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Abstract. AlGaInN ridge waveguide laser diodes are fabricated to achieve single-mode operation with optical powers up to 100 mW at ∼420 nm for visible free-space, underwater, and plastic optical fiber communication. We report high-frequency operation of AlGaInN laser diodes with data transmission up to 2.5 GHz for free-space and underwater communication and up to 1.38 GHz through 10 m of plastic optical fiber. [DOI: 10.1117/1.OE.55.2.026112]

Keywords: GaN laser; GaN array; GaN systems; underwater communications; plastic fiber communications.

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1 Introduction

AlGaInN laser diodes (LDs) and light-emitting diodes (LEDs) have gained interest for visible-light communications (VLC), including underwater and optical fiber communications, since the AlGaInN material system allows for devices to be fabricated over a very wide range of visible wavelengths. Recently, it has been shown that micro-LEDs have MHz modulation bandwidths.[1,2] However, the performance of LEDs is limited by moderate bandwidths, low power, and a rapidly divergent beam giving short reach performance hence potential system applications are limited.

In comparison, AlGaInN laser diodes have the potential for much higher modulation frequency, higher powers, and better beam quality giving long reach performance, therefore allowing many new VLC applications to be realized, including, free-space data links using the 422- and 486-nm Fraunhofer lines for low solar background, blue-green underwater data communication, and wavelength multiplexing for plastic fiber communication.

In this paper, GHz data transmission using directly modulated AlGaInN laser diodes, both underwater and through plastic optical fiber (POF), is reported.

2 Results

One of the major limiting factors in nitride laser diode development has been the lack of a suitable low defectivity and uniform GaN substrate. Recently, single crystal growth of large area, very low dislocation density, and uniform GaN substrates are grown using a combination of high temperature and high pressure, enabling a range of AlGaInN laser technology to be developed.[3,4]

A typical AlGaInN laser diode epitaxy structure grown by metal organic chemical vapor deposition (MOCVD) consists of (i) 0.8-μm $Al_{0.08}Ga_{0.92}N$ lower cladding layer, (ii) 50-nm GaN lower waveguide layer, (iii) 50-nm $In_{0.02}Ga_{0.98}N$ injection layer, (iv) $In_xGa_{1-x}N/In_{0.02}Ga_{0.98}N$ quantum wells ×3 (3.5/9 Å)—the indium composition x ($x = 0.05$ to 0.2) and well thickness can be varied to change the emission wavelength, (v) 20-nm $Al_{0.2}Ga_{0.8}N$ electron blocking layer, (vi) 80-nm GaN waveguide, and (vii) 350-nm $Al_{0.08}Ga_{0.92}N$ upper cladding. All of the data presented in this paper are for AlGaInN laser diodes grown on the c-plane of the Wurtzite crystal.

AlGaInN epitaxy structures are processed into ridge waveguide LDs, with a typical mesa etch depth of 420 nm, cavity length of 700 μm, and a stripe width varying from 2 to 10 μm (depending on the application). After cleavage, the LDs are HR coated (5× ZrO_2/SiO_2 quarter-wavelength layers) with 95% reflectivity and AR coated with ∼5% reflectivity. Single emitters are mounted p-side up in TO5.6mm packages, laser bars are mounted on custom designed packages as described later in this paper.

Optical power–current–voltage (LIV) and beam profile characteristics for a 2-μm ridge waveguide LD structure packaged in a TO5.6mm package are shown in Fig. 1(a). The device has an optical power of ∼80 mW, threshold current of ∼65 mA, a threshold voltage of ∼5 V, a lasing wavelength of 410 nm, and a characteristic temperature T_0 of ∼120 K. A single transverse mode optical beam profile is observed in both the slow and fast axis [see Fig. 1(b)].[5]

High resolution spectral measurements on 4 different AlGaInN LDs with nominally the same structure, except the indium content is different in the $In_xGa_{1-x}N/In_{0.02}Ga_{0.98}N$ quantum well (QW) active region with $x = 0.05$, 0.08, 0.12, and 0.16 giving a wavelength emission of ∼382, ∼405, ∼425, ∼439 nm at ∼10 mW cw, 20°C (see Fig. 2).

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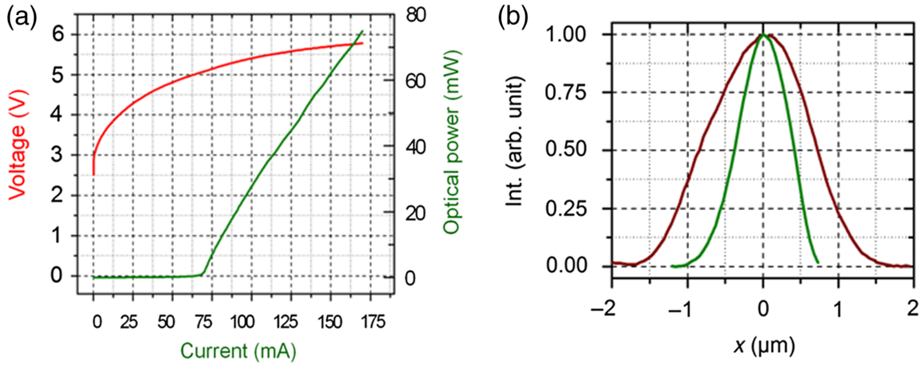


Fig. 1 AlGaInN 410-nm laser diode characteristics: (a) LIV and (b) near-field (slow axis: red line; fast axis: green line).

High-resolution spectral measurements of the AlGaInN LDs reveal the fine mode structure with a characteristic dominant single-longitudinal mode in all of these devices. At first glance, this is a surprising result, since single-longitudinal mode operation is more reminiscent of a DFB type of laser device with etched grating, providing optical feedback for mode selection, rather than a more standard Fabry–Pérot device with no etch grating.

The spectral output of a ~422-nm laser is measured as a function of increasing drive current. For 200 mA (14 mW) operation, a dominant single-longitudinal mode at 421.6 nm with multiple small side modes is observed. As the drive current increases to 250 mA (24 mW), the dominant single longitudinal mode remains, and small side modes change position and intensity. At a higher drive current of 300 mA (36 mW), the dominant single-longitudinal mode jumps to a spectrally wide (~1 to 2 nm) mode comb as it is more typical of a Fabry–Pérot LD device (see Fig. 3).

The single-longitudinal mode operation in a GaN Fabry–Pérot LD has also been observed in the spectral output of other AlGaInN LDs and was explained by surface roughness inadvertently introduced during growth.[6,7] Furthermore, it has been proposed that the single mode is stabilized by longitudinal mode competition caused by optical gain saturation.[8]

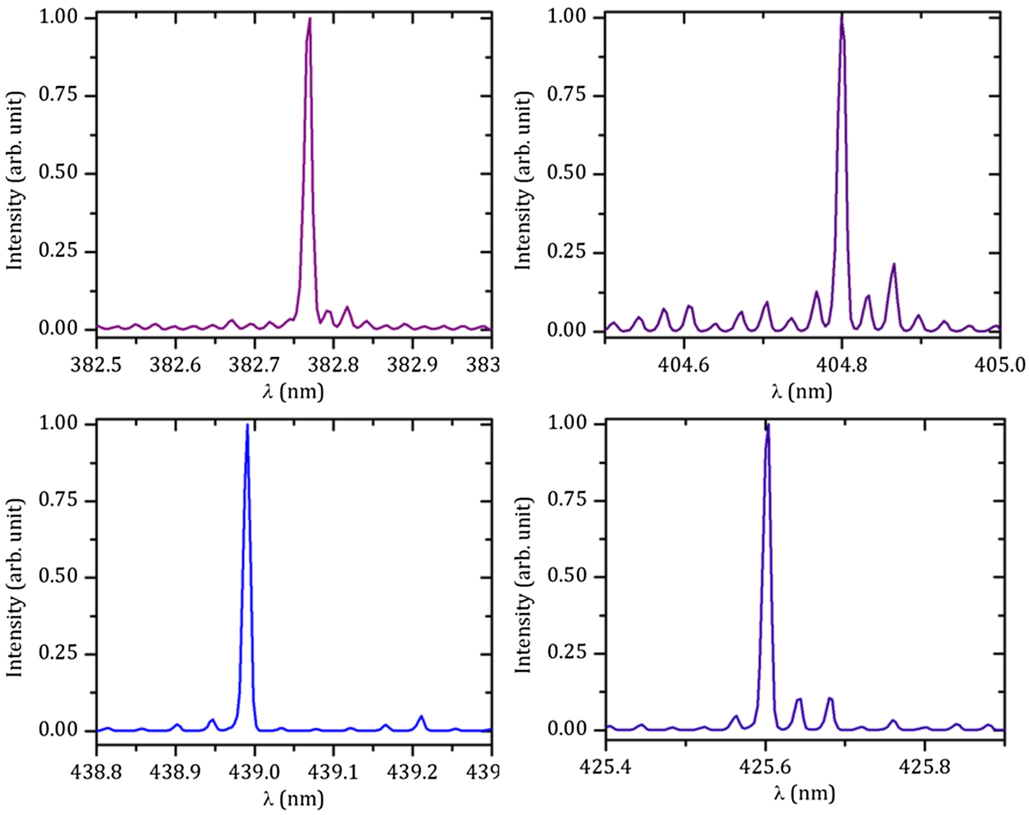


Fig. 2 High-resolution spectra of four different LDs with QW indium compositions $In_xGa_{1-x}N$/$In_{0.02}Ga_{0.98}N$ QWs of $x = 0.05$, 0.08, 0.12, and 0.16 giving a wavelength emission of ~382, ~405, ~425, ~439 nm at ~10 mW cw, 20°C.

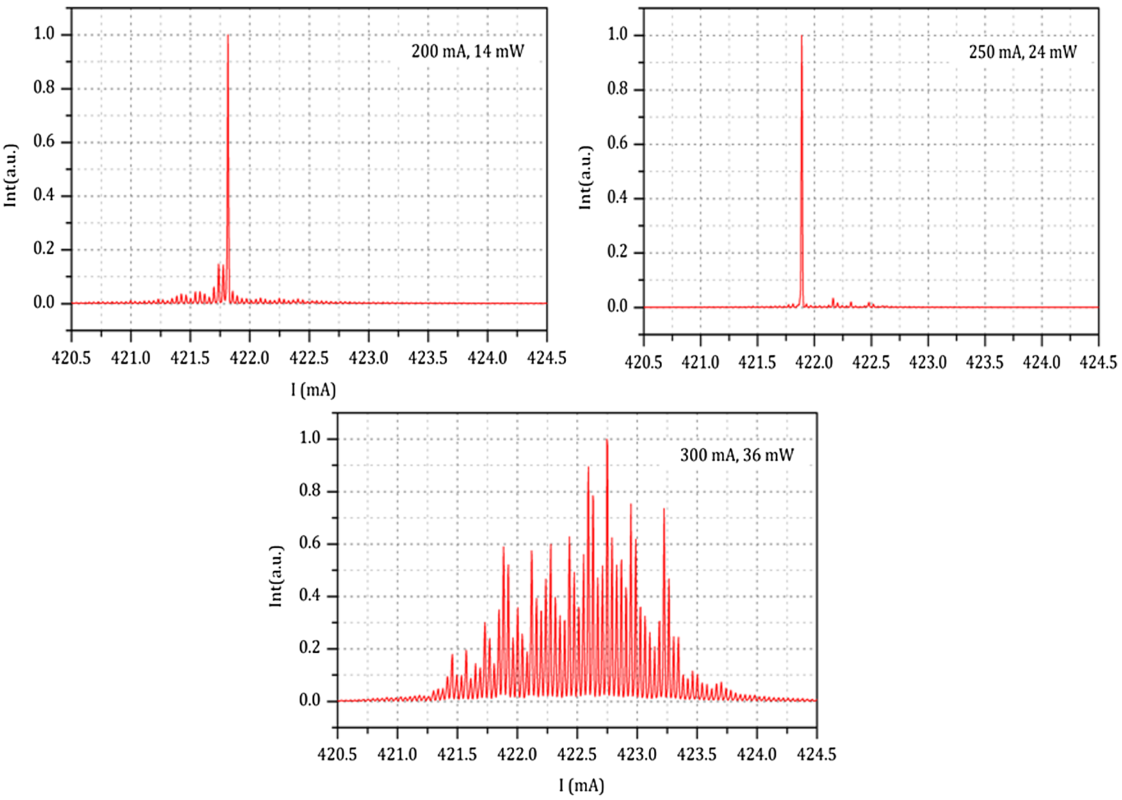


Fig. 3 The evolving spectra of an LD versus increasing drive current mA/optical power mW (cw) at 20°C.

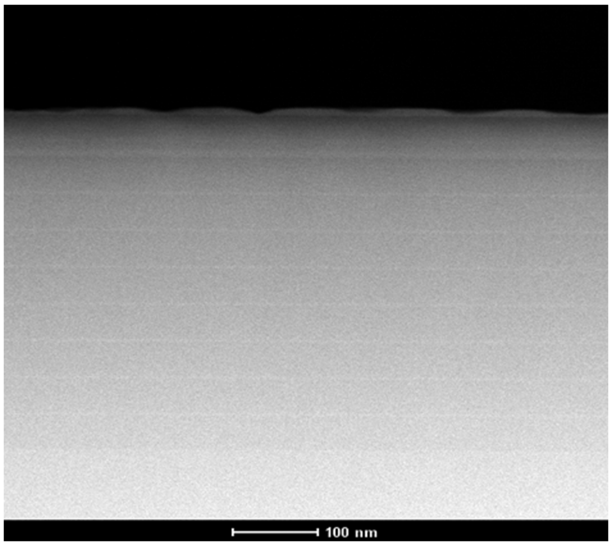


Fig. 4 SEM image of the cross-section of AlGaInN laser epitaxy.

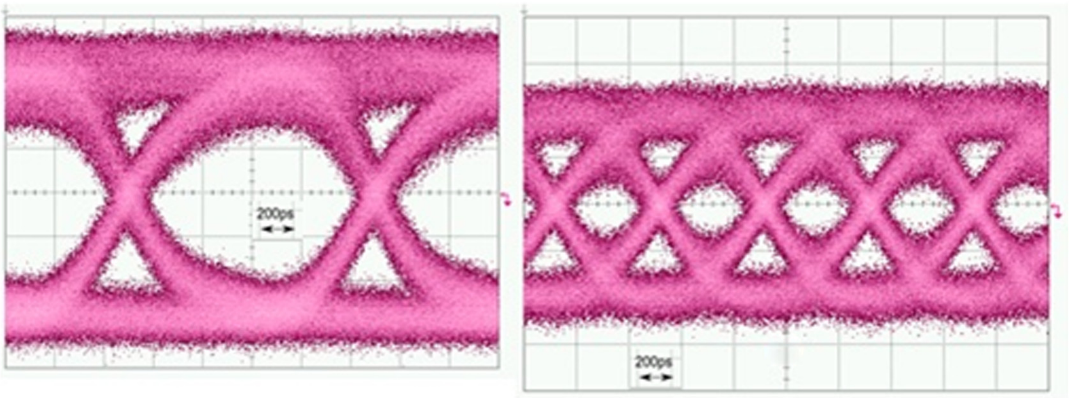
Similarly, we observe a surface topology of the order of ∼10 nm in height and a periodicity of 100 nm (see Fig. 4). The AlGaInN epitaxy growth is done on very low defectivity ($<5 \times 10^4$ cm^{-2}) GaN substrates with a flatness of <0.1 nm.[9] Regardless of the substrate flatness, the surface topology features inadvertently appear in the last epitaxy layer of growth. Thus, we attribute the observed single-mode behavior to the surface topology, creating a periodic refractive index variation, in a similar manner to an etched DFB grating. At higher drive current, the refractive index steps become washed out due to thermal heating and the laser diode operates more like a Fabry–Pérot device and a broad mode-comb is observed in the spectral output of the laser diode.

Free-space data transmission measurements were carried out using GaN blue laser diodes. Eye diagrams, measured using an Agilent 86105B digital sampling oscilloscope, are shown in Fig. 5. High-frequency data transmission (small signal modulation) at 1.1 Gbit/s was measured for a laser drive current of 115 mA and 2.5 Gbit/s for 120 mA, at which the best Q-factor margins are achieved.[10]

High-frequency data transmission underwater at similar Gbit/s rates has also been measured using a 422-nm GaN laser diode, demonstrating the suitability of GaN system technology for underwater sensing and communications.

To test the suitability of GaN laser diode technology for underwater communications, a GaN laser optical tracking system was constructed and submerged in a water tank (see Fig. 6). The optical setup is described in more detail elsewhere.[11] The performance of the GaN laser system was determined as the water conditions were varied by introducing Maalox, which mimics the volume scattering of seawater particles, and it is commonly used in underwater light-scattering experiments. Several GaN laser diodes were tested with their center wavelength in the range of 421 to 425 nm (varying from device to device). These wavelengths are in the range corresponding to lowest attenuation for optical wavelengths in waters classed as "oceanic clear," whereas with increasing turbidity the lowest attenuation shifts to longer wavelengths.

A GaN laser was fired over a short underwater path length of ∼1 m, to conduct data transmission experiments. An initial investigation into underwater data transmission using high-frequency GaN laser diodes is described. The frequency response of the GaN laser device was measured and



(a) (b)

Fig. 5 Eye diagrams at (a) 1 Gbit/s and (b) 2.5 Gbit/s at photoreceiver output.

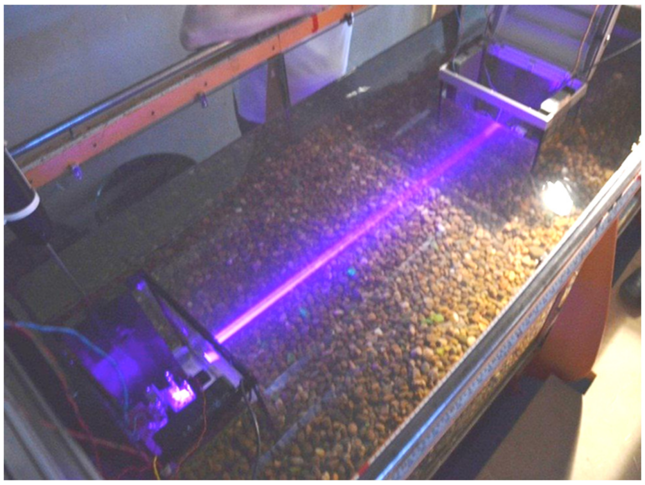


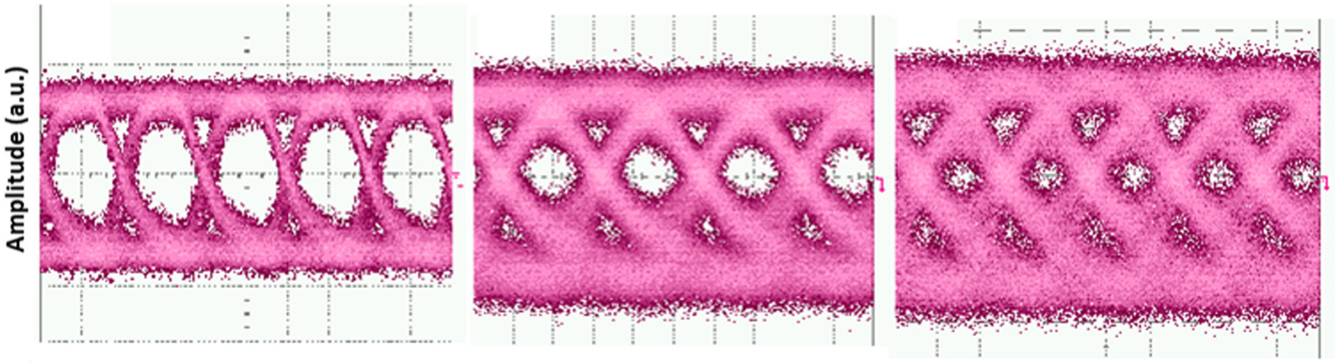
Fig. 6 Collimated laser fired underwater from node to node in harbor type water, over a ∼1-m distance.

eye-diagram data transmission experiments were carried out underwater. In order to measure the bandwidth, the device was driven with a bias current from a constant current source which was combined with an RF signal from a network analyzer to produce a modulated laser output signal. Light from the laser diode was collimated and directed to a high-speed silicon PIN photoreceiver. The underwater path setup was 1.7 m in length and the frequency response measurements were carried out as a function of drive current.[12]

For both the air path and water path measurements, the optical −3 dB bandwidth values above the laser threshold (at ∼100 mA) are very similar, showing that the intervening water path has no effect on the bandwidth values. The maximum bandwidth value achieved using this device was 883 MHz at 120 mA.

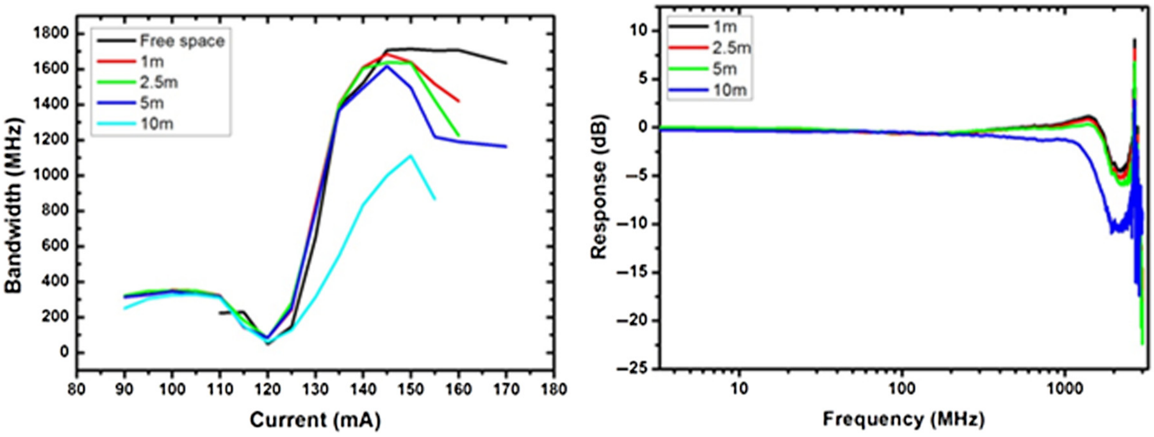
The relative openness of the "eyes" is a standard measure of the quality of data transmission. A data rate of up to 2.488 Gbit/s under water can be measured, despite the relatively noisy eye diagram (due to the modulation rate approaching the bandwidth limit of the photoreceiver), there is still sufficient distinction between pulses to resolve the "eyes" of the signal—a visual indication that data transmission is achievable (see Fig. 7). Ultimately, the bandwidth of an underwater optical communication scheme will be limited for longer ranges and higher turbidity levels.

These results show the potential of AlGaInN laser diodes for high-speed data transfer underwater, but also their potential for use in POF. High-speed measurements were conducted through varying lengths of 1-mm diameter step-index POF (SI-POF). A different laser (from the same batch) emitting at a wavelength of 429 nm was used to conduct frequency response measurements through the fiber. Fiber lengths of 1, 2.5, 5, and 10 m were tested in order to see the trend of bandwidth against fiber length. This



(a) (b) (c)

Fig. 7 Eye diagrams showing data transmission for a signal transmitted through water at (a) 1 Gbit/s at 125 mA laser drive current, (b) 2 Gbit/s at 132 mA, and (c) 2.488 Gbit/s at 132 mA.



(a)

(b)

Fig. 8 (a) Current versus bandwidth for varying lengths of SI-POF and (b) fiber response as a function of length.

device had a −3-dB bandwidth of 1.71 GHz in free space and could achieve error-free data transmission at 2.5 Gbit/s, in a similar manner as reported above. The maximum bandwidth values achieved for transmission through 1, 2.5, 5, and 10 m of fiber were 1.68, 1.63, 1.62, and 1.1 GHz, respectively. This can be seen in Fig. 8.

By subtracting the free-space response from measured through different lengths of fiber, the fiber response can be obtained and dispersion analysis carried out. (It should be noted that the laser diode is not optimized for high-frequency operation nor is the laser diode optimized for fiber coupling.) In Fig. 8(b), the bandwidth of a fiber of 10 m has dropped to 1.38 GHz, due to modal dispersion. The dispersion increases as the wavelength decreases and these figures predict values in excess of 10,000 ps/nm.km. Ultimately, these high dispersion coefficients below 430 nm will limit the transmission distance when working at this wavelength.[13]

In conclusion, we show Gigabit data transmission using a GaN laser diode in free-space, underwater, and through POF. Different underwater scenarios were tested using a scattering (Maalox) solution that resembles a turbid coastal or harbor region. This work shows the potential for realistic high-bandwidth, laser-based underwater optical communications links using GaN laser diode technology.

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Henry White joined the Sowerby Research Centre of British Aerospace in 1983, which became the Advanced Technology Centre of BAE Systems in 2000. In 2015, he took up the position of lead technologist sensing within the Military Air & Information part of BAE Systems. Technical expertise covers fiber optic digital communications, EO sensor technologies, novel imaging systems, high power laser systems, optical wireless communications, and underwater optical systems.

Scott Watson graduated from the University of Glasgow and received his BE degree in electronics with music in 2011. He recently finished his PhD in the School of Engineering at the University of Glasgow, where his main area of research has been visible light communications using LEDs and laser diodes. He is now continuing to work at the University of Glasgow as a postdoctoral researcher.

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