High speed visible light communication using blue GaN laser diodes

S. Watson[1], S. Viola[1], G. Giuliano[1,6], S.P. Najda[2], P. Perlin[2,3], T. Suski[3], L. Marona[3], M. Leszczyński[2,3], P. Wisniewski[2,3] , R. Czernecki[2,3], G. Targowski[2], M. A. Watson[4], H. White[5], D. Rowe[6], L. Laycock[6], A. E. Kelly[1]

[1]School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK
[2]TopGaN Ltd, Sokolowska 29/37, 01-142 Warsaw, Poland
[3]Institute of High Pressure Physics PAS, Sokolowska 29/37, 01-142 Warsaw, Poland
[4]AVoptics, 3 Limber Road, Yeovil, BA22 8RR, UK
[5]BAE Systems, MAI, FPC 267, PO Box 5, Bristol, BS34 7QW, UK
[6]BAE Systems, Applied Intelligence Laboratories, Great Baddow, Chelmsford, Essex, CM2 8HN, UK

ABSTRACT

GaN-based laser diodes have been developed over the last 20 years making them desirable for many security and defence applications, in particular, free space laser communications. Unlike their LED counterparts, laser diodes are not limited by their carrier lifetime which makes them attractive for high speed communication, whether in free space, through fiber or underwater. Gigabit data transmission can be achieved in free space by modulating the visible light from the laser with a pseudo-random bit sequence (PRBS), with recent results approaching 5 Gbit/s error free data transmission. By exploiting the low-loss in the blue part of the spectrum through water, data transmission experiments have also been conducted to show rates of 2.5 Gbit/s underwater. Different water types have been tested to monitor the effect of scattering and to see how this affects the overall transmission rate and distance. This is of great interest for communication with unmanned underwater vehicles (UUV) as the current method using acoustics is much slower and vulnerable to interception. These types of laser diodes can typically reach 50-100 mW of power which increases the length at which the data can be transmitted. This distance could be further improved by making use of high power laser arrays. Highly uniform GaN substrates with low defectivity allow individually addressable laser bars to be fabricated. This could ultimately increase optical power levels to 4 W for a 20-emitter array. Overall, the development of GaN laser diodes will play an important part in free space optical communications and will be vital in the advancement of security and defence applications.

Keywords: visible light communication, laser, free-space, underwater, tracking, laser bars

1. INTRODUCTION

The use of GaN-based devices for optical communications has been an ever-growing topic in recent years [1,2]. In order to match the exponential growth of wireless data throughput caused by the increase of mobile devices used for multimedia and streaming, other parts of the electromagnetic spectrum have been explored for communication purposes. The visible spectrum has a large amount of unregulated bandwidth which can be exploited for this purpose [3,4]. Laser based visible light communication systems using non-return-to-zero, on-off keying (NRZ-OOK) have shown data rates up to 4 Gbit/s [5]. Here, we report a data rate of 4.7 Gbit/s using a directly modulated InGaN laser diode, emitting at a wavelength of 450 nm. Also, an underwater optical tracking system was put in place which allowed not only tracking, but data transmission to be achieved under the water. Different water qualities were tested and a data rate of 2.5 Gbit/s was achieved. High power laser bars and arrays can be fabricated which can produce up to 4 W of power. These can be packaged in a way that allows each laser to be individually addressable, meaning the number of lasers and hence the power can be altered easily.

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2. LASER BASED VLC IN FREE SPACE

Experiments have been conducted to analyse the performance of different laser diodes for communications in free space and underwater. The free space measurement was carried out using a commercially available laser diode (Osram PL450B) [6], emitting at 450 nm. The temperature was kept constant at 16.6°C using a Peltier cooler and a temperature controller to avoid any unwanted wavelength shifts throughout the measurements. The basic laser characteristics were measured and the LVI and spectra plots can be seen in Figure 1 and Figure 2, respectively.

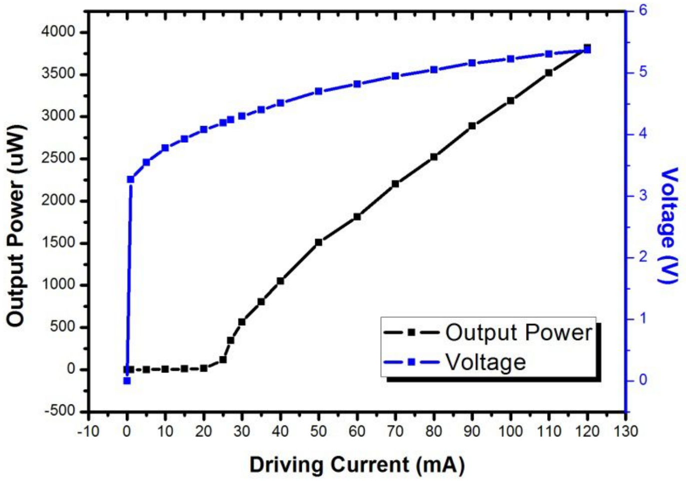

Figure 1: LVI characteristics of laser diode at 16.6°C.

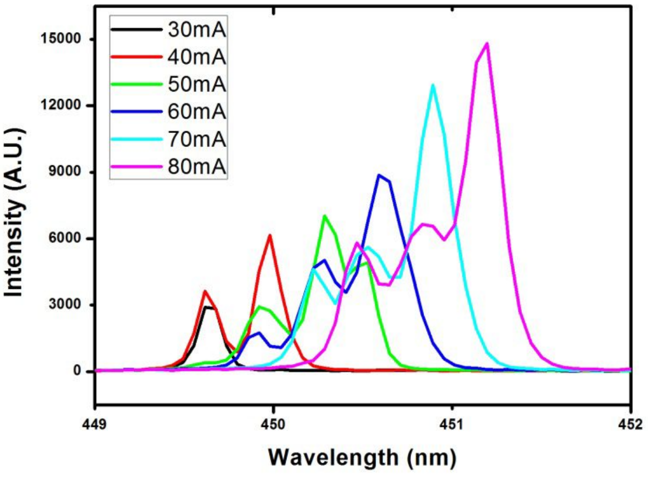

Figure 2: Optical spectra of laser diode at increasing bias currents.

As shown in Figure 1, the threshold of this laser diode is approximately 25 mA which corresponds to a voltage of 4.29 V. These lasers are capable of producing tens of milliwatts of power when measuring directly from the output; however a setup has been put in place for these measurements which focuses the light onto the power meter or photodetector using lenses and is not optimised for collecting all of the light. A power level of 3.8 mW was achieved in this setup at a corresponding current of 120 mA. There is already more than enough power from the laser at this point for these applications. There is a small red-shift in the optical spectra with increasing current which is due to the increasing junction temperature, reducing the bandgap of the device [2].

Frequency response measurements were carried out in order to calculate the optical bandwidth of the system. An RF signal from a network analyser (Agilent HP8753ES) was combined with the DC bias using a bias tee, and the output was connected to the laser diode. The light was collected and collimated using two microscope lenses and was focussed onto a high speed PIN photoreceiver (HSA-X-S-1G4-SI) which has a bandwidth of 1.4 GHz. The frequency response of the system was measured at varying current values and is shown in Figure 3.

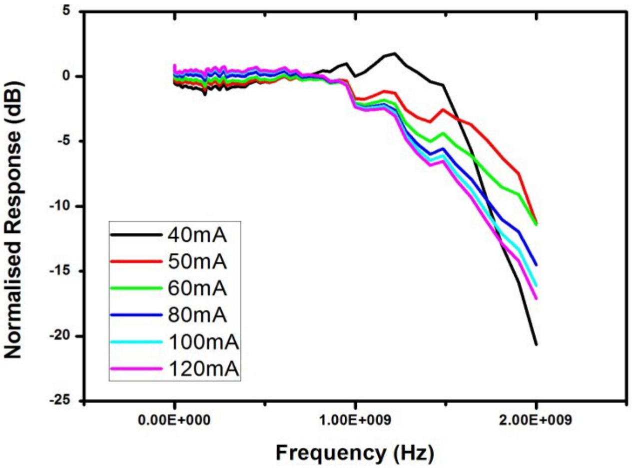

Figure 3: Frequency response at different bias currents.

The current was varied from 40 mA up to 120 mA, with the maximum optical bandwidth shown at 50 mA. The system bandwidth appears to be limited by the bandwidth of the photoreceiver; however a bandwidth value of 1.8 GHz was achieved at 50 mA. Higher values would be expected if the measurement was repeated using a photoreceiver with a higher bandwidth. It can be seen in Figure 4 that the bandwidth of the system reaches a maximum point and then rolls over and flattens off due the photoreceiver used.

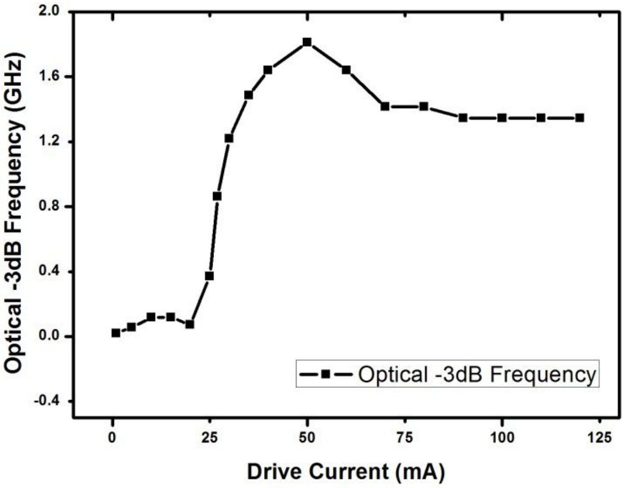

Figure 4: Optical -3dB bandwidth vs drive current.

Data transmission experiments were conducted by using a bit-error rate test (BERT) system to supply a pseudo-random bit sequence (PRBS) to the laser. The laser diode was driven by this NRZ-OOK signal combined with a DC bias using a bias tee, as before. A 2 V peak-to-peak signal of 2^7-1 bits was used for these experiments. Eye diagrams were captured using a digital sampling oscilloscope and Figure 5 shows open eye diagrams at (a) 1.5 Gbit/s and (b) 4.7 Gbit/s.

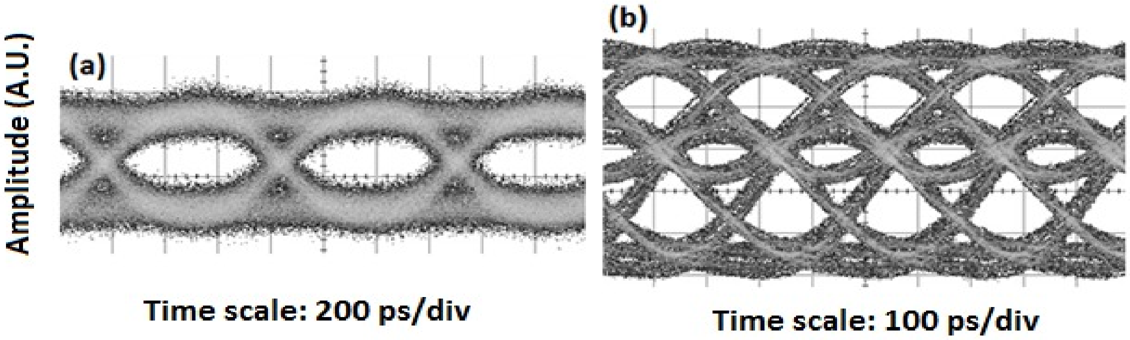

Figure 5: Eye diagrams at (a) 1.5 Gbit/s and (b) 4.7 Gbit/s.

By inserting a neutral density filter, it is possible to vary the optical power that reaches the photoreceiver and the corresponding error rate can be measured. Figure 6 shows the bit-error rate as a function of received optical power giving a better understanding of the data transmission behaviour. Different bit rates were measured and the current was varied to find the optimal drive current for each bit rate.

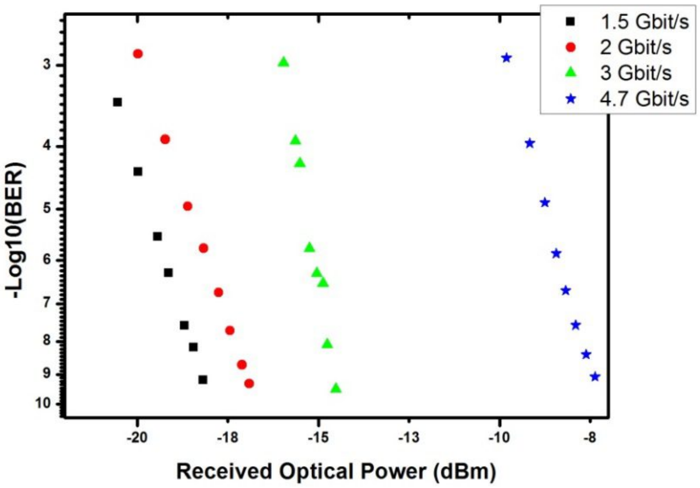

Figure 6: Bit-error rate vs received optical power at 1.5, 2, 3 and 4.7 Gbit/s at the optimum bias current for each bit rate.

The optimal drive current ranged from 54.1 mA to 107.1 mA and the power required to achieve error free data transmission ($< 1\times10^{-9}$) at 1.5, 2, 3 and 4.7 Gbit/s was -18.81, -16.90, -14.20 and -7.37 dBm, respectively. The expected power increase required from 1.5 Gbit/s to 3 Gbit/s whilst maintaining error free transmission would be 3 dB, however an increase of 4.61 dB is seen here. This means that there is a power penalty of 1.61 dB which is due to the limited response of the photoreceiver. This becomes even more apparent as the data rate increases to 4.7 Gbit/s and this effect can be seen in the corresponding eye diagram too.

3. UNDERWATER DATA TRANSMISSION AND LASER TRACKING

Further measurements have been carried out using similar blue laser diodes for underwater data transmission and laser tracking. Lasers designed, grown and fabricated by TopGaN [7] were used for these experiments which had an emission wavelength between 421 nm and 425 nm. These wavelengths are ideal as they match the lowest attenuation coefficients for oceanic water [8]. A setup was constructed which contained two main sections – the transmitter side and the receiver side. A laser diode, connected to a temperature controller, was mounted on a controllable stage and contained in one tank. A second tank was initially placed 1 m away and contained another translation stage which holds either a quadrant detector for tracking purposes or the high speed PIN photoreceiver, as mentioned before, for the data transmission experiments. The distance was increased to 1.7 m for the data transmission experiments. The components contained in the tanks can be seen in Figure 7.

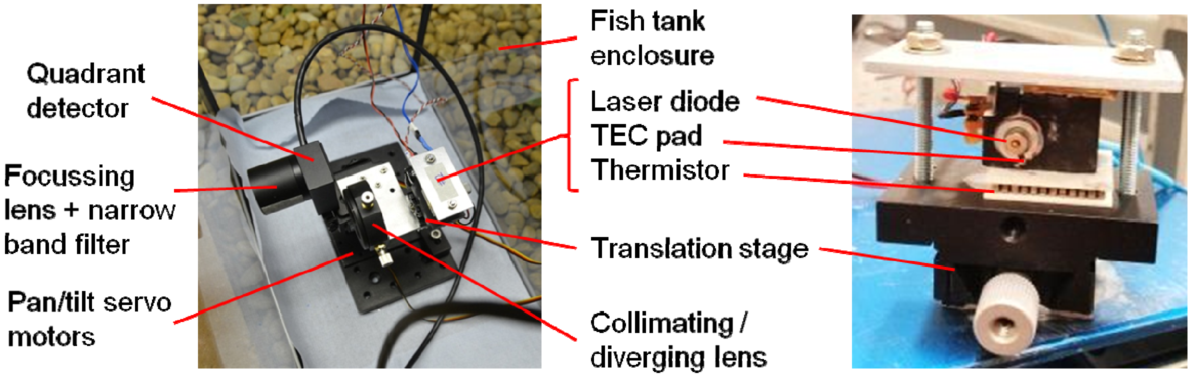

Figure 7: Experimental setup showing the components for tracking/detection (left) and the laser diode (right).

Both tanks were submerged into a larger flume so that the optical path was underwater. In order to test the tracking system in different water qualities, Maalox was added in controlled doses to mimic the effects of scattering in seawater. With no Maalox present, the water quality was still relatively murky and showed an attenuation coefficient of approximately 1.2 m^{-1}. However, the tracking system was able to pick up the laser signal easily and track its movement. Doses of Maalox were then added to the flume which contained 8000 litres of water. 200 ml of Maalox corresponds to 0.25 Maalox in 10^4 parts water. The maximum dosage of Maalox added to the water was 4 litres, which by this point the detector had lost all tracking capability. Further details can be found in [9].

Figure 8: Full setup showing laser firing underwater and hitting detector 1m away with no Maalox added (left) and the scattering caused by adding 4 litres of Maalox (right).

Similar measurements were carried out using this laser diode underwater to those discussed in section 2. Frequency response and data transmission experiments were conducted in order to characterise the lasers underwater behaviour. The detector used for tracking was replaced with the PIN photoreceiver and the flume was refilled with water which contained no Maalox. Again, the setup involved a network analyser providing an RF signal which was combined with the DC bias and sent to the laser diode. A maximum bandwidth value of 883 MHz was measured underwater for this laser diode, which was very similar to the measurement conducted above water, showing that the water does not have much effect on the bandwidth. The BERT system was then put in place and a PRBS was sent to the device. The output of the photoreceiver was connected to the oscilloscope to capture the eye diagrams and these are shown in Figure 9.

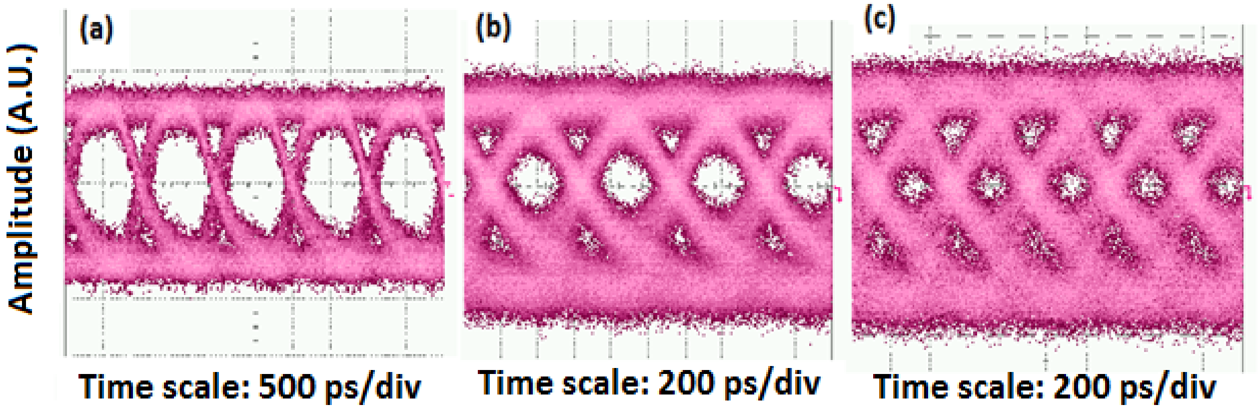

Figure 9: Eye diagrams showing data transmission at (a) 1 Gbit/s, (b) 2 Gbit/s and (c) 2.488 Gbit/s.

Successful error-free data transmission was achieved at 2.488 Gbit/s using this system. The eye diagram is beginning to close in Figure 9 (c) which is due to the bandwidth limit of the photoreceiver, but data transmission is still achieved. The ability to have gigabit transmission underwater is an important development which allows advancements in communications between UAVs for security and defence applications.

High power laser bars and arrays can be fabricated which can take this technology further. Alternative packaging allows each individual laser in the array to be individually addressable allowing complex free space or fibre optic system integration. As well as this, multi-wavelength optical integration is possible which could be beneficial for underwater communications in changing water conditions.

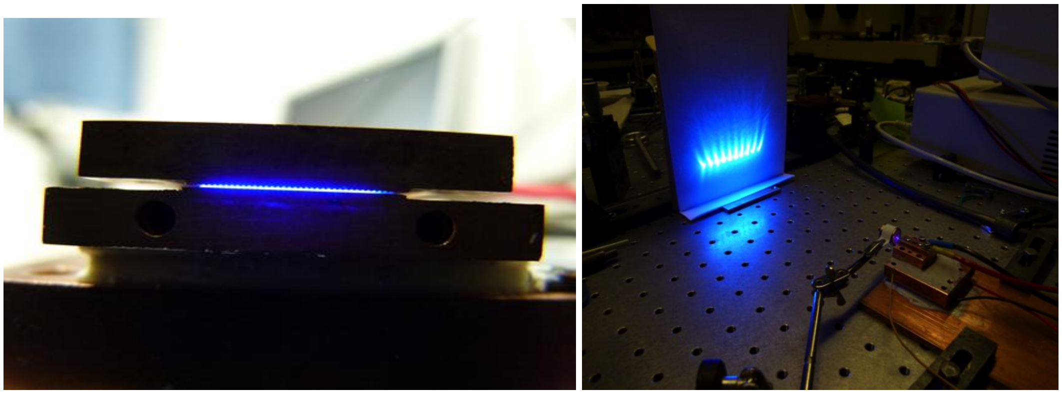

Figure 10: Laser array in operation.

4. SUMMARY / CONCLUSIONS

In summary, it has been shown that data transmission at rates approaching 5 Gbit/s has been achieved and that higher data rates using laser diodes for visible light communication will be possible once certain limitations are overcome. Lasers showing bandwidths up to 1.8 Gbit/s have been shown and their data transmission characteristics were presented. The ability to conduct these type of measurements underwater has also been shown with successful data transmission at 2.5 Gbit/s. Different water qualities have been tested and the ability to track the light has been explored in depth. New advancements have allowed the fabrication of laser bar arrays which allows much higher power and the ability to have individually addressable lasers. These could be beneficial for communication purposes and taking the work on this forward.

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