This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology

VCSEL Array-based Gigabit Free-space Optical Femtocell Communication

Spencer Liverman, Hayden Bialek, Arun Natarajan, and Alan X. Wang

School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, United States, 97331

***Abstract*— We present an indoor free-space optical communication system to augment traditional short-range radio frequency wireless links. In this system, we integrated a high-frequency, high-current laser driver with an 850 nm wavelength, 500 mW vertical cavity surface emitting laser (VCSEL) array to transmit high speed optical signals with a large spatial coverage. The large current-bandwidth capability of the laser driver is enabled by a distributed current driver design utilizing three enhanced-mode pseudomorphic high electron mobility transistors. At the optical receiver end, a high-sensitivity avalanche photodiode is used to achieve high speed optical signal detection without any light concentrating optical device and is tolerant to angular deviation up to 27°. The communication link described in this paper forms an optical femtocell with an area of 100 cm^2 at a distance of three meters from the transmitter. A bit error rate of less than 10^{-4} is achieved throughout the optical femtocell in a normal in-door environment. On-off-keying and four-level pulse amplitude modulation schemes are both implemented with 1.25 Gb/s and 2 Gb/s data rate respectively, using the hardware described in this paper. Additionally, the overall performance of this free-space optical link is evaluated in terms of viewing angle, distance range, and bit error rate.**

***Index Terms*—Free-space optical communication, optical receivers, optical transmitters, vertical cavity surface emitting laser array**

I. Introduction

The number of wirelessly connected devices, such as laptops and cellphones, has been exponentially growing worldwide. With this growth, the demand for wireless bandwidth has also increased at an exponential rate. For the past two decades, radio frequency (RF) technologies, especially WiFi, have dominated the wireless communication market with data rates steadily improving over the past two decades. In 1997, the first 802.11 WiFi standard was introduced with a data rate of only 2Mb/s. However, ten years later, the 802.11n standard was rolled out with a maximum data rate of 600Mb/s [1]. Although great strides have been made in using RF spectral resources more efficiently, data rates are currently reaching theoretical limits. This is due to the limited bandwidth available in the narrow unlicensed RF bands, in which WiFi systems must operate. Crowding in the RF band has resulted in several efforts to utilize optical technologies with frequencies much higher in the electromagnetic spectrum. As comparison, optical frequencies are unregulated and inherently line-of-sight (LOS) [2]. The LOS nature of optical frequencies allows designers to pack wireless access points (AP) more densely and introduces a physical layer of protection for enhanced security. Optical frequencies tend to be highly directional and do not penetrate through walls, which means that they cannot be intercepted unless the eavesdropper is located directly between the transmitter and intended receiver.

Although the potential for free-space optical (FSO) wireless links is clear, there is considerable debate over which type of light sources should be used. High power light emitting diodes (LEDs) have been suggested as a possible dual-purpose solution, in which the transmitter would serve as both a data link and luminary [3-6]. Other variations on this design have also been proposed using red-green-blue (RGB) LED luminaries [7-9]. Utilizing RGB LEDs presents an opportunity for multichannel operation through wavelength division multiplexing (WDM); however, WDM FSO systems necessitate three independent receivers, each requiring optical filtering. Although coupling illumination and wireless links may initially seem like an attractive solution, there are several distinct disadvantages. First, any reduction in the illumination of a working space would result in a direct reduction in the signal-to-noise ratio (SNR) in that space. Second, the solid angle of the FSO transmitter/luminary is quite large, thereby reducing the power density of the transmitted signal to the receiver. Most importantly, the high-power LED devices currently being used for illumination have large terminal capacitances and long free carrier lifetime, which severely limit their modulation bandwidth.

In contrast, using independent light sources in FSO systems allows designers to leverage state-of-the-art technologies developed for the photonics industry. For example, vertical cavity surface emitting laser (VCSEL) diodes have been widely used in high-speed fiber-optic system for data centers [10]. The adoption of VCSELs in FSO communication links could result in an unprecedented boost in wireless bandwidth [11]. However, the limited output power of a single VCSEL diode limits its potential in free-space applications.

The vertical cavity configuration used in VCSEL diodes is well suited for fabricating densely packed two-dimensional (2D) arrays. Large 2D VCSEL arrays have been fabricated onto a single substrate with the total output power of the array scaling linearly with the number of array elements [12]. The

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology

development of large 2D VCSEL arrays has dramatically expanded the number of potential VCSEL applications. The output power of a single mode VCSEL diode is generally limited to less than 10mW; however, VCSEL arrays outputting more than 3W of continuous wave (CW) power have been demonstrated [13]. These high power VCSEL arrays have become an attractive option for applications demanding intense levels of optical illumination due to their high efficiency and scalability. One potential application for this technology is LiDAR [14]. LiDAR systems require short, high intensity bursts of light, which can be produced by VCSEL arrays. High output powers and large bandwidths also make these VCSEL arrays an attractive option of FSO communication systems

In the design of indoor FSO communication networks, there is a fundamental tradeoff between bandwidth and output power. With the newest generation of WiFi routers approaching Gb/s data rates, it is imperative that FSO links demonstrate comparable bandwidths. However, user mobility is also a primary concern in any FSO wireless networks. The maximum diameter of a FSO cell is directly related to the maximum output power of a given optical transmitter and the sensitivity of the receiver. Previous work has shown that for a realistic office environment in which the distance between the ceiling and a desk is roughly three meters, a FSO transmitter broadcasting to a femtocell with a 60cm diameter will require an output power greater than 400mW [15]. Although deploying several densely packed optical femtocells in a working environment is beneficial to increase the overall bandwidth, this configuration also creates a problem for mobility. To overcome this issue, hybrid FSO and RF networks have been proposed wherein the downlink is provided by optical transmitters, while the uplink and handoff mechanisms are handled through WiFi links [16-21]. This hybrid architecture provides users with virtually undivided access to bandwidth resources in a given optical femtocell while also providing the flexibility to move freely between cells without interruption to their wireless connection.

II. Related Work

Traditional optical communication systems typically use multichannel ultra-high bandwidth transmitters with each channel being supported by a single VCSEL. The goal of these systems is not to increase the overall output power, but instead to increase the number of independent transmitters on a single chip. Linear VCSEL arrays supporting up to 12 channels transmitting 10Gb/s per channel have been demonstrated [22, 23]. These linear arrays also create an opportunity for WDM due to the tunability of individual VCSEL wavelengths. Other configurations, such as circular VCSEL arrays, have been studied to support multichannel transmission in multicore fiber-optic bundles [24]. In addition to multichannel systems, coupling of WDM transmitters into a single optical fiber using arrayed waveguide grating (AWG) have also been demonstrated with up to four WDM VCSEL transmitters [25]. Each of the examples listed above utilizes a simple non-return to zero on-off-keying (NRZ OOK) modulation scheme. In systems where the channel bandwidth is large, NRZ OOK schemes are highly advantageous because they allow designers to use non-linear saturating amplifiers that improve performance when the channel SNR is low. However, when the modulation bandwidth in a channel becomes the dominate limiting factor and SNR is not a concern, higher order modulation schemes become an attractive method for increasing data rates. Four level pulse amplitude modulation (PAM4) schemes double data rate throughputs when compared to NRZ OOK. For short range applications, an 8-channel VCSEL array transmitter was demonstrated with each channel producing a 25Gbaud PAM4 signal, which resulted in a total aggregated data rate of 400Gb/s [26, 27]. In addition to PAM4, schemes involving for phase modulation have also been investigated. Quadrature phase shift keying (QPSK) has been shown to produce symbols at a rate of 10Gbaud when paired with an injection locked VCSEL array [28]. Amplitude and phase modulations have also been combined in quadrature amplitude modulation (QAM) schemes, which are often implemented with orthogonal frequency division multiplexing (OFDM) to improve channel linearity [29]. While higher order modulation formats might work well in fiber-optic or point-to-point free-space applications, the significant reduction in SNR make implementing such schemes difficult in a FSO femtocell architecture.

Efforts related to producing high quality VCSEL arrays for FSO communication systems have resulted in investigating coherently coupled VCSEL arrays. Coherently coupled VCSEL arrays produce in-phase photons and exhibit properties that are useful in FSO applications such a lens-free beam forming [30]. Additionally, the linewidth of a VCSEL array can be significantly reduced through coherent coupling. This reduction in the linewidth corresponds to a reduction in the divergent angle of the transmitted beam. A three-element coherently coupled VCSEL array with a divergent angle of 4° and a 5×5 element array with a divergent angle of 1.61° have been demonstrated [31, 32]. However, the power output of these devices was limited to just 4mW and 10.25mW respectively. Although the characteristics of coherently coupled VCSEL arrays appear promising, their utility will remain limited until output power can be increased.

Much like the VCSEL arrays themselves, efforts to design appropriate VCSEL array drivers have mostly been focused on fiber-optic applications. One popular format is a four-channel driver based on either 130 nm or 65nm CMOS technology providing 10Gb/s and 20mA per channel [33, 34]. While 20mA might be sufficient for driving a single VCSEL, it is certainly insufficient for driving a VCSEL array. Various other improvements on the 10Gb/s driver format have also been investigated, such as adaptive optical power control and a 12-channel radiation hardened version [35, 36]. More recently, SiGe drivers have been shown to extend data rates to 40Gb/s per channel when paired with a single 1.3µm VCSEL diode [37]. While these driver designs are well suited to the single diode VCSEL transmitters that are currently used in the telecom industry, they cannot provide the electrical current that is required to drive the high power VCSEL arrays that will be used in the next generation FSO links.

III. Free-space Optical Link Design

In this section, an indoor FSO communication link is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology

described in detail. This link consists of a VCSEL array-based transmitter and an optical receiver. The purpose of this link is to create an optical femtocell with an area of approximately 100 cm^2 that will provide a Gb/s data rate. The femtocell diameter size was chosen to balance the demand for high speed connections with the need for moderate mobility. Mobility in this system can be further increased by packing several optical femtocells into a larger working area. Although there are several aspects of this system that require thorough consideration, such as the handoff mechanism between FSO APs, this work will be limited to the design and evaluation of a single optical femtocell consisting of a FSO transmitter and receiver pair.

A. *VCSEL Array Transmitter Design*

In general, commercially available VCSEL arrays are wired together in parallel, which implies that the total amount of current consumed by the device is equal to the current consumed by one device multiplied by the number of devices. In the design of our VCSEL array driver, the goal is to maximize the power output of the transmitter. However, as the current consumption of the transmitter increases, it becomes increasingly difficult to design a driver that can deliver high currents at Gb/s speeds. From our previous research, we have found that robust indoor optical links can be established using light sources that output a few hundred milliwatts. After evaluation, we selected a 60 element 500mW VCSEL array from Vixar operating at the wavelength of 850nm. The 850nm wavelength was chosen because it is invisible to the human eye and matches the peak responsivity of inexpensive and widely available silicon photodetectors. This device meets our requirements for bandwidth and power; however, it also necessitates a driver that can deliver up to 1A of current. Commercially available laser drivers from Texas Interments and Analog Devices operating at Gb/s speeds are currently only offered with maximum current ratings of a few hundred milliamps. Therefore, a custom laser driver design is required. Figure 1 (a) shows the optical image of the Vixar VCSEL array and Figure 1 (b) shows the measured IV curve of that device.

The design of the laser driver needs to strike a balance between the size of the transistors used in the driver and the bandwidth of those devices. To the best of our knowledge, there are no commercially available transistors that are capable of sourcing 1A of current with a bandwidth ranging from DC to 1GHz. As a result, we distributed the current load between several transistors in parallel. This distributed design allows us to scale up the total current drawn through the VCSEL array without sacrificing bandwidth. The red dashed lines in Figure 1(b) indicate the drive current that can be sourced using one or more branches of the distributed current driver deigned for the VCSEL array. This driver design implements three parallel current paths that are then combine before passing through the VCSEL array. Each current path is capable of sourcing 300mA, so it is therefore necessary to use all three branches when driving the array. The VCSEL array drive current is split across multiple transistors to ensure that the capacitance of each driving transistor is not excessively large. Additionally, each of the three driving transistors will be paired with a smaller buffer amplifier to reduce the capacitive load at the input of the driving circuit.

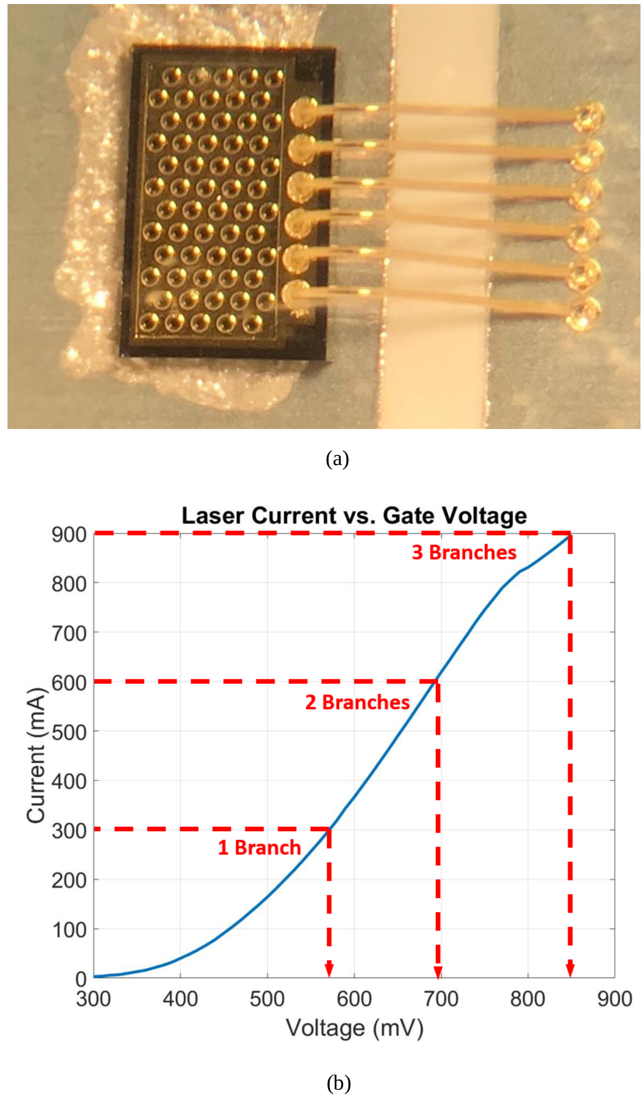


Fig. 1. 850nm VCSEL array light source – (a) image of the 60-element VCSEL array device, (b) VCSEL IV curve showing various regions of operation

Enhanced mode pseudomorphic high electron mobility transistors (E-pHEMT) have been widely adopted for wireless driver applications due to their high linearity, high drain currents, and large bandwidths. However, E-pHEMTs are still limited by parasitic gate capacitance. Driving a large capacitance at high speeds becomes problematic because it is more difficult to match the impedance of a large capacitor to the 50Ω signal source at high frequencies. This is because the capacitor will present a small impedance in parallel with any matching elements that are used, which results in a total impedance of less than 50Ω. In RF designs, this problem is solved using a narrow band resonate matching network that can be tuned to a desired transmission frequency. However, this technique eliminates the possibility of using lower frequency components and is therefore unsuitable for OOK modulation schemes. The goal for this design is to achieve a

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology

wideband match that extends from DC to the highest frequency component possible. To accomplish this goal, we restricted ourselves to an E-pHEMT with a smaller gate capacitance and placed a 50Ω resistor between the transistor gate and ground. After a transistor with an appropriate bandwidth was selected, the current requirement for the VCSEL array driver was met by placing three of the selected transistors in parallel. Table 1 summarizes the capacitance and maximum drain currents for three of the E-pHEMTs devices that were considered.

TABLE 1: E-PHEMT DEVICE SUMMARY

Device	Capacitance @ 1GHz	Maximum Drain Current
ATF- 511P8	15.02 pF	1000mA
ATF-531P8	3.82 pF	300mA
ATF-55143	0.85 pF	100mA

To evaluate the bandwidth of each of these devices listed above, the S11 parameters for each transistor were simulated using Advanced Design System (ADS) simulation software. The results for those simulations are shown below in Figure 2. For the purpose of evaluating each transistor, the useable device bandwidth was defined as the -10dB crossing point, at which point 10% of the total power is reflected. Above the -10dB cross point signal strength declines rapidly. The goal set forth in this paper is to achieve a Gb/s free-space link, which requires a modulation bandwidth of 500MHz using an OOK modulation scheme. It is clear from Figure 2 that the most appropriate transistor is ATF-531P8 with a modulation bandwidth of 590MHz and a maximum drain current of 300mA. A VCSEL array driver employing three ATF-531P8 transistors in parallel could achieve a current swing of 900mA, thereby maximizing the modulation depth of the 500mW Vixar array.

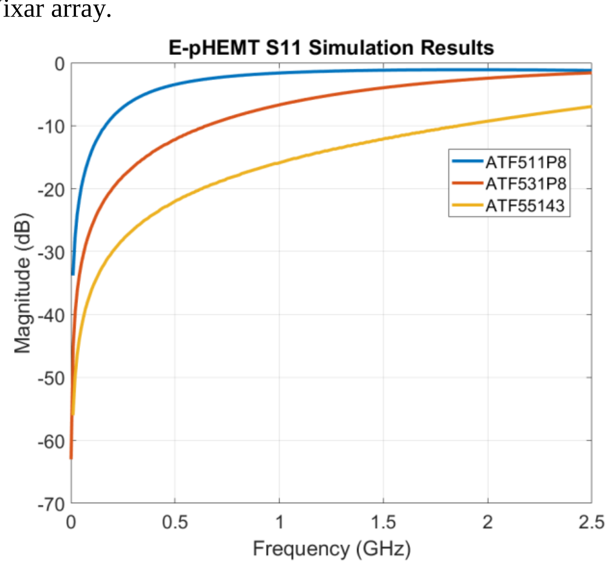
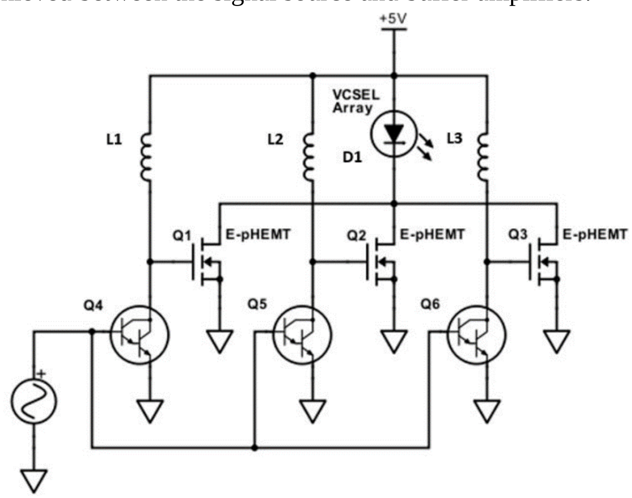
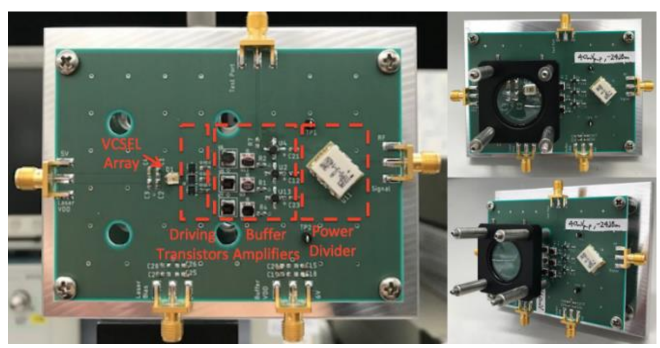


Fig. 2. S11 simulations of E-pHEMT devices as a function of the modulation frequency

Another aspect related to the transmitter design that needs to be considered is the combined gate capacitance between the three driving transistors. If each of the three ATF-531P8 transistors is not buffered, their combined gate capacitance will add linearly, creating a severe bandwidth limitation. To avoid this problem each of the driving transistor was paired with a smaller buffer amplifier. The primary requirement for the buffer in this design is that the amplifier must be well matched to 50Ω. Additionally, the bandwidth of the buffer amplifier must match or exceed that of the driving transistor. The buffers that we selected for this design are Darlington pair amplifiers. A three-way power divider was also placed at the input of the laser driver circuit to ensure that a 50Ω match was achieved between the signal source and buffer amplifiers.



(a)



(b)

Fig. 3. VCSEL array transmitter – (a) schematic of distributed current VCSEL array driver, (b) fabricated transmitter PCB with and without a collimation lens mounted

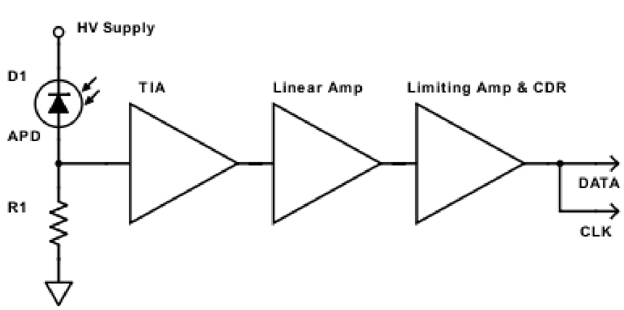
In summary, our VCSEL array driver design consists of three current branches with each current branch driven by a 300mA ATF-531P8 E-pHEMT transistor. At the input of each E-pHEMT transistor a passive RF matching network is designed to ensure that there is a 50Ω impedance match from DC to 1GHz. Each ATF-531P8 transistor is buffered by a Darlington pair amplifier to reduce the overall capacitance seen at the input of the driver. A 50Ω three-way power divider is also placed at the driver's input to eliminate any impedance mismatch caused by the splitting of the input signal between the three current branches. A schematic showing the design described above is shown in Figure 3(a). A printed circuit board (PCB) was designed and fabricated for the FSO transmitter. The transmitter PCB also has four large holes drilled in it so that a LA1951-B collimating lens from Thor

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology

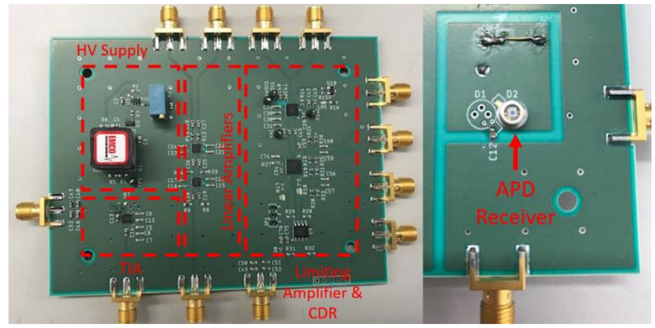
Labs, with a focal length of 25.4mm, can be easily mounted in front of the VCSEL array. The lens is mounted approximately 30mm away from the VCSEL array in an effort to significantly reduce the divergence of the beam without completely collimating it. The VCSEL array device is a collection of 60 individual transmitters, which means that it is impossible to collimate the entire array with a signal lens. Bring the array to a focus simply images the array, resulting in 60 individual points of light. Instead, we chose to slightly de-focus the collimation lens, resulting in the light from each of the 60 VCSEL devices mixing together into a single rectangular shaped beam. Additionally, de-focusing the beam slightly allows us to increase the total area covered by the transmitter down range, resulting in beam with an approximate diameter of 120mm at a distance of 3m. Figure 3(b) shows the fabricated transmitter PCB with and without the collimating lens attached.

B. *Free-space Optical Link Receiver*

The effective design of a high sensitivity optical receiver is critical to the success of any FSO optical network. Optical power densities on the receiving end of a free-space channel are always a concern when designing optical links, so we have chosen to use avalanche photodiodes (APDs) in our design. APDs are advantageous in applications that require high sensitivity detectors due to their large intrinsic gain. The analog front end of our receiver will consist of a standard data path including a transimpedance amplifier (TIA), linear operational amplifiers (op-amps), and a combine limiting amplifier/clock data recovery (CDR) block. When the initial design for the receiver was created, the exact requirements for amplification on the receiving end were unknown, so the receiver PCB design was left as modular as possible. The receiver PCB was split into three main blocks that are each terminated by a SMA connector. These three blocks can be connected in any order using SMA cables. Block 1 consists of a high voltage DC-DC converter that provides a bias voltage to the APD, the APD itself, and a TIA to convert the photocurrent into a voltage. Block 2 consists of two linear op-amps with a total combine gain of 100X. The final block combines the limiting amplifier and the CDR. When connected in series, these functional blocks operate as a highly sensitive optical receiver. However, if the gain in the system is too large, block two can be bypassed to reduce gain. Figure 4(a) shows a schematic of the FSO receiver described above and the fabricated PCB is shown in Figure 4(b).



(a)



(b)

Fig. 4. High-sensitivity optical receiver – (a) block diagram detailing optical receiver data path, (b) optical receiver PCB shown with functional block on the front of the board and an APD mounted to the back of the board

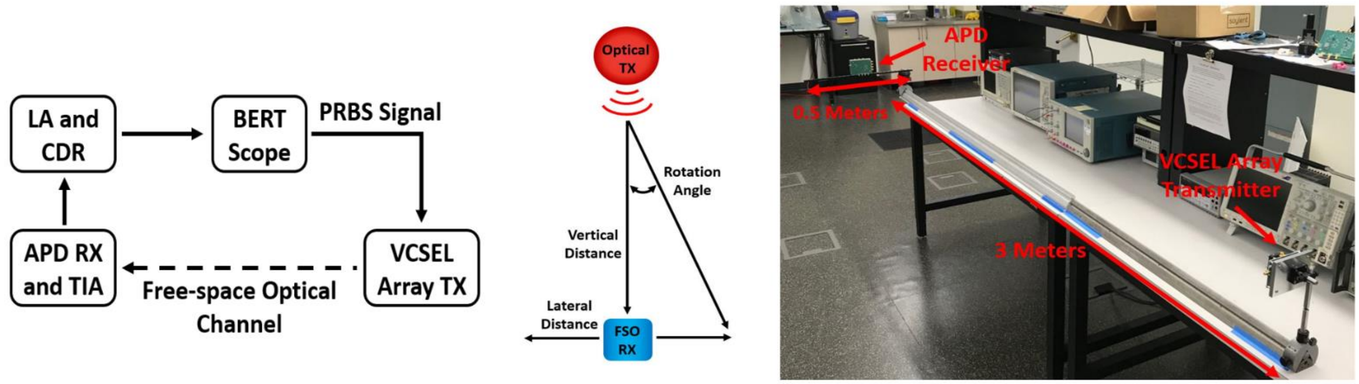
IV. FREE-SPACE OPTICAL LINK EVALUATION

In this section, the FSO transmitter and receiver pair described above are evaluated in terms of bandwidth, range, and angular tolerance. In each evaluation, a bit error rate testing (BERT) scope was used to generate data in the form of a pseudo random bit sequence (PRBS). The PRBS signal was then fed as an input to the VCSEL array FSO transmitter and converted into an optical signal. That signal was then transmitted across the FSO channel. On the other end of the FSO channel, the optical signal was recovered by our receiver and converted back into an electrical signal, which was then passed back to the BERT scope. The BERT scope then compared the recovered signal with the original signal and calculated a bit error rate (BER). A block diagram detailing this process is shown is Figure 5(a).

The VCSEL array transmitter in this system was mounted on a horizontally positioned optical rail. The optical receiver was then mounted to a second 0.5m optical rail that was positioned perpendicular to the first rail at a distance of 3m away from the transmitter. For continuity, positions on the larger rail will be referred to as vertical positions and positions on the smaller rail will be referred to as lateral positions as illustrated in Figure 5(b). Additionally, the receiver was also mounted to a rotational stage, which was used to change the incident angle of the transmitted beam with respect to the receiver PCB. This experimental setup creates three degrees of freedom, which are used to realistically model how a user might move within a FSO femtocell. A photo showing the implementation of this experimental setup is shown in Figure 5(c). In the subsequent system evaluations, the vertical distance will be fixed to 3m to roughly mimic the distance between the ceiling and floor in a standard office environment. Unless otherwise stated, binary OOK modulation symbols are used as the default modulation format.

Although the BER requirements of various data systems can vary greatly, a value of 10^{-4} is used as a benchmark in this paper. When the BER rate in a communications system drops below 10^{-4}, common forward error correction (FEC) codes, such as Reed-Solomon codes, can be applied to the data to dramatically lower the BER. For example, the Reed-Solomon code RS(255, 247) can reduce the BER in a system from 10^{-4} to 10^{-8} with an efficiency of 96.8%. However, if the BER in a

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology



(a) (b) (c)

Fig. 5. FSO channel test configuration – (a) block diagram detailing the components used in the test configuration, (b) diagram showing the FSO test parameters, (c) a photo of the experimental setup showing the 0.5m optical rail mounted orthogonally to the 3m optical rail

system is greater than 10^{-3}, FEC codes will have little or no effect on the system's performance.

A. Lateral Motion Tolerance

Due to the highly directional nature of FSO transmissions, it is necessary to align the optical receiver such that it is located within a cone of light projected from the transmitter. As the solid angle of the transmitted light cone increases, the system becomes more tolerant to lateral movement within the FSO cell. However, if the solid angle of the projected light cone becomes too large, the optical power density within the light cone will drop below the detection threshold and the wireless connection will be lost. This tradeoff between mobility and signal strength is fundamental to all FSO systems and must be balanced to suit the needs of potential users. In our FSO system, the optical transmitter that we have designed maximizes both power output and bandwidth using a 60-element array of high-speed VCSEL didoes. This configuration allows for Gb/s data rates while still providing limited mobility.

Using the experimental setup described above, BER measurements were collected at various lateral positions 3m away from our FSO transmitter and plotted in Figure 6(a). The data rate for those measurements was set to 1.25Gb/s. Applying our BER benchmark of 10^{-4}, we defined the useful light spot diameter to be approximately 11.5cm. Although user mobility is still highly limited in this configuration, the optical spot size is still quite large when compared to LOS FSO communications systems. Eliminating the need for careful optical alignment is a critical step toward producing robust indoor optical links.

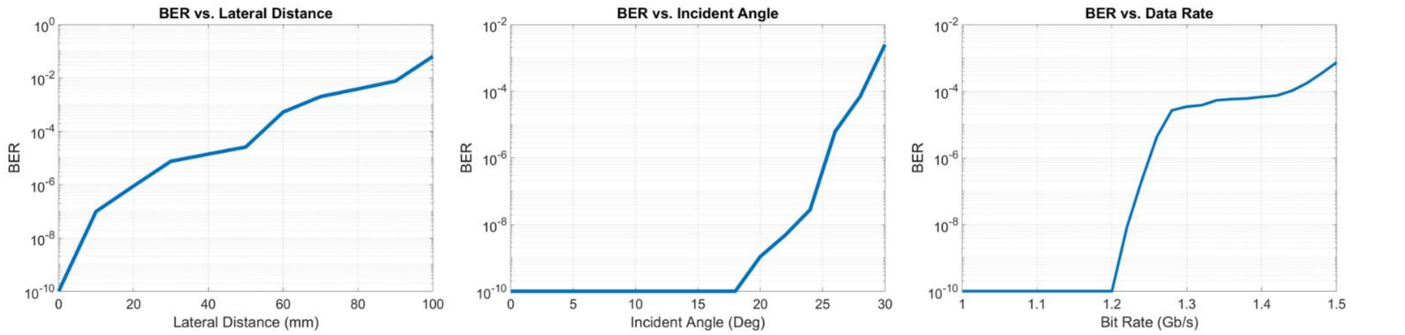
1.25Gb/s optical transmission has been demonstrated using a three-channel red/green/blue WDM LED luminary; however, the transmission distance was limited to just 10cm and was strictly point-to-point LOS with no tolerance for lateral motion [38]. Similarly, high-speed laser transmitters based on single VCSEL devices have been reported [39]. However, with power outputs of <2mW, these transmitters require precise collimation and a receiver side focusing lens to achieve sufficiently high optical power densities. Point-to-point LOS systems are difficult to implement in realistic working environments and are therefore disadvantageous for indoor FSO communications systems. The VCSEL array transmitter presented in this paper does not require careful alignment with an optical receiver and can provide the level of flexibility that is necessary for commercial systems.

B. Angular Motion Tolerance

In addition to variations in lateral positions, it is also important to consider variations in the incident angle of the transmitted beam relative to the optical receiver. As users move through a work space, they will naturally alter the angle of their receiver with respect to a transmitting light source. These variations have a significant impact on the level of received optical power. In Figure 6(b) the relationship between BER and incident angle is plotted for a data rate of 1.25Gb/s at a range of 3m. In the plot the BER remains at a level of 10^{-10} for angles less than 17°. This result is expected because there is no optical component placed in front of the receiving photodiode such as a lens. Therefore, changes in the incident angle have very little effect on the performance of the system. However, the photodiode is packaged in a housing where it is recessed slightly. When the incident angle exceeds 17°, the packaging begins to shadow the photodiode and the BER increases. The angular tolerance in our system could easily be further improved by simply redesigning the photodiode housing so that the diode is flush with the surface of its package.

In our FSO communications system, the lack of optical components concentrating light onto the receiver is an important feature. Optical concentrators such as lenses and parabolic reflectors can be powerful tools when it is necessary to increase power density; however, the penalty for using an optical concentrator is a reduction in the receiver's viewing angle and therefore a reduction in angular tolerance. The reduction in a receiver's viewing angle is directly proportional to the concentration gain factor provided by the concentrating element. In point-to-point FSO systems, a single lens with an arbitrarily large diameter can be used to focus light down to a diffraction limited spot size assuming the transmitted beam is monochromatic. Doing so, however, reduces the viewing angle of the receiver down to a fraction of a degree, necessitating that the receiver be oriented in the exact direction of the transmitter. This configuration is simply not

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JLT.2019.2958733, Journal of Lightwave Technology



(a) (b) (c)

Fig. 6. FSO system BER measurements collected at a distance of 3m – (a) BER as a function of lateral motion, (b) BER as a function incident angle with respect to the optical receiver, (c) BER as a function of data throughput

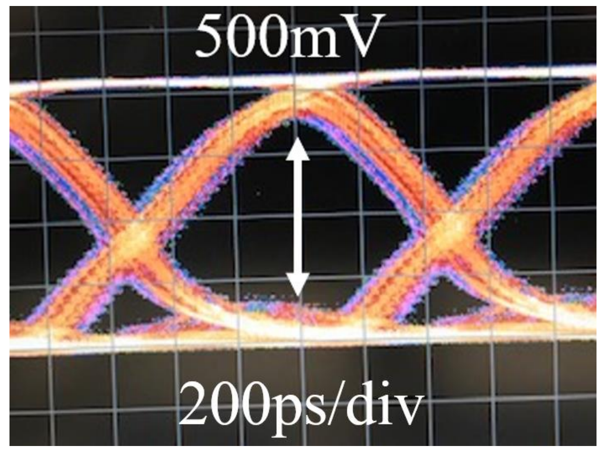
feasible in a scenario in which the exact position and orientation of the transmitter and receiver are not known. Even if it is assumed that such information did exist, each component would require an additional mechanical stage that could align the two halves of the link.

In contrast, our design eliminates these issues by providing 500mW of average output power. On the receiver side, the avalanche gain factor provided by the APD further reduces the need for an optical concentrator. By avoiding the use of a receiver side optical concentrator completely, an angular tolerance of 27° was achieved.

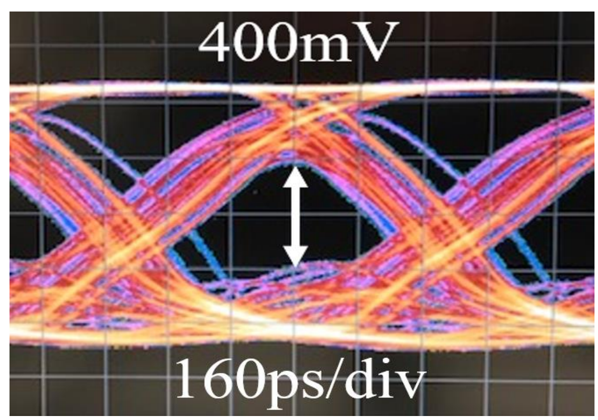
C. Data Throughput Evaluation

Defining the relationship between BER and data rate is critical when evaluating the performance of a communication system. In the two previous evaluations, the data rate was fixed to 1.25Gb/s and the BER rate was measured as a function of spatial parameters. In this evaluation, the receiver is placed 3m away from the transmitter and the BER is measured as a function of data rate. The receiver is also placed on the optical axis and oriented incident normal to the transmitted beam. The results of this evaluation are plotted in Figure 6(c). For data rates less than 1.25Gb/s, the optical transmissions are error free. Between 1.25Gb/s and 1.3Gb/s the BER begins to increase rapidly, but then levels off. A maximum data rate of 1.45Gb/s is achieved while still maintaining a BER below 10^{-4}. Eye diagrams showing recovered optical signals at data rates of 1Gb/s and 1.25Gb/s are shown in Figure 7.

When compared to commercially available single VCSEL diode transmitters, the data rates presented in this paper are highly competitive. For example, Finisar currently markets a 2.5Gb/s VCSEL device with a power output of 2mW. This device is 1.7 times faster than our VCSEL array transmitter but produces 250 times less power. Although there is a slight bandwidth penalty when using a VCSEL array, the increase in power output far exceeds to reduction in bandwidth. From a FSO system design perspective, the VCSEL array device is clearly superior.



(a)



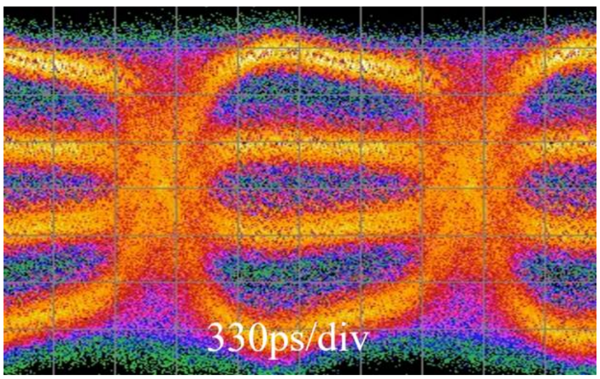
(b)

Fig. 7. Eye diagrams showing FSO signals recovered over a 3m optical channel – (a) 1Gb/s, (b) 1.25Gb/s

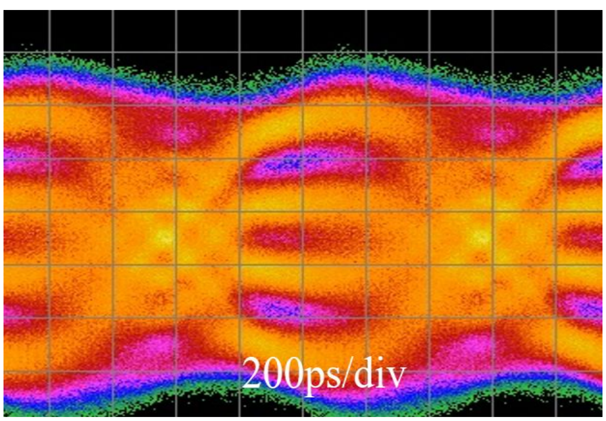
D. PAM4 Data Transmission

In addition to OOK modulation, a higher order PAM4 modulation scheme was also considered. PAM4 signals contain twice as much information as OOK signals but require three times the SNR. Due to the high output power of our VCSEL array transmitter, the SNR of recovered optical signal three meters away from the transmitter still has a sufficiently high SNR to support PAM4 signals. Therefore, a PAM4 modulation scheme might be one way in which bandwidth in our FSO communications system could be increased.

As a proof of concept, PAM4 signals were transmitted across a three-meter free-space channel using the experimental setup described above. The PRBS PAM4 data signals that were used for this demonstration were generated in Matlab and then exported to an arbitrary waveform generator (AWG). The AWG was then used to drive the VCSEL array transmitter. On the receiver end, the recovered PAM4 signals were plotted using the same BERT scope as before. The results of this demonstration are shown in Figure 8(a) and 8(b) at data rates of 1G/s (500Mbaud) and 2Gb/s (1Gbuad) respectively. At a rate of 1Gb/s, each of the four signal levels are clearly distinguishable; however, when the data rate increases to 2Gb/s the signal quality deteriorates significantly. This proof of concept demonstrates that the linearity of our VCSEL array transmitter is adequate for higher order modulation schemes, although more work is required to fully utilize the potential of the PAM4 format.



(a)



(b)

Fig. 8. Eye diagrams showing PAM4 signals recovered over a 3m optical channel – (a) 1Gb/s, (b) 2Gb/s

V. Conclusion

In this paper, we have presented a FSO communication system consisting of a high-power VCSEL array transmitter and a high-sensitivity receiver. Our 850nm VCSEL array transmitter has a maximum throughput of 1.45Gb/s using an OOK modulation scheme and is based on a novel distributed current laser driver design utilizing E-pHEMT transistors. This transmitter delivers 500mW of average optical power and can cover an area of approximately 100cm^2 at a distance of three meters while still maintaining a BER $<10^{-4}$. Our high sensitivity optical receiver does not require light concentrating optical devices and can tolerate angular variations up to 27°. In addition to OOK, a PAM4 modulation scheme was also demonstrated. This FSO communications system offers an effective and scalable solution for increasing bandwidth in indoor optical wireless networks.

Acknowledgment

This work is supported by the National Science Foundation under Grant NSF: EARS 1547450 and the Navy SBIR contract number N6833518C0562.

References

[1] P. Li, "Recent developments in WiFi system and related challenges in power amplifier design," *2012 IEEE 11th International Conference on Solid-State and Integrated Circuit Technology*, Xi'an, 2012, pp. 1-4.

[2] A. T. Hussein, J. M. H. Elmirghani, "Mobile multi-gigabit visible light communication system in realistic indoor environment," *Journal of Lightwave Technology*, vol. 33, pp. 3293–3307, 2015.

[3] M. Z. Afgani, H. Haas, H. Elgala, D. Knipp, "Visible light communication using ofdm," 2nd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities., TRIDENTCOM (2006) 6–134.

[4] H. Al Hajjar, B. Fracasso, and D. LerouxIndoor, "Optical wireless Gbps link dimensioning," National Fiber Optic Engineers Conference, Anaheim, CA (2013) 17-21.

[5] M. Kavehrad, "Sustainable energy-efficient wireless applications using light," *IEEE Communication Magazine* (2010) 66–73.

[6] Y. Zheng, M. Zhang, "Visible light communications-recent progresses and future outlooks," Photonics and Optoelectronic (SOPO) Symposium, pp. 1–6, 2010.

[7] C. Kottke, J. Hilt, K. Habel, J. Vuˇci´c, K.-D. Langer, "1.25 gbit/s visible light wdm link based on dmt modulation of a single rgb led luminary," European Conference and Exhibition on Optical Communication, p. We.3.B.4, Optical Society of America, 2012.

[8] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, E. Ciaramella, "2.1 gbit/s visible optical wireless transmission," European Conference and Exhibition on Optical Communication, p. P4.16, Optical Society of America, 2012.

[9] Y. Wang, Y. Wang, N. Chi, J. Yu, H. Shang, "Demonstration of 575- mb/s downlink and 225-mb/s uplink bi-directional scm-wdm visible light communication using rgb led and phosphor-based led," *Opt. Express*, vol. 21, pp. 1203–1208, 2013.

[10] A. Rissons, J. Perchoux and J. C. Mollier, "Small signal and noise circuit model of vertical-cavity surface-emitting laser (VCSEL) arrays for short range optomicrowave links," *MWP 2003 Proceedings. International Topical Meeting on Microwave Photonics, 2003.*, 2003, pp. 211-214.

[11] A. Al-Omari G. P. Carey S. Hallstein J. P. Watson G. Dang and K. L. Lear "Low thermal resistance high speed top emitting 980nm VCSELs " Photonics Technology Letters vol. 18 pp. 1225-1227 June 2006.

[12] R. Amatya, D. Luerssen, M. Farzaneh and J. A. Hudgings, "Thermal lensing in oxide-confined, single-mode VCSELs," *2006 Conference on Lasers and Electro-Optics and*

2006 Quantum Electronics and Laser Science Conference, Long Beach, CA, 2006, pp. 1-2.

[13] W. Hofmann, M. Gorblich, M. Ortsiefer, G. Bohm and M. C. Amann, "Long-wavelength (λ = 1.55μm) monolithic VCSEL array with > 3W CW output power," in *Electronics Letters*, vol. 43, no. 19, pp. 1025-1026, September 13 2007.

[16] "Strength in numbers," in *Electronics Letters*, vol. 46, no. 10, pp. 667-667, 13 May 2010.

[17] Q. Wang, S. Liverman, Y. Chu, A. Borah, S. Wang, T. Nguyen, A. Natarajan, and A. X. Wang. 2017, "WifO: a hybrid wifi free-space optical communication networks of femtocells,". In *Proceedings of the 20th ACM International Conference on Modelling, Analysis and Simulation of Wireless and Mobile Systems*, 2017.

[18] Wang, Q., Nguyen, T. and Wang, A.X. "Channel capacity optimization for an integrated wi-fi and free-space optic communication system (wififo),". In *Proceedings of the 17th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems* (pp. 327-330). ACM. September 2014.

[19] Spencer Liverman, Qiwei Wang, Yu-Jung Chu, Anindita Borah, Songtao Wang, Arun Natarajan, Alan X. Wang, Thinh Nguyen, "WiFO: A hybrid communication network based on integrated free-space optical and WiFi femtocells," Computer Communications, Volume 132 (2018)

[20] S. Liverman, Q. Wang, Y. Chu, A. Natarajan, T. Nguyen, and A. X. Wang, "Hybrid wireless communication networks: integrating free-space optics and wifi," in *Frontiers in Optics 2016*, OSA Technical Digest, Optical Society of America, 2016.

[21] S. Liverman, Q. Wang, Y. Chu, A. Borah, S. Wang, A. Natarajan, T. Nguyen, A. X. Wang, "Indoor communication networks realized through hybrid free-space optical and wi-fi links," Proc. SPIE 10559, Broadband Access Communication Technologies XII, 105590H, Jamuary 29 2018.

[22] W. Hofmann, E. Wong, G. Bohm, M. Ortsiefer, N. H. Zhu and M. C. Amann, "1.55μm VCSEL Arrays for High-Bandwidth WDM-PONs," in *IEEE Photonics Technology Letters*, vol. 20, no. 4, pp. 291-293, Feb.15, 2008.

[23] Wang, X., Jiang, W., Wang, L., Bi, H. and Chen, R.T., 2008. Fully embedded board-level optical interconnects from waveguide fabrication to device integration. Journal of Lightwave Technology, 26(2), pp.243-250.

[24] P. Westbergh, J. S. Gustavsson and A. Larsson, "240 Gbit/s VCSEL array for multicore fiber interconnects," *2014 IEEE Photonics Conference*, San Diego, CA, 2014, pp. 91-92.

[25] C. W. Chow, L. Xu, C. H. Yeh, H. K. Tsang, W. Hofmann and M. C. Amann, "40-Gb/s Upstream Transmitters Using Directly Modulated 1.55-μm VCSEL Array for High-Split-Ratio PONs," in *IEEE Photonics Technology Letters*, vol. 22, no. 5, pp. 347-349, March1, 2010.

[26] C. Xie *et al*., "400-Gb/s PDM-4PAM WDM System Using a Monolithic 2×4 VCSEL Array and Coherent Detection," in *Journal of Lightwave Technology*, vol. 33, no. 3, pp. 670-677, Feb.1, 1 2015.

[27] S. Spiga, C. Xie, P. Dong, M. C. Amann and P. Winzer, "Ultra-high-bandwidth monolithic VCSEL arrays for high-speed metro networks," *2014 16th International Conference on Transparent Optical Networks (ICTON)*, Graz, 2014, pp. 1-4

[28] X. Xiao *et al*., "High-speed IQ modulator based on injection-locked VCSEL array," *2017 Conference on Lasers and Electro-Optics (CLEO)*, San Jose, CA, 2017, pp. 1-2.

[29] I. Lu, C. Yeh, D. Hsu and C. Chow, "Utilization of 1-GHz VCSEL for 11.1-Gbps OFDM VLC Wireless Communication," in *IEEE Photonics Journal*, vol. 8, no. 3, pp. 1-6, June 2016, Art no. 7904106.

[30] W. Hofmann, M. Gorblich, G. Bohm, M. Ortsiefer and M. C. Amann, "Long-wavelength VCSEL arrays with partly coherent emission," *2009 Conference on Lasers and Electro-Optics and 2009 Conference on Quantum electronics and Laser Science Conference*, Baltimore, MD, 2009, pp. 1-2.

[31] M. Xun *et al*., "High-power in-phase coherently coupled VCSEL array based on proton implantation," in *Electronics Letters*, vol. 50, no. 15, pp. 1085-1086, July 17 2014.

[32] G. Pan *et al*., "Large-Scale Proton-Implant-Defined VCSEL Arrays With Narrow Beamwidth," in *IEEE Electron Device Letters*, vol. 39, no. 3, pp. 390-393, March 2018.

[33] W. S. Oh and K. Park, "Design of a 4-channel 10-Gb/s CMOS VCSEL driver array," *2008 7th International Conference on Optical Internet*, Tokyo, 2008, pp. 1-2.

[34] Z. Zeng *et al*., "A Compact Low-Power Driver Array for VCSELs in 65-nm CMOS Technology," in *IEEE Transactions on Nuclear Science*, vol. 64, no. 6, pp. 1599-1604, June 2017.

[35] Won-Seok Oh, Kang-Yeob Park and Seonyoung Lee, "A 4-CH 10-Gb/s CMOS VCSEL driver array with adaptive optical power control," *2010 The 12th International Conference on Advanced Communication Technology (ICACT)*, Phoenix Park, 2010, pp. 826-829.

[36] K. K. Gan *et al*., "10 Gb/s radiation-hard VCSEL array driver," *2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, Seattle, WA, 2014, pp. 1-4.

[37] A. Malacarne *et al*., "Optical Transmitter Based on a 1.3-μm VCSEL and a SiGe Driver Circuit for Short-Reach Applications and Beyond," in *Journal of Lightwave Technology*, vol. 36, no. 9, pp. 1527-1536, 1 May1, 2018.

[38] C. Kottke, J. Hilt, K. Habel, J. Vuˇci´c, K.-D. Langer, "1.25 gbit/s visible light wdm link based on dmt modulation of a single rgb led luminary," *European Conference and Exhibition on Optical Communication, p. We.3.B.4, Optical Society of America.*, 2012.

[39] C. D. Muñoz, K. Elayoubi, A. Rissons, S. Villamizar and M. Varón, "O-band and C-band VCSEL based optoelectronic oscillator (VBO) for 1.25 Gbit/s pulsed RZ-OOK and RZ-DPSK free space optical transmissions," *2017 International Topical Meeting on Microwave Photonics (MWP)*, 2017, pp. 1-4.