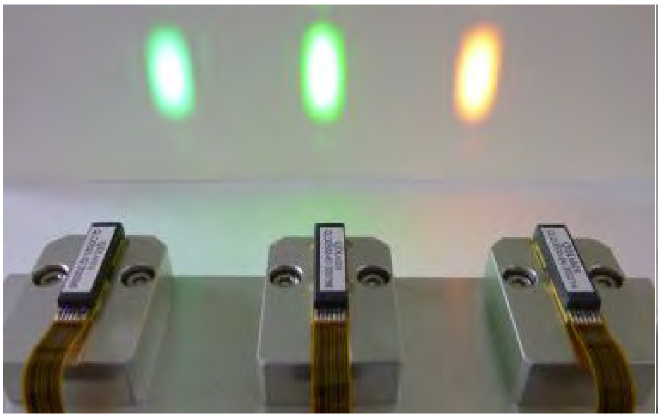
Compact Visible Lasers:

Advanced Solutions for Biomedical Applications



Introduction

Demand in the biomedical field for cell analysers such as flow cytometers and fluorescence microscopes has been steadily increasing. As these instruments have become smaller and more sophisticated, there is a growing need compact laser sources with improved functionality.

A particular challenge in this field involves generating 561nm and 594nm laser light, which cannot be directly produced by semiconductor lasers.

To address this need, QD Laser has developed and patented innovative 532, 561, and 594nm lasers that integrate a near infrared semiconductor laser and a wavelength converting nonlinear crystal in a compact flat package.

Architecture

QD Laser's compact visible laser consists of two key components:

- An integrated single frequency Near Infrared (NIR) DFB/SOA (Distributed Feedback / Semiconductor Optical Amplifier) with a "SPACER" between the DFB and SOA sections. The spacer provides a thermal barrier to prevent heat generated in the SOA section from affecting the DFB, and, under certain operating regimes, a variable optical attenuator.
- A waveguide Periodically-Poled Lithium Niobate (PPLN) nonlinear crystal which functions as a Second Harmonic Generator (SHG) to frequency-double to NIR light to visible wavelengths.

The packaged laser also incorporates a heating element beneath the DFB section along with a thermistor to monitor the temperature of the DFB. The inclusion of a heater allows the user to match the DFB section's wavelength to the PPLN's optimum efficiency under low duty-cycle operation. Otherwise, reduced internal heating would result in a shorter emission wavelength and reduced conversion efficiency.

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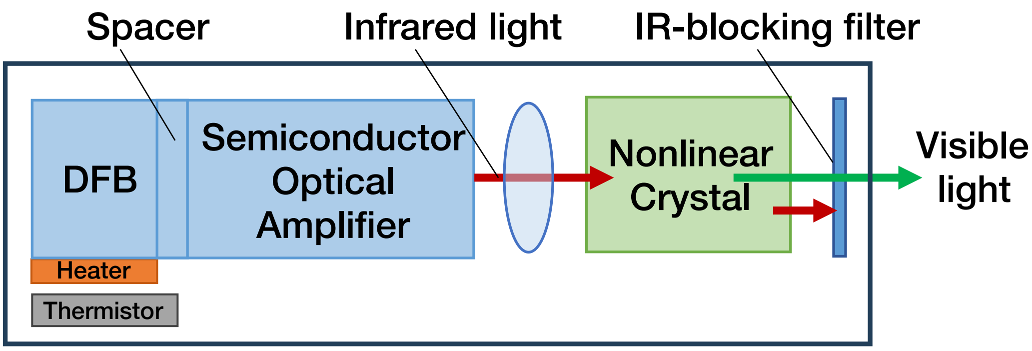
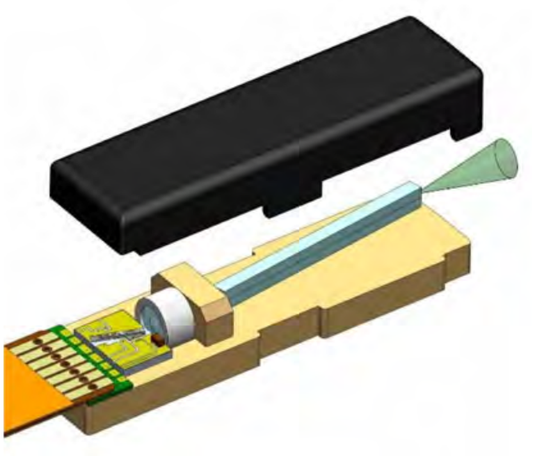


Taking the 561nm laser as an example, the system operates by first generating 1122nm infrared light through the DFB laser, which is then amplified by the semiconductor optical amplifier. This 1122nm light undergoes frequency doubling in the nonlinear crystal to produce 561nm (yellow-green) light.

Similar processes enable laser emissions at 532nm (green), and 594nm (orange) through precise combinations of DFB laser wavelengths and nonlinear crystal phase matching.



Key Features and Advantages

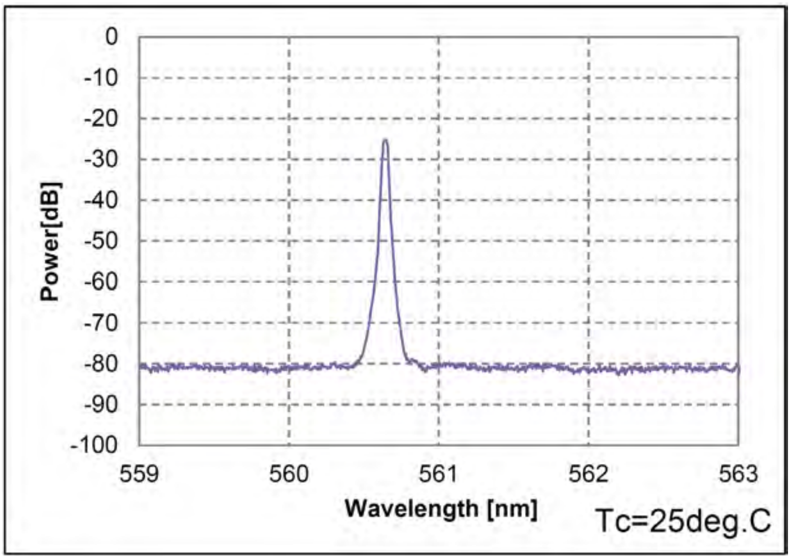
The unique and patented design of QD Laser's visible laser provides a number of significant advantages:-

- Single frequency operation
- Low wavelength temperature dependence
- High stability and low noise
- Compact package
- Low power consumption
- Near-Gaussian beam profile
- Multiple operating modes
  - Continuous wave (CW)
  - Direct SOA modulation, up to 100 MHz
  - High extinction modulation, SOA + Spacer
  - High speed modulation with Heater
  - Gain-switched picosecond pulsed DFB operation

Single Frequency Operation

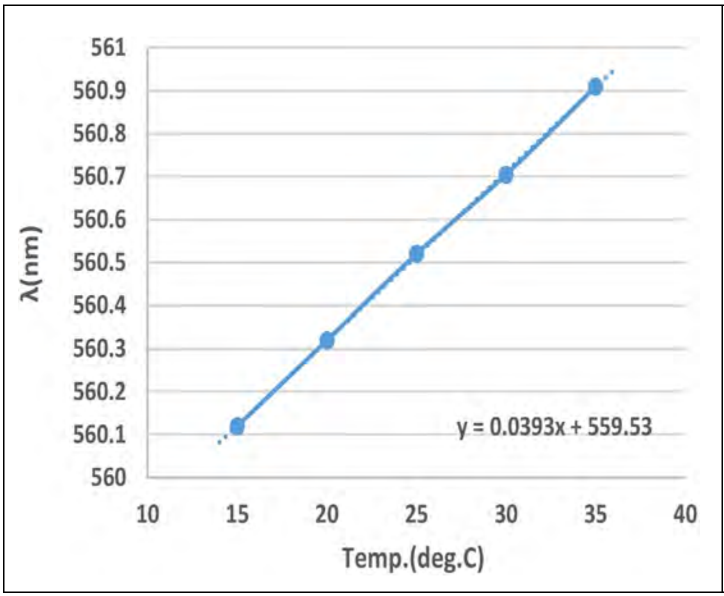
QD Laser's DFB laser technology was developed by optical communication experts experienced in quality and reliability. The two key technologies applied to the DFB laser are the use of Molecular Beam Epitaxy (MBE) to precisely and repeatedly "write" the grating structure and a regrowth technology to bury the grating.

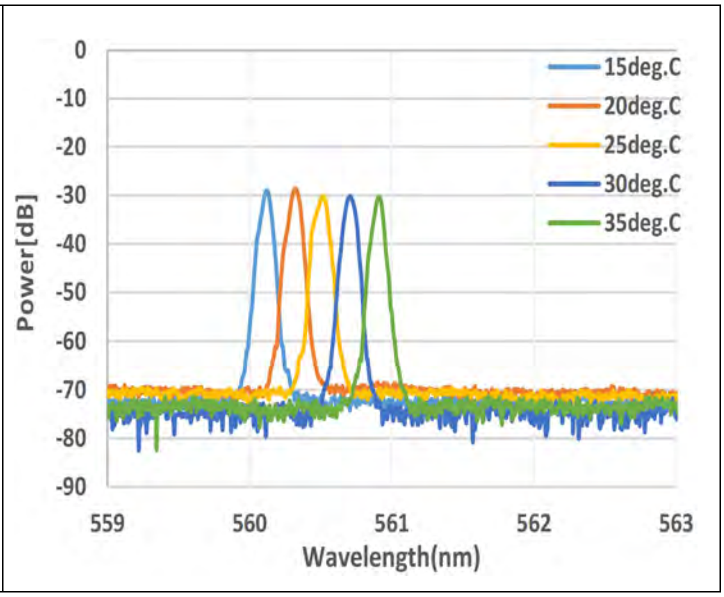
The function of the DFB segment is to generate seed light, to be amplified by the SOA. The high selectivity of the grating within the DFB segment results in narrow spectral linewidth of several MHz. This is maintained within the SOA and PPLN, resulting in single-frequency visible output with exceptional stability, directly enhancing detection accuracy and resolution in applications.



Low Temperature Dependence Of Wavelength

As the seed wavelength is controlled by the DFB section of the laser, changes in the operating temperature have minimal effect on the wavelength. Thermal expansion, or contraction, of the DFB will lead to changes in pitch of the grating resulting in a temperature dependence of ~0.04nm/°C.

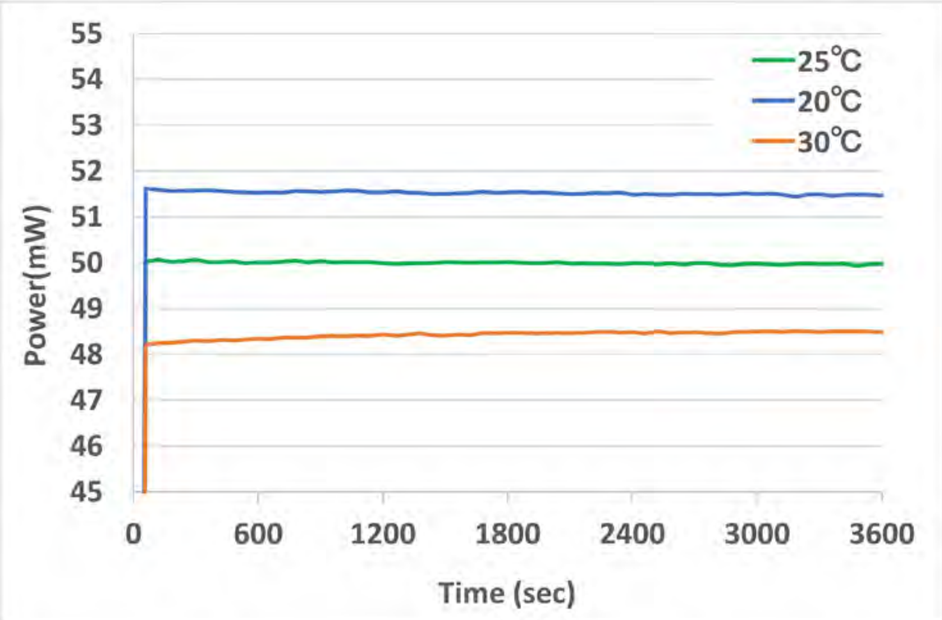




High Stability & Low Noise

QDL's unique DFB/SOA/PPLN structure eliminates warm-up effects and mode-hopping due to temperature changes and optical feedback.

Testing carried out using a temperature-controlled stage with Constant Current operation of the DFB and SOA (no auto power control) shows stability of <2% and RMS Noise of 0.052% at 25°C case temperature.



Case Temp. T_C	RMS Noise
20°C	0.069%
25°C	0.052%
30°C	0.155%

Compact Package (<0.5cc)

Unlike traditional DPSS lasers that require multiple components and complex optical arrangements, QD Laser's solution achieves remarkable compactness (22 x 5.6 x 3.8 mm, <0.5cc) by integrating the DFB laser and SOA in a single die.

This design significantly increases layout flexibility in instruments and is available with an optional integrated mounting plate.

Low Power Consumption

The DFB/SOA/PPLN system achieves superior energy efficiency with just 0.8W power consumption (excluding driver), significantly lower than conventional DPSS lasers.

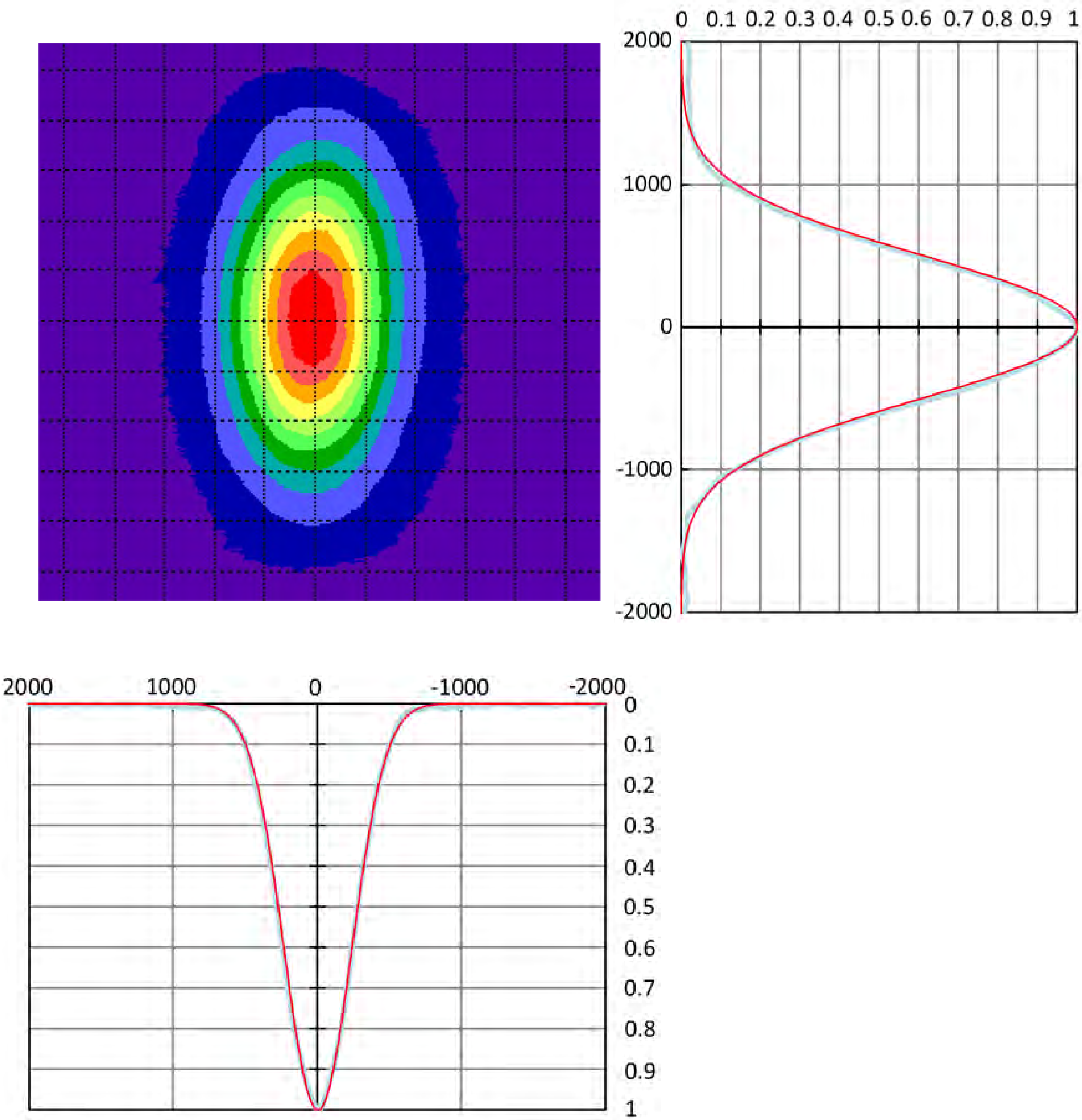
In case of typical DPSS lasers, the Nd:YAG laser crystal is excited by 808nm light from the pump laser diode to obtain infrared light at 1064nm, which is then frequency-doubled to 532nm. In these systems 100% excitation efficiency is not achievable and the energy corresponding to the difference between the 808nm pump light and the 1064nm infrared light is lost.

QD Laser's superior efficiency stems from direct infrared light emission through current injection, eliminating the energy loss of converting 808nm to 1064nm.

Near-Gaussian Beam Profile

Profiling of the beam has been carried out by QD Laser, revealing excellent optical properties with FWHM divergence of 5.3° (H) and 11.1°C (V) and 1/e² of 9.0° and 18.7° respectively.

The beam is near-Gaussian with a Beam Propagation Ratio (M²) of 1.2.



Beam Intensity Plot with Relative Optical Power (Blue) and Gaussian (Red) Profiles

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Multiple Operating Modes

QD Laser's approach of separating the generation of the NIR seed light in the DFB with amplification by the SOA and frequency-doubling using waveguide PPLN ensures narrow spectral width and single frequency operation under a range of operating modes from continuous wave to picosecond pulsing.

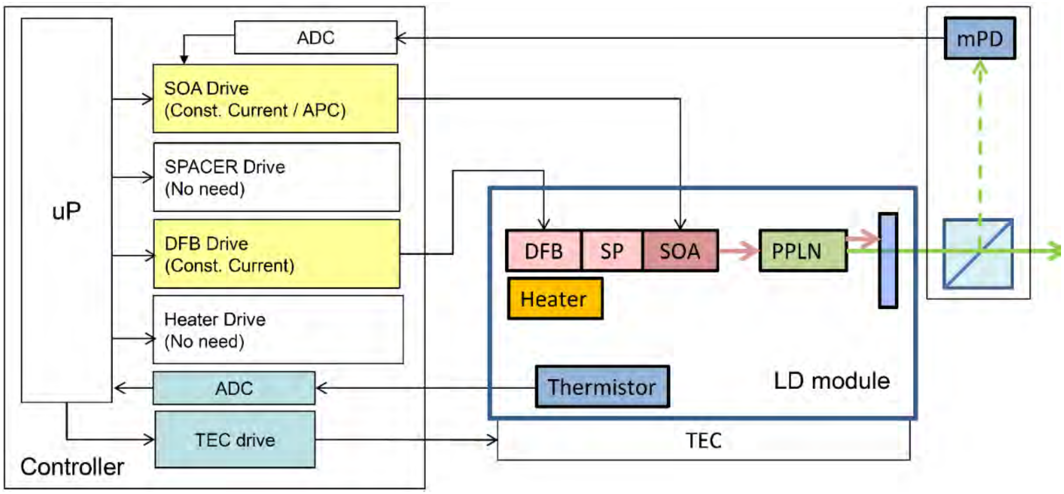
Additionally, it is possible to take advantage of the optical absorption properties of the spacer or the SOA itself by reverse biasing these elements to optimise the extinction ratio of the modulated signal.

Achieving optimum performance requires us to consider the function and characteristics of each element and how they interact:-

> **DFB:** Generates the narrow linewidth near infrared seed light. The seed wavelength is controlled primarily by the grating pitch but will also be influenced by thermally-driven expansion/contraction of the laser chip, which changes the grating pitch and hence the wavelength. The temperature of the DFB is a factor of case-temperature and DFB current.
>
> **Spacer:** Provides a degree of thermal isolation, preventing heat generated within the SOA from affecting the DFB. This element can also be considered a variable optical absorber – applying a reverse bias will actively block seed light from reaching the SOA.
>
> **SOA:** Amplifies the NIR light and modulates the optical power.
>
> **PPLN:** Converts the high power NIR output of the SOA to the visible wavelength. The PPLN has a "gain curve" with a peak conversion efficiency wavelength to which the DFB's seed wavelength should be matched.

With these functions, characteristics and relationships in mind we can consider the different operating modes possible with the compact visible laser technology:-

- ### Continuous Wave (CW) Mode



An example of a typical test report for CW operation at 50mW is shown below, demonstrating that a DFB current of 156mA and SOA current of 205mA will result in an output of 50mW at 560.9nm with case (baseplate) temperature of 25°C.

TEST REPORT

Type QLD0593-6150
S/N AY0298-011565

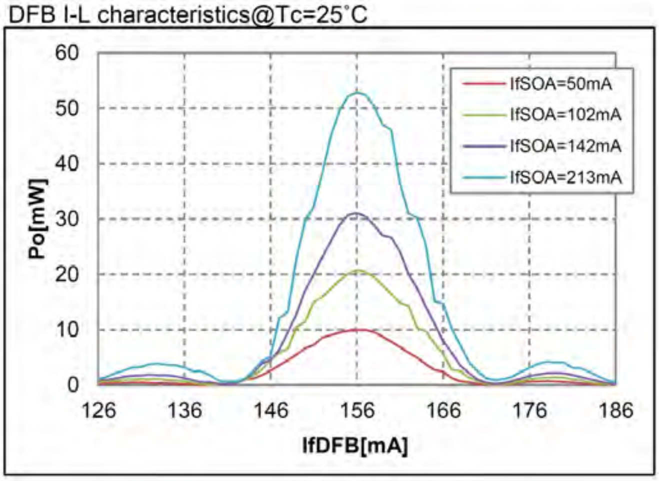
QD LASER

Tc=25˚C

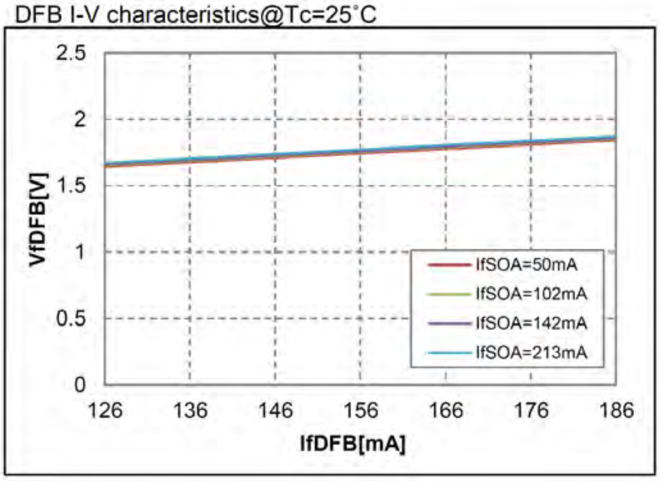
Parameter	Symbol	Condition	Unit	Test result
DFB operation current	I_{opDFB}	CW,Po=50mW	mA	156
DFB operation voltage	V_{opDFB}	CW,Po=50mW	V	1.77
SOA operation current	I_{opSOA}	CW,Po=50mW	mA	205
SOA operation voltage	V_{opSOA}	CW,Po=50mW	V	1.69
Heater operation current	I_{opHT}	CW,Po=50mW	mA	0
Heater operation voltage	V_{opHT}	CW,Po=50mW	V	0.0
Peak Wavelength	λ_p	CW	nm	560.9
Heater resistance	R_{HT}	I_{HT}=60mA	ohm	49.3

Note) Operating condition needs to be optimized by customer.
Tc is the temperature at the module base plate, which is different from the thermistor value inside the module.

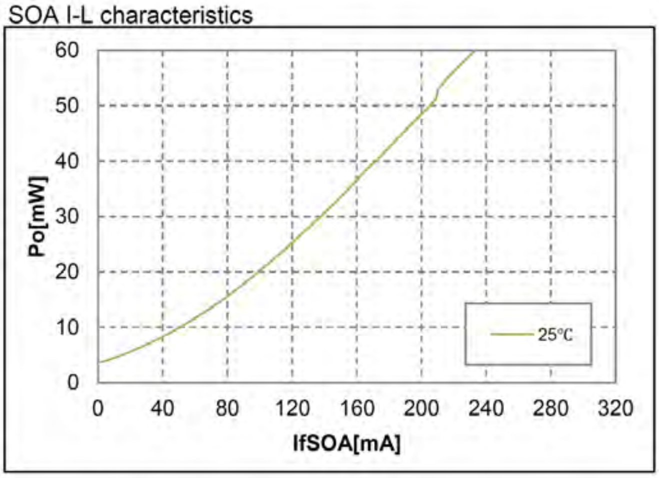
DFB I-L characteristics@Tc=25˚C



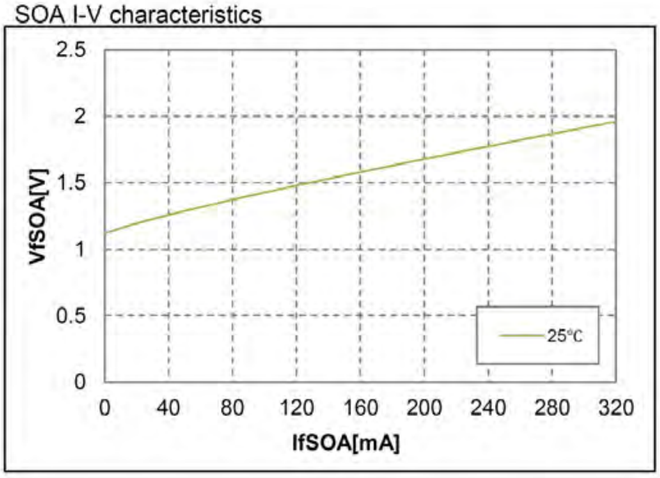
DFB I-V characteristics@Tc=25˚C



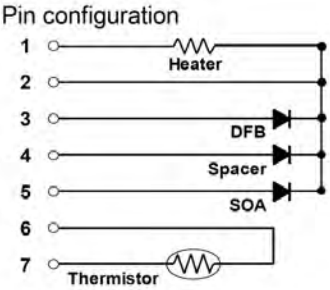
SOA I-L characteristics



SOA I-V characteristics

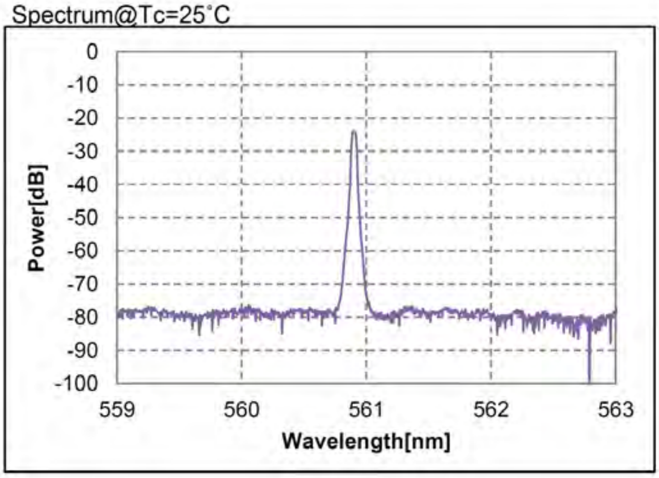


Pin configuration



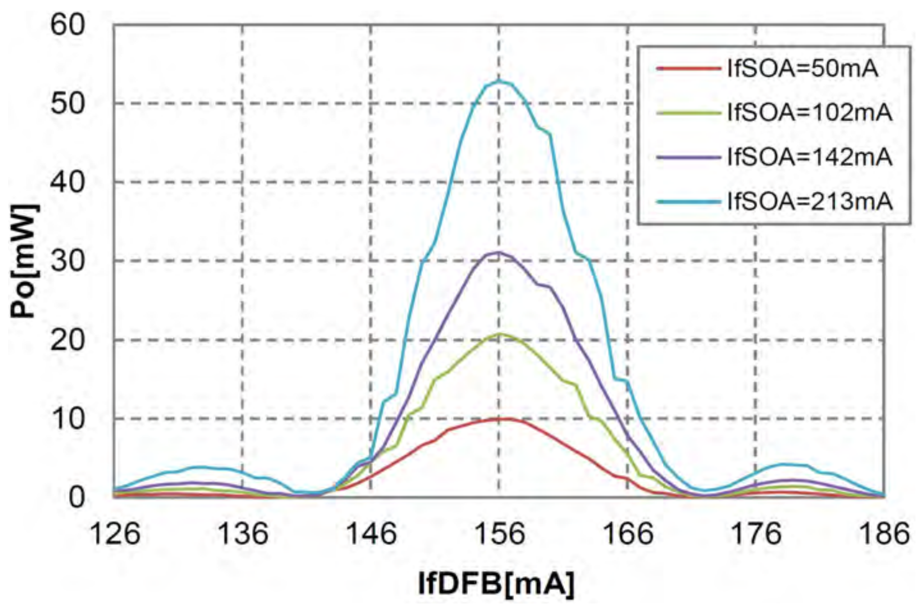
No.	Description
1	Heater
2	Common Cathode
3	DFB Anode
4	Spacer Anode
5	SOA Anode
6	Thermistor (+)
7	Thermistor (-)

Spectrum@Tc=25˚C



Once the temperature is stabilised the DFB and SOA currents are set appropriately per the supplied data. Where an external beam splitter and monitor photodiode are integrated with the user's instrument, or production control, it is possible to fine-tune the DFB current to achieve maximum conversion efficiency and SOA current to the desired output power under customers' own conditions.

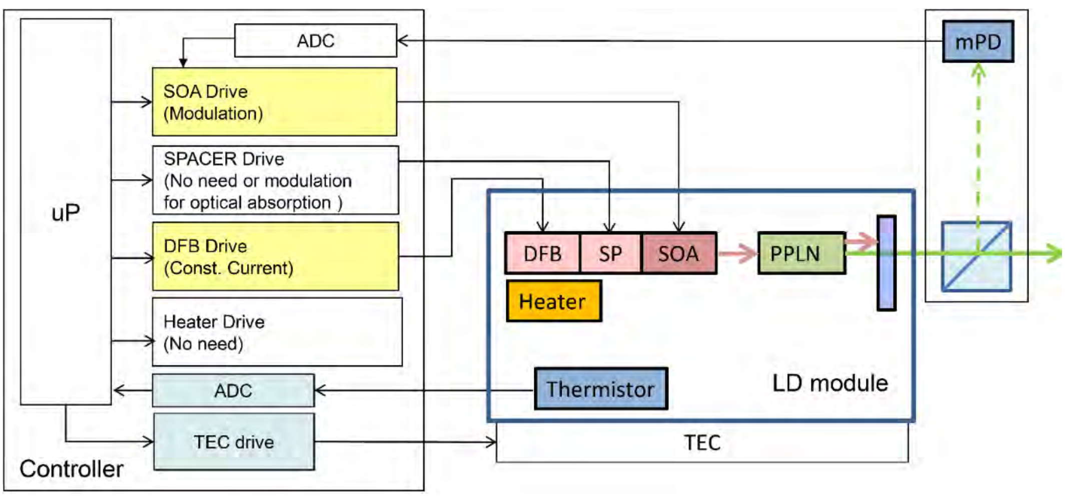
The following plot demonstrates how varying the DFB current from the optimal value provided in the test data will result in reduced optical power due to the mismatch of the seed wavelength with the optimum conversion efficiency of the PPLN.



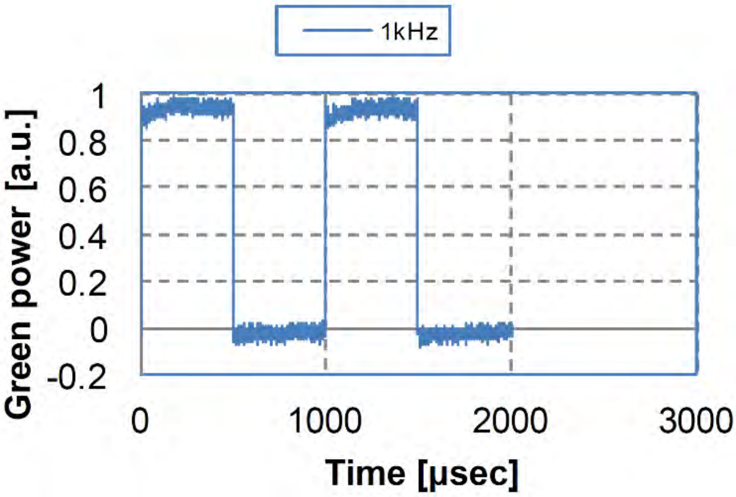
Customers who wish to operate the laser at a range of power levels can use this "peaking" effect to define a matrix of IfDFB and IfSOA current settings.

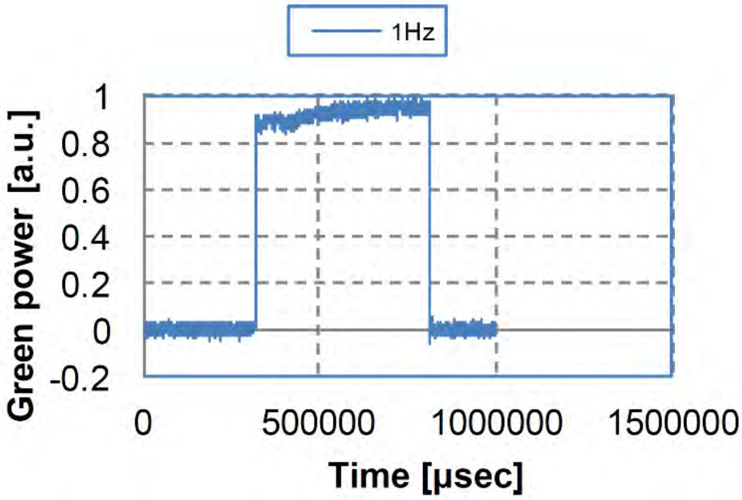
o SOA Modulation Mode

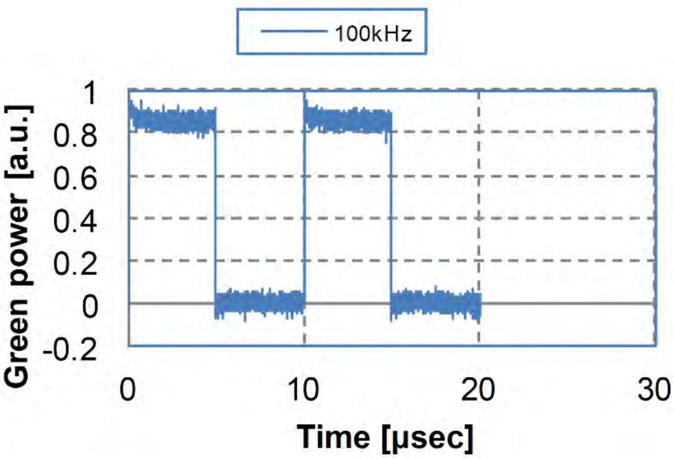
In many applications acceptable performance up to 100MHz can be achieved by SOA modulation alone. In these cases, the DFB is operated in CW mode, providing a constant low power single-frequency seed signal which is amplified by the SOA and doubled to visible wavelengths by the PPLN.

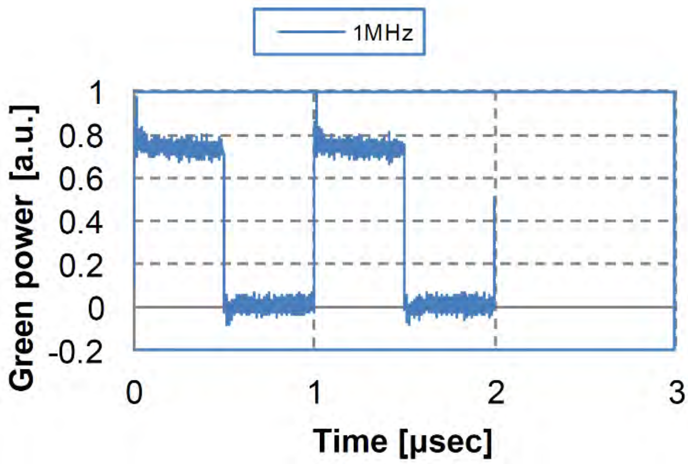


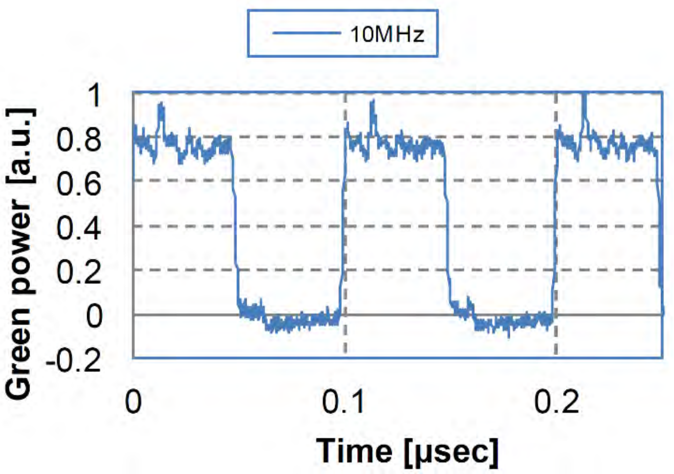
Waveforms the for 532nm laser from 1Hz to 100MHz are shown below:-

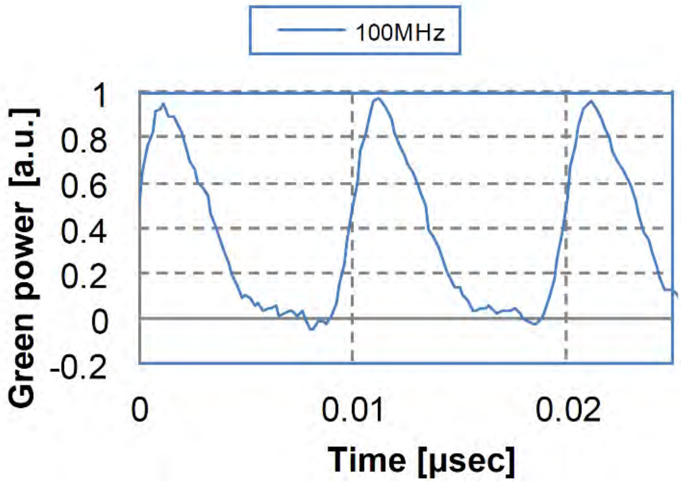




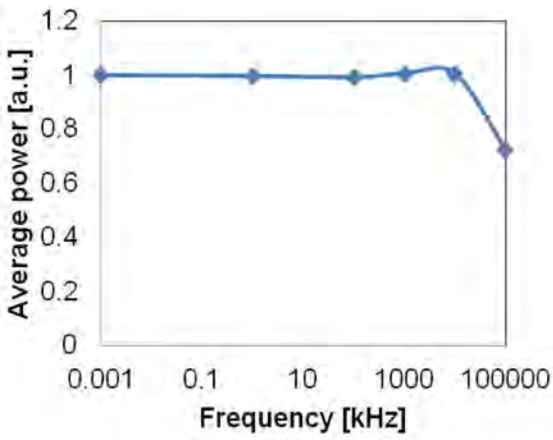




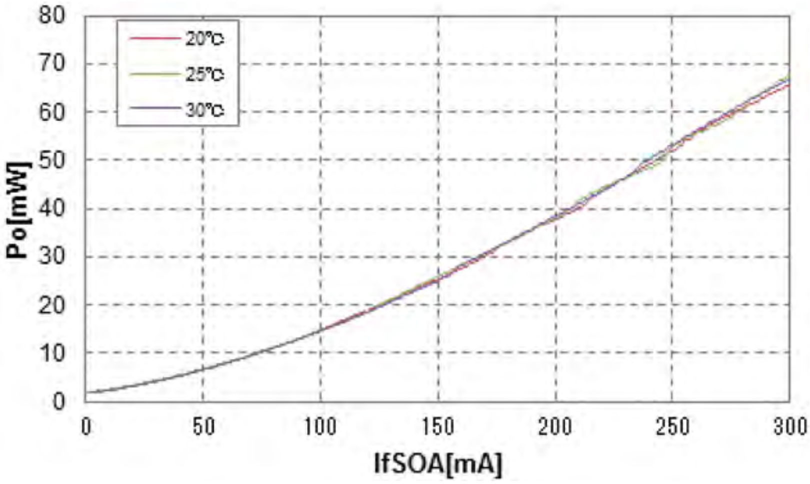




At higher frequencies the average power is reduced:-



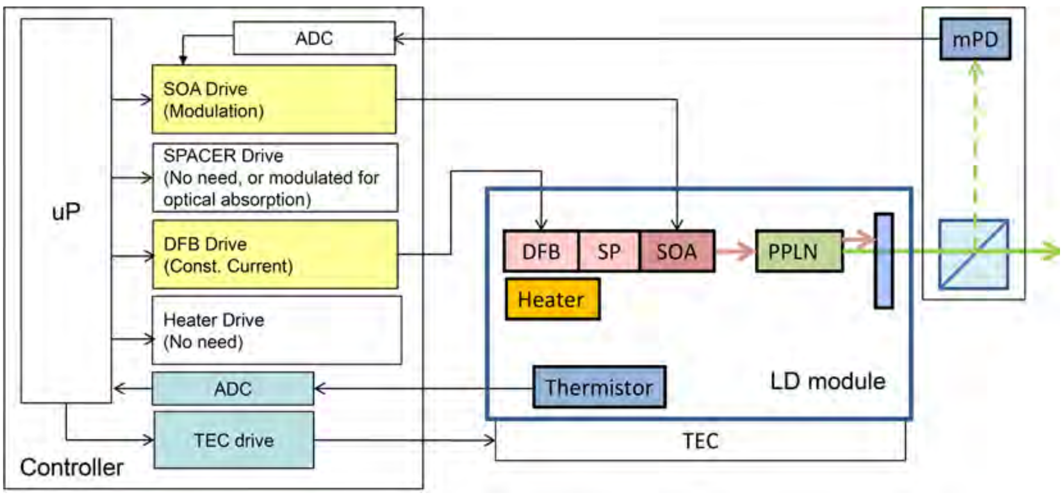
It should be noted that the seed signal from the DFB remains when the SOA is operated at 0mA, as demonstrated below.



This residual optical power limits the extinction ratio of the modulated output to <20dB when using the SOA Modulation operating mode.

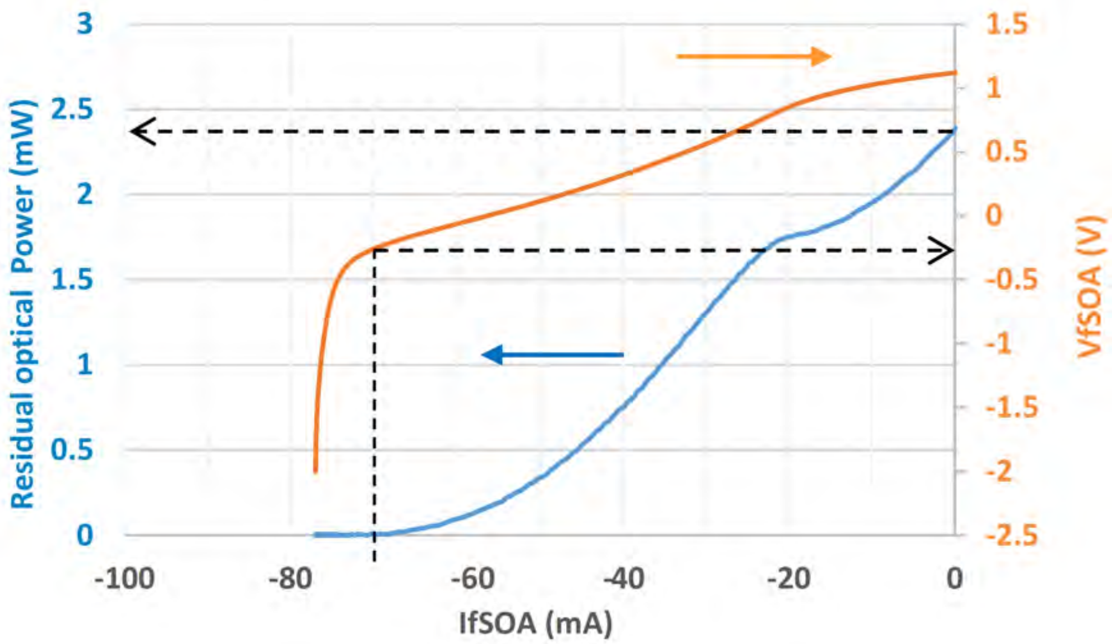
- ### High Extinction Ratio Modulation Mode

When the <20dB extinction ratio of the standard SOA modulation mode is not sufficient it is possible to employ a more sophisticated mode, using the optical absorption characteristics of the SPACER and/or the SOA, by applying a negative bias to these elements during the modulation cycle.

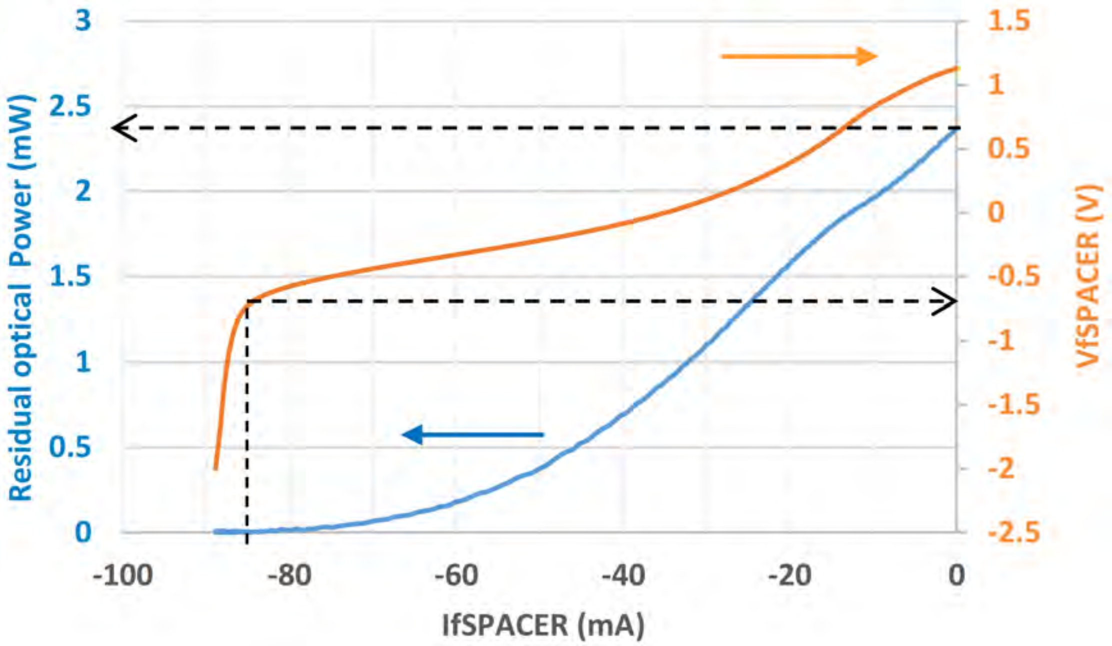


The following graphs show the residual optical power with the DFB section operating under CW mode at the optimal DFB current for the rated power.

In the first image, it can be seen that the SOA voltage is at approximately 1.1V when the SOA Current is 0mA, resulting in a residual optical power of ~2.4mW. By applying an SOA current of -70mA (~-0.3V) the residual optical power is reduced to Zero.



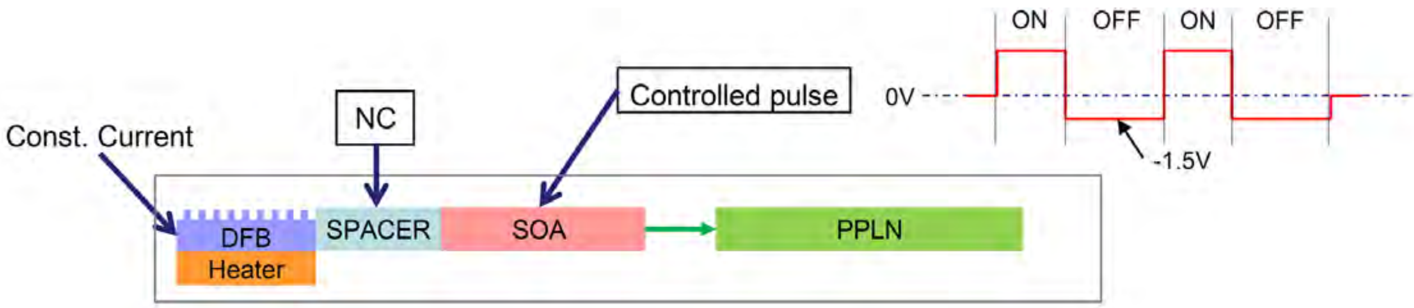
The characteristics of the SPACER are similar with a residual optical power of 2.4mW at 0mA/~1.1V and 0mW at -85mA/~-0.7mV.



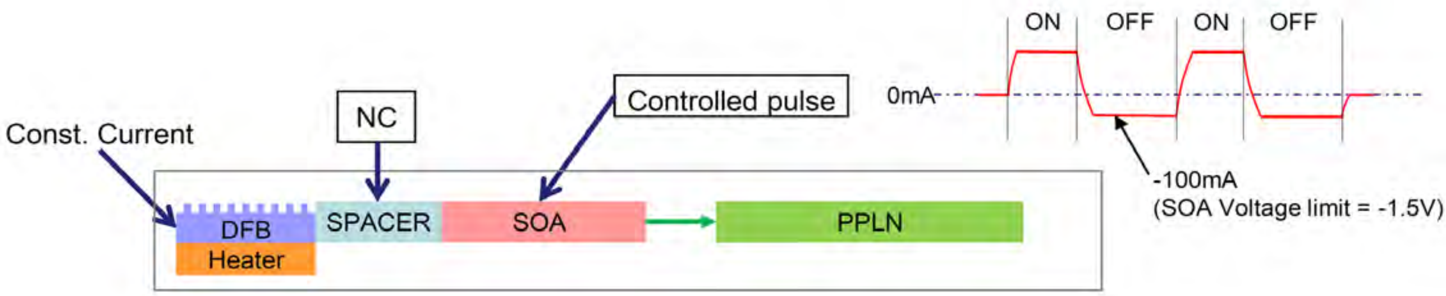
QD Laser apply a limit of -1.5V for reverse bias to the SOA or SPACER elements. This is based on the DFB's absolute maximum current rating of 250mA and the associated breakdown voltage of -2V. This limit negates the risk of damage to the laser.

The absorption characteristics of the SOA and SPACER allow the laser to be operated in several modes:-

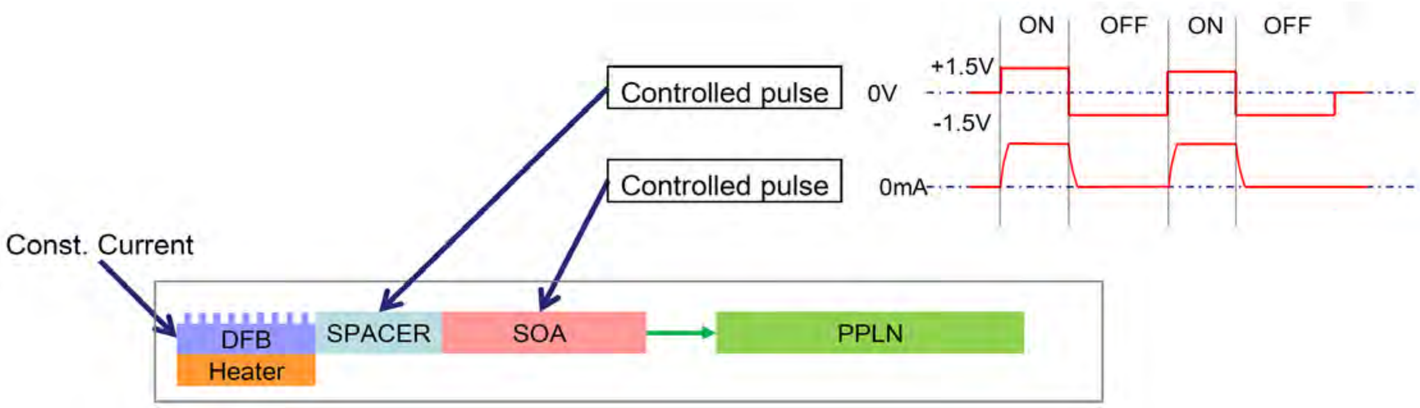
SOA voltage modulation with negative “OFF” voltage



SOA current modulation with limited SOA reverse voltage



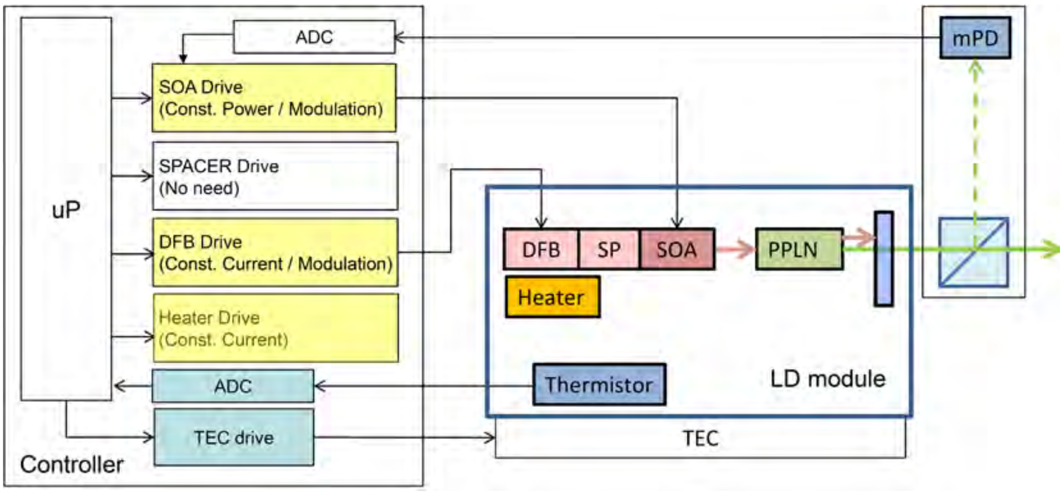
SPACER voltage modulation synchronised with SOA current



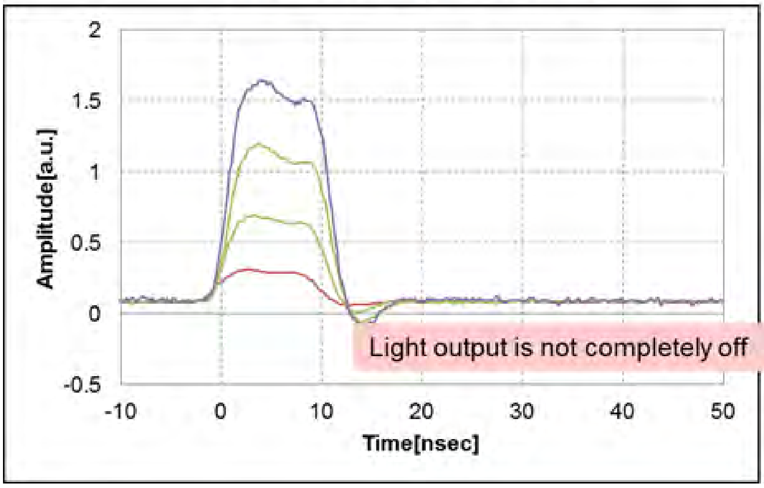
By applying these techniques it is possible to achieve extinction ratios exceeding 30dB.

- ### High Speed Modulation Mode with Heater

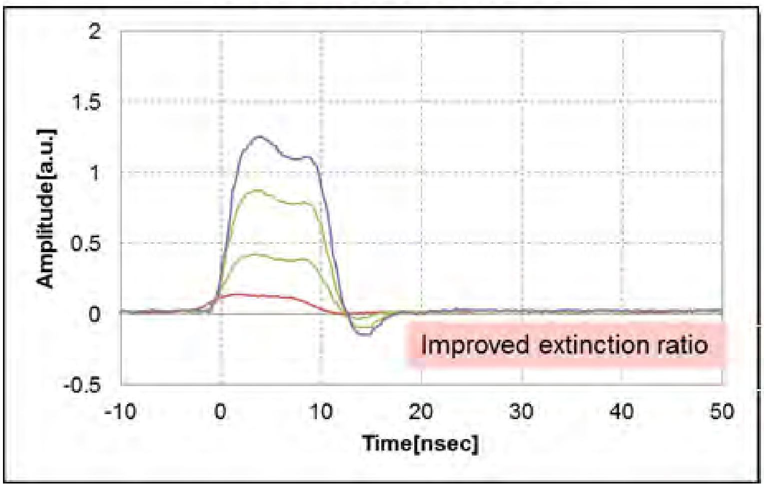
If it is difficult to achieve a high extinction ratio when modulating the SOA at high-speed using positive or negative power supply. To address this issue QDL recommend fine-tuning the DFB and HEATER constant currents.



without heater control



with heater control

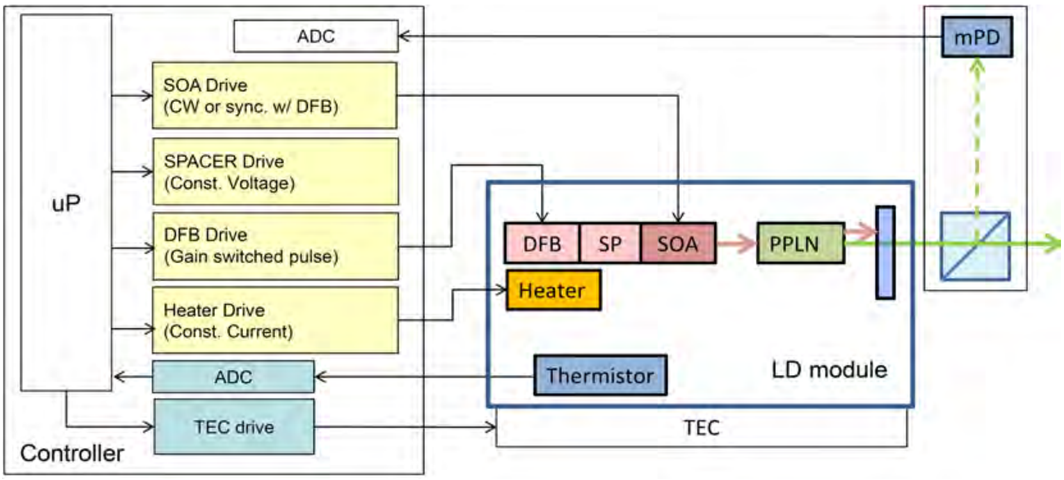


High extinction ratio can be achieved by this approach. However, it should be noted that peak power is also reduced.

o Gain-Switched Picosecond Pulse Modulation Mode

A unique capability of QD Laser's compact visible laser structure is the ability to produce extremely short pulses of the order of 50 picoseconds by operating the DFB in "gain-switched" mode with the SOA operating in CW mode or synchronously modulated.

This characteristic makes the laser extremely well-suited to function as a short pulse laser source for STED microscopy.



Gain switching utilises the phenomenon of a strong short optical pulse which is generated just after the laser reaches the lasing threshold.

The operating conditions required to generate the gain-switched pulse need to be fine-tuned depending upon the specific laser's test data, desired pulse length, repetition rate and optical power, the principles are:-

- HEATER: DC current is applied – the DFB is operated in a low duty cycle mode, therefore it is necessary to match the DFB seed wavelength to the PPLN.
- SPACER: Voltage drive @ ~1V (0mA)
- DFB section is operated via a Bias-T with a current level of ~200mA DC.
- 2nd leg of bias-T is connected to a Pulse Pattern Generator (PPG)
- SOA section can be operated with a simple CW current, or for optimum performance, can be synchronised with the DFB modulation.

QD Laser provide test data for lasers intended for gain-switched operation – this report provides recommended operating conditions to achieve ~50ps pulse width at the laser's rated operating power, i.e. the following data for the QLD0593-3250 (50mW CW) provides settings to achieve 50mWpk at 10MHz.

Note that the test report provides a pulse width figure for both the DFB and SOA sections, rather than operating the SOA under CW conditions.

TEST REPORT

Type QLD0593-3250
S/N AG0045-000936

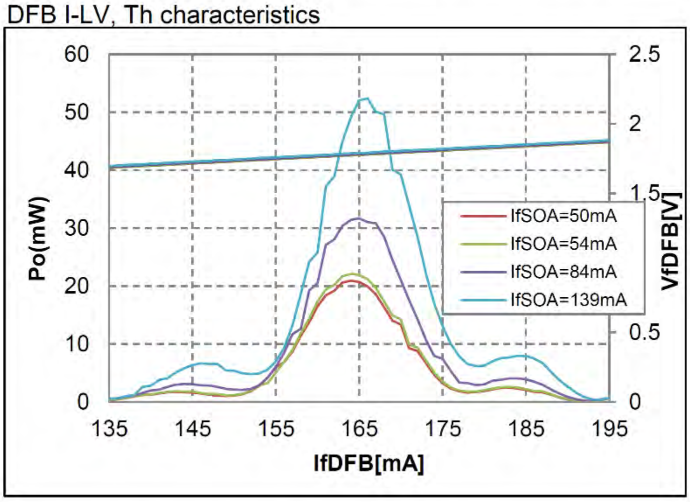
QD LASER

Tc=25°C

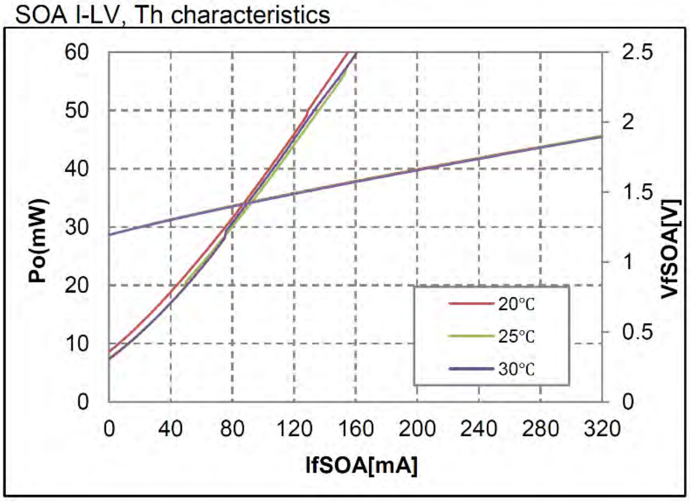
Parameter	Symbol	Condition	Unit	Test result
DFB operation current	I_{opDFB}	CW,Po=50mW	mA	166
DFB operation voltage	V_{opDFB}	CW,Po=50mW	V	1.79
SOA operation current	I_{opSOA}	CW,Po=50mW	mA	136
SOA operation voltage	V_{opSOA}	CW,Po=50mW	V	1.52
SPACER operation current	$I_{opSPACER}$	CW,Po=50mW	mA	0
SPACER operation voltage	$V_{opSPACER}$	CW,Po=50mW	V	1.17
Heater resistance	R_{HT}	I_{HT}=60mA	ohm	32.4
Gain-switching operation		Ppeak=50mW		
Heater operation current	I_{opHT}	Repetition freq.	mA	72
DFB operation current	I_{opDFB}	=10MHz	mA	120
SOA operation current	I_{opSOA}	DFB Pulse width	mA	175
Peak Wavelength	λ_p	=400ps	nm	530.9
Spectral linewidth @-3dB	$\Delta\lambda$	SOA Pulse width	nm	0.04
Spectral linewidth @-20dB	$\Delta\lambda$	=1000ps	nm	0.12

Note) Operating condition needs to be optimized by customer.
Tc is the temperature at the module base plate, which is different from the thermistor value inside the module.

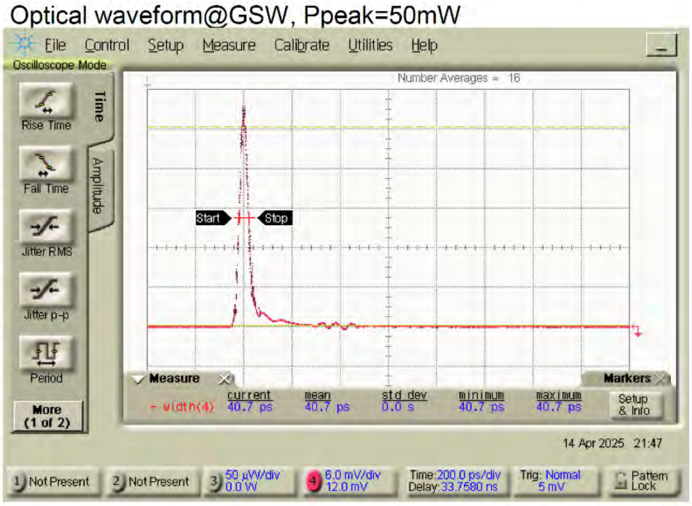
DFB I-LV, Th characteristics



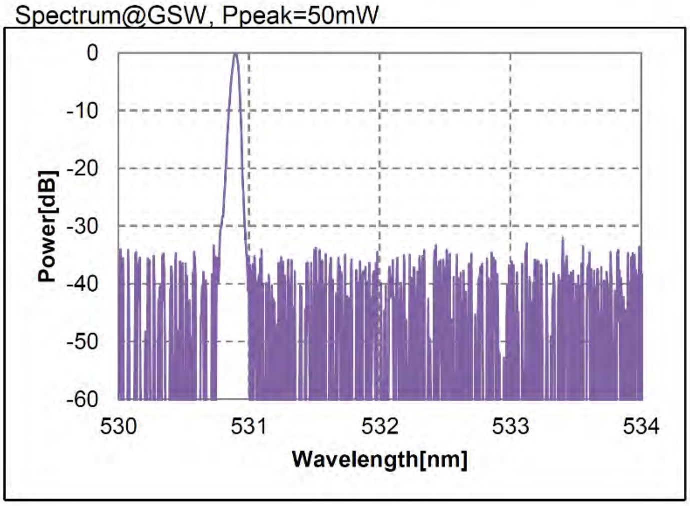
SOA I-LV, Th characteristics



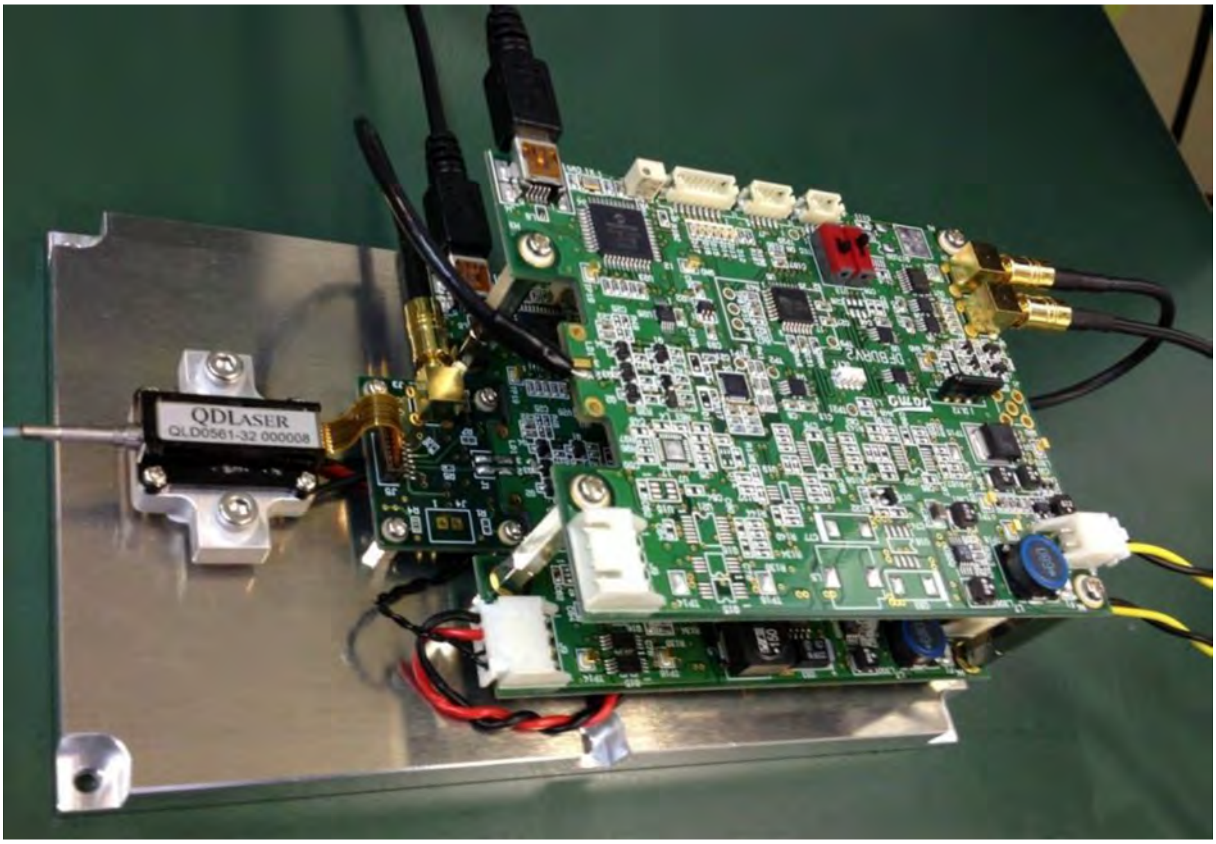
Optical waveform@GSW, Ppeak=50mW



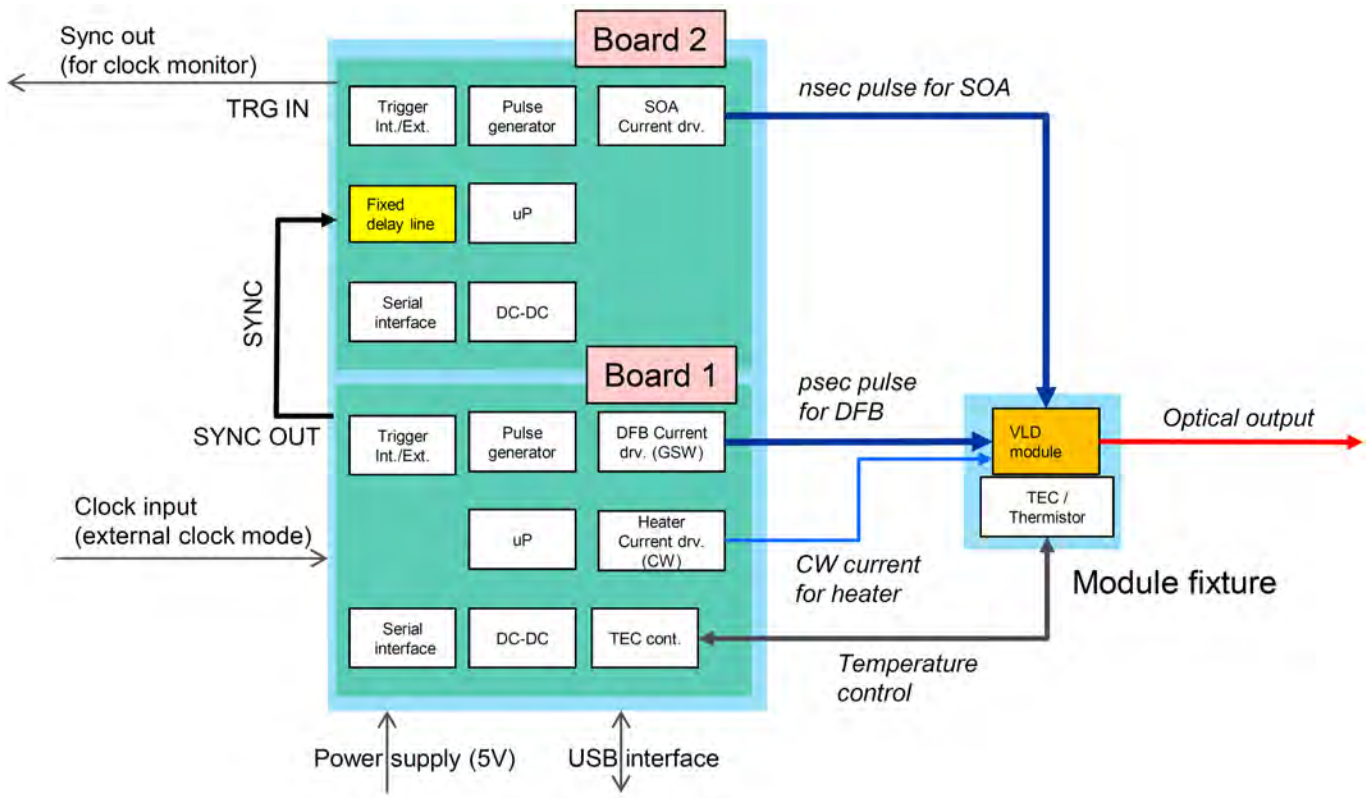
Spectrum@GSW, Ppeak=50mW



QD Laser have produced a driver, QBB0502, designed for operating their lasers under gain-switched mode. The driver comprises two PCBs, one for DFB driver, the second for SOA. The image below shows the two PCBs along with the QLD0593 laser module mounted on a TE-cooled platform and heatsink.

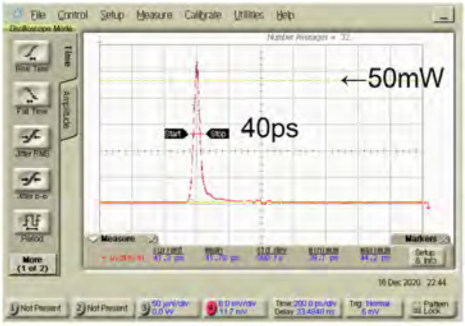


The block diagram shows the key features of the two PCBs:-

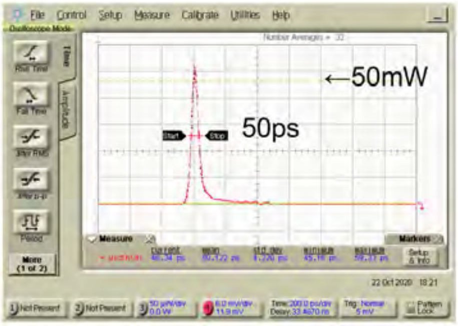


Typical gain-switched performance of 532nm, 561nm and 594nm lasers with the QBB0502 driver is shown below, along with the operating conditions used.

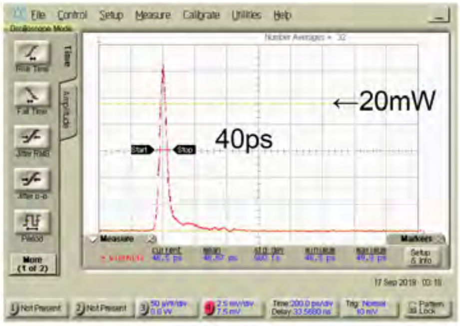
532nm Pulse waveform



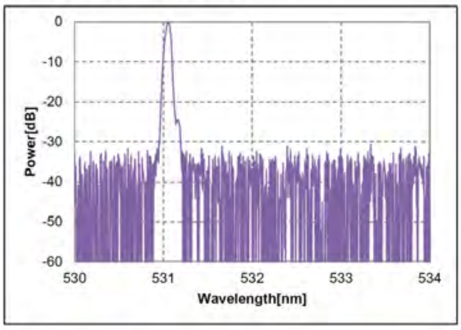
561nm Pulse waveform



594nm Pulse waveform

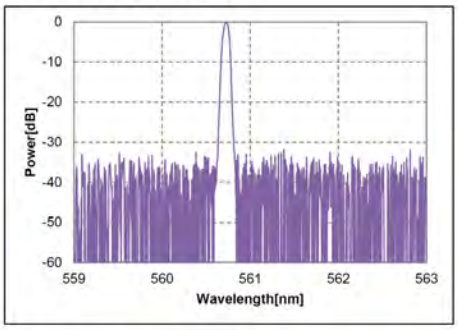


Spectral characteristics



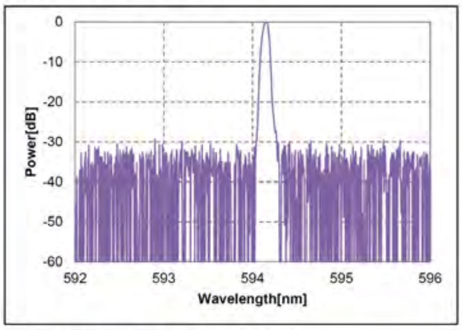
Repetition frequency 10MHz
DFB Pulse width 400ps, Pulse current 113mA
Heater current 79mA
SOA Pulse width 1000ps, Pulse current 180mA

Spectral characteristics



Repetition frequency 10MHz
DFB Pulse width 500ps, Pulse current 98mA
Heater current 76mA
SOA Pulse width 1100ps, Pulse current 185mA

Spectral characteristics



Repetition frequency 10MHz
DFB Pulse width 500ps, Pulse current 120mA
Heater current 89mA
SOA Pulse width 1100ps, Pulse current 200mA

Although these examples are at a 10MHz repetition rate, the QBB0502 can provide operation from single shot to 100MHz with varying pulse length by fine-tuning the drive characteristics.

Comparing QDL's Technology

A comparison of QDL's technology with a competing Optically Pumped Semiconductor Laser (OPSL) and a Diode Pumped Solid State (DPSS) laser technologies:-

		QD Laser			OPSL			DPSS		
Wavelength (nm)		532	561	594	532	561	594	532	561	594
Power (mW)		30, 50	5, 20, 30, 50	5, 20	20, 50, 80, 100, 150		20, 60, 100	300	100, 150	30, 50
Beam Quality	Longitudinal mode	Singlemode			Singlemode			Singlemode		Multi-mode
	Ellipticity	~ 1:2 (Divergent)			≤ 1:1.1 (Collimated)			≤ 1:1.1 (Collimated)		
	M²	≤ 1.2			≤ 1.1			< 1.1		< 1.2
CW Characteristics	Stability	< 2%			< 2%			< ±2%		
	RMS Noise	< 0.2%			< 0.25%			< 0.5%	< 0.2%	< 1%
Modulation Characteristics	Frequency	< 100 MHz			< 1 kHz			N/A		
	Min. Pulse	50ps (Gain-Switched)			~1 ms			N/A		
Operation Temperature		20 – 30 °C			10 – 45 °C			10 – 40 °C		
Storage Temperature		-10 - +50 °C			-20 - +60 °C			-20 - +60 °C		
Power Consumption		0.8 W (Typ.) (LD only, no TEC)			5–8 W (Typ) 12 W (max) (Inc. driver)			< 60 W (Inc. driver)		
Dimensions / Volume		22x5.6x3.8 mm³, 0.5 cc (no TEC)			27x52x13.1 mm³, 19 cc (Optical head only)			115x50x43.5 mm³, 250 cc (Optical head only)		

Product Lineup

QD Laser offer a range of format to meet diverse application requirements:-

QLD0593: Standard free-space emission configuration with optional integrated mounting flange to simplify integration into customer heatsink.

QLD0561: Fibre-pigtailed package with integrated mounting flange and a choice of polarisation maintaining (PM) or singlemode (SM) optical fibre with FC/PC or FC/APC connectors.

QBB0502: Laser driver solution for picosecond pulsing.

Lantana-Series: A new generation of ultra-compact, fully-integrated lasers with built-in driver.

The small and light, 38 x 62 x 22.7 mm³ (53cc) and 157g, plug-and-play modules feature USB communication, ensuring seamless integration with existing systems and providing straightforward operation.

In addition to CW operation under Automatic Power Control (APC) all Lantana models can be directly modulated from 0.1kHz to 50 kHz under Automatic Current Control (ACC) via the USB connection.

QLM4F02 Multi-Wavelength Modules: QD Laser have also integrated the compact visible laser module into a 4-colour fibre-coupled platform.

This compact (80 x 80 x 30 mm³) package combines a 532nm, 561nm or 594nm laser with three TO-packaged laser diodes multiplexed into a single optical fibre. A wide choice of singlemode lasers between 405nm and 905nm are offered.

Examples of possible configurations include:-

- **QLM4F02-40485664-1S:** 405nm, 488nm, 561nm and 640nm with as singlemode optical fibre is well-suited to flow cytometry.
- **QLM4F02-48536678-1P:** 488nm, 532nm, 660nm and 785nm with PM fibre output is suitable for ophthalmology/SLO applications.

QBB4M02: 4-channel control board for QLM4F02 this driver optimises the DFB and SOA current of the 532/561/594nm laser along with the FP operating currents and TEC. Control of the lasers' power, CW or direct modulation and temperature is via USB and the driver board requires a single 12V supply.

Conclusion

These compact visible lasers represent a significant advance in laser technology for biomedical applications.

Their combination of compactness, efficiency, and stability makes them ideal for next-generation analytical instruments, offering manufacturers greater design freedom while enhancing overall system functionality.

The current wavelength options of 532nm, 561nm and 594nm at power ratings of up to 50mW will be extended to cover 488nm, 552nm, and 588nm and power levels will also increase over time.