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Blue InGaN Lasers for Sensing and other Applications

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Abstract: InGaN diode lasers emit green, blue and violet wavelengths depending on the ratios of Indium, Gallium and Nitrogen atoms. Lasers with a lower fraction of Indium are commonly referred to as GaN lasers. Since around 1995, low-power GaN lasers have served as milliwatt light sources in Blu-ray players. Medium-power multimode lasers, capable of up to 50 Watts output, are employed for cutting and joining plastic and polymer materials. The short wavelengths of these lasers enable high-resolution imaging and sensing, making blue and violet lasers particularly valuable in microscopy and biomedical applications. In industrial contexts, high-power blue lasers emitting at 450 nm have become crucial for manufacturing batteries used in electric cars and airplanes. Currently, infrared solid-state and fiber lasers, pumped by infrared diodes, dominate applications such as drilling, cutting, welding and soldering. However, the significantly higher absorption of blue and green wavelengths by copper and other non-ferrous battery materials enhanced production efficiency. This has spurred the development of high-power blue lasers specifically for manufacturing tasks. The 450 nm wavelength of blue lasers results in more collimated beams compared to infrared counterparts, due to reduced diffraction. Combining laser beams from hundreds of single blue diodes by simple stacking allows the creation of laser systems with continuous output powers in the multiple kilowatt range. In pulsed operation, peak powers of up to 10 kW can be achieved. The compact nature of direct electrical excitation systems further enhances the appeal of blue lasers over fiber lasers in certain applications.

Keywords: GaN, InGaN, Laser diodes, Sensing applications, Broad area lasers, Stacking, High power laser systems.

1. Introduction

Blue-violet diode lasers based on GaN, with wavelengths around 405 nm, were initially developed for reading digital information from Blu-ray discs. In general, GaInP lasers cover a wavelength range from approximately 375 to 530 nm. Blue broad-stripe diodes emitting at 450 nm, with output powers up to 5 Watts, are utilized in projection systems and other applications. Higher powers are needed for material processing, which has led to stacking or spatial multiplexing of broad stripe laser emitters into modules capable of delivering more than 50 W. Laser bars are more compact and offer similar power levels as these modules. Multiplexing of modules or laser bars enables the construction of continuous-wave (cw) laser systems with outputs of 2 kW, with pulsed operation potentially achieving even higher powers.

Recently, high-power GaN lasers have found increasing use in material processing, particularly for the welding and soldering of copper. Despite the unique advantages of blue wavelengths over infrared (IR) in these applications, certain challenges remain to be addressed. This article provides an overview of the evolution of GaN lasers, tracing their commercial origins from 1-mW light sources in Blu-ray players to today's multi-kW systems. Notably, power efficiencies of up to 40 % and lifetimes exceeding 50,000 hours have been demonstrated [1].

In 2014, The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources". Their long-lasting research on GaN paved the way for the development of blue laser diodes at Nichia Ltd. in Japan.

2. Single Mode Laser with mW Power

A simplified sketch of an $In_xGa_{x-1}N$ laser emitting a cylindrical single transverse mode is shown in Fig. 1.

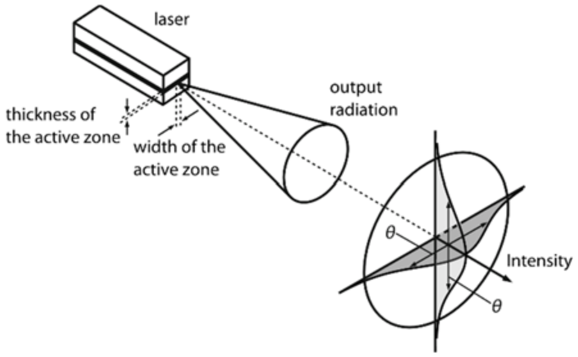

Fig. 1. A laser with a sufficiently small width of the active zone emits a beam with a circular, near-Gaussian intensity distribution with about equal divergence angles θ in the directions parallel and perpendicular to the active (gain) zone.

The chip structure of the laser diode typically consists of a substrate, such as InGaN, and several epitaxial layers including a light-generating quantum well layer of less than 10 nm thickness. Additional layers for wave guiding, current distribution, and metal contacts are also integrated. The chip design must enforce fundamental mode operation by ensuring lateral confinement of the laser beam, which is crucial for achieving the desired beam quality.

A very low threshold current is essential for these devices, as they often operate at high pulse frequencies and are thus usually biased near the threshold current. Achieving a low threshold current involves designing the mirrors with approximately 99 % reflectivity on the high-reflectivity (HR) side and about 90 % reflectivity on the output-coupling side.

GaN laser diodes were first widely applied in 1995 as light sources in Blu-ray players, emitting at 405 nm wavelength. This application requires low output power but demands single transversal mode operation (also referred to as fundamental, ground or basic mode) to ensure high beam quality [2, 3].

In the low output power range, single-mode lasers are also critical for near-to-eye projection systems used in augmented reality (AR) and virtual reality (VR) scenes where red, green and blue light sources are required [1].

The laser beam quality K of a cylindrical beam is reciprocal to the divergence angle θ and the beam waist radius w at the output facet. Therefore, the Beam Parameter Product BPP = w · θ is introduced. BPP is related to the beam propagation factor as follows:

$$M^2 = \pi \cdot \mathrm{BPP} / \lambda = 1/K \qquad (1)$$

The best possible beam quality is K = 1 corresponding to a Gaussian intensity distribution of the fundamental transverse mode (TEM_{00} beam) with $M^2 = 1$.

3. Broad-area Single Emitter Laser Diodes

Blue diode laser chips are supplied by different companies such as Osram Corporation. Material parameters of GaN compared to GaAs are given in [1]. The GaN melting temperature amounts to 2500 ˚C and the surface hardness to 1200-1700 kg/mm^2. Melting point and hardness are twice as high as for GaAs. Fig. 2 illustrates the schematic design of our diode laser chips with the following characteristics:

- Laser chip dimensions: 3 to 4 × 0.5 mm;
- Type: Broad-area (or wide stripe) laser;
- Emitting stripe width: 20 µm (up to 50 µm);
- Front facet reflectivity: 1-5 %;
- Wavelength: 450 nm, range ±10 nm;
- Spectral linewidth: ~2 nm @ 3 W;
- Chirp: ~0,06 nm/K;
- Cooling water temperature: 20-30 °C;
- Threshold current: 300 mA;
- Maximum cw power: 5 W;
- Maximum cw efficiency: 40 %.

4. Laser Modules and Laser Bars

Single emitter diodes are stacked parallel (spatial multiplexing) to form so-called modules (consisting of 5 to 10 individual emitters) to increase the total output power. Diode chips are installed in module boxes, as shown in Fig. 3.

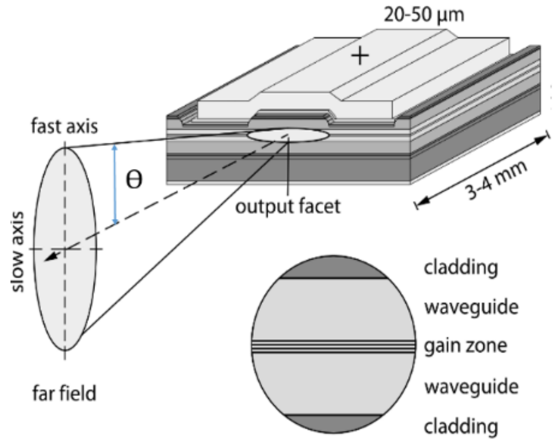

Fig. 2. General scheme of a broad-area diode laser with far field beam profile and sketch of the active waveguide structure. Due to the large width of the gain zone, the beam divergence angle θ in the slow axis direction is smaller than the fast axis divergence angle of an elliptical beam [1, 2].

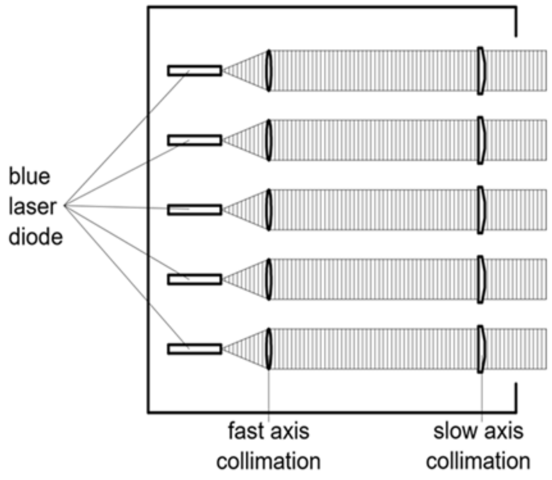

Fig. 3. Laser module consisting of five stacked single emitter diodes in a vacuum box. Cylindrical or aspherical lenses are used for collimation. Stacked laser beams pass a vacuum-tight window resulting in an increased power output of 50 W or more with a sufficient number of single emitter diodes.

Since the effective beam width of a laser module is large compared to the width of a single emitter diode, the beam parameter product BBP increases, and hence, the brightness (or brilliance) decreases.

High power output from a laser chip can also be achieved using laser bars, which typically consist of an array of single emitters. For example, a laser bar might include 23 emitters, each 400 µm wide, resulting in a total bar width of 9.2 mm and a cavity length of 1.2 mm on a single chip. A maximum output power of 107 W at 70 A was achieved from a single bar before thermal rollover. Additionally, a peak efficiency of 44 % was recorded at 90 W and 40 A [1]. Similar performance has been observed with broad-area single emitter lasers when stacked into modules.

5. Stacking Modules to kW Systems

The laser beams from multiple modules can be combined into a main beam using various multiplexing methods, as depicted in Fig. 4. We employed spatial multiplexing, similar to the approach used in stacked modules. This technique of stacking blue laser beams enables the creation of high-power laser systems. For example, blue cw laser systems have been developed with output powers of up to 2 kW.

In one setup, a laser beam transmitted through a 200 µm diameter fiber achieved a circular shape with an output power of 1.65 kW and a BPP of 20 mm·mrad. Operating the laser system at a lower power of 1.5 kW resulted in a BPP of 16 mm mrad, indicating improved beam quality (see Fig. 1). Higher powers up to 4 kW transmitted by a 600 µm fiber have been obtained by Laserline GmbH combining 10 bars.

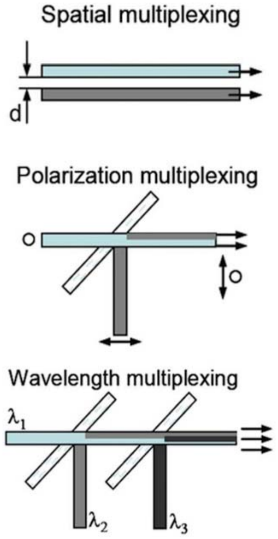

Fig. 4. Schematic multiplexing setups for laser beam combination [4].

Blue kW laser systems have been demonstrated by various providers, as summarized in Table 1. TRUMPF GmbH utilized broadband single emitters, which were stacked as shown in Fig. 3 to form modules. These modules were then further stacked or spatially multiplexed. The resulting beam was fed into a 200 µm diameter optical fiber, producing a circular output beam.

The output powers listed in Table 1 range from 1 to 4 kW. The highest power of 4 kW was achieved using a 600 µm transfer fiber. This large diameter results in the highest BPP of 30 mm·mrad and the lowest beam quality factor K ≈ 0.005 (see Eq. (1)). In contrast, the lowest output powers of about 1 kW were obtained with smaller BPP values leading to higher beam quality factors of approximately K ≈ 0.01. This relationship is expected, as K depends on the beam geometry.

Table 1. Key parameters of blue kW laser systems from different providers. The data of Laserline were given in a press report from May 31,2023. The data of Nuburu are given in an Internet report about the device Nuburu Bl-F™.

Provider	**Max. cw power after fiber**	**Beam Parameter Product, fiber diameter**	***Brightness*** $\mathrm{L} = \pi^2 \cdot L$ **W/(mm*mrad)**
TRUMPF	1.15 kW	16 mm·mrad, 200 µm	4.5
TRUMPF	1.65 kW	20 mm·mrad, 200 µm	4.1
Laserline	4 kW	30 mm·mrad, 600 µm	4.4
Nuburu	1 kW	15 mm·mrad, 200 µm	4.4

Already in 2020, Nuburu reported a power of 1.5 kW with a BPP of 12 mm·mrad [5]. Additionally, Laserline GmbH in cooperation with Osram GmbH presented a 1000 W diode laser system emitting at 450 nm [6]. The beam from this system was coupled into and transmitted through a 1000 µm diameter optical fiber.

Besides the output power *P* also the brightness *L* of a laser beam is important for applications [2]. For a round or cylindrical laser beam behind the coupling fiber, *L* is defined as follows:

$$L = \mathrm{P}/(\pi\cdot \mathrm{w}\cdot\theta)^2 = \mathrm{L}/\pi^2 \qquad (2)$$

The average practiced brightness L of the lasers listed in Table 1 is L = (4.4 ± 0.2) W/(mm·mrad)^2. We observed no significant difference in the performance of the kW laser system from TRUMPF, which was built using single broad-area laser emitters, compared to the results from Laserline and Nuburu, which utilized laser bars. Further investigations are necessary to enhance the power and brightness of the laser systems listed in Table 1.

For comparison, as early as 2019, Laserline reported powerful IR diode laser systems with wavelengths around 1 µm, offering standard outputs of up to 45 kW. The development of high-power laser systems in the IR range has primarily focused on dense wavelength multiplexing (DWM) systems, employing laser bars composed of multiple single emitters.

However, it is important to note that the failure rate of single blue lasers is higher than that of GaAs semiconductor lasers. Consequently, defective single lasers within a blue bar are anticipated. This issue can be mitigated by using selected and stacked single broad-area emitters instead of laser bars.

6. Power Limitation and Overpulsing

The output power of laser diodes is constrained by reversible rollover at high excitation currents [7], as well as by irreversible damage to the semiconductor waveguide and catastrophic optical mirror damage (COMD) [8, 9]. COMD occurs abruptly at a specific excitation current, leading to sudden failure. Thermal COMD suggests that significant power increases are possible in pulsed mode, where heating is generally much lower than in cw operation. However, non-thermal effects such as nonlinear absorption and other optical nonlinearities may also influence performance.

For a rough estimate, if the duty cycle is 10 %, the average temperature rise should be approximately 10 % of that in cw operation. This would imply that the peak current could be up to 10 times higher than the maximum permissible cw current, potentially leading to a tenfold increase in power. Thus, the maximum peak power during pulsed operation could be proportional to the inverse of the duty cycle. This rule is presumed to be valid only within certain limits of the laser output parameters.

High peak powers in pulsed operation can be achieved with multiple overpulsing at short pulse durations and low duty cycles. This has primarily been demonstrated with IR GaAs lasers [10-12]. For instance, the Ferdinand-Braun-Institute in Berlin has successfully overpulsed a single broad-stripe diode 8 times, achieving a peak power of 55 W with a 300 ns pulse duration.

Similar performance is anticipated for blue diode lasers. Consequently, it is expected that the multi-kW powers of continuous systems (Table 1) could be increased to over 10 kW in peak power during pulsed operation.

7. Applications of GaN Lasers

Blue GaN lasers, initially used in Blu-ray players, are now essential in fields such as medical diagnostics and treatment, illumination, projection, and environmental monitoring. Additionally, their advancement to high-power versions has made them vital for various material processing applications. The following sections will explore the diverse uses of GaN-based laser sources in detail.

Lasers for Blu-ray discs and data storage

The extensive commercial use of blue InGaN lasers began with their application as milliwatt light sources in Blu-ray players [13]. Blu-ray movies were first introduced in 2006, and by 2012, twelve million Blu-ray players were in consumer hands. However, with the rise of streaming services, the demand for Blu-ray discs and players appears to be saturating due to strong competition from digital downloads.

Blu-ray players utilize violet lasers at 405 nm wavelength, in contrast to the 780 nm wavelength used in CD players and the 650 nm wavelength used in DVD players. These players and recorders were also used as PC drives for permanent data storage but are increasingly being replaced by solid-state drives (SSDs). Further specifications of a typical Sony laser diode for Blu-ray applications are summarized in [13]:

- Diameter of housing: 3.8 mm;
- Laser output power: max. 200 mW (cw);
- Pulsed output power: max. 400 mW (30 ns, 50 % duty cycle allows twice the power);
- Beam divergence angles (slightly elliptical): 9°/19°.

Medical sensing and laser treatment

Classical gas and solid-state lasers have been traditionally used for medical sensing applications, such as microscopy and flow cytometry [2]. However, these are increasingly being replaced by diode lasers, which enable the development of more compact diagnostic systems. InGaN lasers, in particular, are utilized for powerful fluorescence and Raman spectroscopy, aiding in cancer detection with the support of artificial intelligence (AI). Additionally, laser excitation spectroscopy is gaining traction in environmental quality monitoring [14].

In dermatology, laser treatment for skin diseases is performed using 5 W cw or pulsed dye lasers with wavelengths ranging from 400 to 800 nm. These lasers can be tuned to achieve penetration depths of up to several millimeters [2, p. 426]. Diode lasers offer the potential to construct even more convenient and versatile systems for medical treatments.

Illumination, projection systems, headlights

Currently, blue lasers in the single-digit watt range are employed for illumination applications by converting the 450 nm wavelength into various colors or white light for stage and show lighting. Automotive headlamps, which require power in the 10 W range, are commonly used in high-end vehicles.

For projection applications, such as those in business environments or cinemas, power levels of approximately 100 W per package are becoming increasingly relevant [15]. Additionally, low-power single-mode lasers are used for near-to-eye AR and VR projection, enhancing the visual experience for virtual and artificial reality scenes.

Material processing

Blue lasers with high power and brightness are increasingly important for manufacturing applications, particularly for processing materials such as copper, aluminum, and gold, which are used in the construction of batteries for electric vehicles and possibly airplanes [5, 16]. Thin copper foils and thick connectors are commonly processed for various consumer electronic devices. Currently, near-IR solid-state and fiber lasers pumped by IR diodes are used for drilling, cutting, welding and soldering. However, blue and green lasers offer significant advantages due to their higher absorption in non-ferrous materials. For instance, the absorption of blue light (around 450 nm) by copper and other non-ferrous battery materials can be over 10 times greater than that of IR light at approximately 1 µm wavelength. This enhanced absorption allows for greater production efficiencies, making high-power blue lasers increasingly relevant for manufacturing. The short wavelength of 450 nm additionally results in more collimated beams due to reduced diffraction compared to IR lasers.

Currently, blue broad-stripe diodes at 450 nm and output powers up to 5 W are available for projection systems and other applications. For material processing, higher power levels are obtained with broad-stripe laser emitters that are either stacked or spatially multiplexed into modules, achieving output powers above 50 W. More compact laser bars can deliver similar power levels. By multiplexing or combining beams from these modules or laser bars, cw laser systems with outputs of up to 4 kW can be constructed (see Table 1). Pulsed operation could potentially achieve peak powers of up to 10 kW.

Power levels of 1 kW and above are necessary for effective cutting, welding, and soldering [1]. The development of IR lasers and laser systems took several decades, with advancements in semiconductor chips, packaging technology, materials, and optics all contributing to the development of multi-kW systems. In contrast, the development of GaN-based blue lasers for power applications began after 2000 and has progressed more rapidly. Many of the building blocks developed for IR systems were applicable to 450 nm blue laser systems.

While IR lasers started with short resonator lengths of 300 µm, narrow emitters, and smaller die, they have evolved to resonator lengths of 4 to 6 mm and fill factors of 70 % or more in 10 mm wide laser bars [1]. Today's GaN lasers are still in the early stages of development compared to these features. GaN-based blue lasers for 450 nm light currently exhibit lower efficiency and total output power compared to GaAs-based IR systems. Additionally, production costs remain higher, and production yield for AlGaN devices is lower. However, GaN lasers offer the unique advantage of effective absorption of blue or UV light in materials that poorly absorb IR light [1]. Specific examples of material processing with blue lasers are detailed in references [17-20].

Pulsed high peak powers are expected to further enhance process efficiencies. By using pulsed lasers, the same processing results can often be achieved with less energy input. Pulses allow for more precise material processing, as they result in lower heating and reduce the disruptive absorption of laser light by vaporized metallic plasma. These are significant advantages over the continuous processing systems currently available on the market. Consequently, pulsed blue diode lasers are anticipated to complement cw lasers in specialized applications.

Optical excitation of solid-state lasers

Blue and green InGaN lasers are valuable for pumping Titanium sapphire (TiSa), Pr^{3+} , and other solid-state lasers, offering a simpler alternative to more complex frequency-doubled Neodymium pump lasers [21]. TiSa lasers, which emit ultrashort pulses with Petawatt peak power, are currently of great interest in basic research. InGaN semiconductor lasers, with their capability for direct electrical pumping, are expected to significantly enhance the overall efficiency of various solid-state lasers.

Sensing

GaN diode lasers emitting in the blue spectral range are commercially available and provide sufficient optical output for spectroscopic applications but suffer from non-wavelength-stabilized broadband spectral emission. To address this limitation, efforts have focused on developing tunable sources using external cavity devices with mechanically adjustable gratings. These advancements have achieved output powers of up to 500 mW with high wavelength stability, making the lasers particularly suitable for applications requiring high precision and sensitivity [22, 23].

Blue diode lasers, sometimes realized as vertical cavity surface emitting lasers (VCSELs), are utilized as biosensors based on Raman spectroscopy, where their specific wavelengths enable the detection and quantification of trace gases in the atmosphere. This capability is crucial for monitoring air quality, identifying pollutants, and ensuring environmental compliance. In the biomedical field, GaN lasers are used in fluorescence spectroscopy and imaging to excite fluorescence in biological samples, which is essential for detecting and analyzing biomolecules, cells, and tissues, aiding in early disease diagnosis.

Water quality monitoring systems also benefit from blue lasers due to their ability to detect contaminants through fluorescence-based sensing techniques. These lasers provide rapid and accurate assessments of water purity, ensuring safe drinking water and environmental health. Similarly, blue GaN lasers are employed to detect harmful substances in food products through fluorescence sensing, playing a critical role in preventing foodborne illnesses and safeguarding public health.

The industrial sector utilizes blue GaN lasers for monitoring processes with high precision, including the measurement of chemical compositions and gas concentrations. This precision is essential for optimizing manufacturing processes, enhancing product quality, and maintaining safety standards.

Blue GaN lasers are also of interest for lidar (light detection and ranging) systems in various remote sensing applications. Their specific wavelengths enable accurate distance measurements and detailed environmental mapping, particularly underwater due to low absorption. Additionally, GaN lasers are used in smart headlights in combination with modules for autonomous vehicle navigation based on lidar [24].

9. Summary and Conclusions

Blue lasers are advantageous for efficiently processing non-ferrous metals such as copper, aluminum, and gold. High efficiencies and rapid process speeds can be achieved with blue lasers in cutting, welding, soldering, and surface structuring of battery materials, necessitating laser systems that emit power in the kilowatt range. Such systems have been developed by TRUMPF GmbH by combining the beams from a large number of single broad-area diode lasers.

To construct these high-power systems, approximately 10 parallel individual emitters are mounted on a base plate within a vacuum-tight housing. The laser module also integrates collimating lenses. The beams from about 50 such modules are then combined to form the final output beam. This approach has enabled the creation of blue cw laser systems with output powers up to 2 kW. A laser beam transmitted through a 200 µm diameter fiber achieved a circular shape with an output power of up to 1.65 kW and a brightness of 4.1 to 4.5 W/(mm mrad)^2.

Further advancements have been demonstrated by Laserline GmbH in cooperation with Osram GmbH, achieving up to 4 kW of laser power with a brightness of 4.4 W/(mm mrad)^2 using a 600 µm diameter fiber. This system utilized laser bars instead of the stacked single emitter modules employed by TRUMPF.

Ongoing progress in blue diode laser technology, building on the pioneering research of Nakamura and colleagues, is expected to continue advancing the field [25]. Applications of blue diode lasers, ranging from low to high power, are broadening, particularly in industrial processing.

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