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AlGaInN laser diode technology for systems applications.

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Abstract

Gallium Nitride (GaN) laser diodes fabricated from the AlGaInN material system is an emerging technology that allows laser diodes to be fabricated over a very wide wavelength range from u.v. to the visible, and is a key enabler for the development of new system applications such as (underwater & terrestrial) telecommunications, quantum technologies, display sources and medical instrumentation.

Introduction

One of the major limiting factors in nitride laser diode and laser array 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 [1,2].

A typical AlGaInN laser diode epitaxy structure grown by 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 x3 (3.5/9 Å) - the indium composition x (x=0.05-0.2) 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 LD's, 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 LD's are HR coated (5x 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.

The LIV and the beam profile characteristics for a 2µm ridge waveguide LD structure packaged in a TO5.6mm package are shown in figure 1a). The device has an optical power of ~80mW, threshold current of ~65mA, a threshold voltage of ~5 V, a lasing wavelength of 410nm, 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) [3].

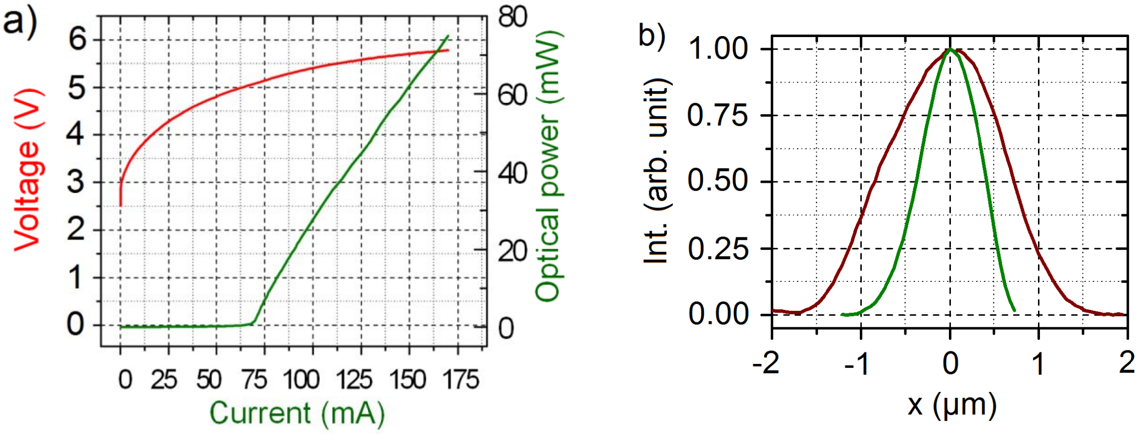

Fig.1 AlGaInN 410nm laser diode characteristics, a) LIV , b) Near-Field (slow axis – red line, fast axis – green line).

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

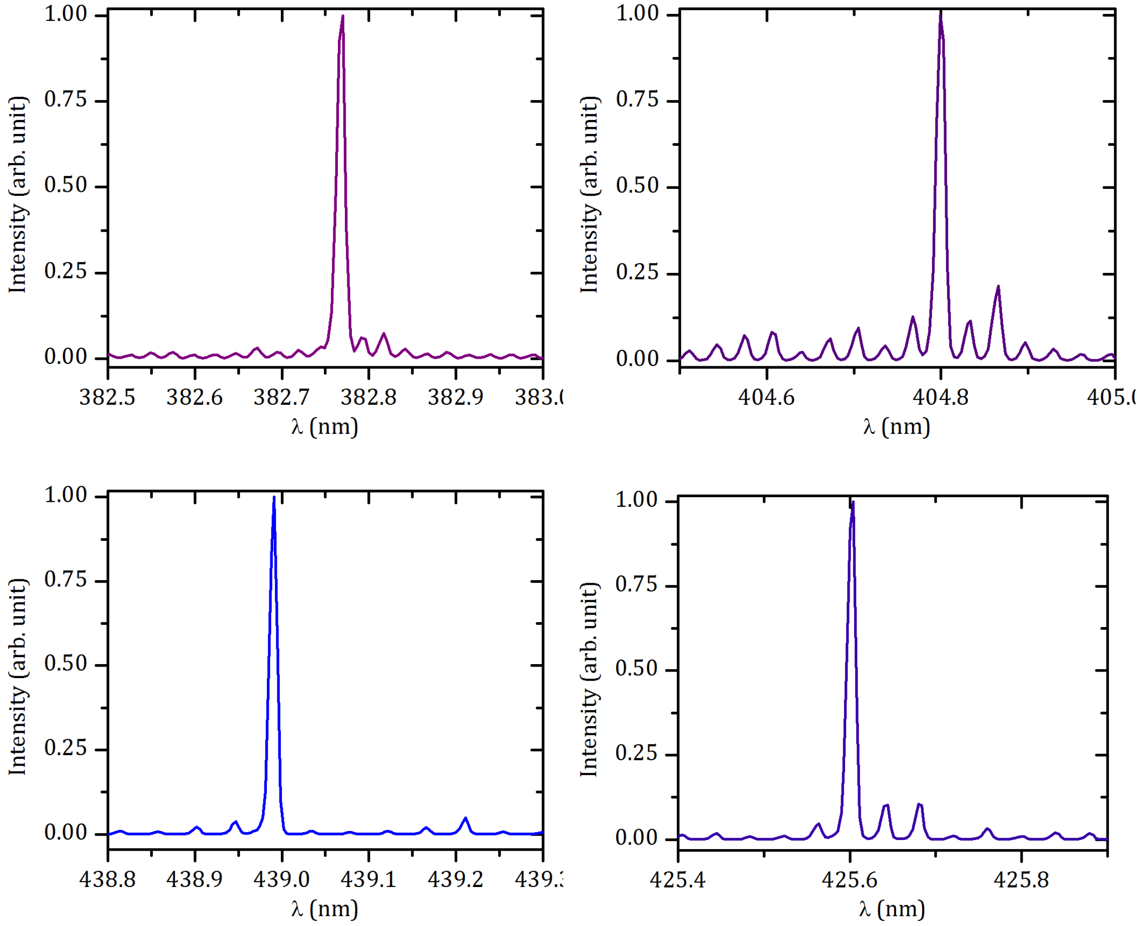

Figure 2: High resolution spectra of 4 different LD's with QW indium compositions $In_xGa_{1-x}N/In_{0.02}Ga_{0.98}N$ QW's of x=0.05, 0.08, 0.12 & 0.16 giving a wavelength emission of ~382nm, ~405nm, ~425nm, ~439nm at ~10mW cw, 20^0C

High resolution spectral measurements of the AlGaInN LD's reveal the fine mode structure with a characteristic dominant single longitudinal mode in all of these devices more reminiscent of a DFB type of laser device with etched grating, providing optical feedback for mode selection, rather than a more standard 'mode comb' Fabry-Perot device with no etch grating.

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

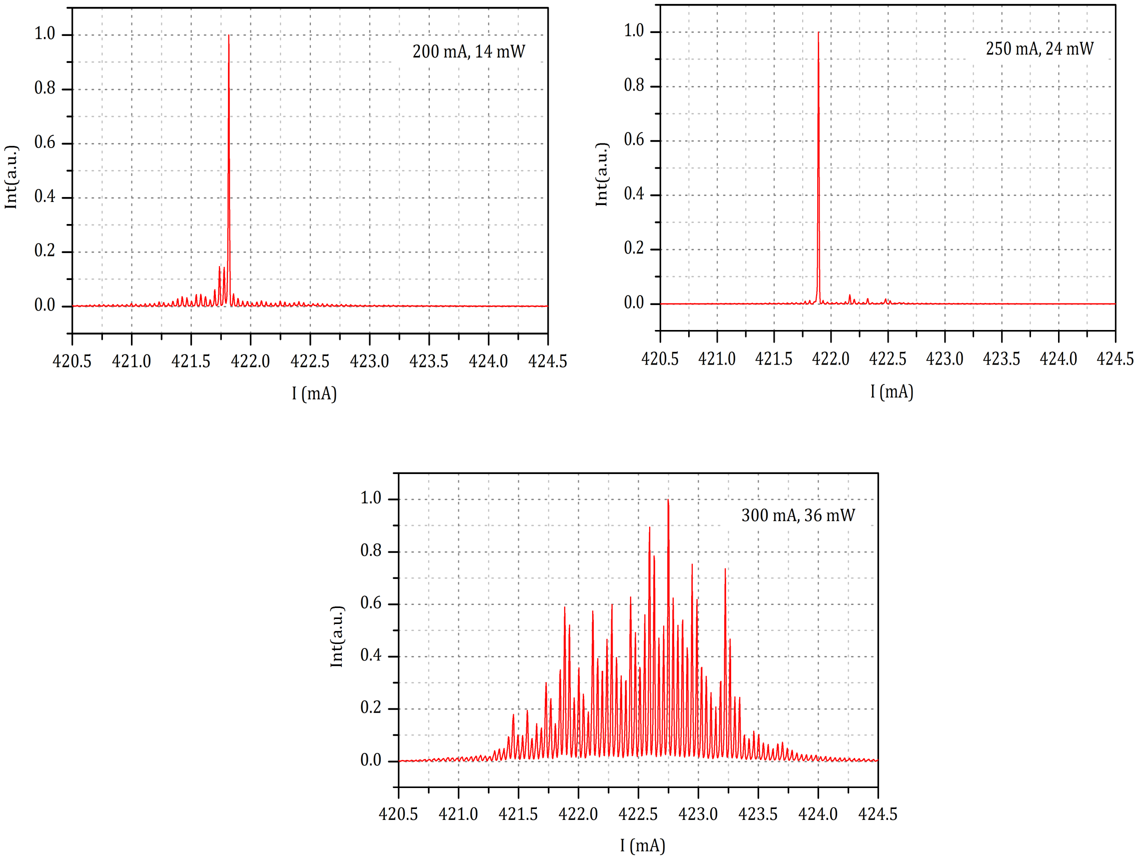

Fig 3 The evolving spectra of a LD's vs increasing drive current mA/optical power mW (cw) at 20^0C

Similar single longitudinal mode characteristics has also been observed in the spectral output of other AlGaInN laser diodes and was explained by surface roughness inadvertently introduced during growth [4] and that the single mode is stabalised by longitudinal mode competition caused by optical gain saturation [5]. Similarly we observe a surface topology of the order of ~10nm in height and a periodicity of 100nm, eventhough the epitaxy growth is done on very low defectivity ($<5x10^4cm^{-2}$) GaN substrates with a flatness of <0.1nm [6], the surface topology features appear inadvertantly in the last epitaxy layer of growth.

There is considerable interest in using GaN laser technology for next generation atomic optical clocks based on Sr (meeting the $_{88}Sr_{+}$ cooling transition [$5s_2S_{1/2}$ -$5p_2P_{1/2}$]by using 422nm & 461nm) and a blue cooling transition for Rubidium (Rb) [$4p_6 5s_2 S_{1/2}$ - $4p_6 6p_2 P_{3/2}$] at 420.2nm). Very narrow linewidths (<1MHz) are required for such applications, however in the present GaN LD's, the single longitudianl mode structure is not stable enough as a function of drive current or temperature and the mode will tend to jump. Ideally, a GaN DFB laser with an integrated etched grating to stabalise the mode would be considered, however there are significant technical challenges to overcome before a GaN DFB laser can be realised. Therefore, in the short term, for stable mode performance, a GaN laser diode in an extended cavity (Littrow configuration) has to be considered for atomic clock applications.

The wide wavelength range available to AlGaInN laser diodes allow potential interesting applications including, free-space, underwater and plastic fibre telecommunication. Free space data transmission measurements were carried out using GaN blue laser diodes. Eye diagrams, measured using an Agilent 86105B digital sampling oscilloscope (DCA), are shown in figure 4. High frequency data transmission at 1.1 Gbit/s was measured for a laser drive current of 115mA and 2.5Gbit/s for 120mA, at which the best Q factor margins are achieved [7].

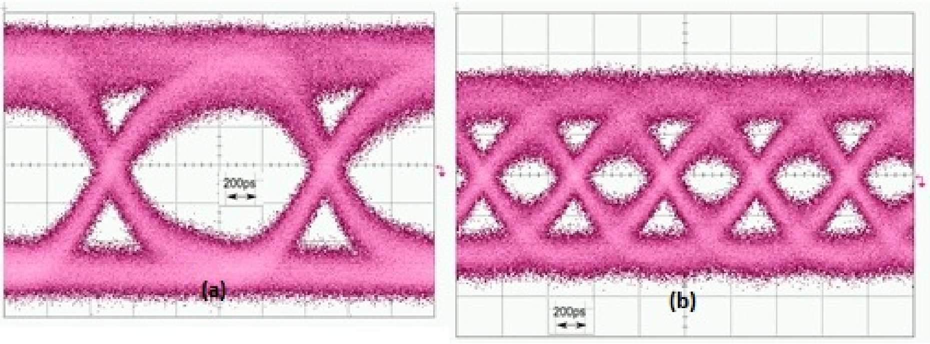

Figure 4. Eye diagrams at (a) 1 Gbit/s and (b) 2.5 Gbit/s at photo-receiver output.

High-frequency data transmission under water at similar Gbit/s rates (see figure 5) has also been measured using a 422nm GaN laser diode demonstrating the suitability of GaN system technology for underwater sensing and communications [8].

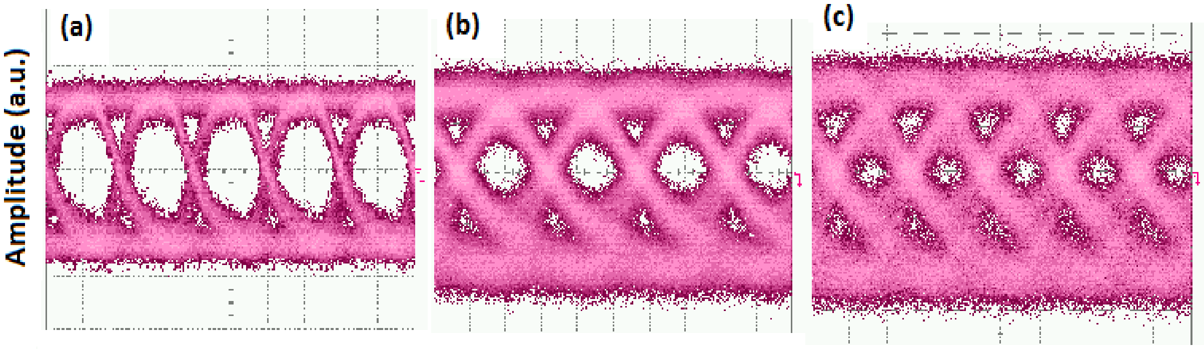

Figure 5: Eye diagrams showing data transmission for a signal transmitted through water at (a) 1 Gbit/s at 125 mA drive current, (b) 2 Gbit/s at 132 mA and (c) 2.488 Gbit/s at 132 mA.

These results show the potential of AlGaInN laser diodes for use in plastic optical fibre (POF). High speed measurements were conducted through varying lengths of 1mm diameter step-index plastic optical fiber (SI-POF). A 429nm laser diode was used to conduct frequency response measurements through the fiber lengths of 1 m, 2.5 m, 5 m and 10 m versus bandwidth. This 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 m, 2.5 m, 5 m and 10 m of fiber were 1.68 GHz, 1.63 GHz, 1.62 GHz, and 1.1 GHz, respectively. This can be seen below in Figure 6.

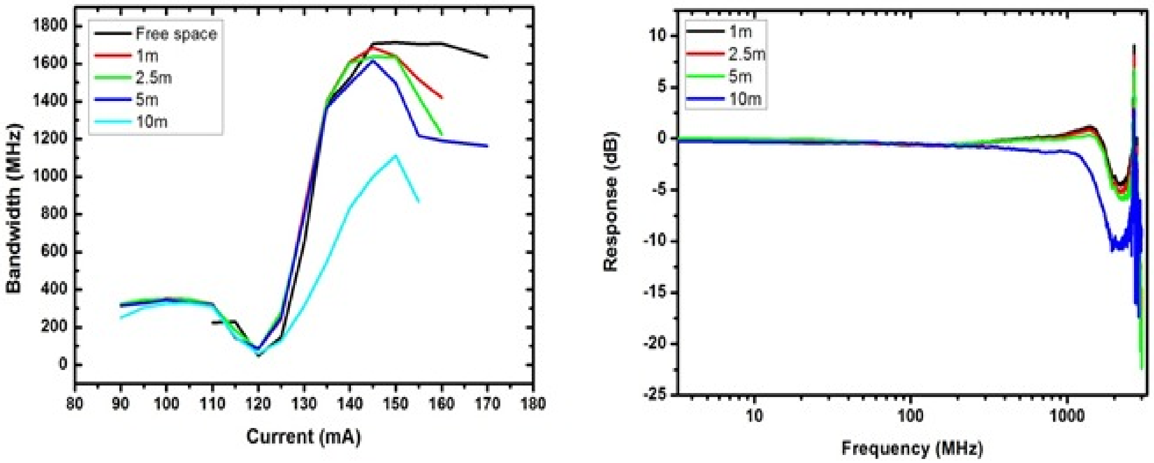

Figure 6: (a) Current vs bandwidth for varying lengths of SI-POF and (b) Fiber response as a function of length.

The wide wavelength range of the AlGaInN material system, from the u.v. to visible, is of interest for novel medical applications and has allowed a photonic system to be developed for the early detection of oral cancer based on illuminating oral tissue using the wide wavelength range and imaging the bio-fluorescence for cancer at a matching excitation wavelength. The wavelength of the laser has to be tunable as the matching wavelength depends on the person, type of illness and the presence of other chemicals [9].

An alternative system application for nitride lasers is for display applications. A highly compact RGB laser light module (with an integrated AlGaInP red laser, AlGaInN green and blue lasers) was developed as a light source for pico-displays. The RGB laser light module can be further integrated with electronics and micro-optics in a hermetically sealed package [10].

An advantage of low defectivity and high uniformity GaN substrates allows the fabrication of GaN laser bars for high power and /or optical system integration applications. The packaging of GaN laser bars has to be carefully considered to achieve high performance otherwise issues such as thermal roll-over, non-uniform current injection, catastrophic optical damage etc., can limit the performance of the bar [11].

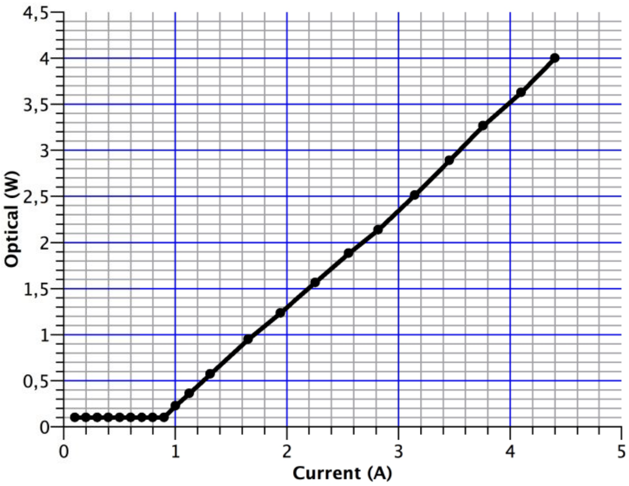

Fig. 7 The optical power vs. current (A) for a 395nm GaN laser bar packaged in a CS mount.

4W of optical power was obtained at 4.4A for a 395nm GaN laser bar mounted in a common p-contact CS mount configuration (see fig.7). The uniformity of emitter performance across the GaN laser bar is shown in figure 8.

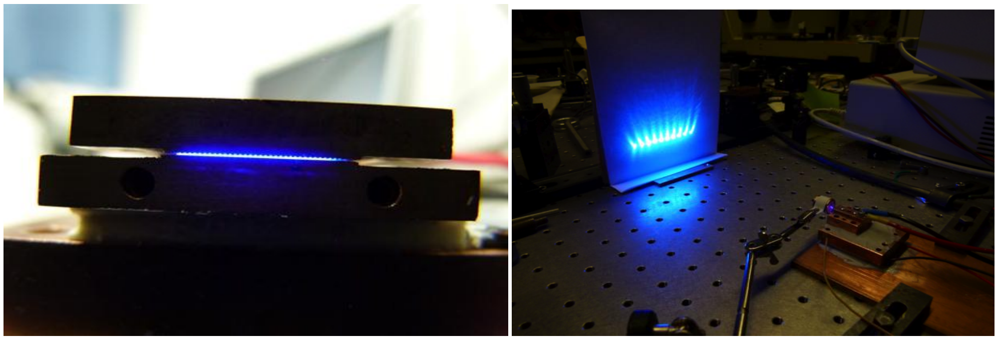

Figure 8 GaN laser bar in operation demonstrating uniformity of performance.

An alternative configuration for a GaN laser array allows for each individual laser element to be individually addressable, allowing complex free-space and/or fibre optic system integration to be developed over the u.v.-visible spectral range (see figure 9).

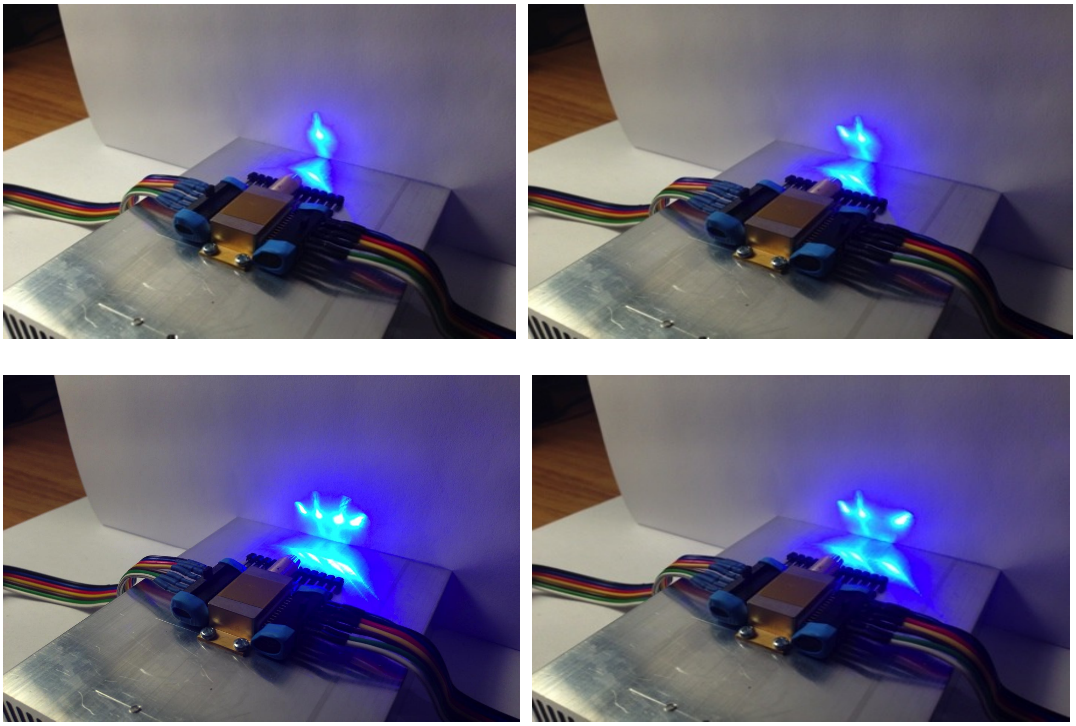

Figure 9 Individually addressable laser array in operation.

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