Becker & Hickl GmbH

BDL-SMN Series with LSB-C

Picosecond Diode Lasers

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Becker & Hickl GmbH
Technology Leader in
Photon Counting

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BDL-SMN Series

Picosecond Diode Lasers

Single-mode fibre coupling or free-beam output
Beam-profile correction optics
Wavelengths from 375 nm to 1064 nm
Pulsed or CW operation
Pulse width down to 50 ps
Power in pulsed mode up to 1.3/3/5 mW @ 20/50/80 MHz
Power in CW mode up to 50 mW
High power stability due to internal intensity regulation loop
Repetition rate 20-50-80 MHz
Input for synchronisation with other lasers
Low skew trigger output
Fast ON / OFF / multiplexing capability
Compact laser module, all electronics integrated
Simple +12V power supply

Contents

Overview

The bh BDL-SMN picosecond diode lasers deliver picosecond light pulses at high repetition rate. They are thus perfectly compatible with advanced TCSPC techniques [1, 2]. The lasers also have a CW mode to generate a continuous high-power beam of light.

In the picosecond mode, the pulse shape is almost gaussian up to an average power of 1 to 2 mW, with a pulse width on the order of 50 to 80 ps. The pulse width typically remains below 200 ps up to an average power of 4 to 8 mW at 80 MHz repetition rate. Both in the ps mode and in the CW mode, the output power is stabilised by an internal power regulation loop. The lasers thus feature low intensity noise and high power stability.

The BDL-SMN lasers have beam-profile correction optics integrated. They deliver beams of about 1 mm diameter, approximately circular cross section, and low astigmatism. The beams can be coupled into single-mode fibres at high efficiency.

The output power of the lasers and the ON/OFF state can be controlled by external signals. Therefore, the lasers are well equipped to multiplex several lasers on the microsecond or millisecond time scale, and to turn off the laser emission during the beam flyback in scanning applications. The ON/OFF input is also used for combined fluorescence and phosphorescence decay applications in combinations with the bh TCSPC devices [3].

The BDL-SMN lasers have a synchronisation input to synchronise their pulse trains with the pulses of a second BDL-SMN lasers or with the pulses of other lasers of appropriate pulse repetition rate.

The complete driver electronics of the BDL-SMN lasers is integrated in the laser head. Operation of the lasers does not require anything but a +12 V power supply, in the simplest case a wall-mounted AC-DC converter. To meet the requirements of laser safety, the lasers come with a connection box that contains the mandatory key switch and the emission indicator.

The lasers are fully compatible with the bh SPC or Simple-Tau series TCSPC devices [2]. They are also part of the DCS-120 confocal scanning FLIM systems [4], and of the bh FLIM systems for various other laser scanning microscopes [5, 6, 7].

General Description

System Components

The BDL-SMN lasers come with a small wall-mounted +12V power supply and a ‘laser switch box’ that contains the key switch mandatory for class 3B lasers. The power supply, the laser switch box, and the laser module are shown in Fig. 1, left to right.

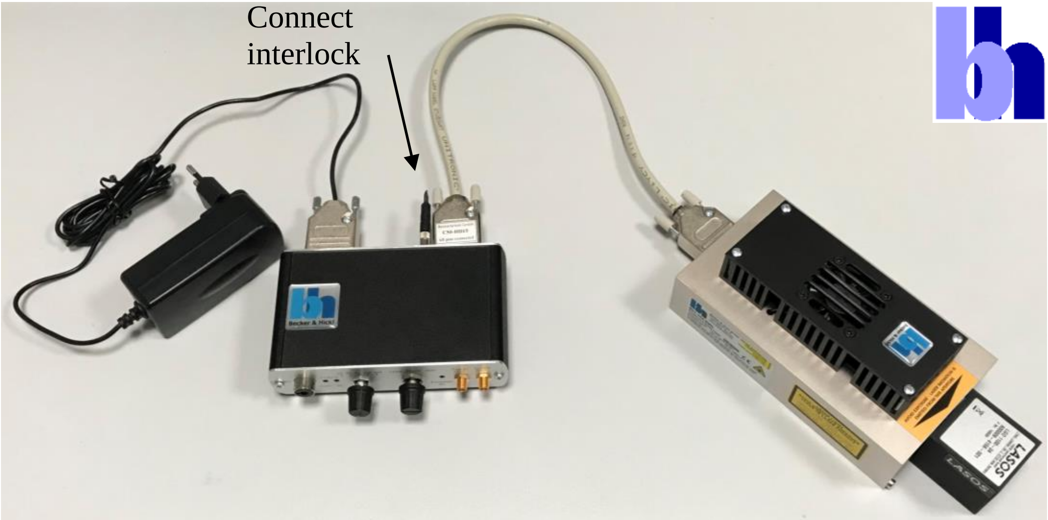


Fig. 1: BDL-SMN laser. Left: Wall mounted power supply. Middle: Switch box with safety key, frequency switch for CW and pulsed operation, power control and SMA connectors for external control. Right: Laser module containing the complete driving and control electronics.

Laser Switch Box

Starting from May 2018, the 3-Frequency BDS lasers are operated via the new LSB-C switch box. The laser switch box is shown in Fig. 2.

Fig. 2: LSB-C Laser Switch Box

At the front panel, the LSB-C box has the mandatory key switch, a switch for the pulse frequency, a potentiometer for the laser power, and SMA connectors for an external power control signal and the laser ON/OFF signal. At the rear panel the box has a 9-pin connector for a +12V power supply, a 15-pin connector to the laser, and a 15-pin connector for external control signals. For pin assignment of the conrol signals please see page 13. The ‘Interlock’ connector of the LSB-C box is used to build up a laser-safety loop when the BDS laser is integrated in larger systems. To enable laser operation the safety cable delivered with the LSB-C box must be connected to the interlock connector, and the blue wire connected to the black wire or to ground either directly or via the laser safety loop.

Laser action is indicated by three LEDs of different colour. The red ‘POWER’ LED indicates 12 V power connection, the green LED key switch and the blue LED laser emission. The laser switch box also contains a switch to select between three pulse frequencies and CW operation, and input connectors for the control signals of the laser.

The connectors for the control signals are shown in Fig. 2. There are two SMA connectors, one for the ON/OFF signal and one for the power control signal. The same signals can be connected to a 15 pin sub-D connector. This connector has also inputs for switching between 20, 50, and 80 MHz, and CW operation. Please note that the frequency switch must be in the ‘ext.’ position when external frequency control is used. For signal specification and pin assignment, please see ‘Input and Output Signals’ and ‘Pin Assignment’, page 13.

The 15-pin connector at the laser side can be used as a ‘remote interlock connector’. The connector can be pulled off or plugged in at any time without causing damage to the laser.

From the technical point of view, the laser switch box is not absolutely required to operate the BDL-SMN lasers. It is, however, part of the laser safety concept. Thus, if the BDL-SMN laser is operated without the box, e.g. in OEM applications, the user is responsible to comply to the usual laser safety regulations by suitable design of the instruments into which the BDL-SMN laser is integrated.

The BDL-SMN lasers may also be operated without the Laser Switch Box when they are integrated in other bh systems. For example, in the DCS-120 confocal scanning FLIM system [4] the laser switch box is replaced with the DCS connection box. This box contains the key switch, the repetition rate selectors for two lasers, and the signal distribution logics to control the lasers from the GVD-120 scan controller of the DCS system.

Fig. 3: Signal distribution and control box of the DCS-120 confocal scanning FLIM system

Laser Module

The laser module contains the complete pulse generator and driver electronics, the control electronics and an active temperature stabilisation of the laser diode. A beam profile corrector is attached to the outside of the laser housing. The front end of the corrector has threaded holes that fit to the standard 1-inch pitch of the commonly used fibre couplers or manipulators. For the BDL-SMN lasers we recommend the Kineflex fibre coupling system of QIOPTIQ, UK, formerly Point Source [10]. Fig. 4 shows the laser module without (left) and with the QIOPTIQ Kineflex fibre manipulator (right).

Fig. 4: Front end of the BDL-SMN laser module. Left: Free beam output. Right: With Qioptiq Kineflex fibre coupling system

The back panel of the laser module is shown in Fig. 5. The left LED indicates that the laser is active. The LED flashes when the power of the laser is on and the ‘Laser OFF’ signal is ‘high’ or unconnected. The other two LEDs show the status of the cooler of the laser diode. The right LED is on when the cooling of the laser diode is active. It may turn off after some time of operation when the diode has been cooled down and almost no cooling power is required to hold it at constant temperature. The red LED in the middle turns on when the cooling power is high. It normally turns off after a few minutes of operation.

The 15-pin sub-D connector connects the power supply and control signals from the laser switch box to the laser. The lasers are delivered with appropriate connecting cables, so that user access to the 15-pin connector is not normally needed. For pin assignment please see page +13. The SMA connectors on the right provide a trigger output for the SYNC signal to a bh SPC module, and an input to synchronise the laser to an external clock source.

Fig. 5: Back panel of the BDL-SMN laser

Input and Output Signals

Power Control Input

The optical output power of the laser can be controlled via an analog input. The ‘Power’ signal is applied to the laser via a SMA connector or via pin 12 of the 15-pin connector of the laser switch box (see Fig. 2). In OEM applications without the laser switch box the signal can be applied directly to pin 12 of the 15-pin connector of the laser. The input voltage range is 0 to +10 V, the source impedance of the power control signal should be less than 100 Ω. If the power input is left open the laser runs at a power that yields optimum pulse shape. (Please note this is about 20 % of the maximum power the laser can deliver!) The reaction to a change in the power control voltage occurs within a time of about 2 µs.

The function of the optical power versus the ‘Power’ input signal is linear within about 5 %. Pulse shapes and pulse amplitudes for different power control voltages are shown in Fig. 6.

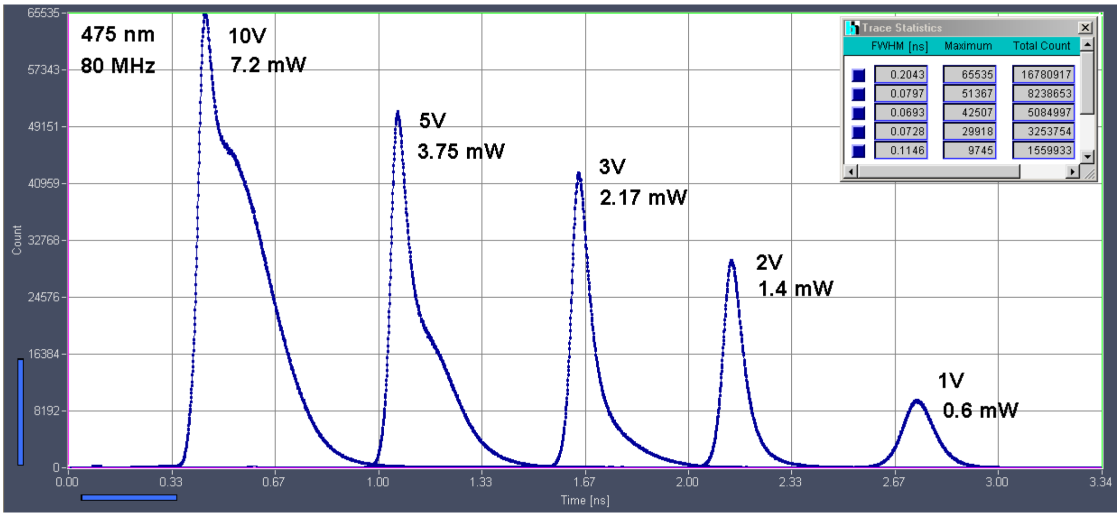


Fig. 6: Optical pulse shape and amplitude for different voltage of Power control signal. BDL-SMN 473 nm, 80 MHz. Power refers to free-beam output. Pulses recorded with SPC-150N TCSPC module and id100-20 SPAD detector.

As can be seen from Fig. 6, the optical pulse shape changes with the output power. Please see ‘Pulse Shape’, page 17, for details.

The dynamic response of the optical output power to the power control input is shown in Fig. 7 and Fig. 8.

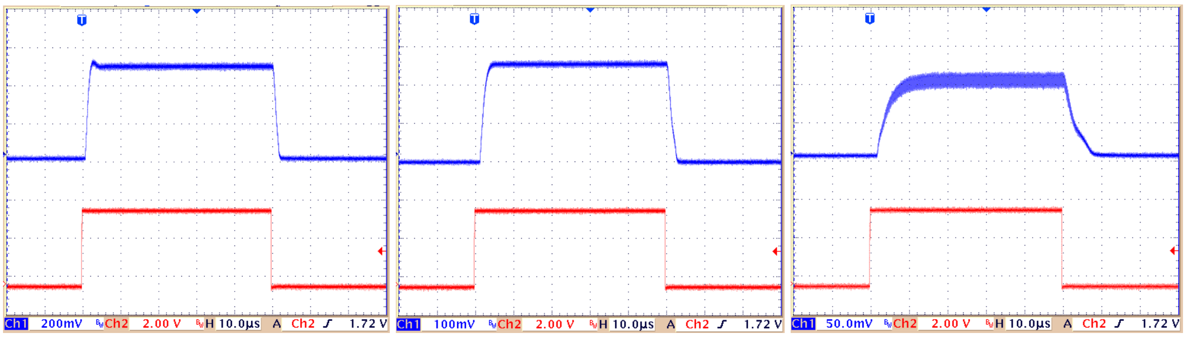


Fig. 7: Dynamic response of the output power to the power control signal. Control signal switches from 0 to +9V. Picosecond mode, 445 nm laser. Time scale 10µs per division. Red: Power control signal. Blue: Optical power. Left to right: Repetition rate 80 MHz, 50 MHz, 20 MHz. The noise in the 20 MHz curve is due to the pulsing of the laser.

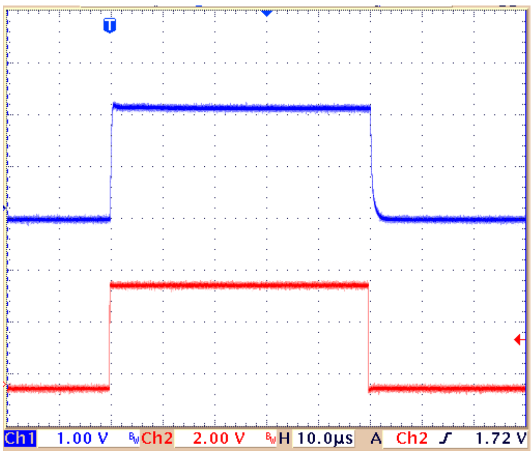


Fig. 8: Dynamic response of the output power to the power control signal CW mode. Control signal switches from 0 to +9 V. Time scale 10µs per division. Red: Control signal. Blue: Optical power.

As can be seen from these figures the reaction time to the power control signal is sufficiently fast for functions like beam blanking in laser scanning microscopes, or ON/OFF modulation for phosphorescence decay measurement. The disadvantage of using the power control input in these application is that the normal intensity control and the modulation has to be performed via the same signal. The BDL-SMN lasers therefore have a second input that can be efficiently be used for fast ON/OFF switching of the optical output.

ON/OFF Control and Multiplexing Control

The ON/OFF control is used to switch the optical output of the laser on and off at sub-microsecond speed. It is used for beam blanking in laser scanning microscopes, for ON/OFF modulation in phosphorescence lifetime and phosphorescence lifetime imaging applications, and for fast multiplexing of several lasers in FLIM and DOT applications [1, 2]. The ON/OFF input is TTL/CMOS compatible. A logical ‘high’ means the output is ‘ON’, a logical ‘low’ means the output is ‘OFF’. The ON/OFF control input has an internal pull-up resistor. That means, the optical output is in the ‘ON’ state if nothing is connected to the ON/OFF input. The dynamic reaction of the output power to the ON/OFF signal is shown in Fig. 9 and Fig. 10.

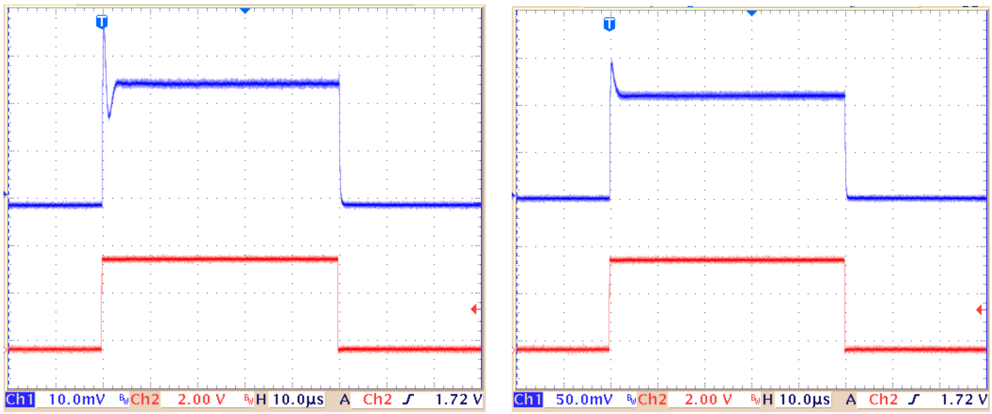


Fig. 9: Reaction of the optical power to the ON/OFF signal, picosecond operation, 50 MHz. Left: 10 % laser power. Right: 50 % laser power. Red curve: ON/OFF signal. Blue curve: Optical power. Time scale 10 µs per division.

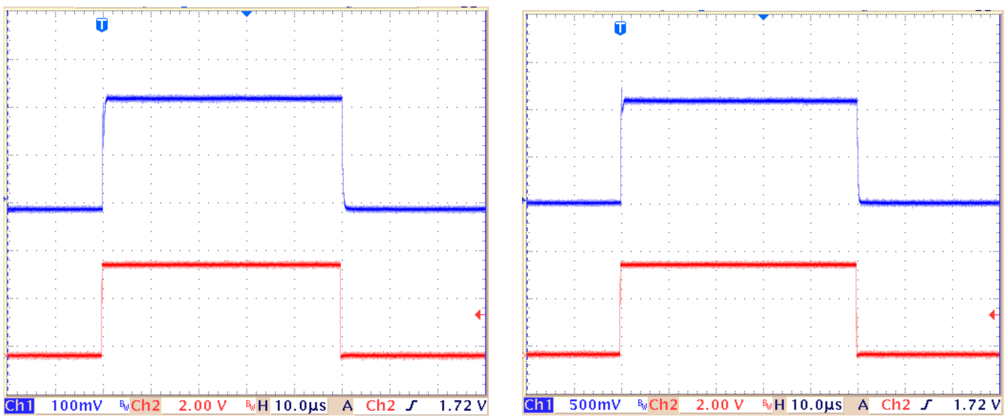


Fig. 10: Reaction of the optical power to the ON/OFF signal, CW operation. Left: 10 % laser power. Right: 50 % laser power. Red curve: ON/OFF signal. Blue curve: Optical power. Time scale 10 µs per division.

Frequency selection

The 3-Frequency-Version BDS laser can be operated at three internal clock frequencies, 20 MHz, 50 MHz and 80 MHz, and in the CW mode. The frequency and the mode are selected by three TTL-input lines, F1, F2, F3 and CW. For pin assignment please see page 13.

Signal	Pin at 15-pin laser connector and 'Ext. Control'
F1	2
F2	3
F3	4

Signal	F1	F2	F3	Function
Encoding of	H	L	L	20 MHz
Frequency	L	H	L	50 MHz
	L	L	H	80 MHz
	H	H	H	CW mode

Important: When the laser switch box is used the frequency select pins are connected in parallel to the frequency select switch. They can only be used when the frequency select switch is in the 'ext.' position. In all other positions of the switch the pin corresponding to the frequency selected is connected to ground. When using the frequency control lines of the laser switch box, please make sure that the source of the control signals connected to pin 2, 3 and 4 is short-circuit proof.

Synchronisation / Trigger Output to TCSPC modules

A synchronisation or trigger output signal for the bh TCSPC modules is available at a SMA connector. The polarity of the signal is *negative*, the pulse width is about 1 ns. The pulse shape is shown in Fig. 11: The signal shape and polarity is compatible with the SYNC inputs of all bh SPC modules and Simple-Tau systems. The amplitude is about -1.2 V into 50 Ω. This is enough to distribute the signal into up to four SPC modules by a power splitter. If the signal is connected into a single SPC module we recommend to reduce the amplitude by a 6-dB attenuator.

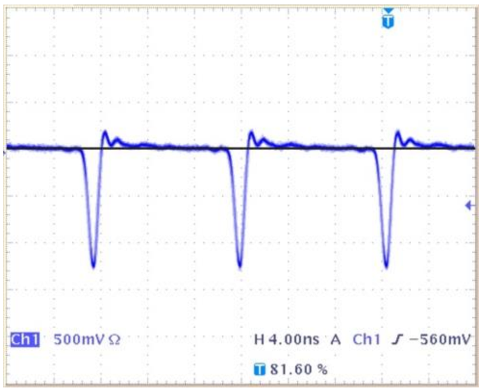


Fig. 12: Synchronisation signal to TCSPC modules. Repetition rate 50 MHz.

Please note that the polarity of the TCSPC sync signal is reversed compared to the older BDL-SMC lasers. *No A-PPI-D pulse inverter is needed for the BDL-SMN.*

Synchronisation signal to other BDL-SMN lasers

An additional synchronisation output is provided at a SMA connector of the laser (TTL-Out Fig. 5). This output is TTL/CMOS compatible. It is used to synchronise the pulse trains of several BDL-SMN lasers. Please see ‘Pulse-Interleaved Operation’ page 22.

The pulse shape and the temporal relation to the TCSPC Sync output is shown in Fig. 13. In principle, the Laser Sync signal could also be used to synchronise TCSPC experiments with the laser. However, we recommend to use the TCSPC Sync in these cases because it provides lower jitter and better timing stability.

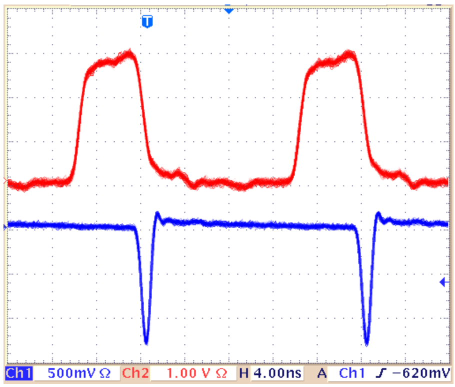


Fig. 13: Upper trace: Synchronisation signal to a second a second BDL-SMN laser, 1 V/div. Lower Trace: Sync signal to SPC modules, 500 mV/div. Time scale 4 ns/div. Repetition rate 50 MHz.

Synchronisation Input

The synchronisation input is used to synchronise a BDL-SMN laser to an external clock source. Normally, this is another BDL-SMN laser, or another pulsed laser running at an appropriate repetition rate. The input signal requirements are that the logical levels are TTL/CMOS compatible and the signal is DC coupled from a 50 Ω source. The pulses must be positive, with a duty cycle of no more than 30 %. With a signal like that, the laser automatically recognises that a synchronisation signal is connected, and switches its clock path from the internal clock generator to the synchronisation input.

The principle of clock source switching is shown in Fig. 14, a few typical situations are shown in Fig. 15. The average voltage at the Sync input connector is sensed via a low-pass filter. The output voltage from the filter sets a switch. If the average voltage is >3 V the clock comes from the internal clock generator, if it is <3 V it comes from the Sync input connector. The active edge of the input signal is the rising edge.

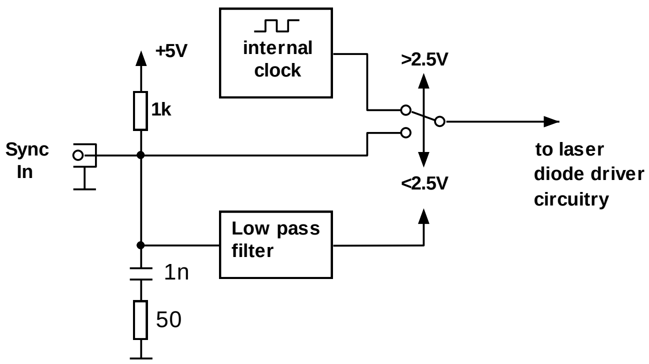
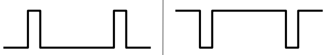


Fig. 14: Principle of switching between the internal clock generator and an external clock source



Sync Input:	open	TTL High	TTL Low	(pulse waveforms, first image)	(pulse waveforms, second image)
Average voltage:	>3 V	>3 V	<3 V	<3 V	>3 V
Clock source:	internal	internal	external, but no clock. Don't use	external	internal Don't use

Fig. 15: Effect of input signals on clock source selection

When you run the BDL-SMN laser from an external clock source, please remember that the laser has an internal power regulation loop. The regulation loop tries to maintain a constant average output power. That means the pulse peak power increases with increasing clock period. Please see 'Power Regulation Loop', page 19.

Pin Assignment

When the BDL-SMN laser is used in combination with the laser switch box the control signals are connected via a 15-pin sub-D connector and two SMA connectors. The connectors at the laser switch box are shown in Fig. 16.

Fig. 16: Control inputs of the laser switch box

The pin assignment at the 15-pin connector 'Laser' of the laser switch box is

1	not connected	9	not connected
2	F1: 20 MHz	10	+12V
3	F2: 50 MHz	11	not connected
4	F3: 80 MHz	12	Power, 0 to +10 V, parallel to SMA connector
5	GND	13	GND
6	reserved, do not connect	14	not connected
7	ON/OFF, parallel to SMA connector	15	GND
8	reserved, do not connect		

The pin assignment at the 15-pin connector of the laser is

1	not connected	9	not connected
2	F1 20 MHz	10	+12V operating voltage
3	F2 50 MHz	11	reserved, do not connect
4	F3 80 MHz	12	Power, 0 to +10 V
5	GND	13	GND
6	reserved, do not connect	14	not connected
7	ON/OFF	15	GND
8	not connected		

The pin assignment at the 15-pin connector ‘Ext. Control’ of the laser switch box is

1	do not connect
2	F1: 20 MHz 1,2)
3	F2: 50 MHz 1,2)
4	F3: 80 MHz 1,2)
5	GND
6	reseved, do not connect
7	Laser ON/OFF, TTL/CMOS, parallel to SMA connector
8	reserved, do not connect
9	not connected
10	not connected
11	not connected
12	Power control signal, 0 to +10 V, parallel to SMA connector
13	not connected
14	not connected
15	GND

Details of Laser Function

Optical Properties

Beam Profile

The free-beam diameter of the BDL-SMN lasers is about 0.8 mm. The beam is emitted from an aperture at the front side of the beam correction optics block, see Fig. 17, top. If a Qioptiq Kineflex coupling system is attached to the laser a free beam is also available through the fibre manipulator, see Fig. 17, bottom.

Fig. 17: Free-beam operation of the BDL-SMN laser

The beam diameter may vary a bit for different laser diodes and is between 0.7 mm to 1 mm. Beam profiles measured at 1 m distance from the laser are shown in Fig. 18.

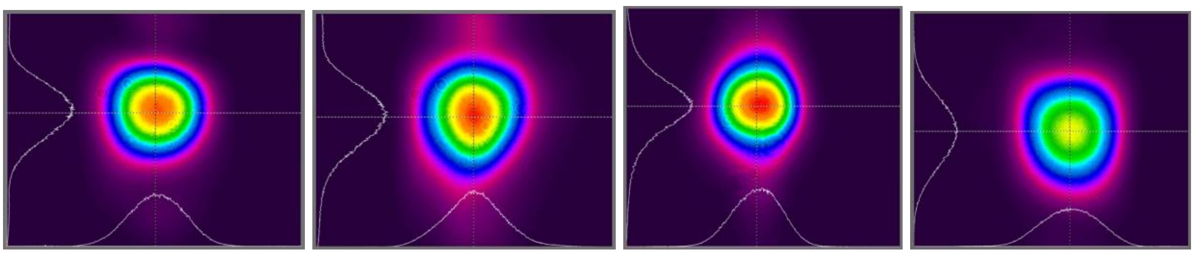


Fig. 18: Beam profile in 1m distance from the BDL-SMN laser, picosecond mode. Left to right: 405 nm, 473 nm, 515 nm, 785 nm version

Beam profiles for the CW mode are shown in Fig. 19. A profile for a 785 nm version is shown in Fig. 19, left, a profile for a 515 nm version in Fig. 19, right. Unlike red and NIR laser diodes, blue and green diodes deliver noticeably different beams in the pulsed mode and in the CW mode. The effect is most pronounced for the ones of longer wavelength, i.e. 488 nm and 515 nm. The optics of the bh BDL-SMN lasers is adjusted to correct the beam parameters in the *picosecond mode*. As a result, the beam shape of the blue and green lasers in the CW mode may be less favourable than in the picosecond mode, compare Fig. 19, right and Fig. 18, second right.

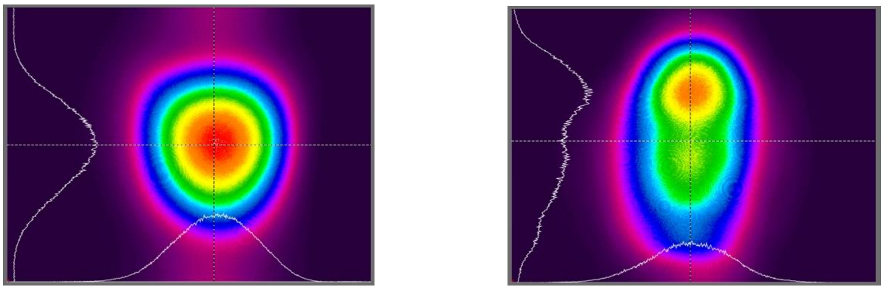


Fig. 19: Beam profiles in the CW mode. Left BDL-SMN 785 nm, Right: BDL-SMN 515 nm.

Single-Mode Fibre Coupling

The BDL-SMN lasers are available with the Kineflex fibre coupling system [10] of Quioptiq, formerly Point Source. The fibres are available with different outputs. A fibre with a collimated output is shown in Fig. 20, left. The output collimator fits into a second Kineflex fibre manipulator. The manipulator provides a stable and reproducible connection to the experiment, and makes fine-alignment easy. Collimated-output fibre are the recommended solution to fibre-couple the laser to optical experiments. Fig. 20, right, shows the beam profile delivered by a collimated-output fibre.

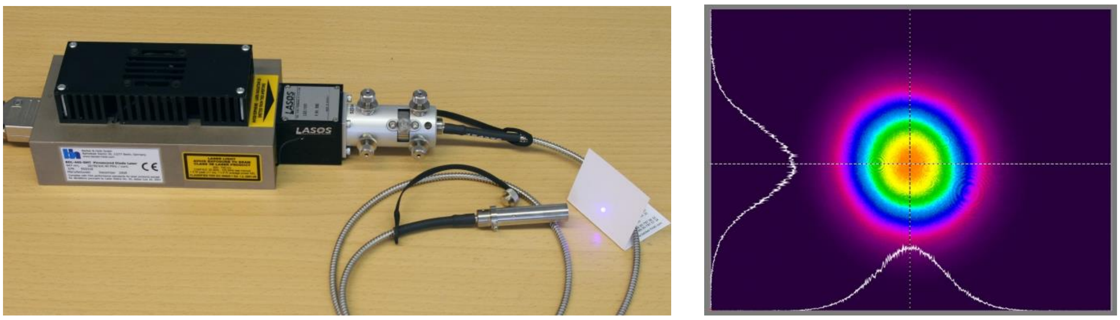


Fig. 20: Left: Collimated output from single-mode fibre. Right: Beam profile at the collimator output

Fibres are also available with FC connectors at the output. However, FC connectors are less reproducible than the Kineflex system. They also do not automatically collimate the beam. Please note also that there are different versions of FC connectors with different front angles of the fibre face.

Please note that single-mode fibre coupling does not broaden the temporal pulse profile. Different than for multi-mode fibres, only a single transversal mode is travelling in the fibre. Transit-time differences for different modes therefore do not exist. Transit time differences can only be caused by refractive-index variation over the emission spectrum of the laser. However, these are below 1 ps, and thus do not broaden the pulses noticeably.

Spectral Properties

The emission spectra of laser diodes are generally broader than those of gas lasers or solid-state lasers. Moreover, the spectra of laser diodes get broader and often blue-shifted in the picosecond mode. The shift is especially pronounced for laser diodes of 488 nm and 515 nm wavelength. It can reach almost 10 nm in some cases. The spectral shift is not really a problem in fluorescence applications: The absorption spectra of the compounds investigated are usually broad enough. However, the shift must be taken into account for the design of optical systems, especially dichroic beam splitters and beam combiners. Emission spectra for three BDL-SMN versions are shown in Fig. 21.

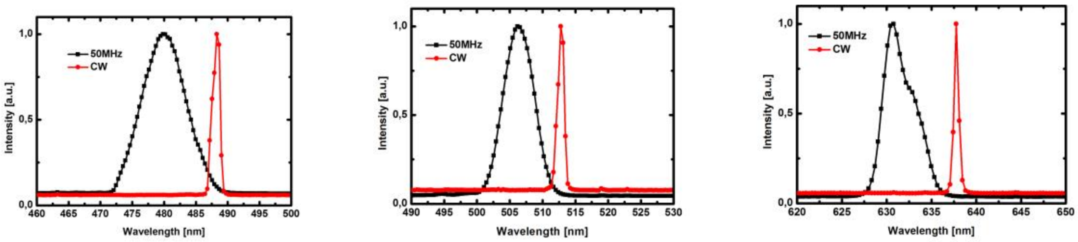


Fig. 21: Emission spectra for BDL-SMN lasers of different wavelength. Left to right: 488 nm, 515 , 640 nm. Please note different wavelength scales.

An unpleasant feature of laser diodes is that they emit a substantial amount of background light [9]. The background is spectrally broad and can extend almost 100 nm beyond the laser wavelength. The temporal shape of the background is broader than that of the laser pulses, and can be several nanoseconds wide. The background can be extremely annoying in fluorescence experiments. The bh lasers (both the BDL-SMN and the older BDL-SMC) therefore contain cleaning filters that block emission at the long wavelength side of the laser line. Please note, however, that the filter transition wavelength is matched to the laser wavelength *in the CW mode*. In the picosecond mode the emission wavelength is shorter, and there may be background emission over a range of several nanometers on the long wavelength side of the laser wavelength.

Pulse Shape

Dependence on Driving Conditions

When a laser diode is driven from the fully off state to the on-state by a sharp pulse edge it emits a fast optical pulse before it settles into the normal steady-state intensity, see Fig. 22, a. The mechanism of the optical overshoot is not entirely clear. It is probably a combination of overshoot in the diode current, nonlinearity of the electrical characteristics, inherent optical nonlinearity, and feedback of the optical emission into the electrical behaviour. With appropriate driving, optical pulses more than 10 times shorter than the electrical pulse can be generated. The task of ps pulse generation is to drive the laser diode a way that only the short ps pulse is emitted, and not the steady-state emission from the rest of the electrical pulse. The obvious way to obtain only the ps pulse is to reduce the width of the electrical pulse, see Fig. 22, b. Unfortunately, the effective current pulse through the laser diode junction cannot be made infinitely short: Even for an infinitely fast voltage pulse applied to the diode the lead inductance and the junction capacitance prevent the current pulse through the diode junction from getting shorter than a few 100 ps. The result is that a sharp peak is obtained up to a certain pulse current level only (Fig. 22, b). If the driving power is increased above this level emission from the full width of the current pulse shows up, see Fig. 22, c and d.

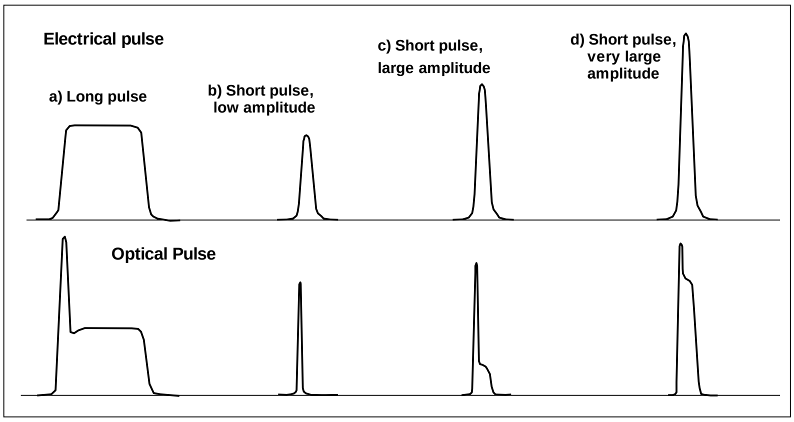


Fig. 22: Dependence of optical pulse on driving conditions of laser diode

Pulse Shapes for Different Lasers and Different Power

Optical pulse shapes for different lasers in the ultraviolet to green range are shown in Fig. 23. As can be seen from the figure, the pulses are generally steeper at shorter wavelength. The general behaviour, however, is the same for all wavelengths: At low peak power the pulses are relatively wide. They get shorter with increasing power. If the power is increased further the pulses develop a tail of increasing amplitude. At very high power, the tail almost reaches the amplitude of the initial peak. For most wavelengths, the FWHM of the BDL-SMN lasers under high-power conditions is on the order of 150 to 200 ps.

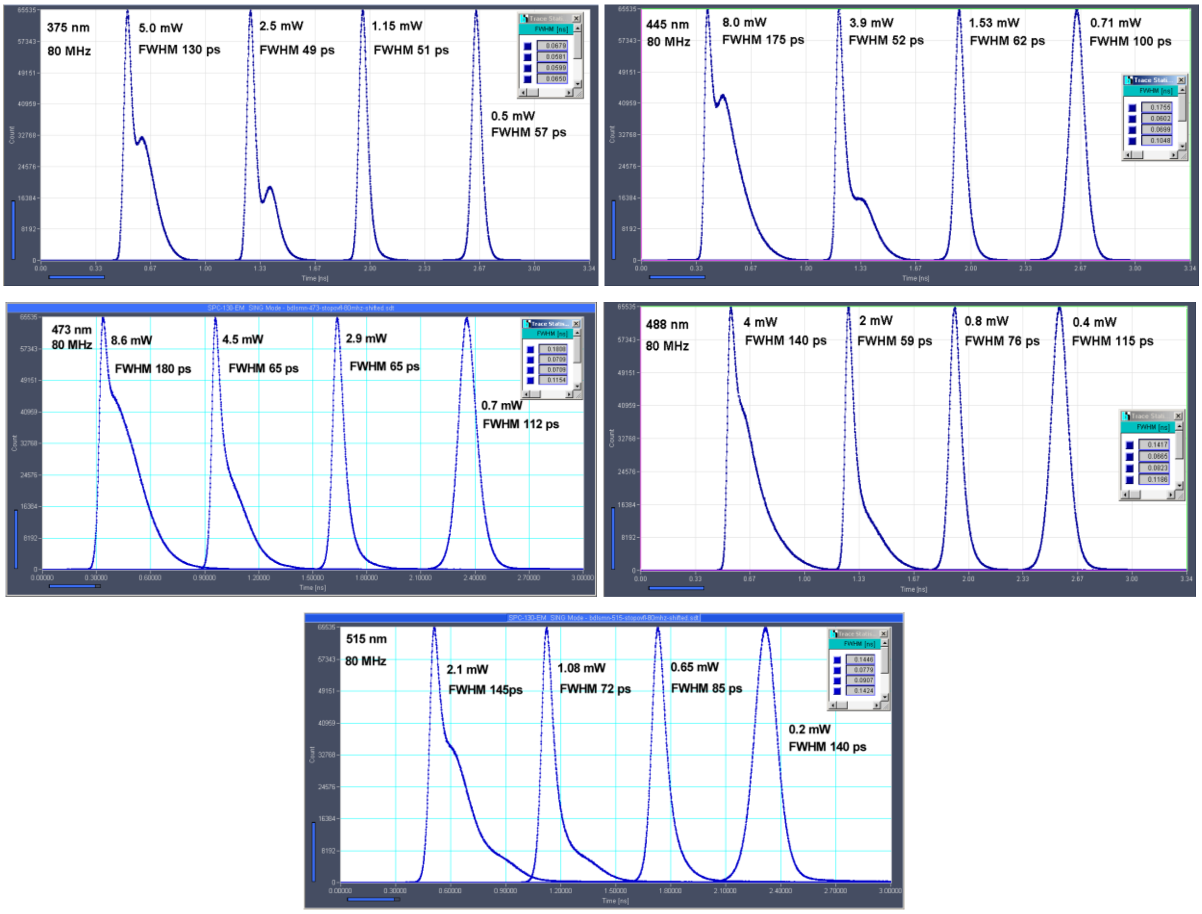


Fig. 23: Optical pulse shape for different laser power. Wavelength versions 375 nm, 445 nm, 473 nm, 488 nm, and 515 nm. Recorded with SPC-150N TCSPC module and id 100-20 detector. FWHM values corrected for 30 ps instrument response width.

Power Regulation Loop

Effect of Power Regulation

Light generation in a laser diode is a highly nonlinear process. Thus, the slightest changes in the driving conditions or junction temperature results in a large change in the optical power. Therefore, the BDL-SMN lasers have an internal power regulation loop, see Fig. 24. The laser power is monitored by a photodiode, and the photodiode current compared with the intensity control signal. The difference of both is amplified, and used to control the electrical driving power to the diode. Thus, the difference between the photodiode current and the power control signal is regulated down to zero. That means the optical power is linearly related to the power control signal. Changes in the optical power due to temperature variation, variation in the supply voltages, or mode fluctuations in the laser diode are largely suppressed.

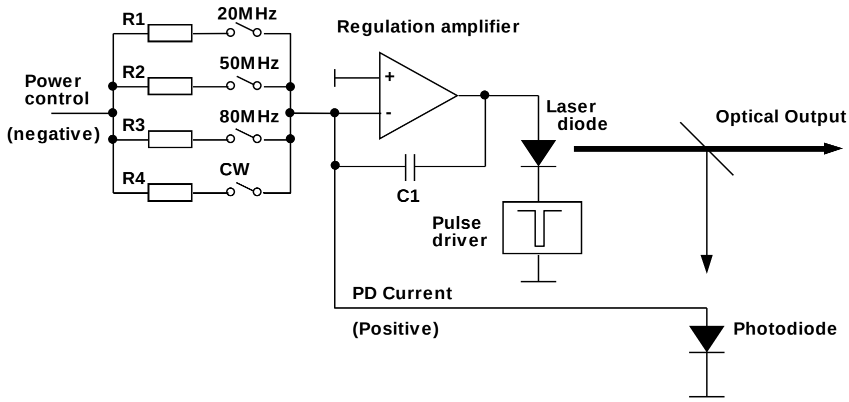


Fig. 24: Principle of power regulation loop

Of course, the circuit shown in Fig. 24 regulates the average intensity, not the peak intensity of the pulses. That means, the peak power changes with the pulse repetition rate. For operation with the internal clock oscillators the variation with the repetition rate is taken into account by switching the resistors, R1 through R4, in proportion to repetition rate selected.

For operation with an external clock such compensation is not possible. The peak power thus changes with the pulse period, see Fig. 25. To obtain a reasonable power regulation range with an external clock we recommend to set the frequency switch of the laser switch box (or the F1, F2, F3 bits) to the value closest to the external clock frequency.

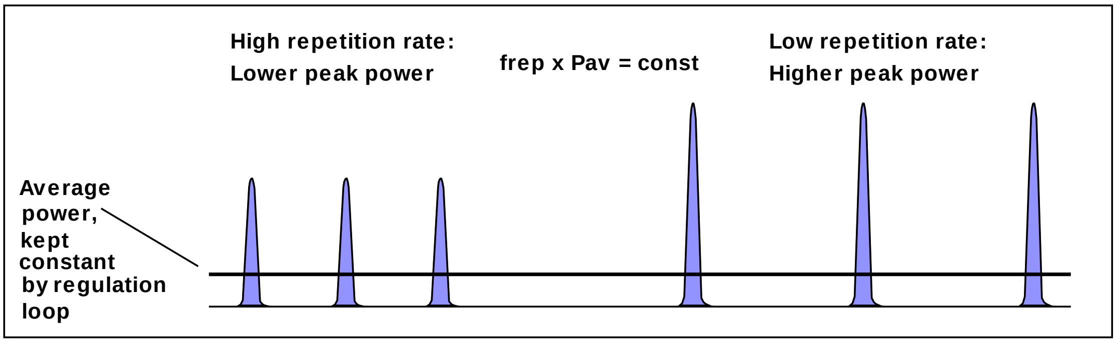


Fig. 25: The regulation loop keeps the average optical power constant. That means the peak power increases with decreasing repetition rate. The effect becomes apparent only with an external clock. For internal clock it is compensated by different resistors, R1 through R4, in the reference signal path.

Pulse Power and Average power

The typical pulse width for a picosecond laser diode is in the range of 50 to 100 ps. As shown in Fig. 26, the result is a relatively high peak power even for low average (CW equivalent) power. For a repetition rate in the 20 to 80 MHz range the duty factor, T_{per}/T_{pw} is on the order of 100 to 500. Thus, the peak power, P_p, can easily reach a several 100 mW.

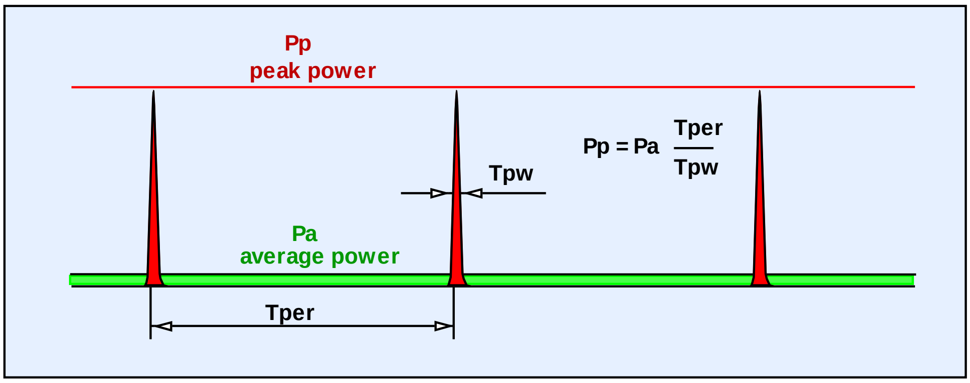


Fig. 26: Relation between peak power, average power, pulse width and pulse period

The peak power is usually beyond the permissible steady state power specified for the laser diode. Fortunately, the short pulse width prevents the diode from being thermally damaged. However, degradation may occur by extremely fast nonlinear optical effects. In the interest of the lifetime of the laser diode, it is therefore recommended to avoid unnecessarily high peak power.

Implementing the BDL-SMN Lasers in TCSPC Experiments

Controlling the BDL-SMN Lasers from a DCC-100 Card

The BDL-SMN lasers can be controlled via the bh DCC-100 detector / Laser controller card [2]. One of the outputs, Con1, is connected to the control input connector of the laser switch box. The laser power can then be controlled via the 'Gain' slider, and the laser output be turned on and off via the +5 V button. The other output, Con3, can be used to control a detector or a second BDL-SMN laser. Con2 is reserved for controlling shutters. Please note that a special cable is required to connect the laser to the DCC card. A standard 15-pin cable (e.g. from a PC monitor) does not work.

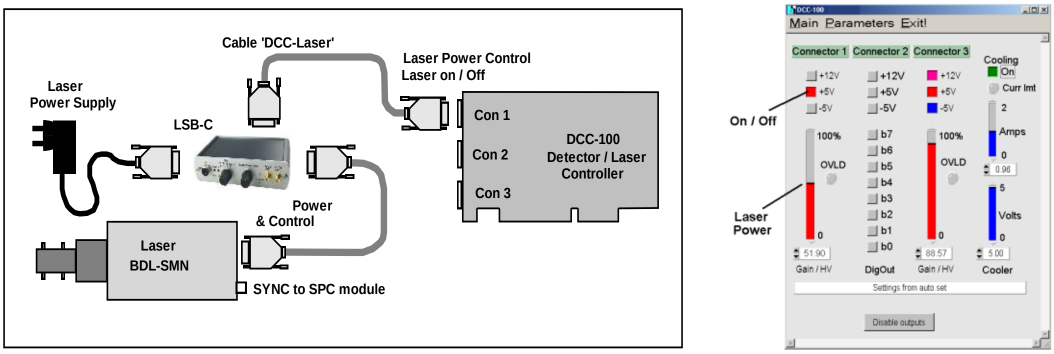


Fig. 27: Controlling the BDL-SMN from a DCC-100 Detector / Laser Controller card

Simple Fluorescence-Lifetime Experiment

The setup shown in Fig. 28 uses a BDL-SMN laser for a simple fluorescence lifetime experiment. The sample is excited by the picosecond pulses from the laser. The fluorescence photons are detected by a bh HPM-100 or PMC-150 detector. The photons are recorded by an SPC-160, SPC-150N or SPC-130-EMN TCSPC module. The timing synchronisation signal for the TCSPC module comes from the TCSPC Sync output of the laser. Both the laser and the detector are controlled by a DCC-100 detector / laser controller card. The entire setup is operated via the bh SPCM TCSPC operating software [2].

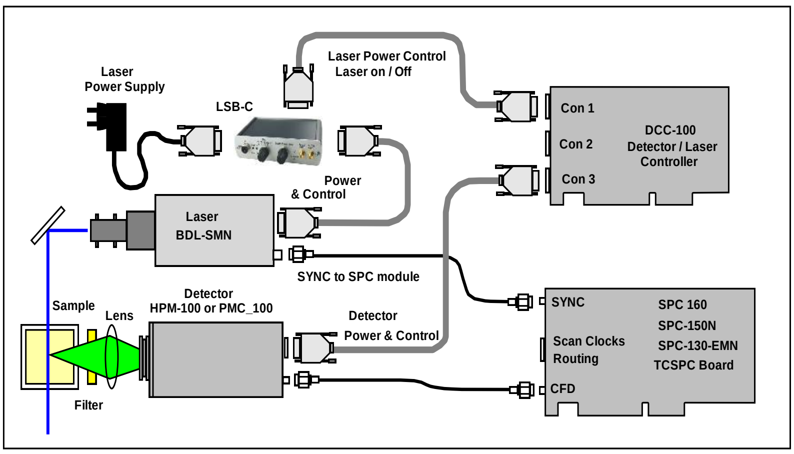


Fig. 28: Simple fluorescence-lifetime experiment

Pulse-Interleaved Operation

Two or more BDL-SMN lasers can be synchronised via the Laser Sync output and the Laser Sync input signals. The optical pulses of the lasers are then interleaved within the same signal period.

The basic connections are shown in Fig. 29. The Laser Sync output signal of the first laser, Laser 1, is connected to the Laser Sync input of the second laser, Laser 2. Laser 1 is running at the repetition rate selected by its laser switch box. The second laser recognises that a signal is connected to its Laser Sync input. It thus disables its internal clock generator, and triggers to the laser sync signal from the first laser. The time between the optical pulses of Laser 1 and Laser 2 is determined by the transit time in the Laser Sync connection cable, C1, plus the internal delay of Laser 2. The transit time on the cable is 1 ns per 20 cm of cable, the internal delay is about 7 ns. The delay between the pulses of laser 1 and laser 2 is thus

$$T_d = L_{cable} / 20\text{cm/ns} + 7\text{ns}$$

The TCSPC Sync signal can be taken from either laser. Because the TCSPC module needs a Sync at the end of the signal period [2] it is usually more convenient to take the TCSPC Sync from laser 2.

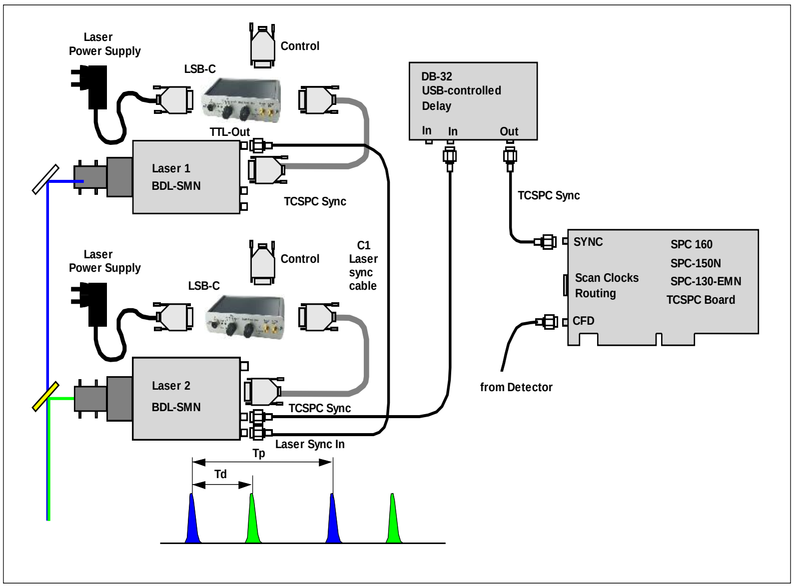


Fig. 29: System connections for pulse-interleaved operation of two lasers. Control connections to lasers not shown.

Pulse-interleaved operation can cause confusing effects if the signal transit times are inappropriately selected. For example, if the delay in the TCSPC sync path is wrong the temporal position of the pulse of laser 2 can wrap around the signal period, Tp. The pulse of the second laser can then appear *before* the first laser in the TCSPC recording. The pulses can also get swapped if the laser sync delay, Td, is so large that the pulse of laser 2 slips into the next period of laser 1. We therefore recommend to use a DB-32 USB controlled delay box at least in the TCSPC Sync path.

Please note also that the BDL-SMN lasers have an internal power regulation loop. The loop maintains a constant *average* optical power corresponding to the power control input signal of the laser. The regulation loop can only control the correct peak power correctly if it knows the repetition rate of the pulses, see Fig. 24. The repetition rate selectors at the switch boxes of both lasers should therefore be set to the same repetition rate.

An example for pulse-interleaved operation of two BDL-SMN lasers is shown in Fig. 30. The repetition rate is 50 MHz, the delay between the pulses of laser 1 and laser 2 is about 11 ns.

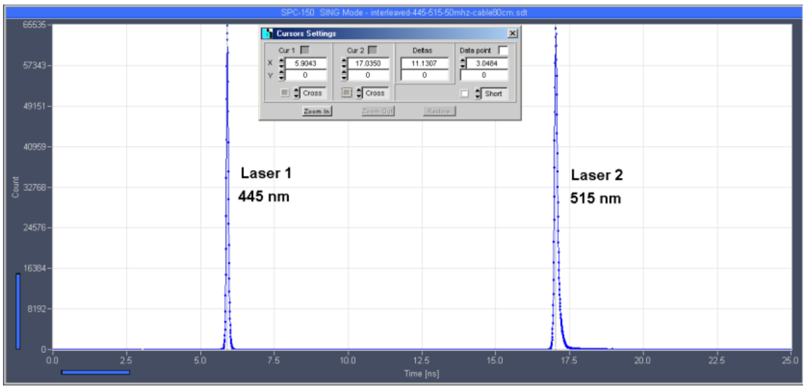


Fig. 30: Pulse-interleaved operation. 445 nm and 515 nm laser, Laser Sync cable 80 cm, repetition rate 50 MHz. The delay between the 445 nm and 515 nm pulse is 11.13 ns.

Laser Multiplexing

The lasers are switched ON/OFF alternatingly with periods in the microsecond or millisecond range. Simultaneously with the switching of the lasers, the memory block in the SPC module is switched. Thus, photons excited by each laser are stored in separate memory blocks in the SPC module [1, 2].

A connection diagram is shown in Fig. 31. The laser ON/OFF signals are generated in a DDG-210 pulse generator card. Switching of the lasers is achieved via the 'Laser ON/OFF' inputs of the lasers. The DDG-210 card also generates the routing signal for the SPC module. It is applied to the lowest routing bit, R0, via the 15-pin control connector of the SPC module.

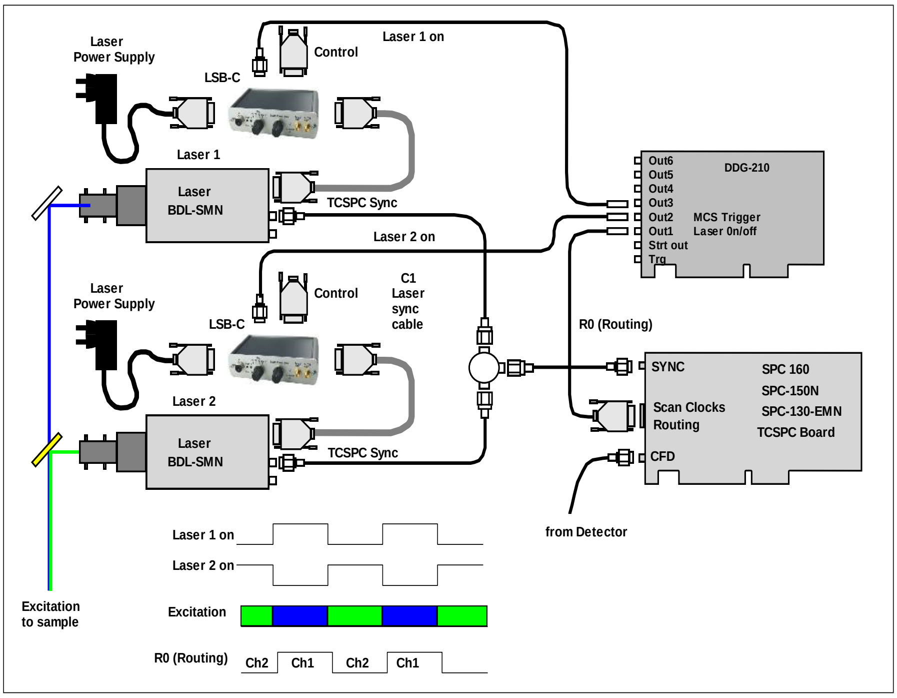


Fig. 31: Laser multiplexing. The lasers are switched ON/OFF alternatingly, the photons excited by each laser are stored in separate TCSPC memory channels

Laser multiplexing has a number of advantages over pulse-interleaved excitation. It avoids that the tail of the fluorescence signal excited by one laser overlaps the signal excited by the other one. Also optical reflections, as they are often occur in optical fibres, do not cause a crosstalk of the two signals. Moreover, there is no mutual influence of the signals via pile-up and counting loss effects. Please see [1] and [2] for detailed discussion.

In FLIM systems laser multiplexing is usually synchronised with the pixels, lines, or frames of the scan. In systems using the bh GVD-120 scan controller a scan-synchronous multiplexing signal is available directly [4]. In other systems the DDG-210 card can be used as shown in Fig. 31 and be triggered by clock pulses from the scanner.

Combined Fluorescence / Phosphorescence Lifetime Detection System

Fluorescence and phosphorescence decay data can be recorded simultaneously by a principle described in [2] and [3]: A high-frequency pulsed laser is ON/OFF modulated at the microsecond time scale, and photon times are determined both within the laser pulse period and the modulation period. Fluorescence decay curves are built up from the times in the laser pulse period, phosphorescence decay curve from the times in the modulation period.

The components and system connections for a fluorescence / phosphorescence decay experiment based on this principle are shown in Fig. 32.

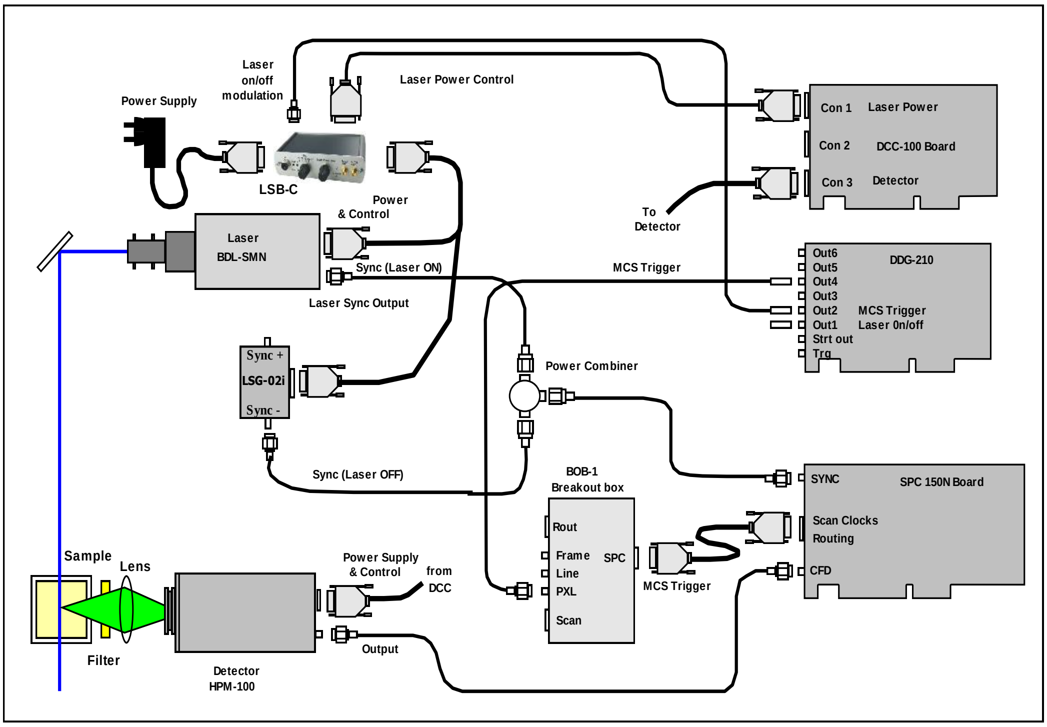


Fig. 32: Combined fluorescence / phosphorescence lifetime experiment

The BDL-SMN laser is ON/OFF modulated by a signal from the DDG-210 pulse generator card. (The control of the card is integrated in the SPCM software, see [2]) The power supply for the laser comes from a wall-mounted +12 V adapter, the intensity is controlled from a DCC-100 card.

During the ‘laser-off’ periods the laser does not deliver a SYNC signal. This signal is, however, needed for the TCSPC module to complete the recording cycle of each individual photon. It is supplied by a LSG-02i SYNC generator module. Electronically, this module behaves like a BDL-SMN laser: It delivers pulses at a frequency controlled by a laser switch box, and can be ON/OFF modulated by a TTL signal. The LSG-02i generator inverts the ON/OFF signal and sends a signal that is exactly reversed compared to that of the laser. Thus, the LSG-02i module delivers SYNC pulses when the laser does not, and vice versa.

The SYNC pulses from the laser and the LSG-02i module are combined and fed into the SYNC input of an SPC-150N board. The timing reference (‘MCS Trigger’) for the times in the modulation period are fed into the SPC module via a BOB-1 box [2].

A result is shown in Fig. 33. The sample contained a mixture of fluorescein and a ruthenium dye. The fluorescein emits fluorescence with a decay time of 4 ns. The ruthenium dye emits essentially phosphorescence. The decay time depends on the oxygen concentration in the sample. It is about 800 ns.

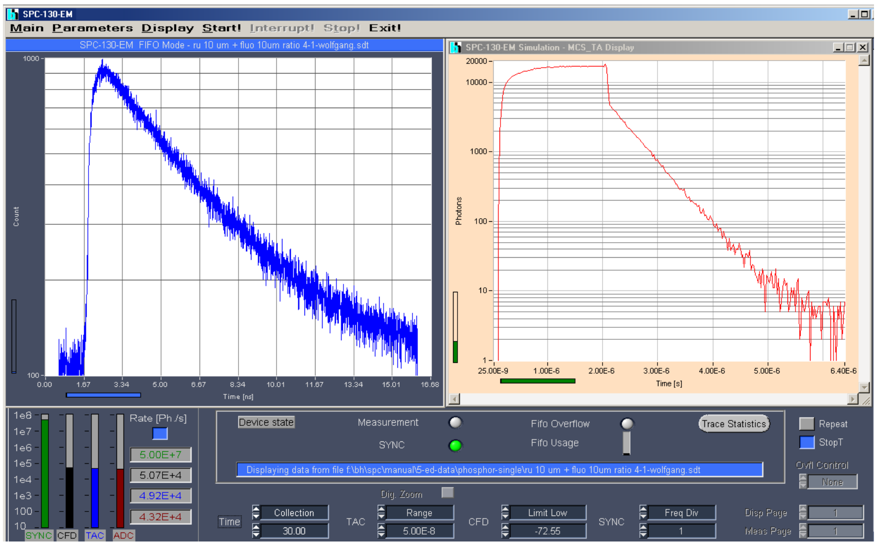


Fig. 33: Result obtained in the setup shown above. Fluorescence decay curve shown left, phosphorescence decay curve right. Both curves are recorded simultaneously.

FLIM Systems

The BDL-SMN lasers are used as excitation sources of the bh FLIM systems. Fig. 34 shows the architecture of the bh DCS-120 confocal scanning FLIM systems [4]. Two BDL-SMN lasers are used for excitation. The DCS-120 scan head scans the sample with the focused laser beams through a microscope, de-scans the fluorescence light beams, and sends the fluorescence photons to the detectors. Both HPM-100 hybrid detectors and 16-channel multi-wavelength detectors can be used. The signals are recorded by two SPC-150N TCSPC / FLIM modules. The scanning is controlled by a GVD-120 scan controller card.

The GVD-120 controls also the BDL-SMN lasers. The lasers are turned on during the forward scan, and turned off during the line and frame flyback. The scan controller is also able to multiplex the two lasers. The multiplexing is synchronous with the scanning: They can be multiplexed frame by frame, line by line, and even within one pixel. Laser multiplexing is also used for combined FLIM / PLIM (phosphorescence lifetime imaging) operation: In that case, one laser is ON/OFF modulated within one pixel of the scan, and photon times are determined both within the pulse period and the modulation period [2, 3].

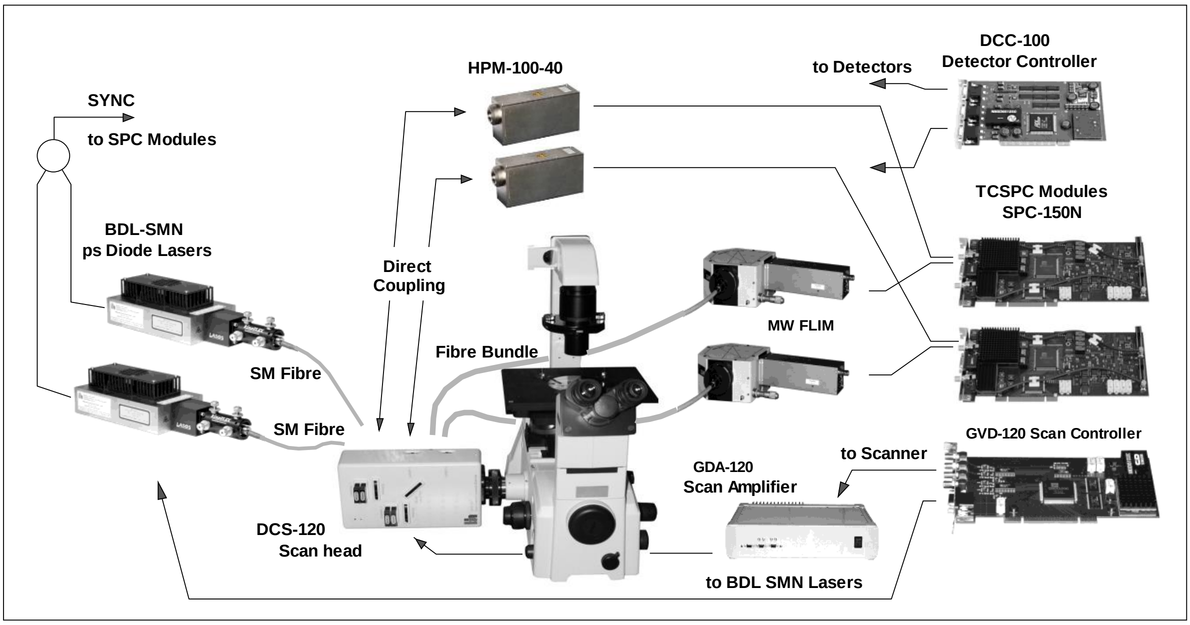


Fig. 34: Architecture of the DCS-120 confocal FLIM systems. Two BDL-SMN lasers are used for excitation

An example of a wavelength-multiplexed recording with two lasers is shown in Fig. 35.

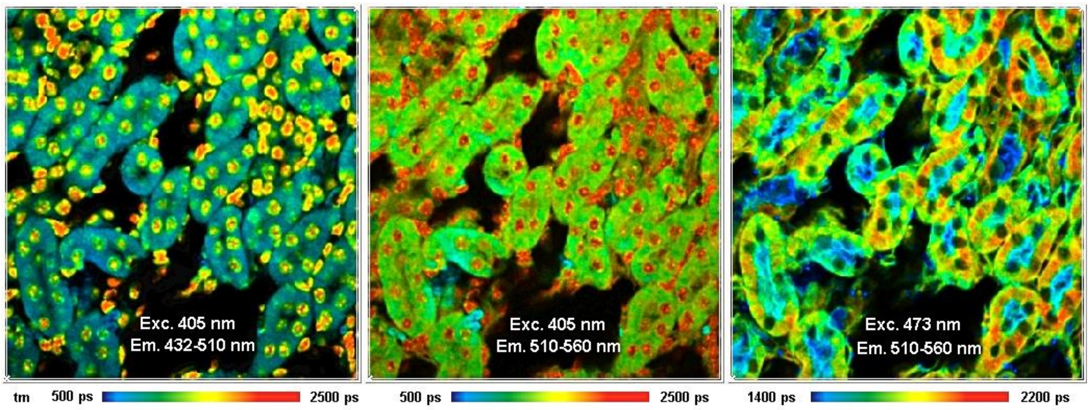


Fig. 35: FLIM with excitation wavelength multiplexing, 405 nm and 473 nm. Detection wavelength 432 nm to 510 nm and 510 nm to 550 nm. Mouse kidney section, stained with Alexa 488 WGA, Alexa 568 phalloidin, and DAPI.

Fluorescence Correlation

Due to their high power stability the BDL-SMN lasers are excellently suitable for FCS experiments. The basic optical setup for a dual-colour FCS experiment is shown in Fig. 36. Two BDL-SMN lasers are used to excite fluorescence in the sample. The sample contains two fluorophores, each of them excited by one of the lasers. The fluorescence is detected by two detectors through different filters. The detection times of the photons are recorded by two separate SPC-150N TCSPC / FLIM modules [2], by one SPC-150N module and a router [2], or by a DPC-230 photon correlator module [8]. The photons of each channels are auto-correlated or cross-correlated online by the instrument software [2].

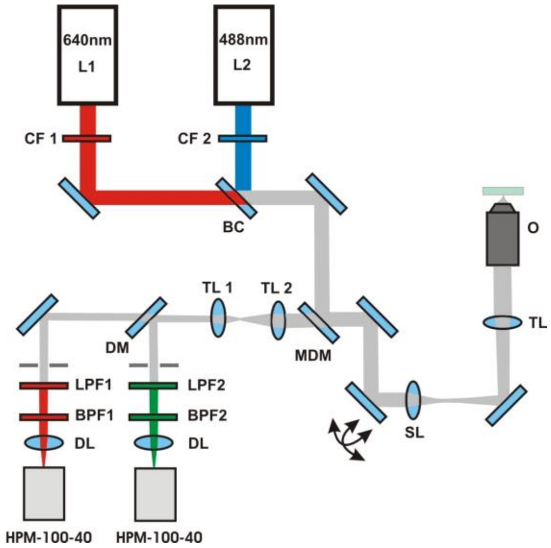


Fig. 36: Dual-colour FCCS setup based on BDL-SMN lasers and DSC-120 confocal FLIM system. L1: B&H BDL-640-SMN picosecond/CW diode laser. L2: B&H BDL-488-SMN picosecond/CW diode laser. CF1: laser cleaning filter from Semrock BrightLine 640/14. CF2: laser cleaning filter from Chroma ET 490/20. BC: beam combiner (Chroma z488rdc-xr). MDM: main dichroic mirror (Chroma z488/647 rpc). SL: scanning lens (achromat f = 35mm). TL: tube lens (f = 180mm). TL1: telescope lens (f = 7.5mm). TL2: telescope lens (f = 45mm). DM: emission dichroic mirror (Chroma 560dcxr). LPF1: Semrock long-pass filter 647LP, BPF1: Chroma band-pass filter 675/80. LPF2: Chroma long-pass filter 495LP. BPF2: Chroma band-pass filter 525/50. DL: detector lens (f = 25mm).

Two typical results are shown in Fig. 37. Auto-correlation and cross-correlation of free Atto 488 carboxy and Atto 647N carboxy fluorophores are shown in Fig. 37, left. There is autocorrelation for the signals from both fluorophores (Red and blue curves) but no cross-correlation between the signals (green). Curves for a 40 base pair double-stranded DNA labelled with Alexa 488 and Cy5 are shown in Fig. 37, right. There is a significant cross-correlation (green curve) showing that part of the DNA strands contain both fluorophores.

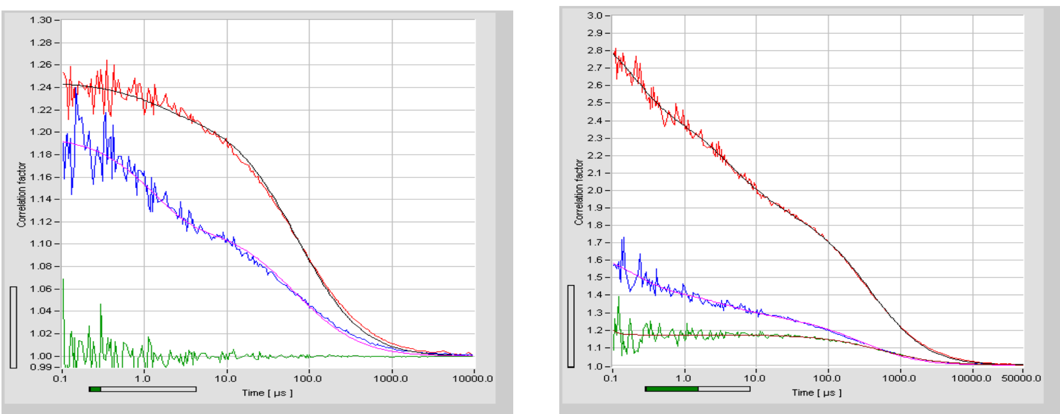


Fig. 37: Left: Atto 488/7 nM Atto 647N, molecules not linked. Right: Alexa 488 and Cy5 linked by double-stranded DNA. Blue and Red: Autocorrelation. Green: Cross-correlation.

Aligning Qioptiq Fibre Couplers

The fibre manipulator of the Qioptiq Kineflex system [10] is shown in Fig. 38. It has four adjustment screws, A1, A2, B1 and B2. Inside the manipulator, the fibre input adapter is pressed against the alignment screws by a spring-loaded counter-bearing. Thus, the fibre adapter can both be shifted and tilted by turning the adjustment screws. Under normal use, e.g. after removing and re-inserting the fibre, only fine adjustments are required. It is then sufficient to adjust the front screws, A2 and B2, for maximum intensity at the fibre output. Do not turn the screws by more than 1/2 turn. Once the manipulator is totally misaligned you have to go through the complete alignment procedure.

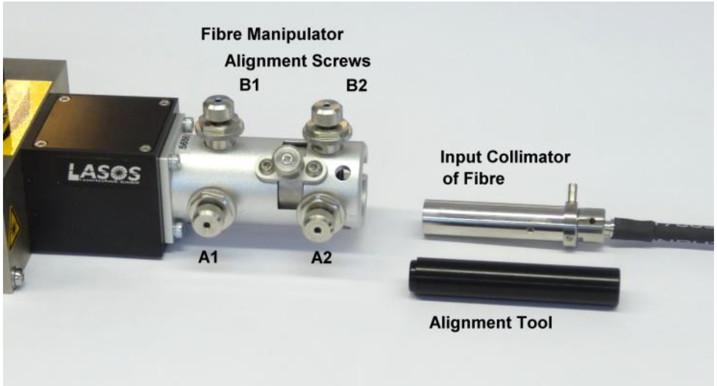


Fig. 38: Front end of the BDL-SMN laser. Beam profile corrector, fibre manipulator with alignment screws, input adapter of the single-mode fibre, and alignment tool.

The complete alignment procedure is illustrated in Fig. 39. For the first steps an alignment tool is required, see Fig. 38. The tool is a tube which has a pinhole in the optical axis.

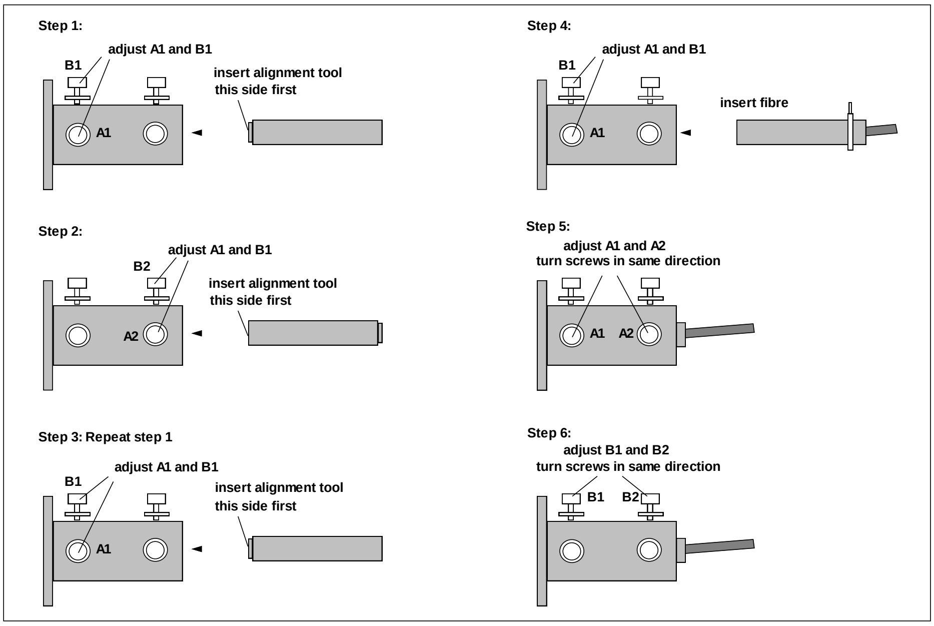


Fig. 39: Steps of the alignment procedure

To align the fibre coupler, proceed as follows:

1) Insert the alignment tool as indicated in Fig. 39 and adjust A1 and B1 for maximum throughput.
2) Reverse the alignment tool and adjust A2 and B2 for maximum throughput.

3) Repeat step 1. After step 3 the optical axis of the fibre manipulator is aligned with the axis of the laser beam.
4) Insert the fibre. Adjust A1 and B1 for maximum output intensity.
5) Adjust A1 and A2 for maximum intensity. This step is a lateral shift of the optical axis. Therefore turn both screws in the same direction until you find the setting that yields maximum intensity.
6) Adjust B1 and B2 for maximum intensity. This step is a lateral shift of the optical axis. Therefore turn both screws in the same direction until you find the setting that yields maximum intensity.

Laser Safety

The BDL-SMN lasers are class 3B laser products. The laser safety regulations require that the lasers be labelled with the stickers shown in Fig. 40, and that the labels and the location of the labels on the lasers be described in the manual. The laser class is indicated on the laser by an ‘explanatory label’, Fig. 40, left. The laser aperture is marked with the aperture labels, Fig. 40, middle and right.

Fig. 40. Left to right: Explanatory label, aperture labels.

Moreover, each laser has a manufacturer identification, as shown in Fig. 41.

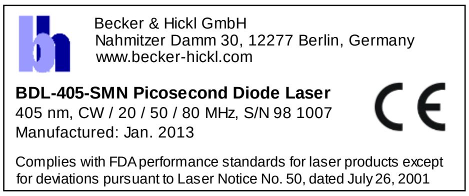


Fig. 41: Manufacturer identification label

The position of the labels on the laser modules is shown Fig. 42.

Fig. 42: Location of the labels on the lasers

Laser safety regulations forbid the user to open the housing of the laser, or to do any maintenance or service operations at or inside the laser. Use of controls or adjustments or performance of procedures other than specified herein may result in hazardous radiation exposure or damage to the laser module.

Moreover, do not look into the laser beam through lenses, binoculars, microscopes, camera finders, telescopes, or other optical elements that may collimate the light into your eye. When using the lasers in combination with a microscope make sure that the beam path to the eyepieces is blocked for the laser wavelength when the laser is on. If an optical fibre connected to a 3B laser has to be replaced, the laser has to be turned off.

It is required to have a ‘remote interlock connector’ that can be pulled to turn off the laser reliably. The ‘Interlock’ connector of the LSB-C box is used to build up a laser-safety loop when the BDS laser is integrated in larger systems. To enable laser operation the safety cable delivered with the LSB-C box must be connected to the interlock connector, and the blue wire connected to the black wire or to ground either directly or via the laser safety loop. The connector can be pulled off or plugged in at any time without causing damage to the laser.

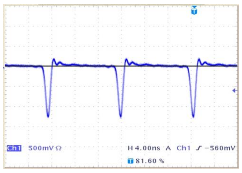
Specifications

Optical

Repetition Rate	20-50-80 MHz, or CW operation
Wavelength, nm	375, 405, 445, 473, 488, 515, 640, 685, 785, 1064, other on request
Pulse width (FWHM, at medium power)	40 to 90 ps [2]
Pulse width (FWHM, at maximum power)	200 to 300 ps [2]
Peak Power	40 to 500 mW [1]
Power control range (Average CW equivalent power, adjustable via external power control signal)	20 MHz: 0 to 0.6 mW .... 0 to 2 mW [2] 50 MHz: 0 to 1.5 mW .... 0 to 5 mW [2] 80 MHz: 0 to 2.4 mW .... 0 to 8 mW [2] CW mode: 0 to 20 mW .... 0 to 50 mW [2]
Diameter of laser beam	0.7 mm, TEM_{00} mode
Polarisation	horizontal
Fibre coupling	Kineflex system of Qioptiq
Coupling efficiency into single-mode fibre, typically	60 %
Stability of Repetition Rate	± 100 ppm
Pulse-to Pulse Jitter	< 20 ps
Reaction time to 'Laser on' signal (pulsed mode)	3 µs
Reaction time to 'Laser on' signal (CW mode)	3 µs
Power and pulse shape stabilisation after switch-on	2 min [5]

Trigger Output

Pulse Amplitude	1 V (peak) into 50 Ω
Pulse Width	1 ns
Output Impedance	50 Ω
Connector	SMA
Delay from Trigger to Optical Pulse	< 1 ns
Jitter between Trigger and Optical Pulse	< 10 ps



Synchronisation Input

Amplitude	+3.3 to +5 V into 50 Ω
Duty cycle	10 to 30 %. DC equivalent must be < 2.5 V
Frequency	20 to 80 MHz
Switching from internal clock to Sync input	Automatic, by average voltage at Sync input connector

Control Inputs

Frequency 20 MHz	TTL / CMOS high [3]
Frequency 50 MHz	TTL / CMOS high [3]
Frequency 80 MHz	TTL / CMOS high [3]
CW operation	TTL / CMOS high [3]
Laser ON / Off	TTL / CMOS low [3]
External Power Control	analog input, 0 to + 10V

Power Supply

Power Supply Voltage	+ 9 V to +12 V
Power Supply Current	300 mA to 1.5 A [4]
Power Adapter	AC-DC power adapter, with key switch and control box in cable

Mechanical Data

Dimensions	160 mm x 90 mm x 60 mm
Mounting Thread	two M6 holes

Maximum Values

Power Supply Voltage	0 V to +15 V
Voltage at Digital Control Inputs	-2 V to +7 V
Voltage at Ext. Bias Input	-12 V to + 12 V
Ambient Temperature	0 °C to 40 °C [5]

1) Typical values, sample tested. Depends on pulse width and selected power.
2) Depends on wavelength version.
3) All inputs have 10 kΩ pull-up resistors. Open input is equivalent to logic 'high'.
4) Dependent on ambient temperature. Cooling current changes due to temperature regulation of laser diode
5) Operation below 13 °C may result in extended warm-up time.

Caution: Class 3B laser product. Avoid direct eye exposure. Light emitted by the device may be harmful to the human eye. Please obey laser safety rules when operating the devices. Complies with US federal laser product performance standards.

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