi-Gb/s visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 19, pp. 2023–2026, Oct. 2016, doi: 10.1109/LPT.2016.2581318.

[19] C. Shen *et al.*, "High-speed 405-nm superluminescent diode (SLD) with 807-MHz modulation bandwidth," *Opt. Exp.*, vol. 24, no. 18, Sep. 2016, Art. no. 20281, doi: 10.1364/OE.24.020281.

[20] M. S. Islim *et al.*, "Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED," *Photon. Res*, vol. 5, no. 2, Apr. 2017, Art. no. A35, doi: 10.1364/PRJ.5.000A35.

[21] A. Rashidi *et al.*, "High-speed nonpolar InGaN/GaN LEDs for visible-light communication," *IEEE Photon. Technol. Lett.*, vol. 29, no. 4, pp. 381–384, Feb. 2017, doi: 10.1109/LPT.2017.2650681.

[22] S. Watson *et al.*, "Visible light communications using a directly modulated 422 nm GaN laser diode," *Opt. Lett.*, vol. 38, no. 19, Oct. 2013, Art. no. 3792, doi: 10.1364/OL.38.003792.

[23] C. Lee *et al.*, "4 Gbps direct modulation of 450 nm GaN laser for high-speed visible light communication," *Opt. Exp.*, vol. 23, no. 12, Jun. 2015, Art. no. 16232, doi: 10.1364/OE.23.016232.

[24] C. Lee *et al.*, "Dynamic characteristics of 410 nm semipolar $(20\bar{2}\bar{1})$ III-nitride laser diodes with a modulation bandwidth of over 5 GHz," *Appl. Phys. Lett.*, vol. 109, no. 10, Sep. 2016, Art. no. 101104, doi: 10.1063/1.4962430.

[25] C. Lee *et al.*, "2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting communication system," *Opt. Exp.*, vol. 23, no. 23, Nov. 2015, Art. no. 29779, doi: 10.1364/OE.23.029779.

[26] Y.-C. Chi *et al.*, "Phosphorous diffuser diverged blue laser diode for indoor lighting and communication.," *Sci. Rep.*, vol. 5, Dec. 2015, Art. no. 18690, doi: 10.1038/srep18690.

[27] H. Chun, S. Rajbhandari, D. Tsonev, G. Faulkner, H. Haas, and D. O'Brien, "Visible light communication using laser diode based remote phosphor technique," in *Proc. IEEE Int. Conf. Commun. Workshop*, London, UK, 2015, pp. 1392–1397, doi: 10.1109/ICCW.2015.7247373.

[28] Y.-C. Chi, D.-H. Hsieh, C.-T. Tsai, H.-Y. Chen, H.-C. Kuo, and G.-R. Lin, "450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM," *Opt. Exp.*, vol. 23, no. 10, May 2015, Art. no. 13051, doi: 10.1364/OE.23.013051.

[29] B. Janjua *et al.*, "Going beyond 4 Gbps data rate by employing RGB laser diodes for visible light communication," *Opt. Exp.*, vol. 23, no. 14, Jul. 2015, Art. no. 18746, doi: 10.1364/OE.23.018746.

[30] C.-Y. Su *et al.*, "Color-Converting violet laser diode with an ultrafast BEHP-PPV + MEH-PPV polymer blend for high-speed white lighting data link," *ACS Appl. Electron. Mater.*, vol. 2, no. 9, pp. 3017–3027, Sep. 2020, doi: 10.1021/ACSAELM.0C00619.

[31] C. Lee *et al.*, "Advanced lifi technology: Laser light," in *Light-Emitting Devices, Materials, and Applications XXIV*, Feb. 2020, vol. 11302, pp. 38, doi: 10.1117/12.2537420.

[32] M. D. Soltani *et al.*, "Safety analysis for laser-based optical wireless communications: A tutorial," , Feb. 2021, Accessed: Jul. 31, 2021. [Online]. Available: https://arxiv.org/abs/2102.08707v3

[33] "SLD laser technology and applications." , Accessed: Jan. 30, 2020. [Online]. Available: https://www.displaydaily.com/article/display-daily/sld-laser-technology-and-applications

[34] E. Xie *et al.*, "High-Speed visible light communication based on a III-Nitride series-biased Micro-LED array," *J. Lightw. Technol.*, vol. 37, no. 4, pp. 1180–1186, Feb. 2019, doi: 10.1109/JLT.2018.2889380.

[35] "Forward error correction for high bit-rate DWDM submarine systems," 2004. Accessed: Jan. 30, 2020. [Online]. Available: https://www.itu.int/rec/T-REC-G.975.1-200402-I/en

[36] B. P. Smith, A. Farhood, A. Hunt, F. R. Kschischang, and J. Lodge, "Staircase codes: FEC for 100 Gb/s OTN," *J. Lightw. Technol.*, vol. 30, no. 1. pp. 110–117, 2012, doi: 10.1109/JLT.2011.2175479.

[37] L. M. Zhang and F. R. Kschischang, "Staircase codes with 6% to 33% overhead," *J. Lightw. Technol.*, vol. 32, no. 10, pp. 1999–2002, May 2014, doi: 10.1109/JLT.2014.2316732.

[38] A. Alvarado, E. Agrell, D. Lavery, R. Maher, and P. Bayvel, "Replacing the soft-decision FEC limit paradigm in the design of optical communication systems," *J. Light. Technol.*, vol. 33, no. 20, pp. 4338–4352, Oct. 2015, doi: 10.1109/JLT.2015.2450537.

Changmin Lee received the Ph.D. degree in materials emphasizing photonics from the University of California, Santa Barbara (UCSB), CA, USA, in 2017. During his Ph.D., he pioneered on the development of laser based visible light communication and LiFi. He is currently a Senior Engineer with Advanced Development R&D Group, Kyocera SLD Laser, Inc. He particularly focused on studying about semi-polar III-nitride laser diodes for high speed performance. He has coauthored 37 conference and journal papers related to diode lasers, optoelectronics, and LiFi.

Mohamed Sufyan Islim (Member,IEEE) received the M.Sc. degree in signal processing and communications and the Ph.D. degree in digital communications from The University of Edinburgh, Edinburgh, U.K., in 2014 and 2019, respectively. He is currently a Postdoctoral Research Associate with the LiFi Research and Development Centre, University of Strathclyde. He has coauthored 14 conference papers, 17 journal papers, two book chapters and two patents. His main research interests include optical OFDM, LiFi, and optical wireless communications. In addition, he was the recipient of the IEEE communications chapter prize for the best M.Sc. project in 2014.

Sovan Das received the B.E. degree in telecommunication engineering from the PES Institute of Technology, Bangalore, India, in 2017. He is currently working toward the Ph.D. degree in optical wireless communication with the University of Edinburgh. He is also currently working as a Development Engineer with the LiFi Research and Development Centre, University of Strathclyde, U.K. His primary research interests include photovoltaics as FSO receivers, LiFi, optical wireless communications and autonomous aerial robotics.

Adrian Sparks biography not available at the time of publication.

Stefan Videv received the B.Sc. degree in electrical engineering and computer science and the M.Sc. degree in communications, systems and electronics from Jacobs University, Bremen, Germany, in 2007 and 2009, respectively. He received the Ph.D. from the University of Edinburgh, Edinburgh, U.K., in 2013 for his thesis titled “Techniques for Green Radio Cellular Communications.” He is the Director of Engineering for the LiFi Research and Development Centre. As the Director of Engineering, Stefan leads industry engagement, all prototyping and development work, as well as driving the technology roadmap continued renewal and implementation. He has coauthored mored than 60 conference and journal papers as well as more than ten patents. His research interests include high performance energy efficient wireless networking, rapid prototyping and machine learning.

Paul Rudy received undergraduate physics the B.S. degree from Duke University, the Doctoral degree in physics from the University of Rochester, and the MBA degree from USC. Dr. Rudy is the Co-Founder, CMO, and SVP of Business Development with KYOCERA SLD Laser, a Leader in the commercialization of GaN based laser light sources. Paul has worked in the field of photonics for more than 20 years, and has extensive experience in photonics general management, technical product marketing, business development, and product management. He has more than 75 patents and has authored more than 100 technical marketing papers and conference talks. Prior to KSLD, Paul worked as the Director of Marketing with Coherent, the world’s largest commercial laser manufacturer, specifically working to commercialize laser devices based on gallium arsenide.

Binith Shah biography not available at the time of publication.

Melvin McLaurin received the Ph.D. degree in materials from the University of California, Santa Barbara, CA, USA, in 2007 for his work on the growth of non-polar and semi-polar orientations of GaN with molecular beam epitaxy. He is currently the Senior Principal Scientist with Kyocera SLD Laser where he leads the Advanced Development Research and Development Group. He has coauthored 15 conference and journal papers and more than 140 patents. His primary research interests include development of semi-polar and non-polar GaN edge emitting laser epitaxial designs and novel edge emitting laser chip fabrication process development. In 1989, he was the recipient of the McDonald’s Certificate of Acheesement for being an ‘”A” – “B” Student’.

Harald Haas (Fellow, IEEE) FREng FRSE FIEEE FIET received the Ph.D. degree from The University of Edinburgh, Edinburgh, U.K., in 2001. He is a Distinguished Professor of Mobile Communications with the University of Strathclyde and the Director of the LiFi Research and Development Centre. He also set-up and Co-Founded pureLiFi Ltd which it currently is a Chief Scientific Officer. He has authored more than 550 conference and journal papers. Haas’ main research interests include optical wireless communications, hybrid optical wireless and RF communications, spatial modulation, and interference coordination in wireless networks. His team invented spatial modulation. He introduced LiFi to the public at an invited TED Global talk in 2011. LiFi was listed among the 50 best inventions in TIME Magazine in 2011. He gave a second TED Global lecture in 2015 on the use of solar cells as LiFi data detectors and energy harvesters. In 2016, he was the recipient of the Outstanding Achievement Award from the International Solid State Lighting Alliance. In 2019, he was the recipient of the IEEE Vehicular Society James Evans Avant Garde Award. Haas was elected a Fellow of the Royal Society of Edinburgh (RSE) in 2017. In the same year he was the recipient of the Royal Society Wolfson Research Merit Award and was elevated to IEEE Fellow. In 2018, he was the recipient of the three-year EPSRC Established Career Fellowship extension and was elected Fellow of the IET. Haas was elected Fellow of the Royal Academy of Engineering (FREng) in 2019.

James Raring received the Bachelors of Science degree in materials engineering from California Polytechnique State University, San Luis Obispo, CA, USA, in 2001, and the Ph.D. degree in materials science from the University of California, Santa Barbara, CA, USA, in 2006. While earning the Ph.D. degree and is as a Postdoctoral Researcher with the University of California, Santa Barbara, CA, USA, Dr. Raring developed an advanced photonic integration platform based on indium phosphide to demonstrate the world’s first single-chip 40 Gb/s optical transceiver. Dr. Raring has more than 200 patents and applications and has authored or coauthored more than 100 technical papers and conference presentations. As the Co-Founder, President, and CEO of Kyocera SLD Laser, Dr. James Raring leads the organization in the commercialization of LaserLight products based on KSLD’s breakthrough gallium nitride laser diode technology. Previously, Dr. Raring was the Vice President of Laser Engineering and a founding employee with Soraa Inc. where he played a key role in the company’s launch in 2008. Prior to his role with Soraa Inc, Dr. Raring was a Senior Member of Technical Staff with Sandia National Laboratories in the Photonic Integrated Circuit (PIC) Group.