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Chao Shen, Omar Alkhazragi, Xiaobin Sun, Yujian Guo, Tien Khee Ng, Boon S. Ooi, "Laser-based visible light communications and underwater wireless optical communications: a device perspective
," Proc. SPIE 10939, Novel In-Plane Semiconductor Lasers XVIII, 109390E (1 March 2019); doi: 10.1117/12.2504681

Event: SPIE OPTO, 2019, San Francisco, California, United States

Laser-based visible light communications and underwater wireless optical communications: a device perspective

(invited paper)

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ABSTRACT

High-speed visible light communications (VLC) has been identified at an essential part of communication technology for 5G network. VLC offers the unique advantages of unregulated and secure channels, free of EM interference. Compared with the LED-based VLC transmitter, laser-based photonic systems are promising for compact, droop-free, and high-speed white lighting and VLC applications, ideal for ultra-fast 5G network and beyond. Besides the potential for achieving high data rate free-space communication links, i.e. the Li-Fi network, laser-based VLC technology can also enable underwater wireless optical communications (UWOC) for many important applications.

In this paper, the recent research progress and highlights in the fields of laser-based VLC and UWOC have been reviewed with a focused discussion on the performance of various light sources, including the modulation characteristics of GaN-based edge emitting laser diodes (EELDs), superluminescent diodes (SLDs) and vertical-cavity surface-emitting lasers (VCSELs). Apart from the utilization of discrete components for building transceiver in VLC systems, the development of III-nitride laser-based photonic integration has been featured. Such on-chip integration offers many advantages, including having a small-footprint, high-speed, and low power consumption.

Finally, we discuss the considerations of wavelength selection for various VLC and UWOC applications. Comparison of infrared (IR) and visible lasers for channels with high turbulence and the study of ultraviolet (UV) and visible lasers for non-line-of-sight (NLOS) communications are presented.

Keywords: Gallium Nitride, laser diode, semiconductor laser, visible light communication, Li-Fi, solid state lighting, optical wireless communication, underwater communication.

1. OVERVIEW OF LASER BASED VLC AND UWOC RESEARCH

The use of light sources such as laser diodes (LD) and light emitting diodes (LED) emitting in the visible band of the electromagnetic spectrum as means of data transmission offers numerous advantages. For example, these sources can provide high data rates while simultaneously serving as efficient lighting sources. They can also transmit the data at long distance in both free space channel and water channel, making it a promising technology for enabling Internet of underwater things (IoUT). In this section, we will present an overview of the research achievements in laser-based visible light communications (VLC) and underwater wireless optical communications (UWOC).

1.1 Laser-based VLC

Laser-based VLC has seen remarkable advancements in recent years, which are summarized in Figure 1 [1-19] where the data rates are plotted versus the distance of transmission. The use of LDs in VLC has many advantages over LEDs such as having a much higher modulation bandwidth and enabling narrow beam transmission for long distance applications. For instance, a 100-m VLC link was demonstrated with a data rate of 2.3 Gbps was achieved using on-off keying (OOK) with a bit error ratio (BER) of 1.8×10^{-3}, which is below the forward error correction (FEC) limit of 3.8×10^{-3} [4].

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Novel In-Plane Semiconductor Lasers XVIII, edited by Alexey A. Belyanin,
Peter M. Smowton, Proc. of SPIE Vol. 10939, 109390E · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2504681

However, there is a trade-off between the transmission distance and the quality of the white lighting to be taken into consideration. Depending on the application, a collimated beam generated by laser diodes would be preferred for long-distance transmission, but a divergent beam can be preferred for lighting. While the OOK modulation technique is simple and thus, commonly used [2, 4-6], there are many other modulation schemes that have been used in laser-based VLC. The use of more spectral efficient techniques, such as orthogonal frequency division multiplexing (OFDM), has shown great results in increasing the data rates of VLC systems [7, 13, 15]. Other methods, including pulse amplitude modulation (PAM) [18] and carrier-less amplitude and phase (CAP) modulation [1], are also useful techniques that have been demonstrated.

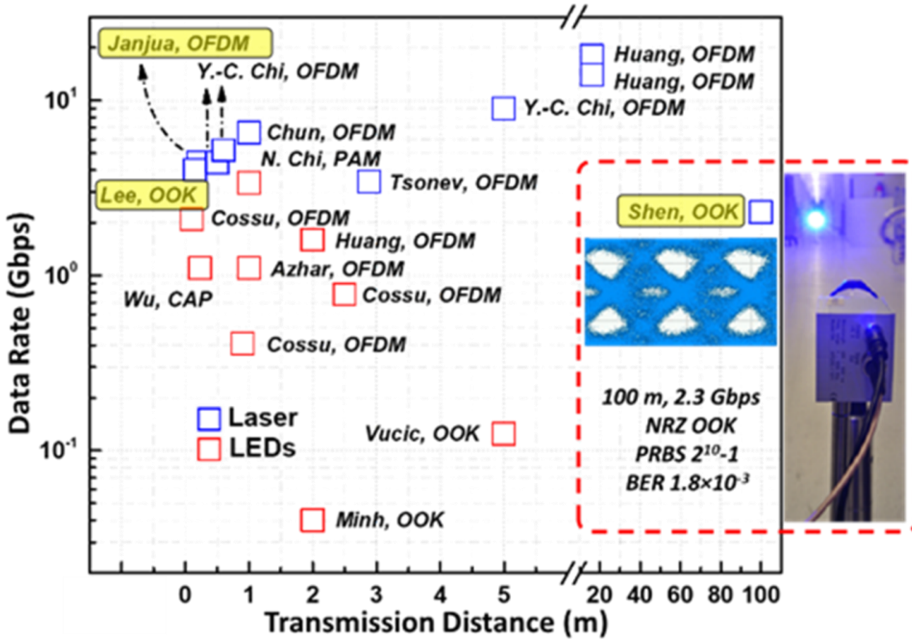

Figure 1. A summary of research progress in laser-based VLC and its comparison with LED-based VLC, showing the data rates and the transmission distances. (Data set can be accessed at https://photonics.kaust.edu.sa/Pages/Research-VLC.aspx)

1.2 Laser-based UWOC

Laser-based UWOC has attracted many researchers due to the variety of applications in which it can be deployed. These applications include underwater pipeline monitoring and maintenance, oceanography and environmental studies, and military applications. Laser-based UWOC become attractive due to the fact that the conventional acoustic communications cannot meet the bandwidth demands in many applications, such as live video streaming [20-23], and they also suffer from high latency. While radio frequency (RF) can be used for underwater wireless communication, it suffers from very high attenuation in water which limits the transmission range [24-26]. Because of the limitations of the aforementioned alternatives, UWOC has received a lot of attention in recent years, and Figure 2 shows the recent progress in the field [27-43]. These demonstrations range from test-bed experiments, such as presented in [32], and real environment tests [42]. The modulation schemes and multiplexing techniques used in VLC can also be implemented in UWOC. Furthermore, in UWOC, non-line-of-sight (NLOS) communication has been demonstrated [44], which removes the strict alignment conditions between the transmitter and the receiver. In a NLOS system, the scattering of the light in water is utilized since it can help in directing the randomly-scattered photons toward the receiver, which will be discussed in a later section. A comprehensive review related to the transmitter and receiver technologies, key components, underwater optical channel models, and effects of turbulence in UWOC systems has recently published [45].

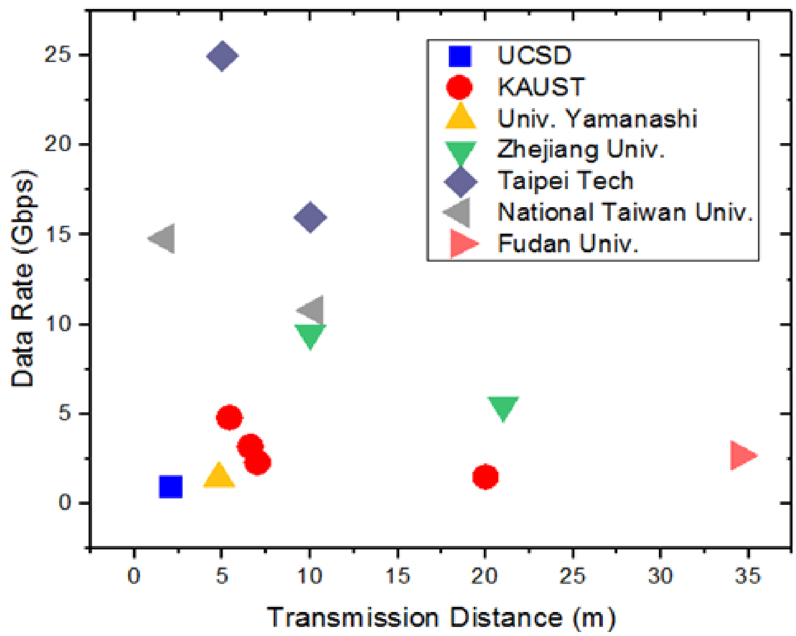

Figure 2. A summary of research progress in laser-based UWOC, showing the data rates and the transmission distances. (Data set can be accessed at https://photonics.kaust.edu.sa/Pages/Underwater-Wireless-Optical-Communication.aspx)

2. GAN BASED EELD, SLD AND VCSEL

In laser-based VLC and UWOC systems, the light source is one of the key components to enable high-speed data communication. Since the blue-green light emitters were based on GaN materials, the high-speed VLC system requires a fast GaN-based transmitter. There are three kinds of transmitters including the edge emitting laser diodes (EELDs), superluminescent diodes (SLDs) and vertical-cavity surface-emitting lasers (VCSELs).

The first demonstration of pulsed-operated InGaN/GaN/AlGaN-based room-temperature EELD was reported by Nakamura et al. [46]. Since then, the reliability of InGaN-based lasers has improved significantly, and the output power has been increased from a few mW to a few W per diode [47]. A high power GaN laser diode with output power over 7W was reported in [48]. The modulation characteristics of GaN-based laser diodes were studied in various works for VLC and UWOC applications [49-55]. A 1 GHz modulation bandwidth was measured in a commercial high power blue laser diode [55] and a later study suggested the modulation bandwidth for GaN-based violet laser could reach beyond 5 GHz [56]. Utilizing the injection locking technique, it has been reported that the bandwidth of the laser diode can be enhanced, making it promising for high data rate VLC systems [50].

The GaN-based SLDs are light emitters generating amplified spontaneous emission (ASE). SLDs have been found to have attractively-combined optical characteristics, *i.e.* a broadband spectrum similar to that of light-emitting diodes (LEDs) and high spatial coherence similar to that of LDs [57, 58]. SLDs are typically used as the source in optical coherence tomography (OCT) and fiber optic gyroscopes (FOG) systems. Recently, high power and high speed violet-blue SLDs have been reported, suggesting its potential for VLC and UWOC applications [59]. In one of the earliest demonstrations, a blue SLD emitting at 420 nm was demonstrated to have an output power of 100 mW in pulse mode and 2.8 mW in continuous wave (CW) operation [13]. Since then, there are continuous reports of III-nitride SLDs with increasing optical power, such as over 100 mW blue SLD in CW operation [60], 350 mW violet SLD in CW operation [35], and 474 mW blue SLD in pulse operation [61]. The modulation characteristics in GaN-based SLD is first studied by Shen et al. showing a modulation bandwidth of 560 MHz [62]. Utilizing violet-blue SLDs as transmitters, the VLC links with data rates of 1.3 Gbps [63] and 1.45 Gbps [61] have been reported, suggesting their attractive properties for VLC applications.

VCSELs are ideal for high speed operation owing to their short cavity and small form factor [64]. However, unlike conventional VCSEL based on distributed Bragg reflectors (DBRs) based on lattice matching material system, such as GaAs/AlGaAs, GaN based VCSEL suffers from the large lattice-mismatch AlGaN/GaN DBRs, leading to cracking of material structure after growth. Until very recently, the output power of the violet-blue VCSEL increased from μW to above 10 mW [65]. Therefore, significant efforts are required to develop high power, high speed GaN-based VCSELs. The recent advances and challenges of GaN-based VCSELs are summarized in [66]. Nonetheless, the investigation of nonpolar InGaN/GaN quantum-well VCSEL shows a modulation bandwidth beyond GHz [67], confirming the fact that GaN-based VCSEL has great potential for high-speed VLC transmitters.

3. INTEGRATED PHOTONICS AT VISIBLE COLOR REGIME

GaAs- and InP-based photonic integration has been achieved in telecommunication wavelength regime for many commercial applications [68]. Though there are significant advances in III/V photonic integrated circuits (PIC) in far-red and infrared wavelength regime, the realization of photonics integration in the visible wavelength regime remains a challenging topic. There are a few studies on integrating different optical functionalities with GaN-based LEDs, photodetectors in particular. Monolithic integration of nitride multi-quantum well (MQW) LEDs with ultraviolet (UV) Schottky barrier PDs has been demonstrated by Jiang et al. [69]. Such devices can function as the transmitters to emit visible light signals, and as receivers to analyze incoming UV signals for bi-directional optical wireless communication applications. By joining a forward biased LED, a suspended waveguide, and a reverse biased PD together, an integrated p-i-n junction device sharing the same InGaN/GaN MQW active region has been demonstrated on GaN-on-silicon platform [70]. Apart from the planar structures, Tchernycheva et al. reported a nanowire photonic platform consisting of InGaN core-shell nanowire LEDs and PDs optically coupled by SiN waveguides [71].

Recently, we have discussed and demonstrated the first monolithic integration of EELDs together with modulators, amplifiers, and detectors, for VLC applications [72]. The first blue-emitting integrated waveguide modulator-laser diode with a high modulation efficiency of 2.68 dB/V has been demonstrated in [73]. For higher efficiency, group-III-nitride electro-absorption modulator operating at a reduced modulation bias, semipolar $(20\overline{2}\overline{1})$ MQWs was utilized and characterized [73-75]. The modulation effect, as evident from the red-shifting of absorption edge, is due to external-field-induced quantum-confined-Stark-effect (QCSE) [73]. An integrated short-wavelength semiconductor optical amplifier with the laser diode at ~404 nm is demonstrated with a large gain of 5.32 dB at 6 V [74]. The integrated waveguide modulator shows a modulation bandwidth of 1 GHz, which enables Gbps data rate VLC links. The integrated GaN-based semiconductor optical amplifier (SOA) - laser diode was demonstrated in [76], showing a large gain of 5.7 dB. By using the modulated amplifier scheme, the SOA-LD shows a high-speed modulation capability of Gbps [77]. Hence, this device platform will also be useful as the transmitter in VLC systems. Besides, a high-performance InGaN-based waveguide photodetector integrated LD sharing the single active region is presented [78] with a responsivity of 0.051 A/W at 405 nm and a large modulation bandwidth of 230 MHz. The results are significant in developing the platform technology to enable III-nitride PIC for smart lighting and display, VLC, optical switching, clocking and optical interconnect [79].

4. WHEN TO CONSIDER LONG WAVELENGTH LASERS

The visible-light-based VLC and UWOC links were associated with attenuation and turbulence effects, and those effects are in particular important for UWOC. The working distance of the communication system is largely depending on the power attenuation caused by the absorption and scattering effects during the propagation of optical signals.

The performance of UWOC links is severely limited by optical turbulence in the water channel which is mainly due to temperature and salinity fluctuations. Optical turbulence induces random temporal and spatial irradiance and phase fluctuations (scintillations) which ultimately deteriorate the optical quality and the coherence properties of laser beams leading to performance degradation [80, 81].

Detailed understanding of scintillations in underwater turbulent media is crucial in evaluating the reliability of UWOC systems. The probability density functions of laser beam intensity fluctuations due to salty and bubbly underwater channels under various channel conditions were experimentally obtained by Jamali [82]. A more comprehensive study to characterize turbulence-induced fading in UWOC channels in the presence of air bubbles for fresh and salty waters, based on experimental data was proposed by Zedini et al. [83]. Recently, radiations with long wavelength (red light) are reported to outperform shorter wavelengths in terms of circumventing the effect of turbulence [84].

The scattering effect, which is also a wavelength-dependent phenomenon, results in the changes of direction of the beam propagation. Theoretical- and simulation-based studies have been carried out to investigate the inherent characteristics of the UWOC channel and examine the feasibility of the related mitigation strategies [85, 86]. The feasibility of using Maalox to emulated the scattering scenario in the real seawater was validated by Laux et al [87]. Lee et al. reported on the experimental investigation of the effects of particulates in-suspension with increasing concentrations in the water medium on the optical beam for underwater wireless transmission [88, 89]. The Gbps NIR-based UWOC system is also feasible. UWOC systems with long wavelength light sources are more resilient to the effects of particulates in-suspension over the underwater channel with a smaller scattering effect, as evident by the smaller variations in transmittance. The forward scattering potentially directs the resultant beam towards the receiver. The adoption of directly modulated long wavelength LDs would spur the realization of future high-speed, large-bandwidth and long-distance UWOC systems that are robust to different water types.

5. WHEN TO CONSIDER SHORT WAVELENGTH LASERS

While most of the high-speed VLC and UWOC links were based on line-of-sight (LOS) configurations, there are strict requirements on positioning, acquisition, and tracking (PAT). However, turbulence [90, 91], turbidity [92], and obstacles [90] in the air or water channel are reported to cause severe signal fading, and even complete signal loss, in LOS VLC/UWOC links. To this end, non-line-of-sight (NLOS) communication links can be implemented to mitigate the abovementioned issues. Such studies are important for laser-based UWOC systems to address issues related to the PAT requirements. Diffuse-LOS and NLOS UWOC links can be established either through light reflection from the water surface [93] or light scattering [94] from the molecules in the water. Therefore, short-wavelength, including UV light emitters are typically favorable to be utilized in NLOS UWOC owning to the high scattering coefficients in this range of wavelength.

There are Monte Carlo simulations [95] and the Henyey–Greenstein (HG) phase function [96] studies to develop models describing the transmitted photons' trajectory. A recent demonstration of NLOS UWOC link reveals the advantage of using a short wavelength, 375-nm laser [12] to achieve enhanced NLOS UWOC link and the path loss has been reported under various geometries. The experiments suggest that path loss decreases with smaller azimuth angles, higher water turbidity, and shorter wavelengths due in part to enhanced scattering utilizing short wavelength lasers.

6. CONCLUSIONS

In this paper, the recent progress in laser-based visible light communications and underwater wireless optical communications was discussed with a focus on light emitting devices. The advantages, properties, optical power, and modulation characteristics of GaN-based edge emitting laser diodes, superluminescent diodes and vertical-cavity surface-emitting lasers have been introduced. The pathway towards integrated photonics in the visible color regime using III-nitride laser platform for high-speed applications is reviewed. The work also features the utilization of long wavelength lasers for VLC and UWOC links in high turbulence channels and the utilization of short wavelength lasers for non-line-of-sight VLC and UWOC links.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from King Abdulaziz City for Science and Technology (KACST) Grant No. KACST TIC R2-FP-008, and KACST-KAUST-UCSB Solid-State Lighting Program. This publication is based on work supported by the King Abdullah University of Science and Technology (KAUST) (baseline funding, BAS/1/1614-01-01, KAUST funding KCR/1/2081-01-01, and GEN/1/6607-01-01).

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