Gallium Nitride Light Sources for Optical Coherence Tomography

Graham R. Goldberg*[a], Pavlo Ivanov[a], Nobuhiko Ozaki[b], David T. D. Childs[a], Kristian M. Groom[c], Kenneth L. Kennedy[c] and Richard A. Hogg[a]
[a]School of Engineering, University of Glasgow, Rankine Building, G12 8LT, UK.
[b]Faculty of Systems Engineering, Wakayama University, 930 Sakaedani, Wakayama 640-8510, Japan.
[c]Department of Electronic and Electrical Engineering, University of Sheffield, 3 Solly Street S3 7HQ, UK.

ABSTRACT

The advent of optical coherence tomography (OCT) has permitted high-resolution, non-invasive, *in vivo* imaging of the eye, skin and other biological tissue. The axial resolution is limited by source bandwidth and central wavelength. With the growing demand for short wavelength imaging, super-continuum sources and non-linear fibre-based light sources have been demonstrated in tissue imaging applications exploiting the near-UV and visible spectrum. Whilst the potential has been identified of using gallium nitride devices due to relative maturity of laser technology, there have been limited reports on using such low cost, robust devices in imaging systems.

A GaN super-luminescent light emitting diode (SLED) was first reported in 2009, using tilted facets to suppress lasing, with the focus since on high power, low speckle and relatively low bandwidth applications. In this paper we discuss a method of producing a GaN based broadband source, including a passive absorber to suppress lasing. The merits of this passive absorber are then discussed with regards to broad-bandwidth applications, rather than power applications. For the first time in GaN devices, the performance of the light sources developed are assessed though the point spread function (PSF) (which describes an imaging systems response to a point source), calculated from the emission spectra. We show a sub-7μm resolution is possible without the use of special epitaxial techniques, ultimately outlining the suitability of these short wavelength, broadband, GaN devices for use in OCT applications.

Keywords: absorber, broadband, gallium nitride, optical coherence tomography, resolution, SLED, superluminescent,

1. INTRODUCTION

Group III-nitride semiconductors have experienced increased interest since Nakamura *et al.*, first reported a viable gallium nitride (GaN) light emitting diode (LED) in 1991 [1] and laser diode in 1995 [2]. This has led to rapid advancements in GaN growth and fabrication [3], improving crystal quality, permitting higher powers and yielding longer device lifetimes [4]-[6]. As such, short wavelength (~400 nm) LEDs and lasers are now commonplace in solid state lighting [7] and high-density optical storage systems [8]. The disclosure of a GaN superluminescent light emitting diode (SLED) in 2009 by Feltin *et al.*, with 10 mW output power and 4.6 nm bandwidth [9] expanded the list of possible applications to include pico-projectors [10] and fibre optic gyroscopes (FOGs) [11]. SLEDs are optical devices that take advantage of amplified spontaneous emission, where light is generated through spontaneous emission and experiences gain due to stimulated emission as it propagates along the waveguide; resulting in a broader bandwidth than observed in lasers and higher output powers than in LEDs. The emitted light is also directional, can be coupled to fibres and is coherent.

As pico-projectors and FOGs require light sources with high output powers and only modest (>1 nm) bandwidths, to date the development of GaN SLEDs has aimed at increasing device tolerances to high current densities, through improved thermal management and heat dissipation [12], or methods of feedback suppression to increase the lasing threshold [13]. In the quest for ever-increasing output powers, high reflectivity (HR) coatings have been applied to the rear facets of several reported SLEDs [14]. The HR coating is designed to reflect almost all backward propagating light, which then undergoes another pass through the waveguide before ideally being coupled out of the device. This increases real-estate,

Gallium Nitride Materials and Devices XII, edited by Jen-Inn Chyi, Hiroshi Fujioka, Hadis Morkoç, Yasushi Nanishi, Ulrich T. Schwarz, Jong-In Shim, Proc. of SPIE Vol. 10104, 101041X
 · doi: 10.1117/12.2252665

as it effectively doubles the cavity length, therefore increasing gain and output power; with >200 mW being achieved in continuous wave operation [15], [16]. Thus far, there has been limited drive to develop broad bandwidth (>5 nm at high current densities) devices.

Recent interest in expanding the optical coherence tomography (OCT) wavelengths beyond the traditional 800 nm and 1300 nm has produced a desire to produce broad bandwidth, short wavelength devices. OCT makes use of the coherent properties of light to conduct high-resolution, non-invasive, *in vivo* imaging of biological tissue, most notably of the eye and skin. Since OCT was first reported in 1991 by Huang *et al.*, [17] axial resolution and imaging speed have both been increased, with the former limited by the device central wavelength and bandwidth [18]. In lieu of broad bandwidth GaN SLEDs and in an attempt to access shorter wavelengths, super-continuum lasers [19] and non-linear fibre-based light sources [20] have been demonstrated. This showed *in vivo* imaging of the human skin using OCT is possible at ~400 nm and ultraviolet light is able to propagate to the dermal layer [21]. However, these are complex systems, and it has already been identified that if broader bandwidths can be reached for GaN SLEDs, sub-cellular resolution is possible [22], with an enhancement in lateral resolution also likely. Although methods of cavity suppression have been proposed [13], [23], only limited research has been conducted on the use and role of absorbers in GaN SLEDs.

Figure 1 plots the calculated axial resolution of an OCT imaging system as a function of central wavelength and -3dB bandwidth of the source. Typical commercial OCT systems and their stated resolutions are indicated along with the state of the art GaN SLEDs and their predicted resolutions.

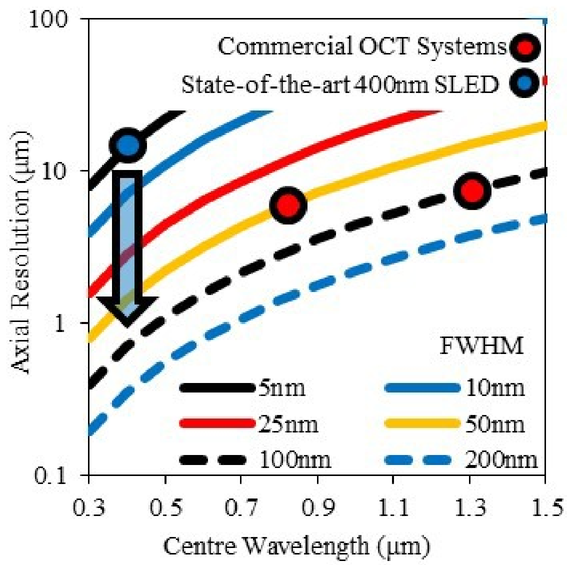

Figure 1. Axial resolution for OCT systems as a function of spectral-bandwidth and central wavelength

This graph shows that the axial resolution of an OCT system can be improved by using a short wavelength light source with a broad emission spectrum. Blue/violet optical emitters such as LEDs and lasers emit at ~400 nm. As SLEDs offer a higher optical power than LEDs and a broader optical bandwidth compared to lasers, blue/violet SLEDs could become optical sources of choice for OCT systems. In this paper we report blue SLEDs fabricated by segmenting the top contact of a GaN edge-emitting laser. Section 2 briefly introduces the laser diode fabrication steps and discusses its characteristics. Section 3 describes the process of segmenting the device top contact and its measurement results.

2. LASER DEVICE FABRICATION AND CHARACTERISTICS

A 2250 µm long, GaN optical device was fabricated from a 2 InGaN quantum well (QW) laser epi-wafer, which had been grown by metalorganic vapour phase epitaxy (MOVPE) on a 2 inch GaN substrate by Novagan [9], [12]. Shown schematically in Figure 2, it does not feature tilted facets, but instead these were fabricated perpendicular to the waveguide. W_R is the ridge width (10 µm), L is the length of the ridge (1125 µm).

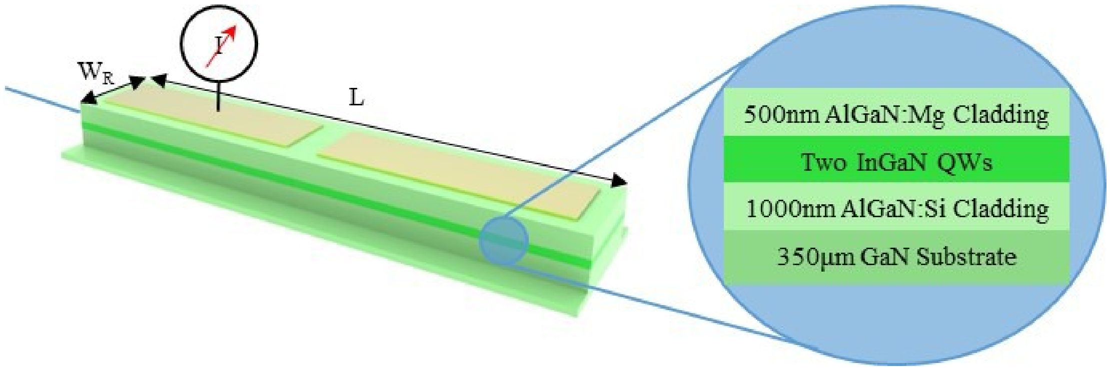

Figure 2. Schematic of GaN device

Figure 3a) plots the normalised emission spectra obtained operating the device pulsed (10 µs pulses with 2.5% duty cycle) in arbitrary units against wavelength for the device depicted in Figure 2 for 5 current densities. 1 is 2222 A/cm^2, 2 is 3333 A/cm^2, 3 is 4444 A/cm^2, 4 is 5555 A/cm^2 and 5 is 6666 A/cm^2. At ~6000 A/cm^2 lasing is observed, which quickly dominates the spontaneous emission spectrum. Figure 3b) plots the output power against current density for the power-current (LI) curve, featuring markers that denote where the emission spectra correspond to. At 7777 A/cm^2 (not shown in 3a)), the device is lasing with a -3dB bandwidth <1 nm, making it unsuitable for OCT applications.

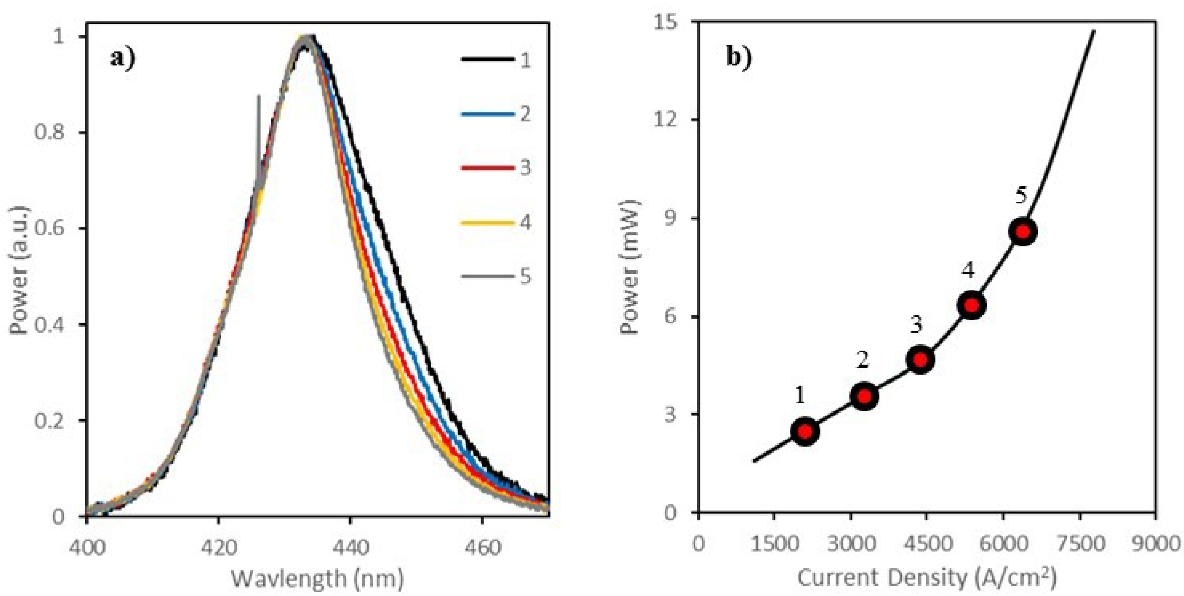

Figure 3. GaN device a) emission spectra, b) LI curve

3. DEVICE MODIFICATION AND RESULTS

A focused ion beam (FIB) was used to mill the top contact in to two halves, as shown schematically and in the scanning electron microscope image, in Figure 4. This electrically isolated the front section from the rear whilst leaving them optically connected. L_1 is the front, pumped section (1125 μm) and L_2 the rear, passive absorber section (1125 μm). W_R remains unchanged at 10 μm.

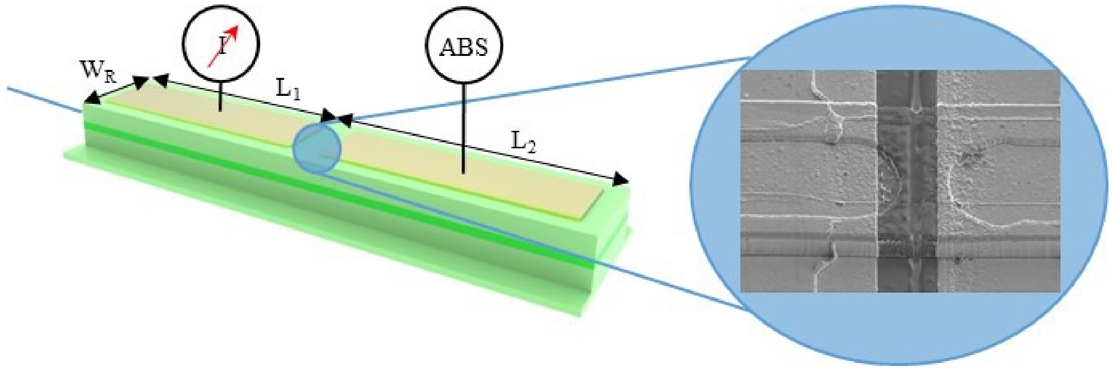

Figure 4. Schematic of GaN device after FIB milling of the top contact

Figure 5a) plots the normalised emission spectra also obtained operating the device pulsed (10 μs pulses with 2.5% duty cycle) in arbitrary units against wavelength for the device pictured in Figure 4 after the FIB milling of the top contact for 4 current densities. 1' is 2222 A/cm^2, 2' is 4444 A/cm^2, 3' is 6666 A/cm^2 and 4' is 8888 A/cm^2. The lasing threshold has been moved to >8888 A/cm^2, as evidenced by the smooth and continuous emission spectrum. Figure 5b) plots the output power against current density for the LI curve, with markers that denote where the emission spectra correspond to. The maximum measured output power is lower than before the device was modified, at ~12 mW, but that is attributed to the shorter length of the pumped section. The -3dB bandwidth of the GaN SLED at 12 mW, or 8888 A/cm^2, is ~10 nm which would offer <10 μm axial resolution as shown in Figure 1.

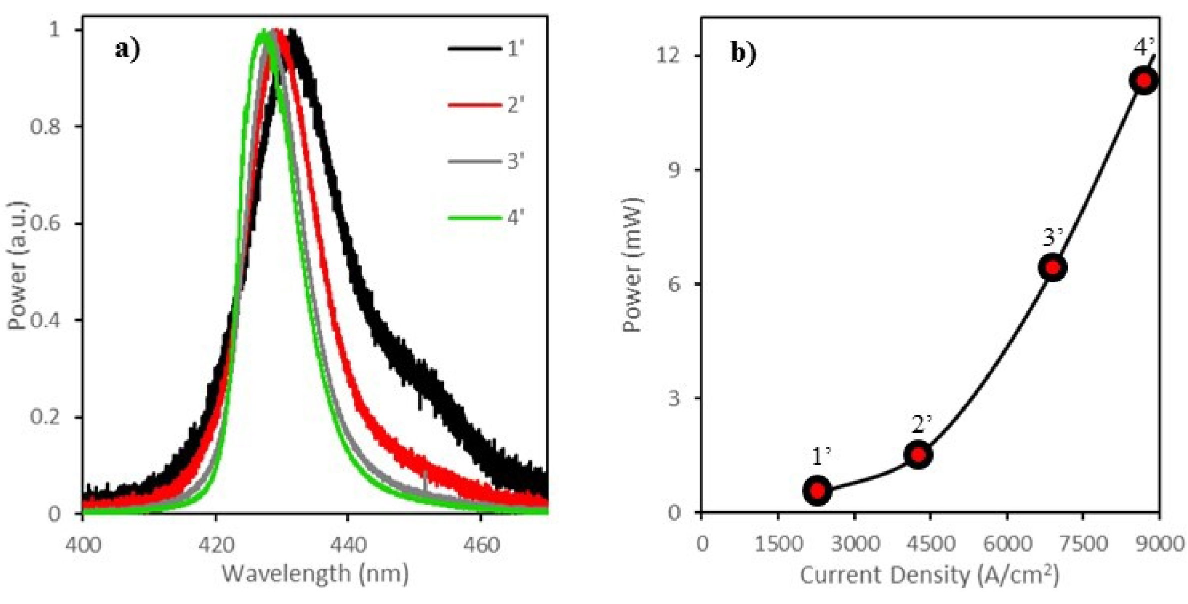

Figure 5. GaN device after FIB milling of the top contact a) emission spectra, b) LI curve

Figure 6 plots the point spread functions (PSFs), calculated from the currents 1'-4' described in Figure 5a). By performing an inverse Fourier transform on the emission spectrum [24], the waveforms in Figure 6 can be produced from those in Figure 5a). This offers a more accurate estimate of the axial resolution than the formula for coherence length used to generate Figure 1, because that formula assumes the emission spectrum forms an ideal Gaussian. It is also worth noting these functions do not exhibit side lobes and therefore demonstrate that the SLED would be suitable for OCT systems. Had there been side lobes, they would indicate a high likelihood that ghost images would appear on the output.

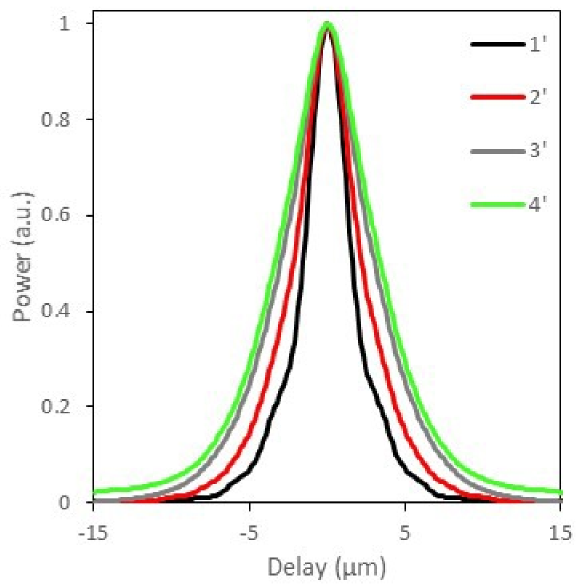

Figure 6. Predicted resolution obtained from the PSF of the emission spectra

Figure 7 plots the -3dB bandwidth against current density for the emission spectra 1'-4' in Figure 5a) on the primary axis. The secondary axis plots the predicted axial resolution calculated from the -3dB bandwidths from the PSFs in Figure 6 against current density.

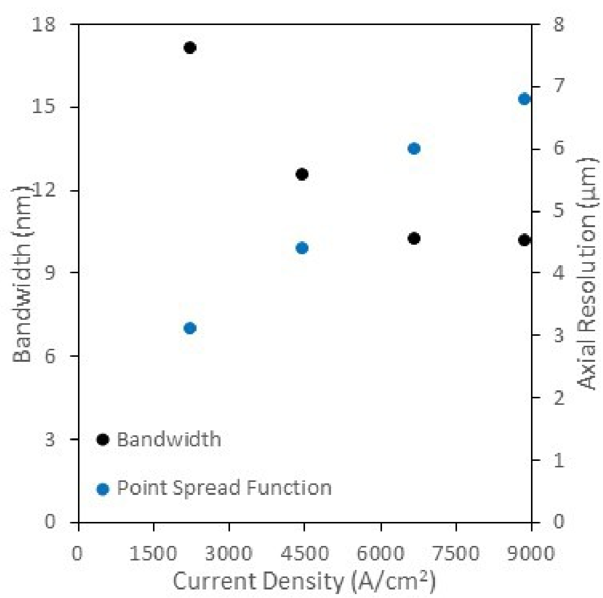

Figure 7. GaN SLED optical bandwidth and resulting estimated axial resolution of the OCT system after FIB milling

As the injection current increases, the bandwidth decreases and the axial resolution increases to ~7 μm. This effect is accompanied by the high optical power of the SLED. The axial resolution can be improved by reducing the injection current, which in turn would reduce the output power. However, this is not always the best scenario as it demands the OCT system utilising the SLED be equipped with highly sensitive detectors or suffer from a poor signal to noise ratio.

SUMMARY

A technique to broaden the bandwidth of semiconductor devices has been applied to a GaN light sources in this paper, with a view to producing broadband light sources applicable to medical imaging. We, for the first time in GaN devices, calculate the PSF from the measured emission spectra and assess device performance, demonstrating a <7 μm resolution that is competitive with current, longer wavelength, commercial OCT systems.

ACKNOWLEDGEMENT

Graham. R. Goldberg gratefully acknowledges financial assistance from EPSRC and The University of Glasgow. Assistance from Guangrui Li in figure preparation is also acknowledged.

REFERENCES

[1] Nakamura, S., Mukai, T. and Senoh, M., "High-Power GaN P-N Junction Blue-Light-Emitting Diodes," Jpn. J. Appl. Phys. Vol. 30, No. 12A, pp. L1998-L2001 (1991).

[2] Nakamura, S., Senoh, M., Nagahama, S., Iwasa, N., Yamada, T., Matsushita, T., Kiyoku, H. and Sugimoto, Y., "InGaN-Based Multi-Quantum-Well-Structure Laser Diodes," Jpn. J. Appl. Phys. Vol. 35, pp. L74-L76 (1996).

[3] Nakamura, S., Senoh, M. and Mukai, T., "P-GaN/N-InGaN/N-GaN Double-Heterostructure Blue-Light-Emitting Diodes," Jpn. J. Appl. Phys. Vol. 32, pp. L8-L11 (1993).

[4] Nakamura, S., Senoh, M. and Mukai, T., "High-power InGaN/GaN double-heterostructure violet light emitting diodes," Appl. Phys. Lett. 62, 2390 (1993).

[5] Nakamura, S., Senoh, M., Nagahama, S., Iwasa, N., Yamada, T., Matsushita, T., Sugimoto, Y. and Kiyoku, H., "Continous-wave operation of InGaN multi-quantum-well-structure laser diodes at 233 K," Appl. Phys. Lett. 69, 3034 (1996).

[6] Nakamura, S., Senoh, M., Nagahama, S., Iwasa, N., Yamada, T., Matsushita, T., Sugimoto, Y. and Kiyoku, H., "High-Power, Long-Lifetime InGaN Multi-Quantum-Well-Structure Laser Diodes," Jpn. J. Appl. Phys. Vol. 36, pp. L1059-L1061 (1997).

[7] Miyoshi, T., Yanamoto, T., Kozaki, T., Nagahama, S., Narukawa, Y., Sano, M., Yamada, T. and Mukai, T., "Recent Status of White LEDs and Nitride LDs," Proc. SPIE 6894 (2008).

[8] Kasami, Y., Kuroda, Y., Seo, K., Kawakubo, O., Takagawa, S., Ono, M. and Yamada, M., "Large Capacity and High-Data-Rate Phase-Change Disks," Jpn. J. Appl. Phys. Vol. 39, pp.756-761 (2000).

[9] Feltin, E., Castiglia, A., Cosendey, G., Sulmoni, L., Carlin, J.-F., Grandjean, N., Rossetti, M., Dorsaz, J., Laino, V., Duelk, M. and Velez, C., "Broadband blue superluminescent light-emitting diodes based on GaN," Appl. Phys. Lett. 95, 081107 (2009).

[10] Davis, W. O., Sprague, R. and Miller, J., "MEMS-Based Pico Projector Display," Proc. IEEE/LEOS Optical MEMS and Nanophotonics (2008).

[11] Böhm, K., Marten, P., Petermann, K., Weidel, E. and Ulrich, R., "Low-Drift Fibre Gyro Using A Superluminescent Diode," Electronics Lett. Vol. 17, No. 10 (1981).

[12] Rossetti, M., Dorsaz, J., Rezzonico, R., Duelk, M., Velez, C., Feltin, E., Castiglia, A., Cosendey, G., Carlin, J.-F. and Grandjean, N., "High Power Blue-Violet Superluminescent Light Emitting Diodes with InGaN Quantum Wells," Applied Physics Express 3, 061002 (2010).

[13] Kafar, A., Stanczyk, S., Grzanka, S., Czernecki, R., Leszczynski, M. and Suski, T., "Cavity suppression in nitride based superluminescent diodes," J. Appl. Phys. 111, 083106 (2012).

[14] Kopp, F., Eichler, C., Lell, A., Tautz, S., Ristic, J., Stojetz, B., Höß, C., Weig, T., Schwarz, U. and Strauss, U., "Blue Superluminescent Light-Emitting Diodes with Output Power above 100 mW for Picoprojection," Jpn. J. Appl. Phys. Vol. 52 (2013).
[15] Ohno, H., Orita, K., Kawaguchi, M., Yamanaka, K. and Takigawa, S., "200mW GaN-based Superluminescent Diode with a Novel Waveguide Structure," IEEE Photonic Society 24th Annual Meeting, pp. 505-506 (2011).
[16] Kafar, A., Stanczyk, S., Targowski, G., Oto, T., Makarowa, I., Wisniewski, P., Suski, T. and Perlin, P., "High-Optical-Power InGaN Superluminescent Diodes with "j-shape" Waveguide," Applied Physics Express 6, 092102 (2013).
[17] Huang, D., Swanson, E. A., Lin, C. P., Schuman, J. S., Stinson, W. G., Chang, W., Hee, M. R., Flotte, T., Gregory, K., Puliafito, C. A. and Fujimoto, J. G., "Optical Coherence Tomography," Science, Vol. 254, pp. 1178-1181 (1991).
[18] Shibata, H., Ozaki, N., Yasuda, T., Ohkouchi, S., Ikeda, N., Ohsato, H., Watanabe, E., Sugimoto, Y., Furuki, K., Miyaji, K. and Hogg, R. A., "Imaging of spectral-domain optical coherence tomography using a superluminescent diode based on InAs quantum dots emitting broadband spectrum with Gaussian-like shape," Jpn. J. Appl. Phys. Vol. 54, 04DG07 (2015).
[19] Drexler, W., Morgner, U., Ghanta, R. K., Kartner, F. X., Schuman, J. S. and Fujimoto, J. G., "Ultrahigh-resolution ophthalmic optical coherence tomography," Nature Medicine, Vol. 7, No. 4, pp. 502-507 (2001).
[20] Unterhuber, A., Povazay, B., Bizheva, K., Hermann, B., Sattmann, H., Stingl, A., Le, T., Seefeld, M., Menzel, R., Preusser, M., Budka, H., Schubert, Ch., Reitsamer, H., Ahnelt, P. K., Morgan, J. E., Cowey, A. and Drexler, W., "Advances in broad bandwidth light sources for ultrahigh resolution optical coherence tomography," Phys. Med. Biol. Vol. 49, pp. 1235-1246 (2004).
[21] Nakamura, S. and Hirayama, H., "Development of ultraviolet- and visible-light one-shot spectral domain optical coherence tomography and *in situ* measurements of human skin," J. Biomed. Opt. Vol. 20, 076014 (2015).
[22] Shidlovski, V. R., [Optical Coherence Tomography], Springer International Publishing, Switzerland, 505-526 (2015).
[23] Kafar, A., Stanczyk, S., Wisniewski, P., Oto, T., Makarowa, I., Targowski, G., Suski, T. and Perlin, P., "Design and optimization of InGaN superluminescent diodes," Phys. Status Solidi A, Vol. 212, pp. 997-1004 (2015).
[24] Ozaki, N., Childs, D. T. D., Sarma, J., Roberts, T. S., Yasuda, T., Shibata, H., Ohsato, H., Watanabe, E., Ikeda, N., Sugimoto, Y. and Hogg, R. A., "Superluminescent diode with a broadband gain based on self-assembled InAs quantum dots and segmented contacts for an optical coherence tomography light source," J. Appl. Phys. 119, 083107 (2016).