Evaluation Kit Picosecond Fiber Laser PSFL1030

(REV. 3.6 2019-06-07)

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1. General description

The evaluation kit PSFL1030 allows the realization of different picosecond fiber laser configurations using a saturable absorber mirror (SAM) as nonlinear optical device for passive mode-locking and standard fibers in the laser cavity. The active fiber is Yb doped. The fiber laser design can be changed easily to study the influence of certain elements on the laser output signal.

The discussion of experimental results supports the understanding of important phenomena in a passive mode-locked Yb-doped fiber laser. The user gets the needed knowledge to construct its own ps laser setup.

The following fiber laser setups can be realized with the evaluation kit PSFL1030:

- passive mode-locked ps fiber laser with a saturable absorber mirror (SAM)
- ps oscillator + fiber amplifier combination
- continuous wave fiber laser at 1030 nm wavelength
- amplified spontaneous emission (ASE) broadband emitter.

Your comments

Comments and proposals for improvement the evaluation kit PSFL1030 with respect to hardware configuration, experimental results and their discussion are very welcome. You can help us to improve this evaluation kit and to support the distribution of knowledge about passively mode-locked fiber lasers and to extend their use in different applications.

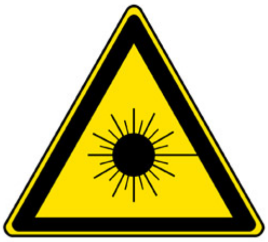
Please send your comments to info@batop.de

2. Needed additional equipment

The evaluation kit contains all components to build and run a picosecond fiber laser. To measure the laser output parameters besides the evaluation kit PSFL1030 the following additional equipment is needed for the proposed laser experiments:

Item	Symbol	Description
1		laser safety goggles with OD3+ for 975 nm
2	PD	Fast photo diode to trace the time dependent laser output signal
3	PM	Optical power meter, 100 mW to measure the average laser output
4		Oscilloscope 200 MHz for measurement of the photodiode output signal
5		PC or Laptop for controlling DL-975-100 Windows 7 or higher; FTDI drivers, Microsoft Visual C++ 2015, LabVIEW Runtime Engine 2016, one free USB port
6		Fiber scope for visual inspection of connector end face, for instance Thorlabs FS200
7	OSA	***Optional equipment:*** OSA – optical spectrum analyzer
8		***Optional equipment:*** Autocorrelator for pulse duration measurement

3. Laser safety



Class 3b Laser

Always wear appropriate laser safety goggles with OD3+ for 975 nm.

Recommendation:

Protector 008.T0004.0 (OD4+ for 960 – 1400 nm) from LaserVision

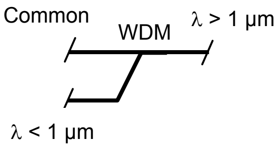
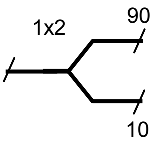
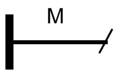
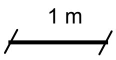
Be aware of hazardous and invisible laser light which can escape from fiber ends.

4. Parts of the evaluation kit

4.1 Evaluation kit PSFL1030 list of components

The evaluation kit PSFL1030 consists of the following components:

Item	Qty	Part No. and symbol	Description
1	1	SAM-1030-32-1ps-FC/APC-PM980-XP SAM	Saturable absorber mirror, wavelength 1030 nm, absorptance 32 %, relaxation time 1 ps, mounted on a 15 cm long fiber PM980-XP with FC/APC connector
2	1	PHS	Passive heat sink for fiber coupled SAM
3	1	PM-YSF-HI-20-FC/APC Yb	Panda-Type Yb-doped PM fiber, 20 cm long, FC/APC connectors
4	1	PM-YSF-HI-30-FC/APC Yb	Panda-Type Yb-doped PM fiber, 30 cm long, FC/APC connectors
5	1	FBG-1030-0.8-87-PM980-XP-100-FC/APC FBG	PM Fiber Bragg grating, wavelength 1030 nm, spectral width 0.8 nm, maximum reflectance 87 %, 100 cm fiber PM980-XP, FC/APC connectors
6	1	PMFWDM-1x2-T1030/R980-FC/APC	PM filter WDM, pass band wavelength 1010 - 1080 nm, 25 cm fiber length

Item	Qty	Part No. and symbol	Description
			reflection wavelength 940 – 990 nm, 50 cm fiber length common, 25 cm fiber length FC/APC connector
7	1	DL-975-100 DL975	Diode laser 975 nm wavelength maximum output power 100 mW fiber coupled with FBG FC/APC connector NA = 0.21
8	1	1x2 SM-coupler 10/90 	Single mode fiber coupler 1x2, ratio 10% : 90%
9	1	M-PM980-XP-15-FC/APC 	100 % mirror reflection wavelength 980 – 1080 nm, mounted on a 15 cm long fiber PM980-XP with FC/APC connector
10	1	PM980-XP-100-FC/APC 	100 cm passive fiber PM980-XP, FC/APC connectors
11	6	Mating Sleeve	ADAFC2 FC/PC to FC/PC Mating Sleeve, Wide Key (2.2 mm), Square Flange
12	1	FCC	Fiber connector cleaner, 20' spool
13	1	FCS3	Precision fiber cleaning fluid
14	1	MC-5	Lens tissues, 25 sheets per booklet

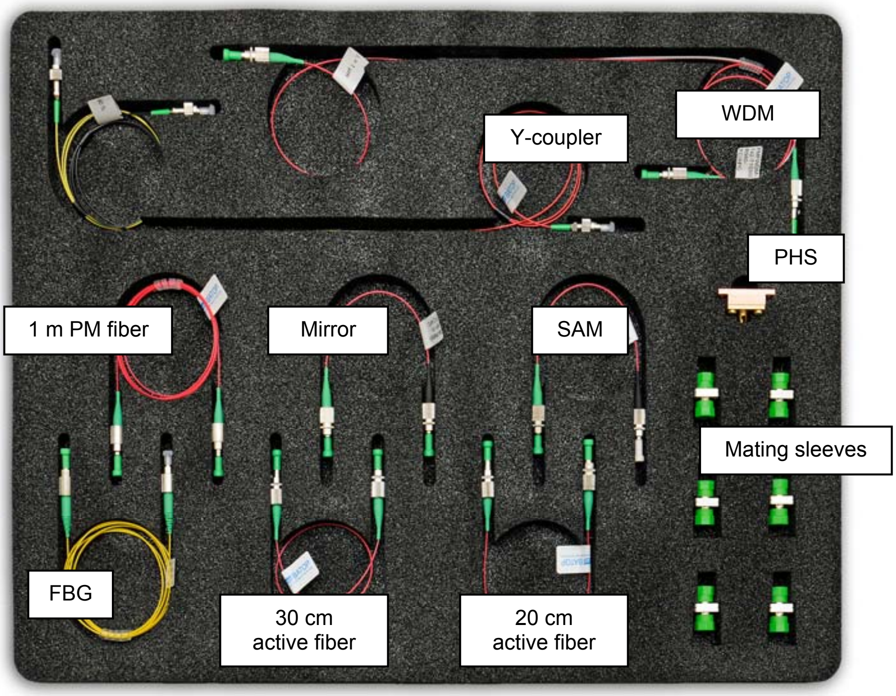


Fig. 4.1.1 Parts on the top plate

Fig. 4.1.2
Parts on bottom plate

4.2 Information on operation diode laser DL-975-100

Diode laser DL-975-100

Emission wavelength λ = 975 nm

Maximum output power P_{out} = 100 mW

Fiber connector: FC/APC

Power supply: 12 V

Control software: either Console software or LabVIEW software

General information

The DL-975 comes with some additional equipment:

- Power supply (Input 110V – 230V 50Hz; Output 12V DC, 5A)
- USB Cable
- Key

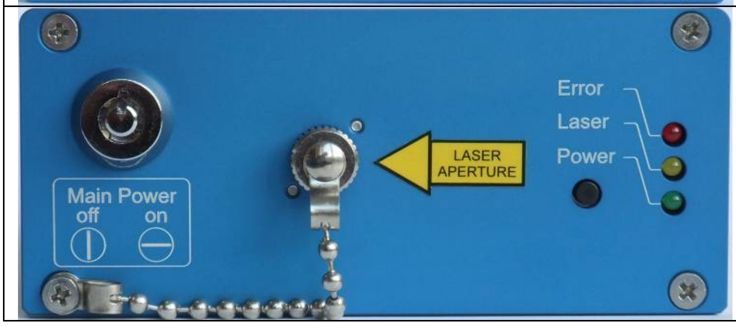
To work with the DL-975 a PC or Laptop with Windows 7 or higher, a free USB-Port (USB 2.0 is sufficient), FTDI drivers and Microsoft Visual C++ 2015 is required. The FTDI drivers are installed automatically by Windows if the PC is connected to the internet. For manual downloading and installing of the FTDI Drivers please refer http://www.ftdichip.com/Drivers/D2XX.htm. The LabVIEW control software needs the LabVIEW runtime engine 2016, which can be found on the homepage of National Instruments (www.ni.com).

If the DL-975 is connected the first time to a PC, Windows will install the FTDI drivers. This could take several minutes.

Controlling of the DL-975 should be done by control software, either by console software or by LabVIEW software (See chapter controlling software). It is also possible to switch on the DL-975 by pressing the black 'Laser' button on the front side without a connection to PC. After each power down the pump current is set to 0 mA.

The following pictures show the front and back panel of the DL-975. The connector for the power supply and the USB port are located on the back panel. On the front panel are the main controlling interfaces like

- Key lock switch to turn on main power
- state LED's
- Laser button
- FC/APC fiber connector (marked with 'LASER APERTURE')

	**Fig. 4.2.1** back panel with power supply connector an USB port
	**Fig. 4.2.2** front panel with key lock switch, FC/APC fiber connector, Laser button and LED's

The three LEDs on the front side of the DL-975 indicate the state. The following table shows the possible LED states.

LED	Description	What to do
Green	Power	
Green flash	Temperature Warning T>45°C inside the case	Cool down the module (shut off or cool the case)
Orange	Laser on	
Green and Orange flash together	Temperature Limit T>50°C inside the case	Cool down the module (shut off or cool the case)
Red	Error	Try to restart. Have a look at the status, if DL-975 is connected to PC.
Green and orange flash alternately	Configuration error	Have a look at the status, if DL-975 is connected to PC. Contact support.

On the bottom of the DL-975 are 4 holes (metric thread M4), which can be used to fix the module on an optical table for example. See the figure 4.2.3 for the details of the holes.

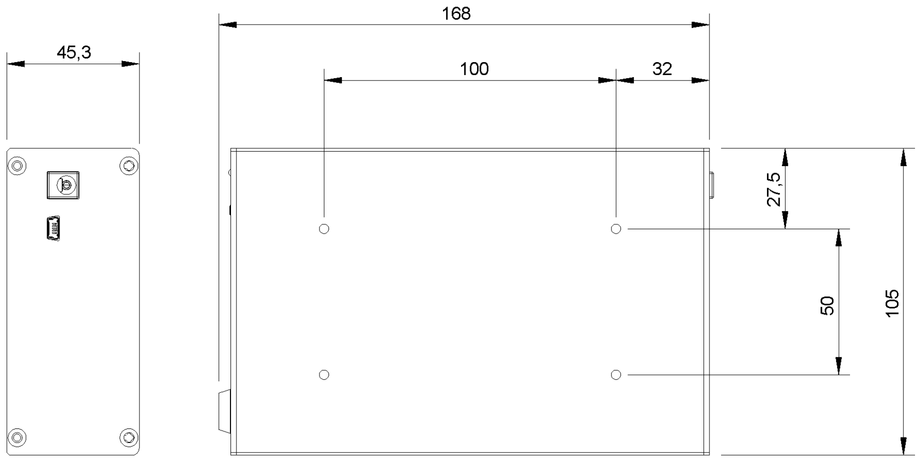


Fig. 4.2.3
Dimension of DL-975 and position of mounting holes

Operation of the DL-975 should be done as follows:

- put the DL-975 on a dry and clean surface
- connect the power supply to the DL-975
- connect the DL-975 to the PC via USB-Cable
- Make sure the PC is switched on
- Switch on the DL-975 with the key
- Start control software

IMPORTANT: If you switch on the DL-975 before connecting it to PC, you have to restart the DL-975.

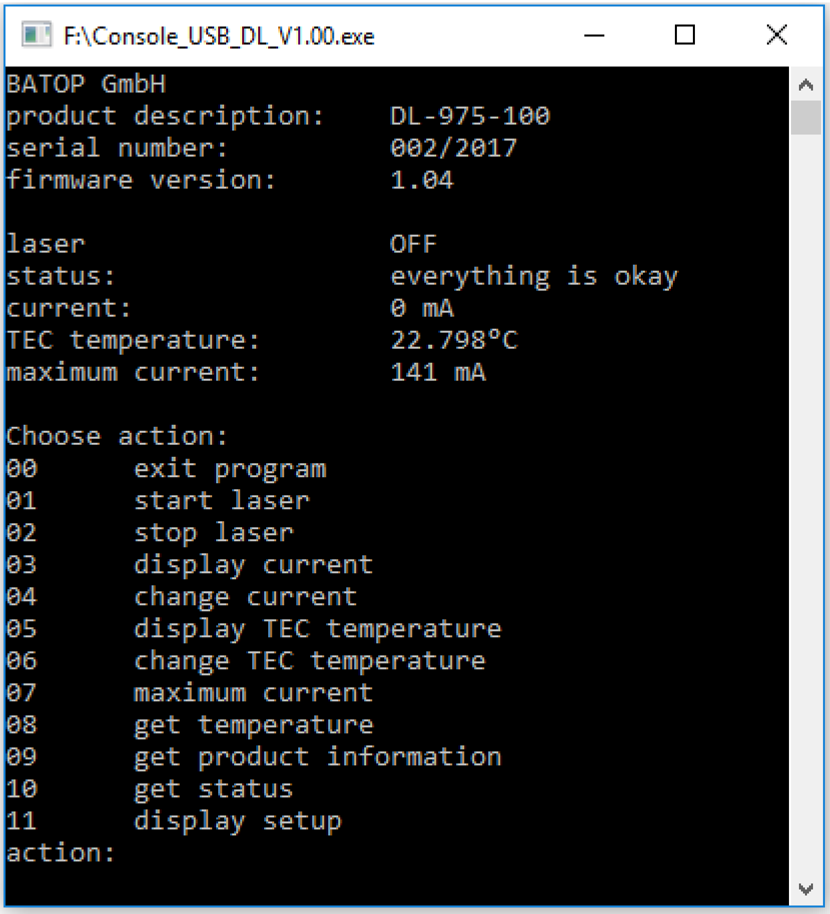
IMPORTANT: It is not possible to reconnect the USB cable or restart the PC without restarting the DL-975.

Controlling software

Attention	To avoid possible damages of parts of the set up by turning on the laser at a high pump power, it is recommended to set the pump power to 0 mA. This is important due to the reason that the value of current is not shown before turning on laser operation.

Console software

The console software is a small application that needs only the FTDI drivers (installed automatically, see chapter General information) and Microsoft Visual C++ 2015 redistributable.
After installing FTDI drivers and connecting the DL-975 to the PC it is possible to start the console program by opening Console_USB_DL_1.0.exe. The console starts and gathers some information about the connected DL-975. The next picture shows a possible output.

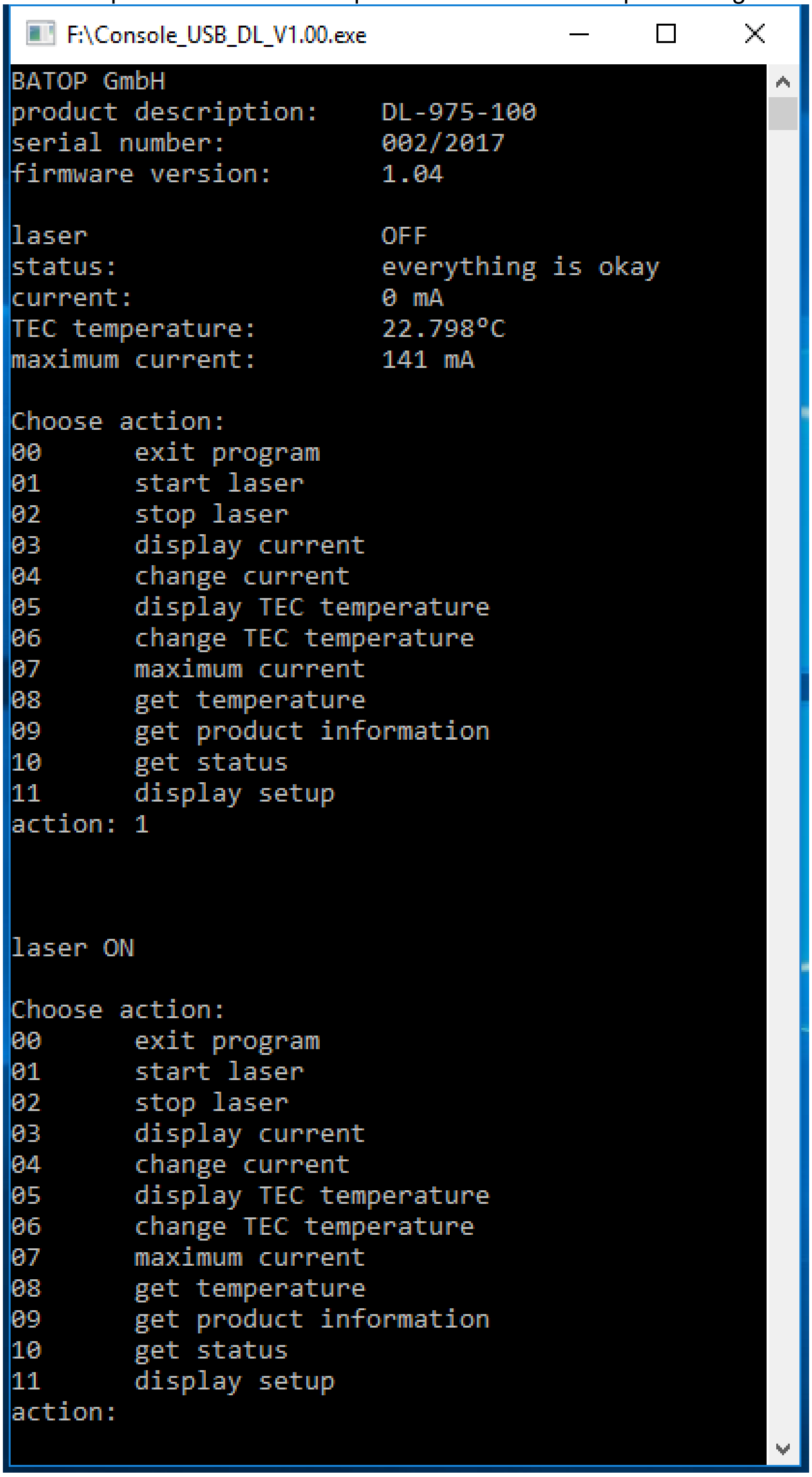


Now it is possible to type in the number of the action that should be performed. The leading zero is not necessary. After pressing enter the action will be executed. The ‘Choose action’ list will be displayed again after every action.

The following table lists the several actions with an explanation.

Action number	Description	Explanation
00	Exit program	Closes the program; Laser will NOT be shut off
01	Start Laser	Switches the Laser on. It is the same like pressing the black Laser button.
02	Stop Laser	Switches the Laser off. It is the same like pressing the black Laser button.
03	Display current	Shows the actual current on the Laser diode. If the Laser is switched off, 0 mA will be displayed.
04	Change current	Changes the operating current of the Laser diode. The current can be changed from 0 mA to maximum current with a step size of 1 mA
05	Display TEC temperature	Shows the actual target temperature of the TEC of the Laser diode.
06	Change TEC temperature	Changes the actual target temperature of the TEC of the Laser diode. The temperature can be changed from 15°C to 35°C with a step size of 0,001°C
07	maximum current	Shows the maximum operating current of DL-975
08	Get temperature	Shows the actual temperature inside the case. It is NOT the temperature of the Laser diode
09	Get product information	Shows the product information: product description, serial number, firmware
10	Get status	Shows the actual state of the DL-975. For more information see chapter status overview
11	Display setup	Shows the actual information like shown at start up

The next picture shows the output of the console after performing action 1 ‘start laser’.

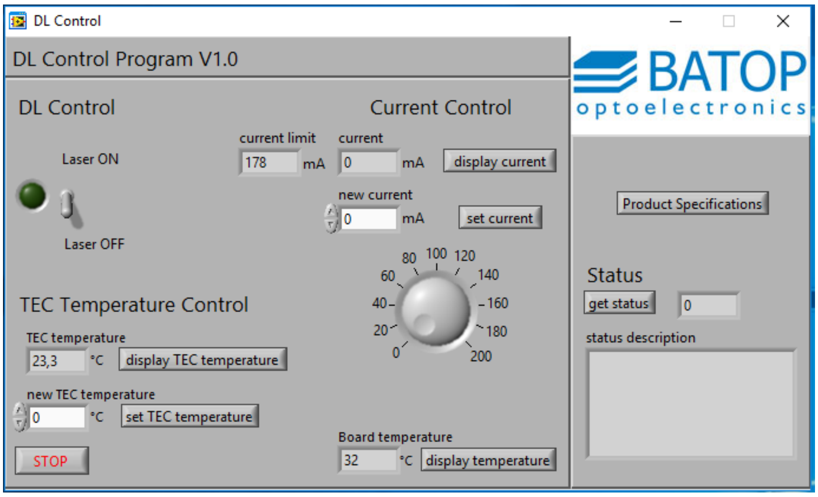


F:\Console_USB_DL_V1.00.exe

```
BATOP GmbH
product description:    DL-975-100
serial number:          002/2017
firmware version:       1.04

laser                   OFF
status:                 everything is okay
current:                0 mA
TEC temperature:        22.798°C
maximum current:        141 mA

Choose action:
00      exit program
01      start laser
02      stop laser
03      display current
04      change current
05      display TEC temperature
06      change TEC temperature
07      maximum current
08      get temperature
09      get product information
10      get status
11      display setup
action: 1



laser ON

Choose action:
00      exit program
01      start laser
02      stop laser
03      display current
04      change current
05      display TEC temperature
06      change TEC temperature
07      maximum current
08      get temperature
09      get product information
10      get status
11      display setup
action:
```

LabVIEW software
Alternatively it is possible to control the DL-975 with a LabVIEW program. The LabVIEW RunTimeEngine 2016 (RTE2016) is required for this program. The RTE2016 can be found on the homepage of National Instruments (www.ni.com).
After connecting the DL-975 to the PC start LabView_USB_DL_1.0.exe. At startup the program shows the actual pump current and the case temperature. For controlling the pump laser just use the specified buttons. If you want to change the pump for example just type in the pump current in the box next to the 'change' button and then press 'change' button or simply turn the rotation knob. The behavior and the limits of the parameters are equal to the console software. The next picture shows the front panel of the LabVIEW program.

- LabVIEW program
  1. Switch on /off
  2. Change pump current
  3. Read temperature and status
  4. Product specification
  5. Firmware
  6. LabVIEW RTE 2016 required



LabVIEW program

Status overview

Status Code	Description	What to do	LED
00	Status ok		
01	High Temperature	Cool down the module (shut off or cool the case)	Green and Orange flash together
02	Temperature warning	Cool down the module (shut off or cool the case)	Green flash
04	Init read fail	Contact support	Green and orange flash alternately
08	Checksum fail	Contact support	Green and orange flash alternately
10	Data Storage error		
80	Watchdog Crash	Try to restart or contact support	Red
ff	Critical error	Try to restart or contact support	Red

4.3 *SAM-1030-32-1ps data*

4.3.1 Main SAM data

The saturable absorber mirror (SAM) serves as nonlinear optical device to start and maintain continuous wave (cw) mode-locking. The main parameters of the SAM-1030-32-1ps are:

Laser wavelength	λ = 1030 nm
Absorption	A = 32 % at 1030 nm
Saturation fluence	F_{sat} = 0.3 J/m^2
Relaxation time	τ = 1 ps

Figure 4.3.1

Low intensity spectral reflectance of SAM-1030-32-1ps

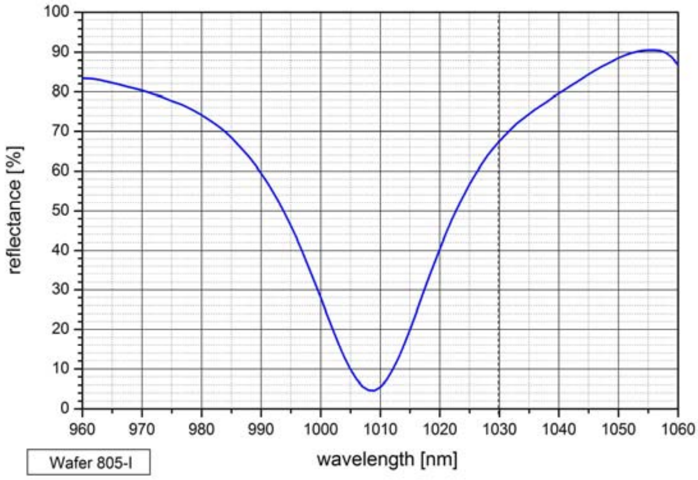
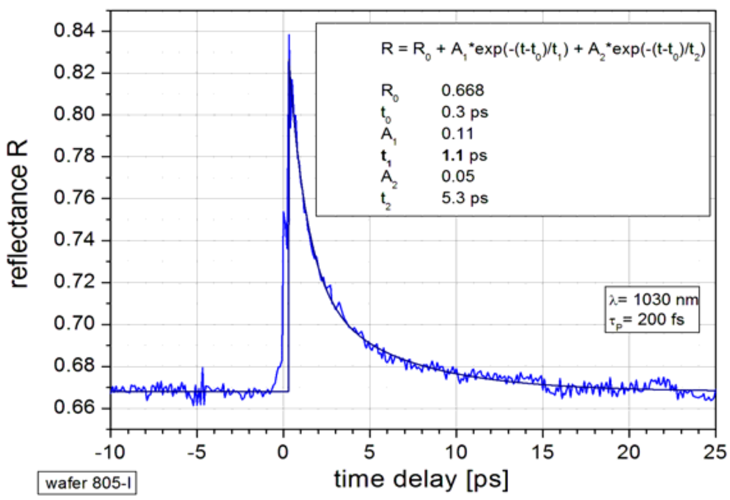


Figure 4.3.2

Relaxation of SAM-1030-32-1ps in a pump-probe measurement. The main part of the relaxation shows a time constant of 1.1 ps.



4.3.2 Discussion of SAM parameters

The SAM consists of a mirror for the laser wavelength and an absorber layer in front of this mirror. The reflectance R = 1 - A of the SAM is determined by the absorption A of the absorber layer because the transmission though the mirror is zero. The absorber consists of thin layers of a semiconductor material with band gap energy E_g somewhat smaller then the photon energy $h \cdot \nu$ of the laser light. Near the band gap the electronic density of states in the absorber is small and already a few absorbed photons can partially saturate the absorber, increase the SAM reflectance and therefore decrease the loss in the laser cavity.

Besides the decrease of absorption with increasing illumination also the influence of the heating in the absorber must be considered because the absorption increases significantly with temperature

Saturation

Taking into account the typical lateral intensity distribution on the SAM surface according to a Gaussian beam the nonlinear reflectance of the SAM can be described in case of a long relaxation time as follows:

$$R = 1 - A_0 \cdot \frac{F_{sat}}{F} \cdot \left(1 - e^{\frac{F}{F_{sat}}}\right) \qquad (4.3.1)$$

with the parameters A_0 – low intensity absorption
F - pulse fluence
F_{sat} – saturation fluence

In a laser cavity with an optical amplifier and a SAM a small increase of the amplified luminescence light can partially saturate the absorber and increase the SAM reflectance. This results in increasing amplitude of the fluctuation and a formation of a pulse during several round trips in the cavity. The periodic saturation of the SAM during the round trip of the pulse locked all luminescence modes with different wavelengths together to a short pulse with a broad spectrum. This process is called mode-locking and results in a single pulse in the laser cavity with a fixed repetition rate given by the cavity length and the speed of light in the cavity. This is equivalent to the phase condition in a continuous wave laser, where the cavity length determined the lasing wavelength.

Two photon absorption - TPA

Two photon absorption (TPA) must be considered in case of short pulses, especially if the pulse duration t_P is < 1 ps. But also in case of puse duration of a few ps it must be considered because it decreases the SAM modulation depth ΔR.

The two-photon absorption A_{TPA} increases the total absorption as follows:

$$A_{TPA} = \beta \cdot I \cdot d = \frac{\beta \cdot F \cdot d}{t_P} \qquad (4.3.2)$$

With β - two-photon absorption coefficient
I - pulse intensity
d - absorber layer thickness
F - pulse fluence
t_P - pulse duration.

The integration of the time dependent intensity I(t) over the pulse duration tP results in the pulse fluence F. Therefore the pulse fluence can be approximated as $F \sim I \cdot tP$.
The two-photon absorption coefficient β is a material dependent parameter. For GaAs the value is $\beta = 2.5 \cdot 10^{-10}$ m/W.

SAM saturation including TPA

The dependency of the SAM reflectance on pulse fluence F including the TPA can be written as

$$R(F) = 1 - A_0 \cdot \frac{F_{sat}}{F} \cdot \left(1 - e^{\frac{F}{F_{sat}}}\right) - \frac{\beta \cdot F \cdot d}{t_P} \qquad (4.3.3)$$

The TPA decreases the reflectance for high pulse fluence and short pulses. For a SAM useful in a fiber laser the typical thickness of the absorber layer including the top part of the AlAs/GaAs Bragg mirror is about d ~ 2 µm. The typical pulse duration using the fiber laser evaluation kit is ~ 5 ps. In this case the TPA is not important. The figure below shows the saturation curve.

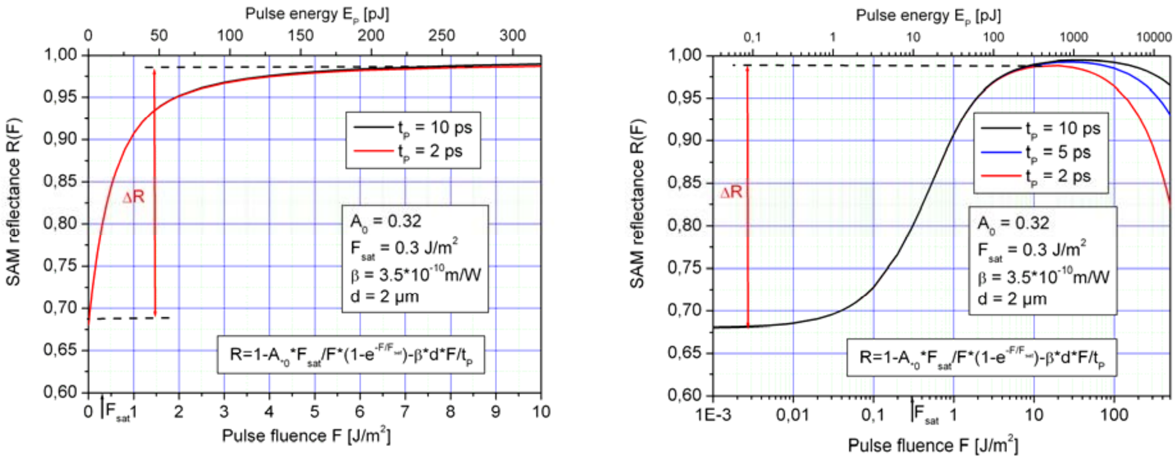


Figure 4.3.4 Saturation curve R(F) in a linear (left) and logarithmic scale (right) for SAM-1030-32-1ps according to equation (3).
ΔR is the modulation depth and A_{ns} is the non-saturable loss. The pulse energy E_P is calculated using $E_P = r^2 \cdot \pi \cdot F$ with r = 3.2 µm (mode field radius).

The TPA causes a roll-over of the saturation curve before complete saturation. Therefore the modulation depth ΔR is smaller then the absorption A_0. The difference $A_{ns} = A_0 - \Delta R$ is called non-saturable loss.

4.4 Spectral reflection and transmission of FBG

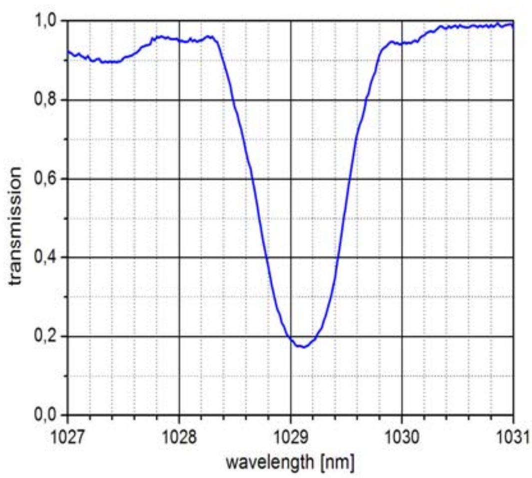
The fiber Bragg grating FBG-1030-0.8-87-FC/APC-PM980-XP serves as wavelength locker at the maximum reflectance of 1030 nm wavelength.

The main parameters are:

Maximum reflectance wavelength	λ_0 = 1030 nm
Reflectance at λ_0	R_0 = 0.87
Reflectance spectral width	$\Delta\lambda_{FBG}$ = 0.8 nm (Full width at half maximum)

Figure 4.4.1

Measured spectral transmission of the FBG



The FBG is used as output coupler in the ps laser setup. As a result of nonlinear spectral pulse broadening in the optical fiber at high optical intensity the spectral pulse width depends on the pulse fluence. Therefore the transmittance of the FBG depends on the pulse fluence F or spectral pulse width $\Delta\lambda$. To calculate the FBG transmittance T on the pulse width $\Delta\lambda$ the FBG transmittance can be approximated as

$$T(\lambda)=1-R(\lambda)=1-R_0\cdot e^{-\frac{4\cdot\ln 2\cdot(\lambda-\lambda_0)^2}{\Delta\lambda_{FBG}^2}} \qquad (4.4.1)$$

with the parameters R_0, λ_0, and $\Delta\lambda_{FBG}$ given above.

The spectral intensity distribution of a Gaussian optical pulse can be written as

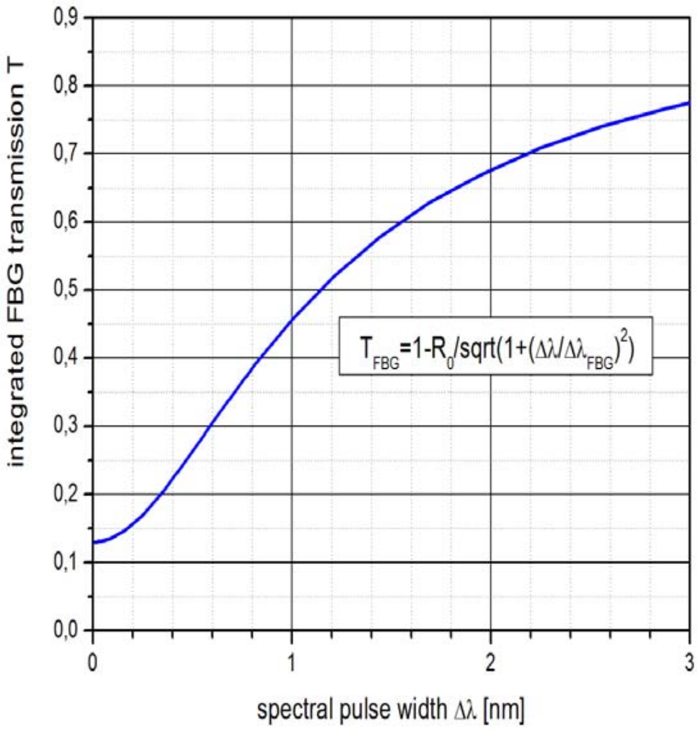
$$I(\lambda)=I_0\cdot e^{-\frac{4\cdot\ln 2\cdot(\lambda-\lambda_0)^2}{\Delta\lambda^2}} \qquad (4.4.2)$$

Here I_0 is the pulse intensity at λ_0 and $\Delta\lambda$ is the full width at half maximum spectral pulse distribution. Using (4.4.1) and (4.4.2) the wavelength integrated FBG transmission T in dependence on the Gaussian pulse width $\Delta\lambda$ can be calculated as

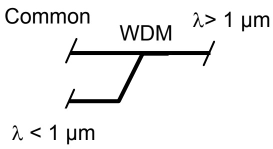
$$T(\Delta\lambda)=\frac{\int_0^\infty I(\lambda)\cdot(1-R(\lambda))\cdot d\lambda}{\int_0^\infty I(\lambda)\cdot d\lambda}=1-\frac{R_0}{\sqrt{1+\left(\frac{\Delta\lambda}{\Delta\lambda_{FBG}}\right)^2}} \qquad (4.4.3)$$

This dependency is shown in figure 4.4.2 below. The transmission increases with increasing spectral pulse width $\Delta\lambda$ from $1\text{-}R_0 = 0.13$ to about 0.8 at a spectral width of 3 nm.

Fig 4.4.3
Calculated total transmission of the FBG in dependency on the spectral width $\Delta\lambda$ of a Gaussian pulse



4.5 Transmission of the PM filter WDM



The polarization maintaining filter wavelength division multiplexer PMFWDM-1x2-T1030/R980 can be used to couple the 980 nm pump light into the laser cavity. The pump light is reflected via a dichroitic mirror from the “Reflect” fiber into the “Common” fiber. For the 1030 nm laser wavelength the mirror has a high transmission, so that for this wavelength the “Common” fiber is connected with the “Pass” fiber.

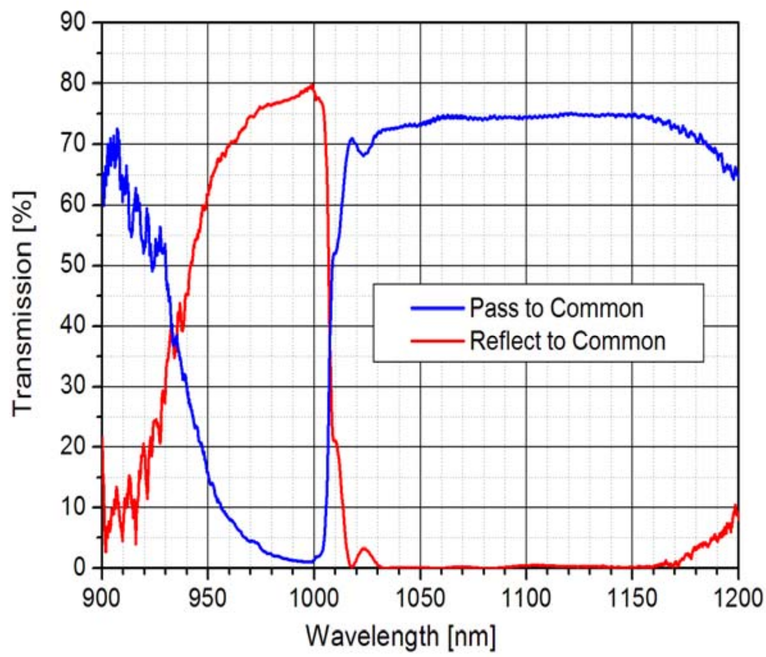
The “Reflect” fiber is marked with a black line.

Measured transmission between Reflect and Common (Low Pass) T_{LP} = 0.78

Measured transmission between Pass and Common (High Pass) T_{HP} = 0.75

Figure 4.5.1

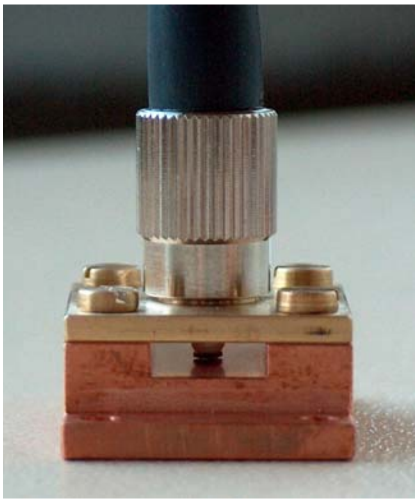
Measured spectral transmittance of the wavelength division multiplexer PMFWDM-1x2-T1030/R980



4.6 PHS – Passive heat sink for fiber coupled SAM

Figure 4.6.1

Fiber coupled SAM inserted into the passive heat sink



The SAM chip is fixed on the fiber end. Thermal contact between the SAM and the copper baseplate is made with a small amount of a thermal conducting paste. The copper baseplate can be placed on a larger metal plate with good thermal conductivity.

Assembly instructions

(note: during shipment the connector of the fiber patch cable is not plugged into the passive heat sink)

A small portion of a heat conducting paste should be applied to the lower side of the RSAM chip (e.g. by the use of a utility, like a needle or a similar tool) mounted on the end face of the FC/PC connector. Do not use too much of the conducting paste! For example see figure 4.6.2.

This procedure ensures a good thermal contact between the SAM chip and the copper heat sink.

Figure 4.6.2: SAM chip on FC/PC connector end face

Figure 4.6.3: same connector as Figure 4.6.2 with heat conducting paste

Carefully insert the FC/PC plug with the chip in the female connector at the top plate. Smoothly tighten the coupling ring until the chip touches the copper surface of the base plate. Do not overtighten the connector, this may damage the chip!

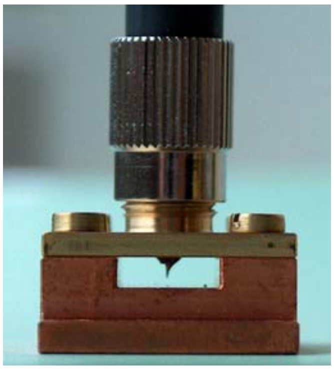


Figure 4.6.4: FC/PC connector inserted in the passive heat sink

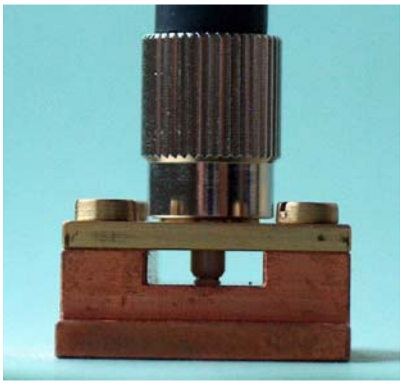


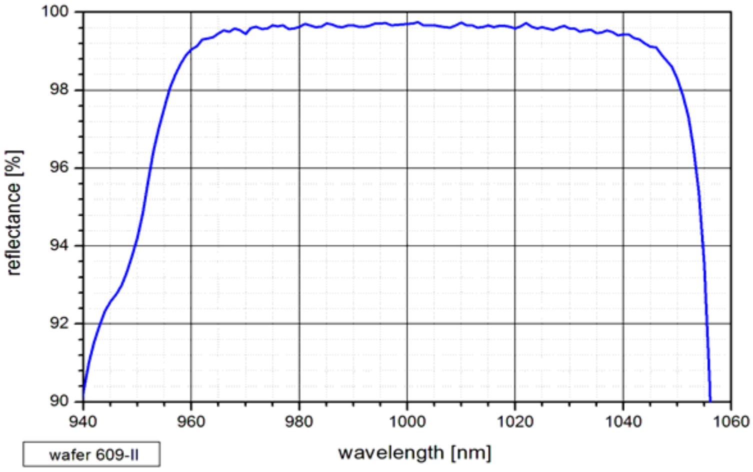
Figure 4.6.5: the SAM chip is in contact with the base plate, stop tighten the coupling ring

4.7 Spectral reflectance of the 100 % mirror M-PM980-XP-FC/APC

Reflectance at 1030 nm	R = 0.995		
Fiber type	PM980-XP	Fiber length	l = 15 cm
Connector	FC/APC		

Figure 4.7.1

Spectral reflectance of the fiber coupled 100 % mirror M-PM980-XP-15-FC/APC



5. Experiments

5.1 Fiber end cleaning and arrangement

Cleaning of fiber connectors

For cleaning of fiber connectors please use a soft and lint-free lens tissue. Best cleaning results are achieved, if you use simultaneously a small amount of ethanol or similar cleaning solvents. For cleaning gently wipe with the ferrule end face over the soaked tissue writing some “figure 8” loops. If the alignment of the ferrule is correct, the end face must be smoothly slide over the tissue surface. For FC/APC connectors, please be sure to tilt the ferrule by approx. 8 degree.
Please check the end face of the ferrule after cleaning using a fiber scope. The whole surface must be free from particles or solvent residuals as shown in the following pictures.

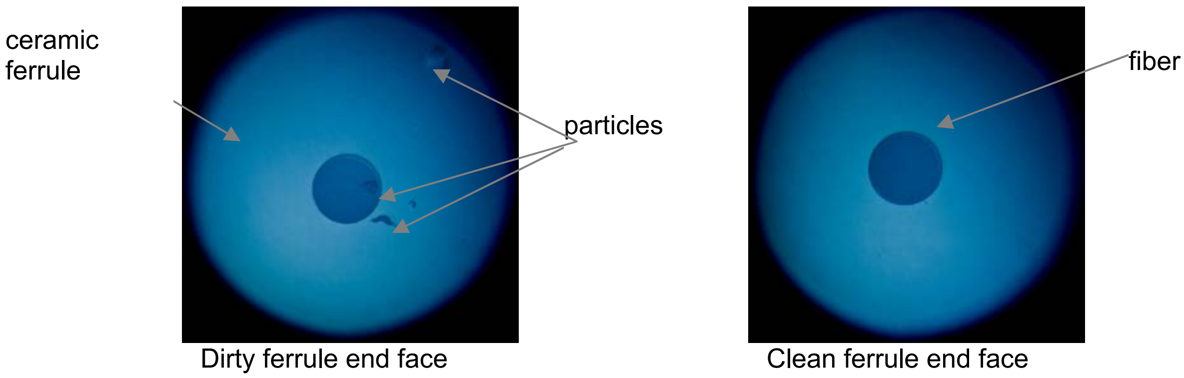


Figure 5.1.1: Microscope images of a dirty (left) and a clean (rifgt) fiber end

In general, please avoid plugging the connectors more than necessary, because the surface quality degrades with each connection process.

Aligment of connectors

Because the mode field diameter in the fiber is only ~ 6.5 µm already a very small misalignment of ~ 0.1 µm between the fiber cores in a mating sleeve can cause a substantial coupling loss. Therefore it makes sense to touch the connectors slightly to maximise the laser output signal by minimizing the coupling losses in the fiber connections. A too strong tighten of the FC/APC connector can result in a small shift of the core axes and an additional coupling loss.

Fiber laser layout

The schematic shown in each chapter helps to connect the fiber parts of the evaluation kit in a right way. The kit contains mainly polarization maintaing fibers to promote the propagation of optical pulses with defined polarization orientation and to support a stable laser output.

Please avoid random twisting of the fiber. A simple way to avoid fiber twisting is to make a cavity layout with fibers arranged in a straight line.

5.2 Pump laser diode output power

To determine the laser threshold and the slope efficiency of the 975 nm pump laser diode DL-975-100. Optional the laser emission wavelength can be measured.

Needed parts from PSFL130 evaluation kit:

DL975	1 m

Additional equipment needed:

PM	Optional OSA

Schematic

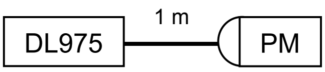


Figure 5.2.1 Setup for measurement of the laser diode LD980 output power as a function of the drive current.The optical power meter is shown on the right side.

Measurement:

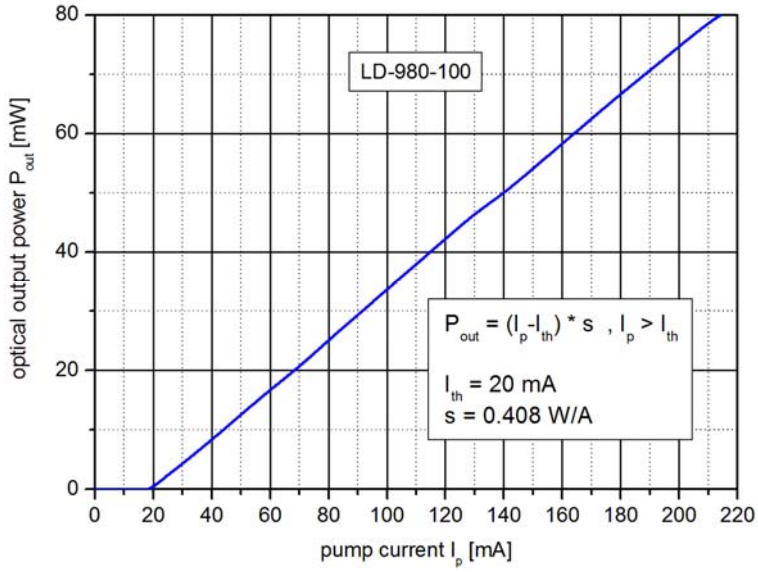
Switch on the DL-975 and increase step by step the drive current of the 975 nm laser diode above the threshold current of ~ 20 mA.
The laser threshold and the differential laser efficiency can be deduced from the measured laser output power as a function of the pump power.

Optional: The spectral distribution of the emitted laser light can be measured using an OSA.

Measurement results

Figure 5.2.2

Laser output power P_{out} versus pump current I_P



The slope efficiency η of the laser diode can be calculated using the relation

$$\eta = \frac{s \cdot e \cdot V}{h \cdot \nu} = \frac{s \cdot e \cdot V \cdot \lambda}{h \cdot c} \qquad (5.2.1)$$

With s – slope of the measured P_{out} – I_P characteristic

e – charge of an electron ~ $1.6 \cdot 10^{-19}$ A·s

V – forward voltage of the laser diode ~ 2 V

λ – laser wavelength ~ $980 \cdot 10^{-9}$ m

h - Planck constant ~ $6.63 \cdot 10^{-34}$ V·A·s^2

c – speed of light ~ $3 \cdot 10^8$ m/s

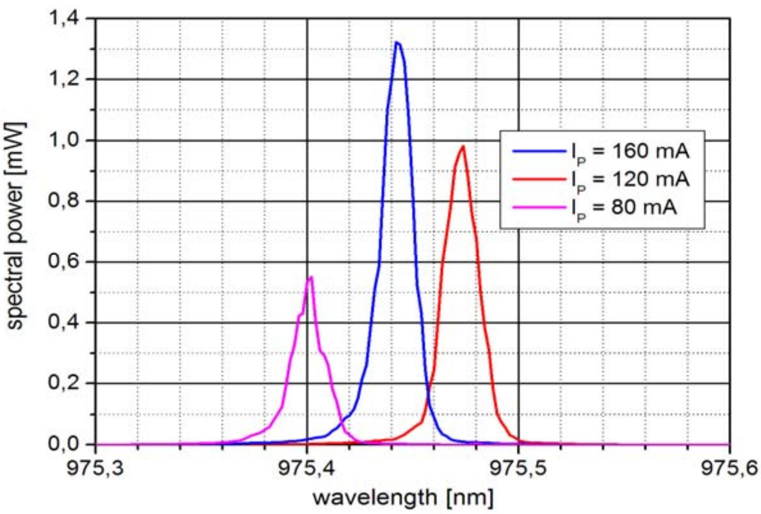
$\nu = c/\lambda$ - laser frequency ~ $3 \cdot 10^{14}$ Hz

The slope efficiency of the pump laser can be calculated to η = 0.66.

Figure 5.2.3

Spectral power distribution of the emitted pump light for three different pump currents I_P.

The emission wavelength of the pump diode is fixed to about 975 nm because the laser cavity is stabilized with a fiber Bragg grating.

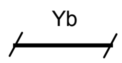
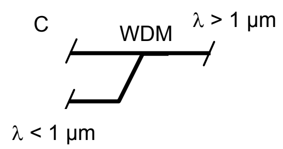


5.3 *Luminescence and gain of Yb-doped fiber PM-YSF-HI*

The luminescence and the gain of the active Yb-doped fiber PM-YSF-HI can be measured as a function of the pump power to determine important material parameters.

5.3.1 Experiment

Needed parts from PSFL130 evaluation kit

2 x 		DL975	2 x Mating Sleeve

Additional equipment needed

PM	optional: OSA

Schematic

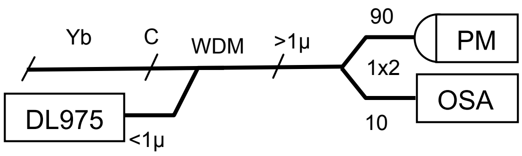
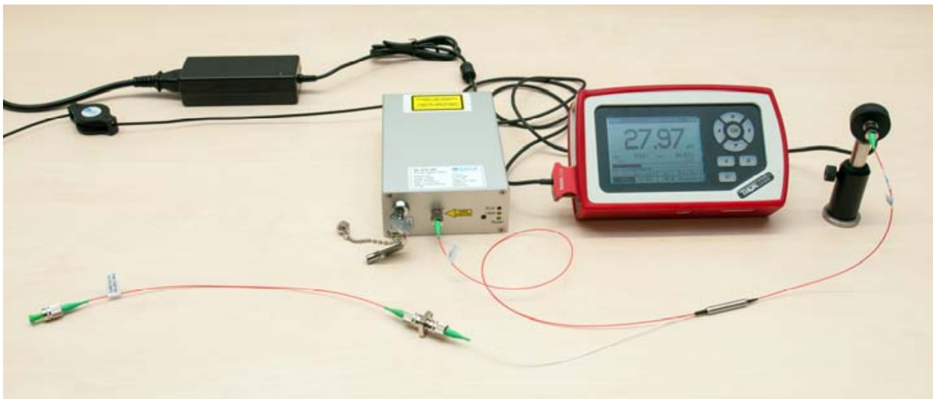


Figure 5.3.1

Photo of the setup for luminescence measurement



Measurement

The luminescence power P_L, which is partially amplified in the active fiber can be measured as function of the pump current I_P. Then the pump power P_P can be calculated using the linear dependency of the laser diode output power on the pump current I_P. This dependency is determined in chapter 5.2 to

$P_P = s \cdot (I_P - I_{th})$ with $s = 0.408$ W/A and $I_{th} = 20$ mA

To get also information about the possible gain of the pumped active fiber a fiber length of about 30 cm is recommended.

Measurement results

Fig. 5.3.2

Amplified luminescence power P_L of the 30 cm long Yb-doped fiber as a function of pump power P_P. The luminescence power P_L is calculated from the measured luminescence considering the WDM transmission T_{HP} = 0.8.

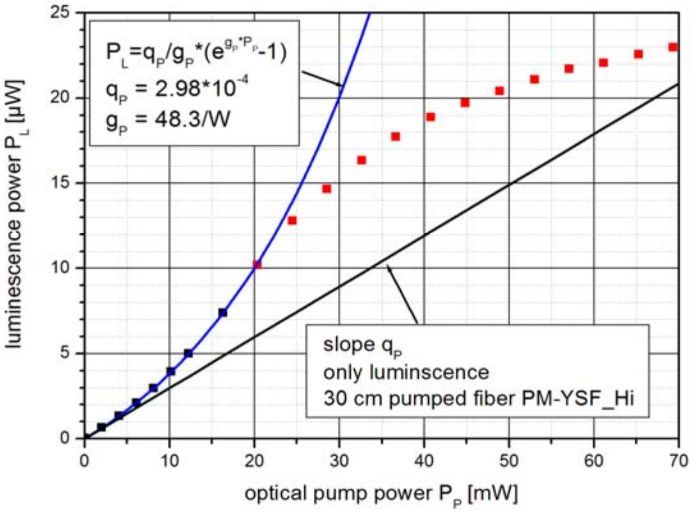


Fig. 5.3.3

Spectral luminescence after transmission through the WDM filter from Common to Pass, measured with an optical spectrum analyzer (OSA)

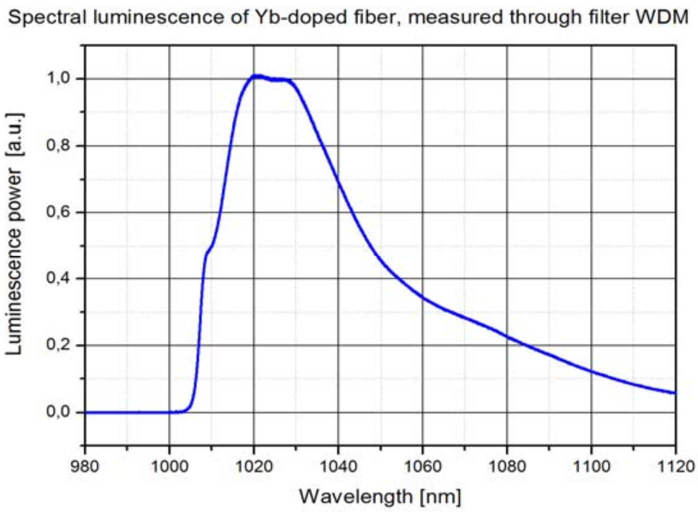
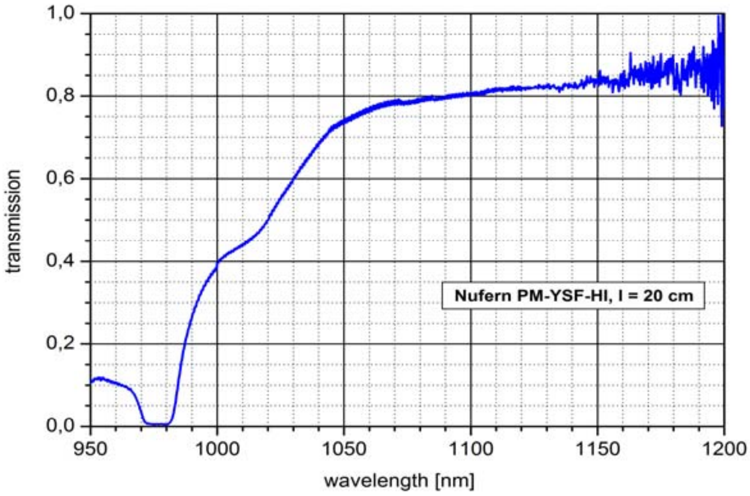


Fig. 5.3.4

Spectral transmission of the Yb-doped fiber, measured with an optical spectrum analyzer (OSA). The signal source is the 30 cm long pumped PM-YSF-HI with the emission spectrum shown in figure 5.3.3. The decreasing signal/noise ratio for longer wavelengths is the result of decreasing luminescence light in this region.



5.3.2 Discussion of the measured results

Spectral luminescence

The WDM filter coupler cuts light with shorter wavelengths then ~ 1010 nm. Therefore the pump light is not measured. The luminescence maximum is in the range between 1020 nm and 1030 nm.

Luminescence amplitude and gain

The pump power saturates a certain length of active fiber L. The saturated fiber length is proportional to the pump power P_P. The result is twofold:

- The saturated fiber emits a part of its luminescence light into the fiber with the numerical aperture NA = 0.11.
- The guided luminescence light is amplified in the saturated part of the fiber.

The amplified luminescence light on the fiber end can be calculated as follows:

$$P_L = \int_0^L q \cdot e^{g \cdot x} dx = \frac{q}{g}(e^{g \cdot L} - 1) \qquad (5.3.1)$$

Here q is the luminescence power per fiber length dx and g is the gain coefficient. The saturated fiber length L is proportional to the pump power P_P with a factor c_P and can be written as $L = c_P \cdot P_P$. Using this relation the above equation can be rewritten to

$$P_L = \frac{q}{g}(e^{g_P \cdot P_P} - 1) = \frac{q}{g_P}\frac{L}{P_P}(e^{g_P \cdot P_P} - 1) = \frac{q_P}{g_P}(e^{g_P \cdot P_P} - 1) \qquad (5.3.2)$$

with

$$c_P = \frac{L}{P_P} = \frac{q_P}{q} = \frac{g_P}{g} \qquad (5.3.2)$$

From the measurement in figure 5.3.2 above it can be deduced, that the amplified luminescence power does not increase further exponential above a pump power of 22 mW in a 30 cm long active fiber. From this observation the coefficient c_P can be determined to c_P = 30cm/22mW = 1.36 cm/mW = 13.6 m/W. This means that in case of low optical signal a pump power of 0.73 mW is needed to saturate a fiber length of 1 cm.

From the measured slope $q_P = 2.98 \cdot 10^{-4}$ without amplification of the luminescence light the luminescence power q in the spectral range around 1030 nm per pumped fiber length can be deduced to $q = q_P / c_P$ = 21.9 µW/m.

If the whole pump power P_P would be converted into luminescence around 1030 nm without any loss and emitted into the full solid angel $4 \cdot \pi$, then the expected luminescence power in one fiber direction can be estimated with the solid angle Ω captured by the guided wave in the fiber. The aperture angle α inside the fiber with the numerical aperture NA is given by the relation $NA = n \cdot \sin\alpha$. Because the fiber aperture is small, the solid angle can be estimated to

$$\Omega = 4 \cdot \pi \cdot sin^2 \frac{\alpha}{2} \approx 4 \cdot \pi \cdot sin^2 \frac{NA}{2 \cdot n} \approx 4 \cdot \pi \cdot \left(\frac{NA}{2 \cdot n}\right)^2 \qquad (5.3.3)$$

The difference between the photon energy of pump light E_P and luminescence light at 1030 nm E_L must be considered in the total energy balance. The expected luminescence light per saturated active fiber length can be estimated by

$$P_L = \frac{\Omega}{4 \cdot \pi} \cdot \frac{E_L}{E_P} \cdot r_L \cdot P_P = \left(\frac{NA}{2 \cdot n}\right)^2 \frac{\lambda_P}{\lambda_L} \cdot \frac{r_L \cdot L}{c} \qquad (5.3.4)$$

The ratio r_L of the luminescence power around 1030 nm and the total luminescence power can be estimated to r ~ 1/3. With the numerical aperture NA = 0.11 of the fiber, the refractive index n = 1.46 of the fiber core, the pump wavelength λ_P= 980 nm, the luminescence wavelength λ_L= 1030 nm the luminescence light per meter in one fiber direction can be estimated to 30 µW/m. The difference between this theoretical value 30 µW/m and the measured value 21.9 µW/m can be explained as losses due to conversion of some optical energy into heat.

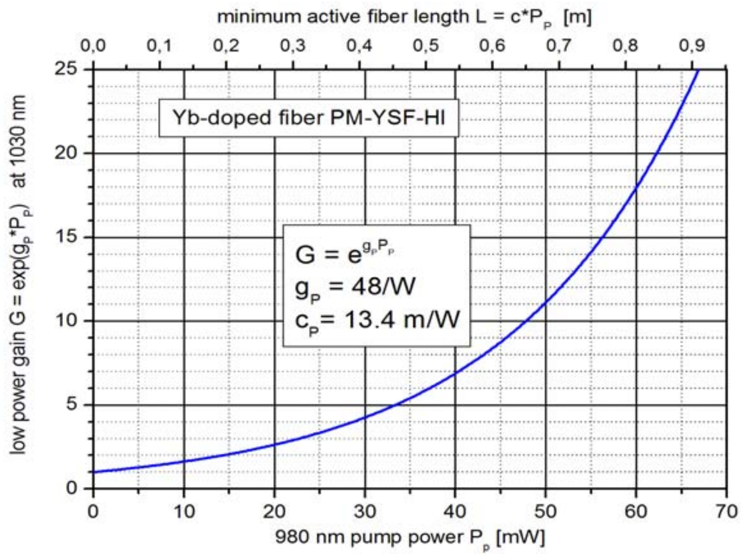
The gain coefficient of the pumped fiber is then $g=g_P/c_P$= 3.5/m = 0.035/cm. With this value the gain of the pumped fiber can be calculated by

$$G = e^{g \cdot L} = e^{g_P \cdot P_P} \qquad (5.3.5)$$

The maximum low power gain of a 30 cm long pumped fiber can be estimated to 2.8.

Fig. 5.3.5

Calculated Gain G of the active fiber as a function of pump power P_P and fiber length L



Time dependency of luminescence and stored energy

Pumping the active fiber increases the stored energy and the luminescence. If stimulated emission can be neglected the time dependent length of the pumped fiber L(t) can be written as rate equation:

$$\frac{dL(t)}{dt} = c_n \cdot P_P - \frac{L(t)}{\tau} \qquad (5.3.6)$$

dL/dt is the change over time of the pumped active fiber length. The first term on the right hand site increases the pumped fiber length proportional to the pump power P_P with a coefficient c_n. The second term describes the decrease of the pumped fiber length by luminescence light with the relaxation time constant τ of the upper state of the Yb-doped fiber. τ depends on the Yb doping concentration and temperature and can be assumed as about τ ~ 900 µs.

The solution of the differential equation (5.3.6) for a constant pump power P_P and a start length L(0) = 0 is

$$L(t) = c_n \cdot \tau \cdot P_P \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \qquad P_P \text{ constant} \qquad (5.3.7)$$

After a long pump time t >> τ the pumped fiber length is $L(\infty) = c_n \cdot \tau \cdot P_P$. Therefore we see now by comparison of equation (5.3.7) with (5.3.2) that the unknown coefficient in equation (5.3.6) is $c_n = c_P / \tau$.

The stored energy for the emission of photons with wavelength λ per pumped fiber length can be estimated from the first term in equation (5.3.6) as

$$\frac{dE}{dL} = \frac{\lambda_P}{c_n \cdot \lambda} = \frac{\tau \cdot \lambda_P}{c_P \cdot \lambda} \approx 63 \mu J/m \qquad (5.3.8)$$

Here the energy difference between photons of luminescence wavelength λ and pump wavelength λ_P has been considered.

Spectral transmission

In figure 5.3.4 it can be seen, that the absorption of the Yb-doped fiber decreases with increasing wavelength in the spectral region above 980 nm. Beside this, the non pumped active fiber absorbs light of 1030 nm wavelength substantially. Therefore the length of the active fiber in a 1030 nm laser oscillator must be adjusted in such a way, that the complete saturated fiber length delivers the needed gain to start the laser. If the active fiber is longer then this criterion, then the non pumped fiber length absorbs a part of the laser light and decreases the laser efficiency.

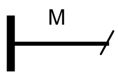
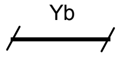
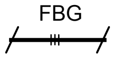
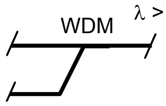
Conclusions

- The luminescence measurement can be used for determination of the active fiber parameters.
- The gain coefficient g increases proportional with the pump power P_P.
- The saturated fiber length L is proportional to the pump power with a coefficient c_P = 13.6 m/W.
- The luminescence power q per pumped fiber length in the spectral range around 1030 nm can be determined to q = 21.9 µW/m.
- The power related gain coefficient of the active fiber is g_P = 47.6/W and the gain coefficient is $g=g_P/c_P$= 3.5/m.
- The stored energy per saturated active finer length can be estimated to dE/dL = $1/c_n$ ~ 67 µJ/m.

5.4 Continuous wave laser

To compare the slope efficiency and the laser threshold of the ps laser with a continuous wave (cw) laser with the same parts the SAM in chapter 5.2. can be replaced by a 100 % mirror to build a cw laser.

Needed parts from PSFL130 evaluation kit:

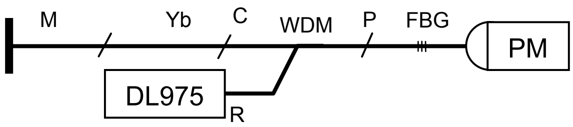
				DL975
3 x Mating Sleeve				

Additional equipment needed:

PM	Optional: OSA

Schematic

Optional the laser wavelength and the spectral width can be measured using an OSA.



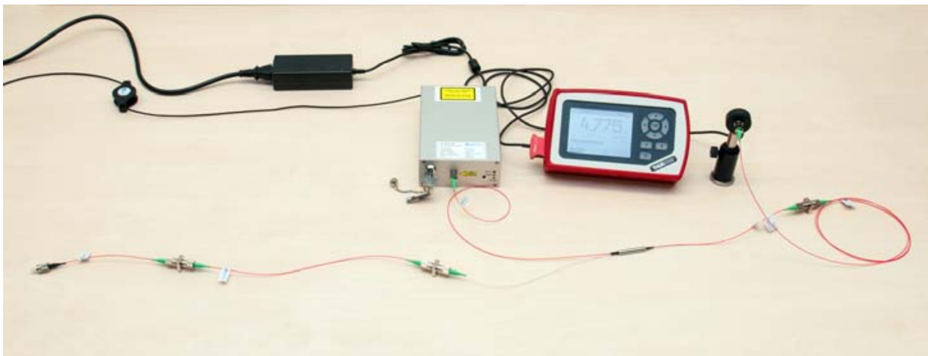


Figure 5.4.1

Photo of the continuous wave laser setup

Measurement:

Switch on the DL-975-100 and increase step by step the drive current of the 975 nm laser diode above the threshold current of ca. 20 mA. The Yb-doped fiber laser starts lasing at 1030 nm above the threshold pump power of ~ 7 mW, which can be monitored with the optical power meter (PM).

The laser threshold and the differential laser efficiency can be deduced from the measured laser output power as a function of the pump power.

Optional: The laser wavelength can be measured with an OSA.

Measurement results

Figure 5.4.2

Measured continuous wave output power at 1030 nm versus 980 nm optical pump power using 30 cm active fiber, a 100 % mirror and the FBG as output coupler.

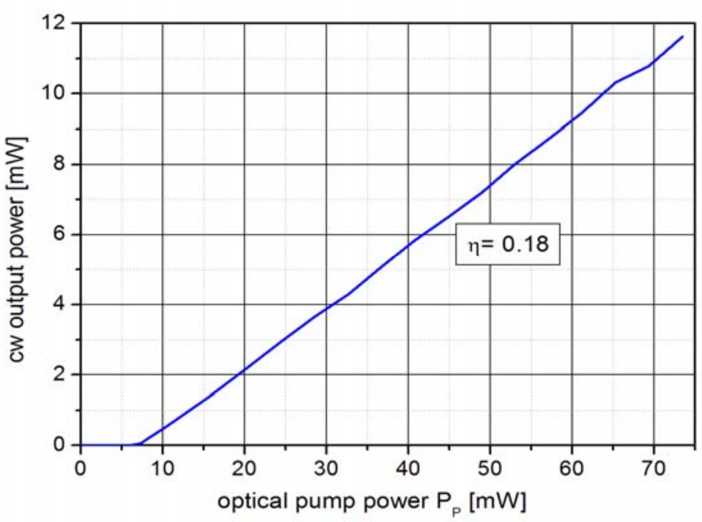
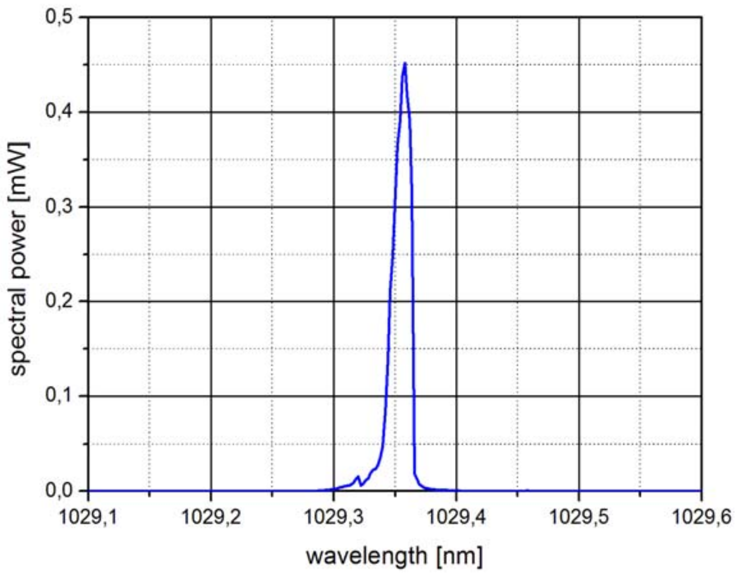


Figure 5.4.3

Measured spectral power distribution of the continuous wave laser, measured with an optical spectrum analyzer. The measured spectral width is mainly determined by the spectral resolution of the OSA.



Main results

The lasing threshold is at a pump power of 7.5 mW and the slope efficiency η = 0.18. The lasing wavelength is fixed by the FBG to about 1029 nm. The spectral width is very small.

5.5 Picosecond laser, WDM coupler outside the cavity

This experiment shows the basic design of a ps fiber laser setup using a SAM as passive mode-locking element, the Yb-doped active fiber as amplifier and a fiber Bragg grating (FBG) to fix the laser wavelength. The WDM filter coupler introduces the pump power of the laser diode.

5.5.1 Experiments

Needed parts from PSFL130 evaluation kit:

SAM	Yb	FBG	C WDM $\lambda > 1$ µm $\lambda < 1$ µm	DL975
1x2 90 10	Optional 1 m	5 x Mating Sleeve	PHS	

Additional equipment needed:

PD	PM	Optional: OSA		Optional: Autocorrelator

Schematic

The photo diode (PD) can be replaced by an optical spectrum analyzer (OSA) to measure the spectral distribution of the emitted picosecond laser pulses.

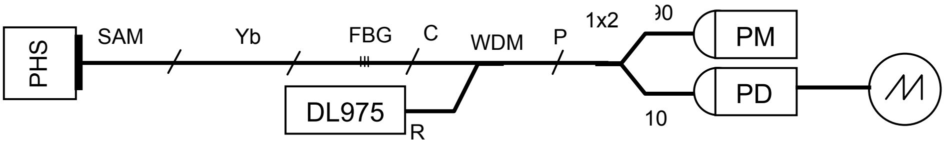


Figure 5.5.1: Photo of the ps laser setup

Important hints

-  Please use laser safety goggles.
- Do not start optical pumping before on all fiber ends are devices or a cap to avoid leaving laser light.
- The laser cavity must be put on the table as a straight line to ensure, that the polarization of the forward and backward travelling pulse is well defined and unchanged. The laser cavity is given by the fiber length between the SAM and the middle of the FBG fiber.
- Please do not forget to put the passive heat sink PHS on the fiber coupled SAM.
- The stability of mode-locking depends significantly on the optical contacts between the FC/APC connectors inside the laser cavity. To optimize these contacts you can gently change the mechanical pressure between the fiber ends during the control of the optical pulses on the oscilloscope.

Measurement

Switch on the DL-975-100 and increase step by step the drive current of the 975 nm laser diode above the threshold current of 20 mA. The Yb-doped fiber emits luminescence light in the µW region.

Lasing at 1030 nm starts above the threshold pump power of ~ 16 mW (I_P ~ 60 mA), which can be monitored with the optical power meter (PM) and the photo diode (PD) with the oscilloscope. It can be seen on the oscilloscope, that at a low pump power level unstable pulses are emitted whereas above a certain threshold stable continuous wave mode-locking (cw ML) with a fixed repetition rate can be obtained.

The photo diode and the oscilloscope are not fast enough to determine the real pulse duration of t_P ~ 3 ps. Instead the measured pulse duration on the oscilloscope is determined by the rise and fall time of the detector.

To reduce the repetition frequency f_{rep} the 1 m long passive fiber PM980-XP can be introduced for instance between the active fiber and the FBG to prolong the cavity length L_C. In this case the cavity length will be L_C ~ 2 m, the pulse period ~ 20 ns and the repetition frequency f_{Rep} ~ 50 MHz.

The differential laser efficiency η can be deduced from the slope of the measured average output power P_{av} as a function of the pump power P_P to $\eta = \Delta P_{av}/\Delta P_P$.

To get information about the pulse duration the photo diode (PD) can be replaced by an autocorrelator or an optical spectrum analyzer (OSA).

With an autocorrelator the pulse duration can be determined after deconvolution of the measured time dependent pulse shape. In case of a Gaussian pulse the deconvolution is equivalent to the division of the measured pulse width by $\sqrt{2}$.

From the measured spectral pulse width $\Delta\lambda$ using an OSA the pulse duration t_P can be estimated for a transform limited Gaussian pulse without spectral chirp using the relation

$$t_P = \frac{0.44}{\Delta v} = \frac{0.44 \cdot \lambda_0^2}{c \cdot \Delta\lambda} \qquad (5.5.1)$$

with $\Delta\nu$ - spectral pulse width in the frequency range

$\Delta\lambda$ - spectral pulse width in the wavelength range

λ_0 - central wavelength of the pulse

c - speed of light in the vacuum.

Measurement results

Figure 5.5.2

Average laser output power P_{av} as a function of 980 nm pump power P_P.

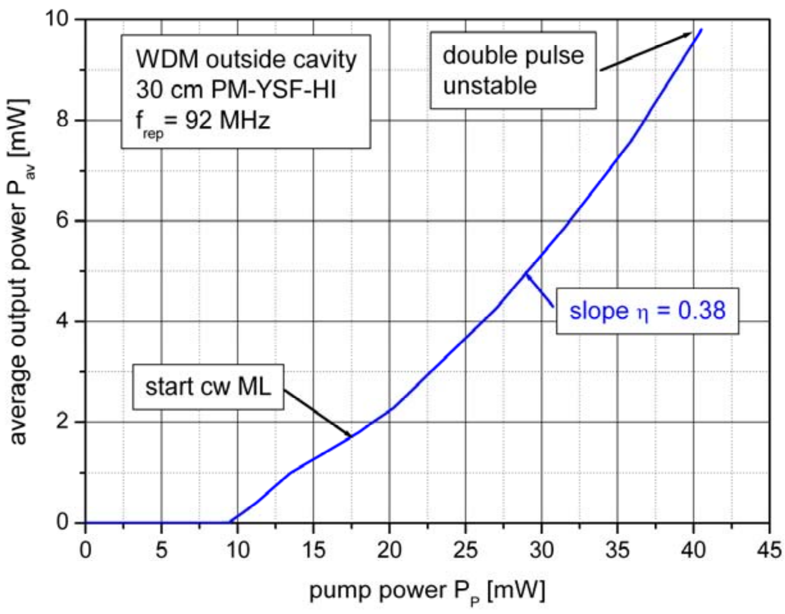


Figure 5.5.3

Average laser output power P_{av} as a function of 980 nm pump power P_P using a longer cavity. A 1 m long passive fiber is inserted between the 30 cm Yb-fiber and the filter WDM coupler.

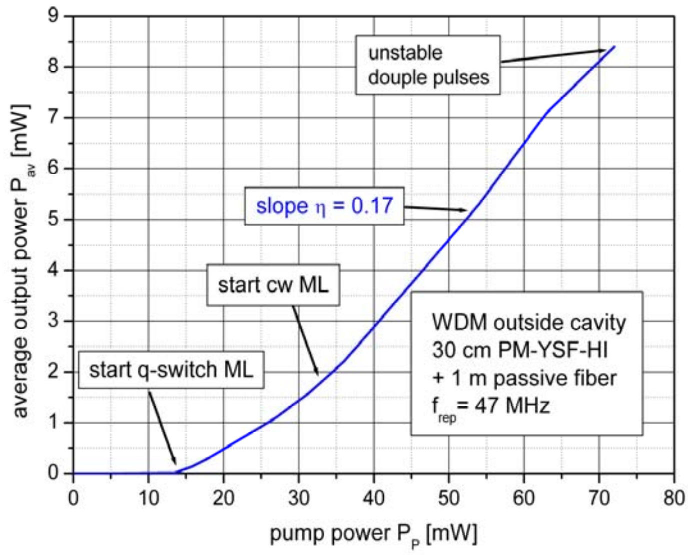


Figure 5.5.4

Oscilloscope trace of a q-switch mode-locking pulse at a pump power of 14 mW. There exist a fixed repetition rate of the mode-locked pulses during the q-switch pulse.

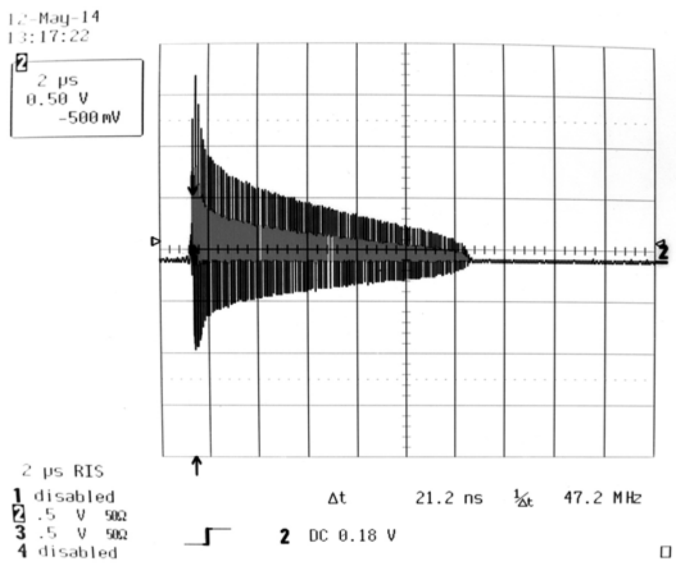


Figure 5.5.5

Oscilloscope trace of two consecutive q-switch mode-locking pulse at a pump power of 13 mW

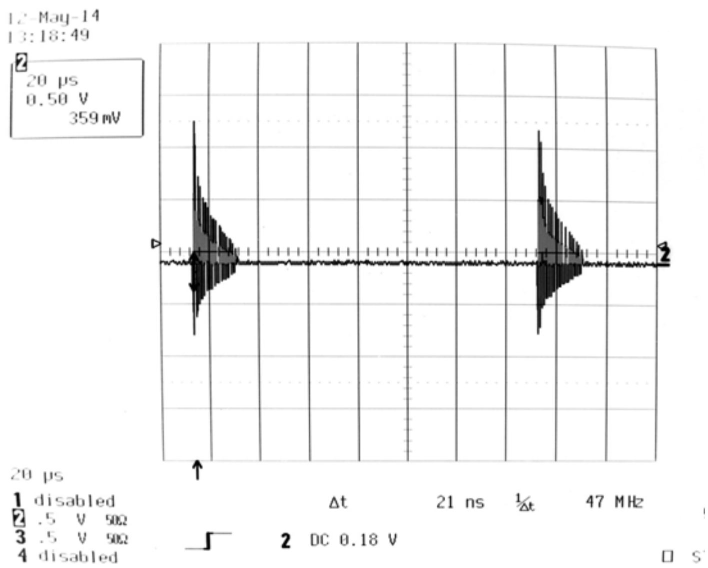


Figure 5.5.6

Oscillоscope trace of two consecutive q-switch mode-locking pulse at a pump power of 16 mW

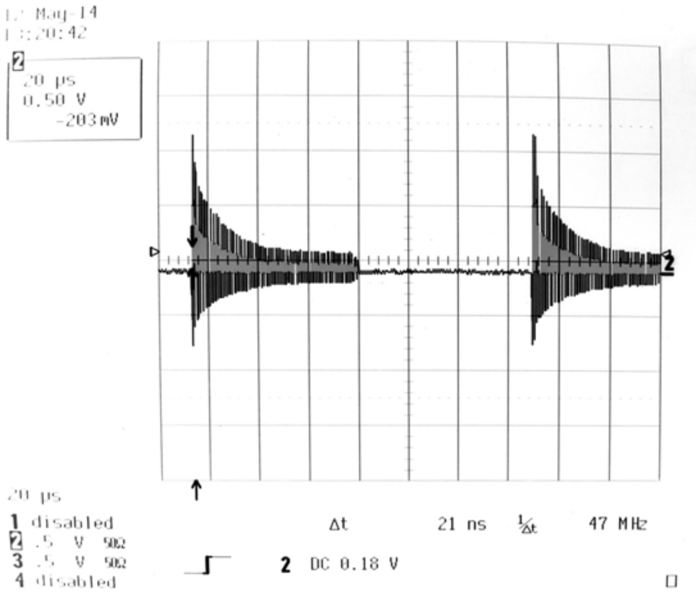


Figure 5.5.7

Oscilloscope trace of stable continuous wave mode-locking pulses at a pump power of 23 mW. The repetition frequency is f_{rep} = 91.53 MHz

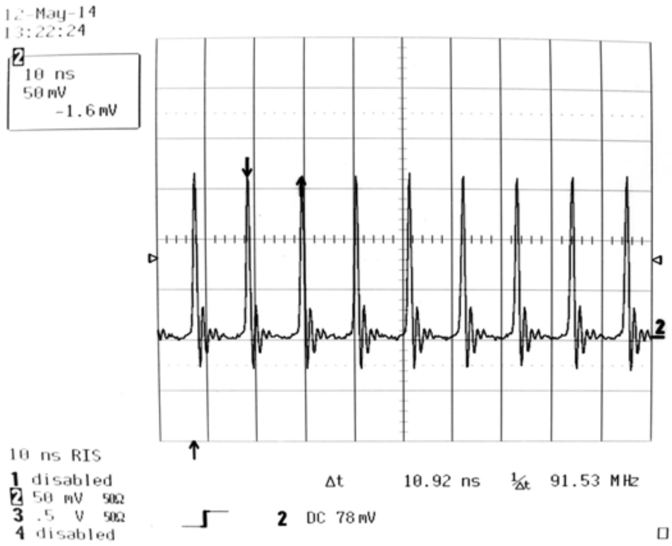
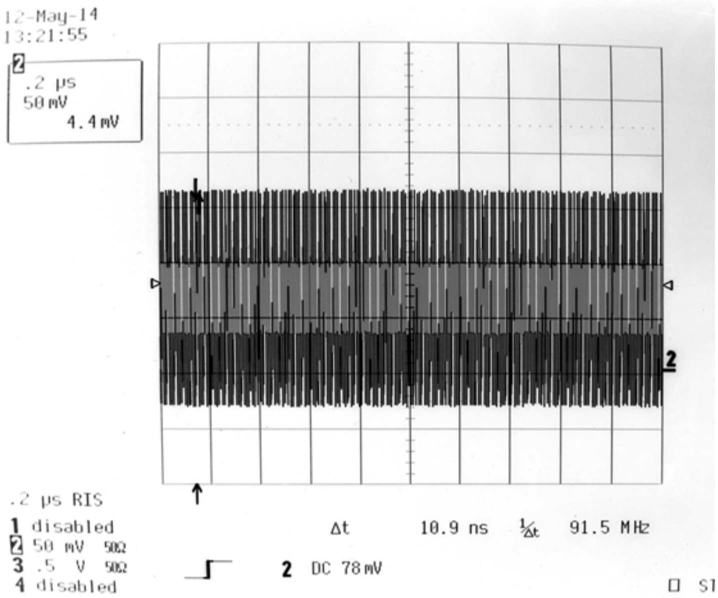


Figure 5.5.8

Oscilloscope trace of stable continuous wave mode-locking pulses at a pump power of 26 mW. The repetition frequency is f_{rep} = 91.5 MHz. The time scale is extended in comparison to figure 5.5.7.



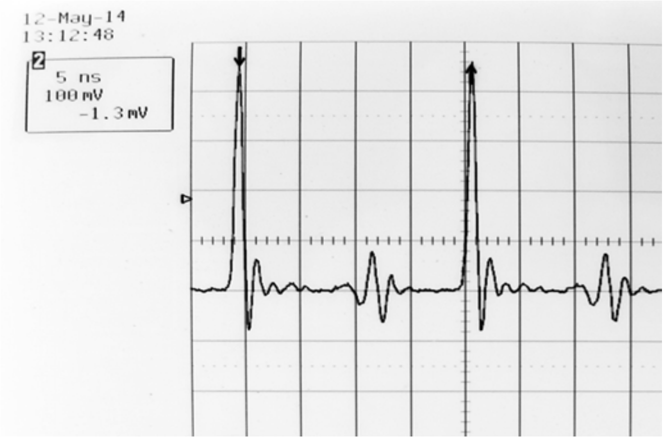


Figure 5.5.9

Oscilloscope trace cw ML pulses at a pump power of 38 mW. The laser cavity is extended by an additional 1 m long passive fiber. The repetition frequency is f_{rep} = 45.5 MHz.

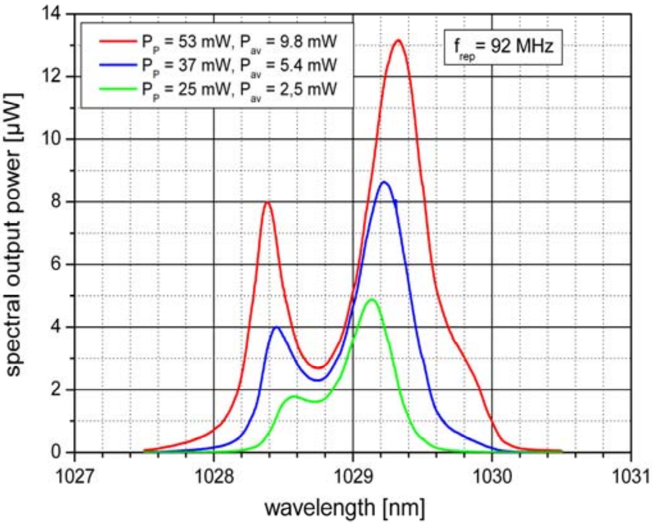


Figure 5.5.10

Spectral laser emission, measured with an OSA at different pump power levels P_P.

The short wavelength leading edge of the pulse is attenuated by the absorption in the SAM.

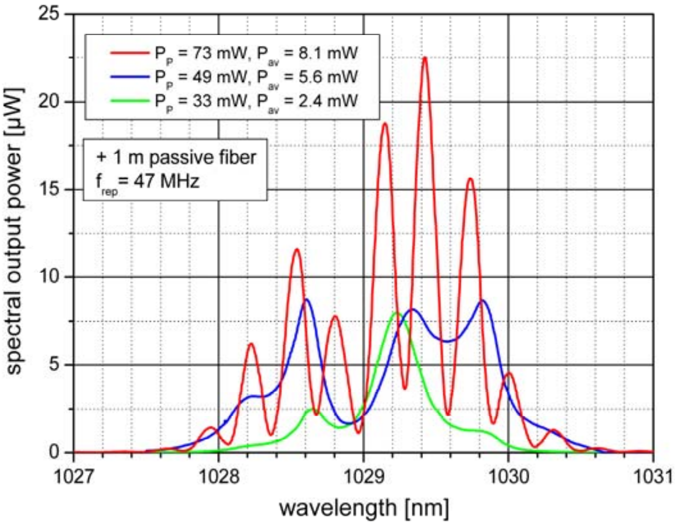


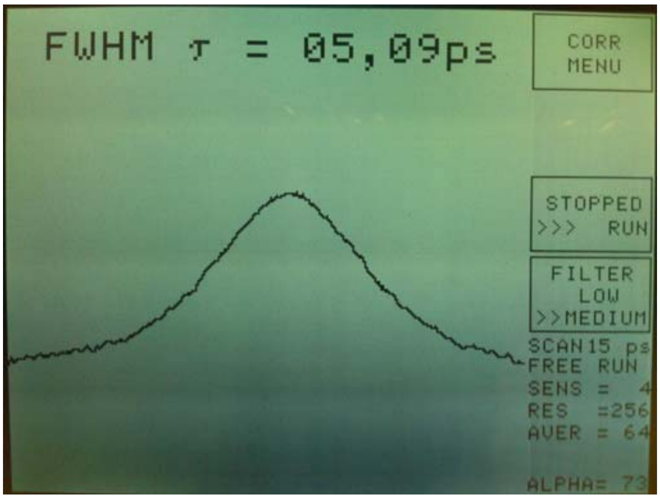
Figure 5.5.11

Spectral laser emission, measured with an OSA at different pump power levels P_P. An additional 1 m long passive fiber is inserted between the active fiber and the FBG inside the laser cavity.

At high pump power a significant self phase modulation results in a oscillating spectrum.

Figure 5.5.12

Pulse duration measurement using an autocorrelator. The measured curve is a convolution of two pulses in the autocorrelator. In case of a Gaussian pulse shape the pulse duration is t_P ~FWHM/√2 = 3.6 ps.



5.5.2 Discussion of the measured results

The following experimental observations have to be discussed:

- Lasing starts with unstable q-switch mode locking.
- The pump threshold for start of continuous wave mode-locking is substantial larger then the threshold for q-switching.
- The maximum pulse amplitude in the q-switch ML regime is larger then the pulse amplitude after start of the cw ML regime.
- The lasing efficiency is lower for a longer cavity
- The spectral pulse width increases with increasing pulse power
- The spectral pulse intensity changes with increasing pulse power from a Gaussian distribution to a distribution with two separated peaks.
- The pulse spectrum in case of an additional passive fiber in the laser cavity shows significant spectral oscillations.

Discussion of Q-switching

At first we discuss the reason for unstable q-switching and mode-locking at low pump power level. Above a certain pump power the overall gain G in the laser exceed the losses (absorption of the SAM, transmission of the FBG, additional cavity losses c_L). This means, that the following amplitude condition holds:

$$1 = e^{g \cdot c_P \cdot P_P} \cdot R_0 \cdot (1 - A_0) \cdot (1 - c_L) \qquad (5.5.2)$$

Here g = 3.5/m is the saturated gain coefficient, $c_P = L/P_P$ = 13.6 m/W the saturated fiber length per pump power P_P, R_0 =0.87 the maximum FBG reflection and A_0 = 0.32 the low intensity SAM absorption. The additional cavity loss can be coupling losses between the fiber connectors or a limited transmission of the WDM coupler in the cavity.

With equation (5.5.2) the pump power threshold for q-switching can be written as

$$P_{P,th} = -\frac{\ln(R_0) + \ln(1 - A_0) + \ln(1 - c_L)}{g \cdot c_P} \qquad (5.5.3)$$

With the parameters mentioned above and c_L=0 the pump power threshold for q-switching results in $P_{P,th}$ = 11 mW. With an additional cavity loss of c_L = 0.2 for the WDM coupler the threshold increases to $P_{P,th}$ = 16 mW.

A fluctuation of the luminescence in the Yb-doped fiber can start a small pulse, which partially saturates the SAM. Therefore the pulse amplitude increases with each round trip in the laser cavity as a result of the gain in the active fiber and decrease of the loss due to the SAM saturation. The pulse amplitude increase can be monitored on the oscilloscope. The repetition frequency of this circulating pulse is given by the round trip time T_P in the laser cavity.

With increasing pulse amplitude the SAM saturates and the gain increases by the modulation depth ΔR. In this case the net gain in the cavity can be so high that the pulse amplitude increases during a few round trips to a level, where the pulse removes by stimulated emission more inversion in the gain fiber then it is pumped during the same time. In this case the gain is substantial reduced by stimulated emission and the laser stops when the round trip gain is < 1. This scenario of a mode-locked pulse with first increasing and then decreasing amplitude is called q-switch mode-locking.

Because the active fiber is permanent pumped their gain increases after vanishing of the last pulse, so that after a certain time lasing starts again. This recovery time decreases with increasing pump power so that the average output power in the q-switch regime increases with pump power.

The scenario of development and dissolving of pulses repeats without any synchronization because the start time of each new q-switch pulse is random. Therefore neither stable repetition rate for q-switching nor stable pulse amplitude can be obtained. The result is an unstable average output power.

Modeling of q-switch and continuous wave mode-locking

For calculating the round trip gain of a circulating pulse the loss and gain of the optical components in the laser cavity must be calculated as a function of the pulse fluence. We can start with the following equations for the SAM reflection $R_{SAM}(F)$, the reflection $R_{FBG}(\Delta\lambda)$ of the fiber Bragg grating (FBG) and the active fiber gain G:

$$R_{SAM}(F) = 1 - A_0 \cdot \frac{F_{sat}}{F} \cdot \left(1 - e^{\frac{F}{F_{sat}}}\right) - \frac{\beta \cdot F \cdot d}{t_P} \tag{4.3.3}$$

$$R_{FBG}(\Delta\lambda) = \frac{R_0}{\sqrt{1 + \left(\frac{\Delta\lambda}{\Delta\lambda_{FBG}}\right)^2}} \tag{4.4.3}$$

$$G = e^{g \cdot L} \tag{5.3.5}$$

The equation for the SAM reflectance contains already the dependence on the pulse fluence F. To calculate the dependence of the FBG reflectance on the pulse fluence we must consider in the first step the spectral pulse broadening due to self phase modulation.

In a first approximation the spectral pulse distribution of a mode-locked pulse can be assumed as Gaussian. In this case the spectral pulse width of a pulse without chirp is related to pulse duration t_P according to formula (5.5.1) for a transform limited pulse

$$\Delta\lambda_0 = \frac{0.44 \cdot \lambda_0^2}{c \cdot t_P} \tag{5.5.4}$$

With increasing pulse fluence F and decreasing pulse duration t_P the optical intensity in the fiber core increases. This results in additional spectral pulse broadening by self phase modulation, which is determined by the second order refractive index of the fiber core $n_2 = 2.6 \cdot 10^{-20}$ m^2/W and the cavity length L_C. This additional spectral bandwidth $\Delta\lambda_{SPM}$ can be estimated to

$$\Delta\lambda_{SPM} = \frac{2 \cdot L_C \cdot n_2 \cdot \lambda_0 \cdot F}{c \cdot t_P^2} \tag{5.5.5}$$

Here the doubled cavity length $2 \cdot L_C$ is taken into account for a full pulse round trip.

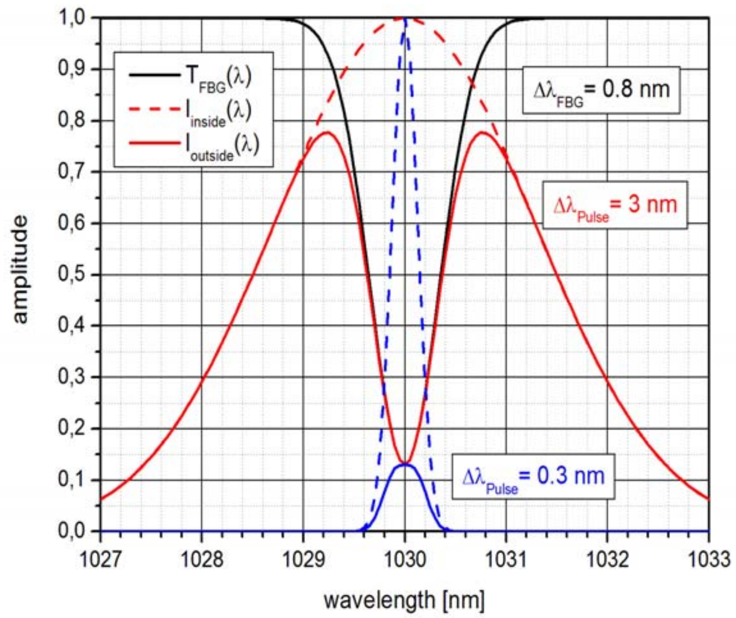
For the total fluence dependent spectral pulse width $\Delta\lambda$ we can write

$$\Delta\lambda = \sqrt{\Delta\lambda_0^2 + \Delta\lambda_{SPM}^2} \tag{5.5.6}$$

The spectral pulse shape outside the laser cavity after the transmission through the FBG is changed depending on the pulse fluence and the corresponding spectral pulse width $\Delta\lambda$. If the pulse width $\Delta\lambda$ is larger then the spectral width $\Delta\lambda_{FBG}$ of the FBG, then the transmitted spectral intensity distribution changes to a double peak curve. This is shown for two different spectral pulse widths in figure (5.5.13).

Figure 5.5.13

Change of the spectral pulse intensity distribution after transmission through the FBG in dependency on the spectral pulse width $\Delta\lambda$. The dashed lines show the pulse intensity inside the laser cavity and the solid lines the out coupled pulse.



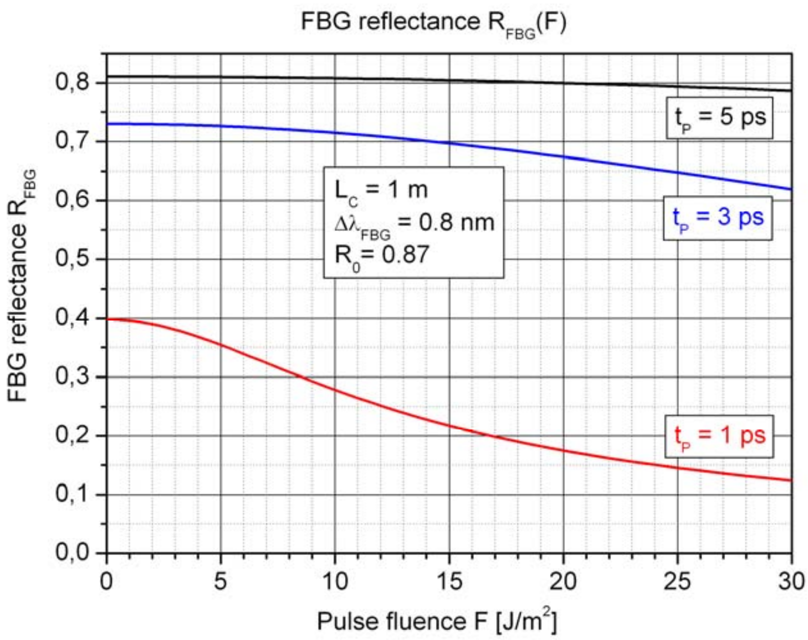
According to equation (4.4.3) the FBG reflectance is not a fixed value, but decreases with increasing spectral pulse width $\Delta\lambda$. The fluence dependent spectral integrated reflectance of the FBG can be calculated using equation (4.4.3) to

$$R_{FBG}(F) = \frac{R_0}{\sqrt{1+\frac{\Delta\lambda_0^2+\Delta\lambda_{SPM}^2}{\Delta\lambda_{FBG}^2}}} = \frac{R_0}{\sqrt{1+\left(\frac{0.44\cdot\lambda_0^2}{c\cdot t_P\cdot\Delta\lambda_{FBG}}\right)^2+\left(\frac{2\cdot L_C\cdot n_2\cdot\lambda_0\cdot F}{c\cdot t_P^2\cdot\Delta\lambda_{FBG}}\right)^2}} \tag{5.5.7}$$

The calculated FBG reflectance and the connection between the measured average pulse power P_{av} outside the cavity with pulse fluence F inside the laser according to equation (5.5.7) are shown in figures 5.5.14 and 5.5.15, respectively

Fig. 5.5.14

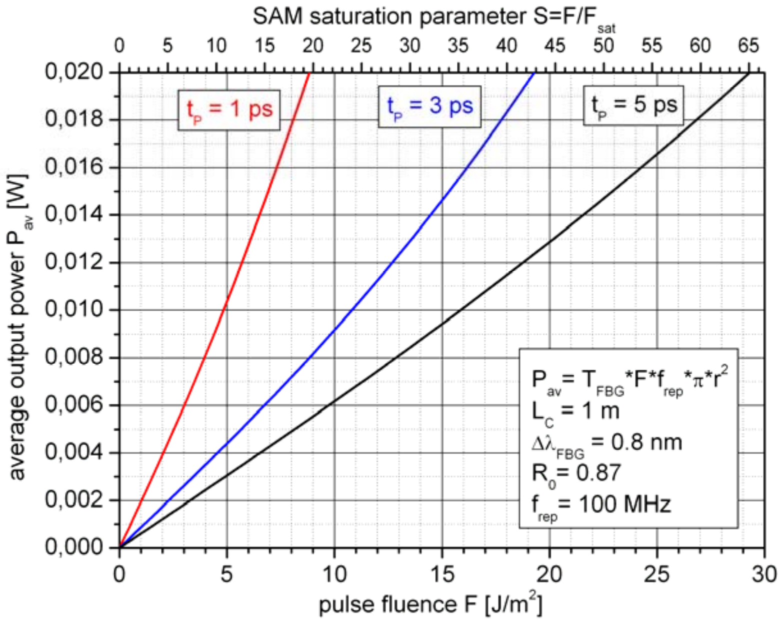
FBG reflectance R_{FBG} calculated using equation (5.5.7) for three different pulse durations t_P. The spectral width of the FBG is assumed as $\Delta\lambda_{FBG}$ = 0.8 nm.



It can be seen in this graph that for reasonable pulse fluences up to 30 J/m^2 the nonlinear self phase modulation has only a remarkable effect for short pulses on the FBG transmission. But the main effect of the narrow band FBG is the decreasing reflectance (increasing cavity loss) with increasing pulse fluence.

Fig. 5.5.15

Relation between pulse fluence F inside the laser cavity and the average output power calculated using equation (5.5.7) for three different pulse durations t_P.



If we consider the dependency of the active fiber gain in equation (5.3.5) on the pulse fluence then we have to take into account the stored energy in the pumped fiber. This means that there does not exist a direct connection between the fiber gain and the pulse fluence because the pumped fiber shows a memory effect. This is the reason why the mode-locked laser starts with q-switch pulses. We can deduce the stored energy in a pumped fiber length of 10 cm from equation (5.3.8) to 6.3 µJ. We consider a typical pulse fluence of 5 J/m^2 which corresponds to an average output power of about 4 mW (see figure 5.5.15). In this case the pulse energy is about E_P ~ 40 pJ. The above mentioned stored energy in 10 cm pumped fiber is enough to deliver 157000 pulses.

This example shows that there does not exist a simple relation between the pulse fluence F and the gain G in the active fiber. Because the history of the pump power and pulse fluence determines the pumped fiber length L a rate equation can be used to describe the time dependent pumped fiber length L as follows:

$$\frac{dL}{dt} = c_n \cdot P_P \cdot \frac{\lambda_P}{\lambda} - \frac{L}{\tau} - c_n \cdot F \cdot r^2 \cdot \pi \cdot f_{rep} \qquad (5.5.8)$$

Here the equations (5.3.2). and (5.3.8) have been used. The first term on the right site describes the increase of the pumped fiber length proportional to the pump power. The second and the third term describe the decrease of the pumped fiber length due to the luminescence with the time constant τ and due to the stimulated emission, respectively.

The change of the pulse fluence dF per round trip in the time interval dt=1/f_{Rep} can be described by

$$dF = F \cdot \left(e^{g \cdot L} \cdot R_{SAM} \cdot R_{FBG} \cdot (1 - c_L) - 1\right) + F_{Lum} \qquad (5.5.9)$$

Only a small part of the luminescence light F_{Lum} according to the second term in equation (5.5.8) contributes to the increase of dF (see also equation (5.3.3)).

With equations (5.5.8) and (5.5.9) the increase of the saturated fiber length L after the start of pumping can be modeled. If the round trip loss is equal to the fiber gain then the saturation of the SAM decreases the loss and the pulse fluence F increases with each round trip substantially. As a consequence the stimulated emission decreases the saturated active fiber length more then the pump power can recover it. Therefore, after several intense pulses the round trip gain decreases below unity and the pulse fluence F decreases with each round trip. In dependency on the saturation fluence and the pump power either the mode-locking stops (end of a q-switch pulse) or cw mode-locking regime starts.

This behavior is shown in figures 5.5.16 to 5.5.21, where the time dependency of the pulse fluence is calculated for different pump power values P_P according to equations (5.5.8) and (5.5.9).

Fig. 5.5.16

Q-switch mode-locking at 20 mW pump power.
At time t~ 45 μ the round trip gain is ~ 1. Then the SAM is saturated and the pulse fluence increases during a few round trips to F ~ 80 J/m^2. Then the pulse fluence decreases step by step because more inversion in the active fiber is removed by stimulated emission than pumped in the same time. At t =+ 185 µs the Q-switch pulse stops.

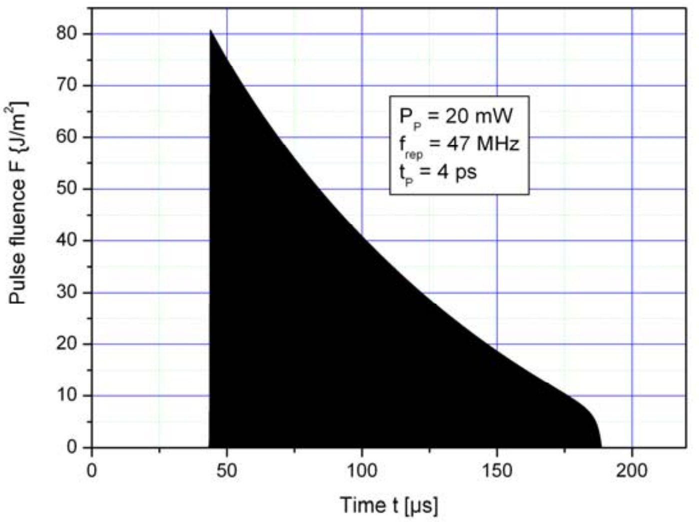


Fig. 5.5.17

Q-switch mode-locking at 22 mW pump power.
The peak fluence is the same as with 20 mW pump power.
After stop of the first Q-switch pulse the fiber gain increases due to continuous pumping until the next Q-switch pulse can start.

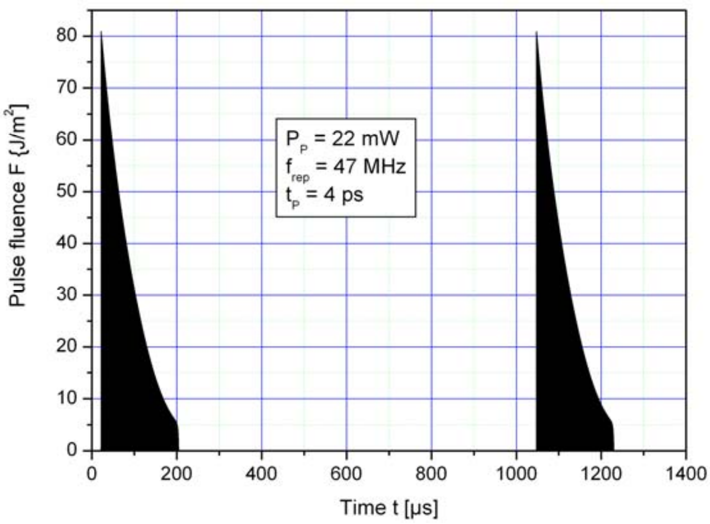


Fig. 5.5.17

Q-switch mode-locking at 22 mW pump power.
The peak fluence is the same as with 20 mW pump power but the duration of the Q-switch pulse is somewhat longer because of the increased pump power.

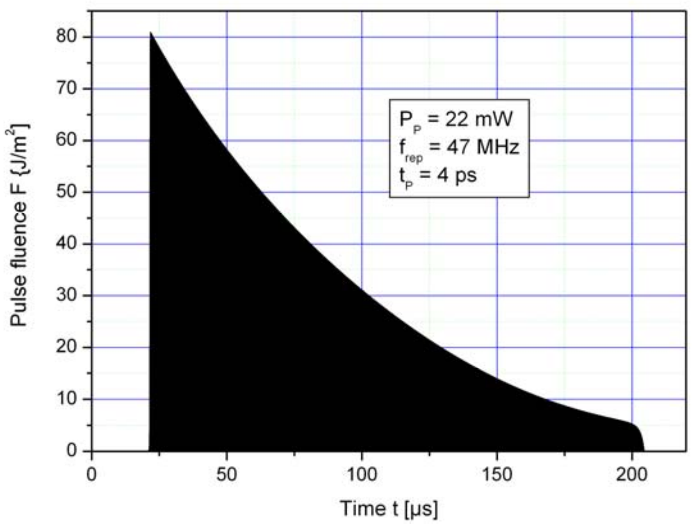


Fig. 5.5.18

Q-switch mode-locking at 22 mW pump power with an extended time scale showing the single mode-locked pulses during the start of the Q-switch pulse train.

During the SAM saturation the maximum gain is about 1.15.

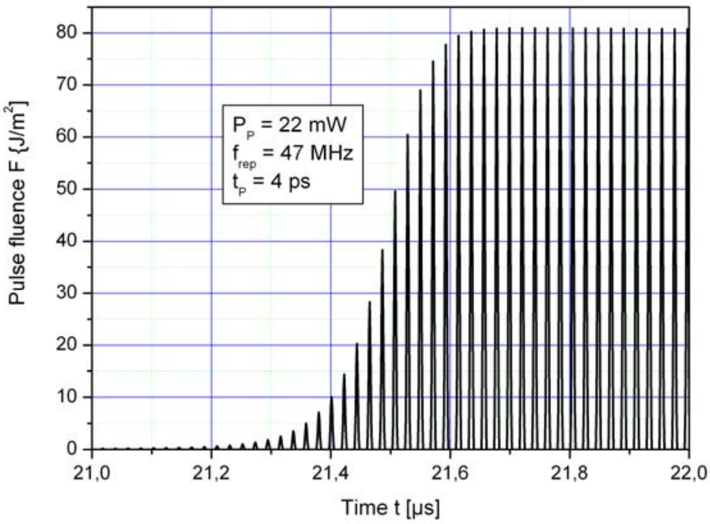


Fig. 5.5.19

Continuous wave mode-locking at 23 mW pump power.

The start phase is the same as in case of a Q-switch train but because of the increased pump power the pulse train does not stop and ends up cw-ML with an average output power of 2.8 mW.

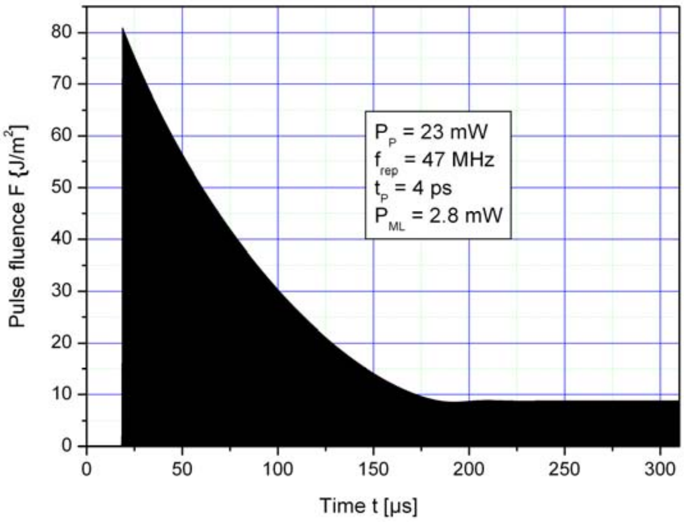


Fig. 5.5.20

Continuous wave mode-locking at 33 mW pump power.

The start phase is similar as for lower pump power. The decrease of the pulse amplitude after its maximum is somewhat weaker resulting in an higher average output power.

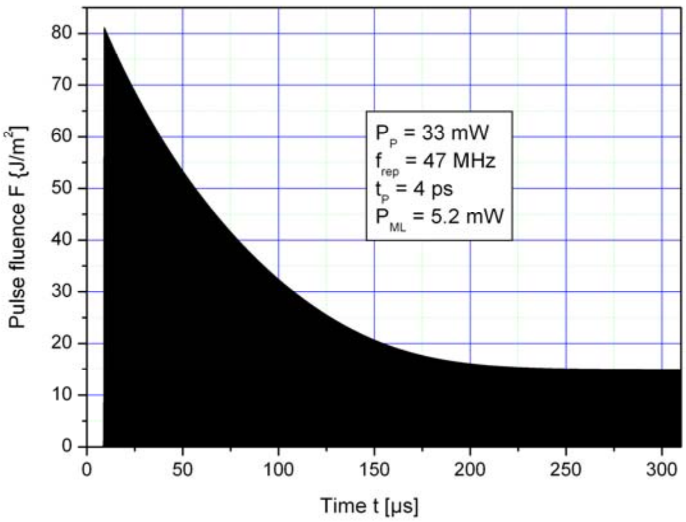
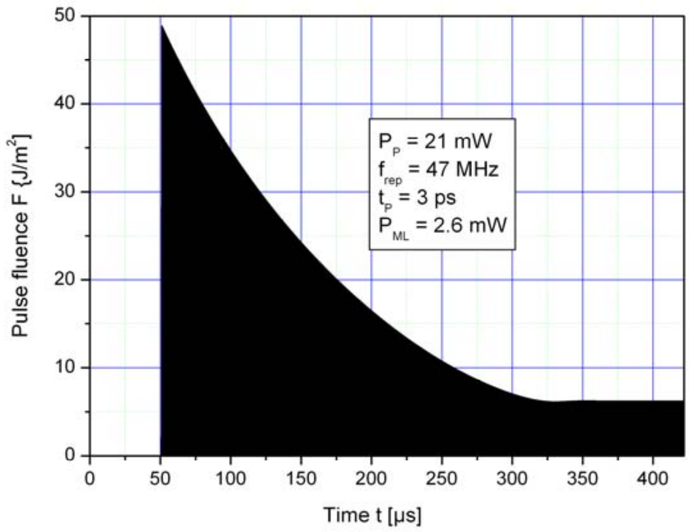


Fig. 5.5.21

Continuous wave mode-locking at 21 mW pump power with a pulse duration t_P = 3 ps.

The shorter pulse duration results in a lower maximum pulse fluence during the start phase and allows also cw-ML at a lower pump power. This shows the influence of the nonlinear transmittance of the narrow band FBG which avoids high pulse amplitude.



Conclusions

- Q-switch mode-locking (Q-ML) starts, if the gain compensates the losses in the cavity according to the amplitude condition of an oscillator.
- Because of decreasing loss in the SAM with increasing pulse fluence the pulse amplitude increases during a few round trips very fast. This is because the saturation fluence of the SAM is substantially lower then that of the active fiber. Therefore, a high pulse amplitude is possible for several cycles without a substantial decrease of the gain. Then the fiber gain decreases because the pump power is too low to compensate the loss of gain due to stimulated emission. With decreasing pulse fluence the absorption loss in the SAM increases and lasing stops.
- The start of a new Q-switched pulse train is possible when the fiber gain is recovered after some pump time. The starting time depends on random fluctuations of the amplified spontaneous emission in the pumped fiber.
- Continuous wave mode-locking (cw-ML) is possible if the pump power exceeds a certain value which ensures the recovery of the gain between two pulses. With increasing pump power the average cw-ML output power increases also.
- The start phase of cw-ML is similar as the start of Q-ML with the same maximum pulse amplitude.
- The maximum pulse amplitude during the start phase decreases with decreasing pulse duration. Shorter pulses have larger peak amplitudes at the same pulse fluence. This results in increased nonlinear spectral broadening and increasing FBG transmission loss.
- In general any nonlinear effect showing an increasing loss with increasing pulse amplitude is helpful to avoid high maximum pulse amplitude and to ensure a low pump threshold for cw-ML. Besides the use of a narrow band FBG as amplitude limiting element also the two photon absorption (TPA) in the SAM (especially at shorter pulsedurations) and the increase of SAM absorption and saturation fluence with increasing SAM temperature are such limiting effects which allow cw-ML at a low pump power level.

5.6 Picosecond laser, WDM coupler inside the cavity

This laser configuration results in a longer cavity and an additional loss in the filter WDM coupler.

5.6.1 Experiment

Needed parts from PSFL130 evaluation kit:

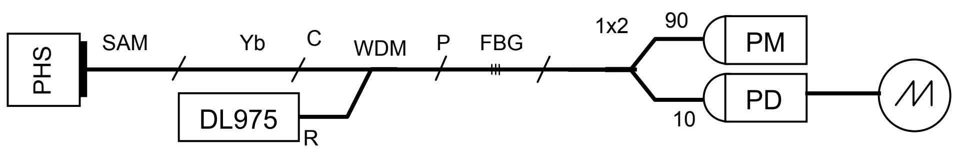
SAM	Yb	FBG	C WDM $\lambda > 1$ µm $\lambda < 1$ µm	DL975
1x2 90 10	Optional 1 m	5 x Mating Sleeve	PHS	

Additional equipment needed:

PD	PM	Optional: OSA		Optional: Autocorrelator

Schematic

The photo diode (PD) can be replaced by an optical spectrum analyzer (OSA) to measure the spectral distribution of the emitted picosecond laser pulses



This experiment differs only in the position of the WDM filter coupler from the setup in chapter 5.5. Because here the WDM filter is positioned inside the laser cavity the repetition frequency is lower due to the longer cavity length L_C. The needed pump power is higher as a result of the additional loss in the filer WDM which must be compensated with a higher gain in the active fiber. A further consequence of the longer cavity length is larger normal dispersion.

Measurement:

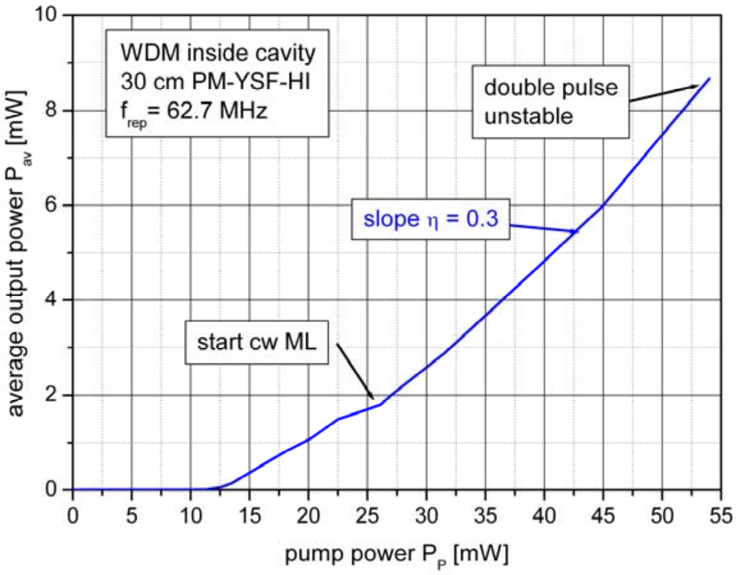
Switch on the DL-975-100 and increase step by step the drive current of the 975 nm laser diode above the threshold current of ca. 20 mA. The Yb-doped fiber laser starts lasing at 1030 nm above the threshold pump power of ~ 15 mW. This can be monitored with the optical power meter (PM) and the photo diode (PD) with the oscilloscope.
The FBG can be placed in the optical path with two different directions. Because of the chirp the lasing threshold and the slope efficiency depend on the FBG direction. This can be experimentally proved.

The repetition frequency can be reduced by insertion of the 1 m long passive fiber PM980-XP in the laser cavity between the SAM and the active fiber.
The pump threshold for q-switching and cw ML and also the pump power region for stable mode-locking $P_{p,max}$ - $P_{p,min}$ can be measured for the different laser configurations.
The spectral pulse width can be measured with an OSA in the same way as explained in the previous chapter 5.5.

Measurement results

Figure 5.6.2

Average laser output power P_{av} as a function of 980 nm pump power P_P.



5.6.2 Discussion of the measured results

Threshold pump power

If we compare the onset of q-switching in figure 5.6.2 with the equivalent result in case of the filter WDM outside the cavity in figure 5.5.2, then the influence of the transmission loss in the filter WDM can be seen. To start the laser with WDM inside the cavity about 5 mW more optical pump power is needed to compensate the transmission loss of the WDM.

Using the gain formula 5.3.5 with the power specific gain coefficient g_P = 47.6/W and the additional pump power of 5 mW the needed extra gain in the active fiber to compensate the WDM loss is 1.27. This value corresponds to the measured WDM transmission of 0.8.

Slope efficiency

The WDM transmission loss in the cavity decreases also the slope efficiency of the laser power characteristic. Clearly, the laser pulses must go through the WDM in both cases, WDM inside and outside the laser cavity before they meet the optical power meter. But if the WDM is insight the laser cavity, the pulses must go through the WDM twice in a cavity round trip whereas if the WDM is outside the cavity the pulse go only once through the WDM.

Conclusions

- To get high laser efficiency the losses inside the laser cavity must be minimized.
- The optimum laser configuration is with WDM outside the cavity.

5.7 Picosecond oscillator + amplifier

It is possible to combine the ps laser in chapter 5.5 with an additional gain fiber, both pumped with the same laser diode because the FBG transmits also the pump power.

Experiment

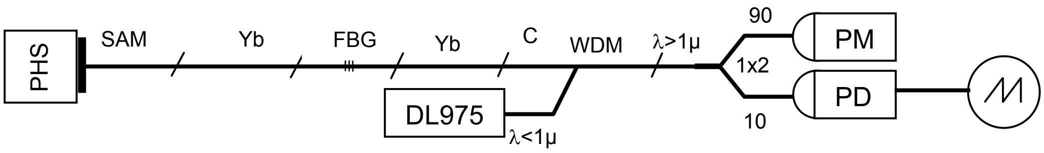
Needed parts from PSFL130 evaluation kit:

SAM	2 x Yb	FBG	C WDM λ > 1 µm λ < 1 µm	DL975
1x2 90 10	Optional 1 m –	5 x Mating Sleeve	PHS	

Additional equipment needed:

PD	PM	Optional:_ OSA		Optional: Autocorrelator

Schematic



Measurement

The ps laser works best with a 30 cm long Yb-doped active fiber. The 20 cm Yb-doped fiber can be used as amplifier outside the laser cavity. The photo diode (PD) can be replaced by an optical spectrum analyzer (OSA) to measure the spectral distribution of the emitted and amplified picosecond laser pulses.

In the first step of pumping the amplifier fiber outside the laser cavity must be saturated. With further increasing of pump power also the active fiber inside the resonator will be pumped. Therefore the needed pump power to start the ps laser is higher then without the additional amplifier.

Figure 5.7.2

Average output power P_{av} of the oscillator + amplifier combination as a function of 980 nm pump power P_P.

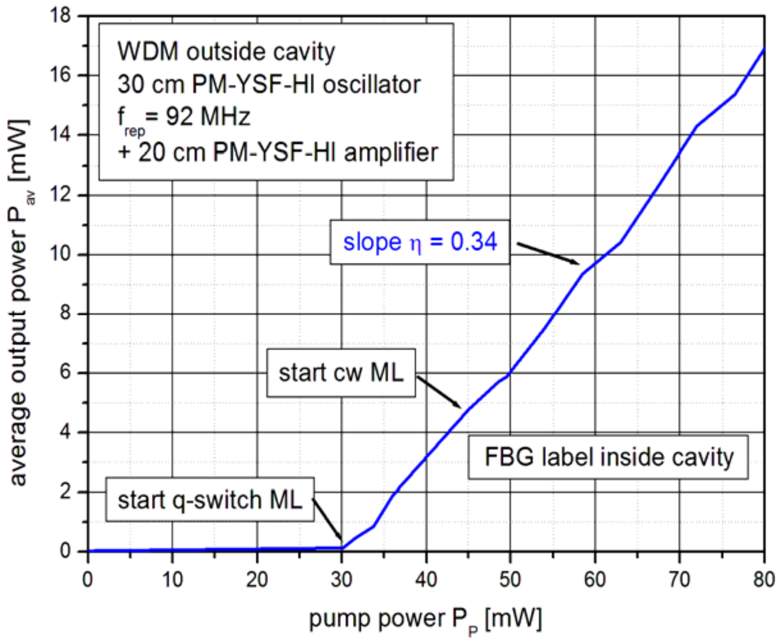
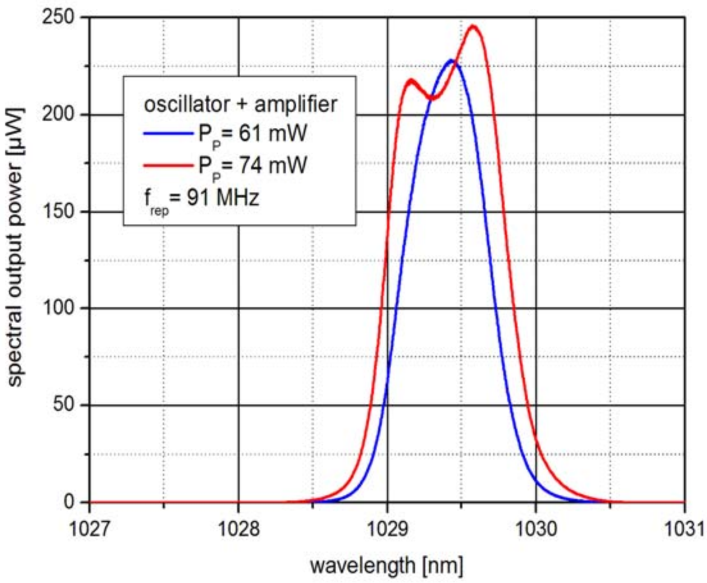


Figure 5.7.3

Spectral laser + amplifier emission, measured with an OSA at two pump power levels P_P..

The laser works at a low power level only somewhat above the threshold for cw ML. The spectrum is therefore small.



Discussion of the measured results

With the oscillator-amplifier combination a reasonable efficiency can be realized for the conversion of pump light into picosecond pulses. An important advantage of this combination over the pure oscillator setup is the lower pulse fuence on the SAM, which ensures a lower temperature of the absorber layer and consequently a lower long time degradation of the saturable absorber mirror. This is important for applications of the ps laser source. With more pump power also a higher output power will be possible.

The spectral width of the output pulses is small because of the low power level in the oscillator. The shape of the spectral power distribution in case of higher pump power is nearly flat top. This can be explained with gain saturation. The pumped active fiber stores an amount of energy. By stimulated emission some energy is added to a pulse traversing the pumped fiber. Because the stored energy is limited, the amplification is higher for a lower signal. This results in spectral equalization of the output power.

5.8 FBG transmittance

The spectral transmittance of the fiber Bragg grating FBG-1030-0.8-87-FC/APC-PM980-XP can be measured using the broadband luminescence of the Yb-doped fiber light source.

Needed parts from PSFL130 evaluation kit:

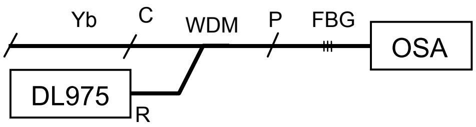
FBG	Yb	C WDM P R	DL975	1 m –
2 x Mating Sleeve				

Additional equipment needed:

OSA

–

Schematic



The FBG can be replaced by the passive fiber FBG-1030-0.8-87-FC/APC-PM980-XP to measure the “100 %” calibration curve

Measurement:

Switch on the DL-975-100 and increase step by step the drive current of the 975 nm laser diode above the threshold current of ca. 20 mA. The Yb-doped fiber laser starts broadband luminescence, which can be measured using the optical spectrum analyzer (OSA). Please be aware, that you work with a low luminescence level to avoid a power damage of the OSA detector.
To calculate the spectral transmittance of the FBG two measurements are needed with the same pump power:

- Spectral transmission through the FBG.
- Spectral transmission through a passive fiber.

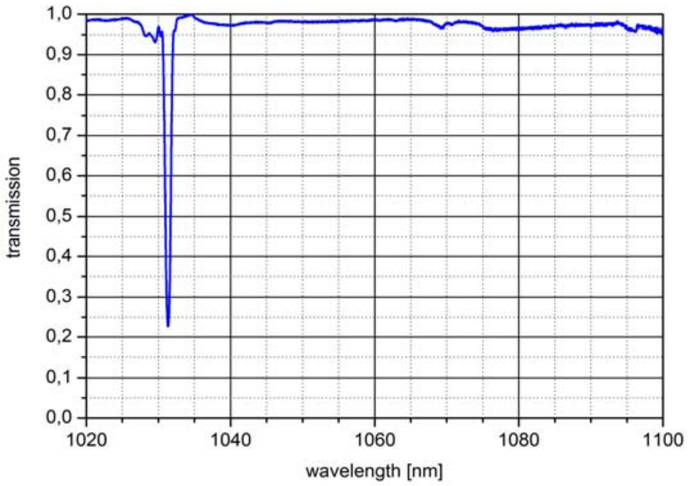
The spectral transmittance T of the FBG results from the transmitted spectral power through the FBG divided by the measured spectral power trough the passive fiber PM980-XP-100-FC/APC

.
The absorption in the FBG is negligible. Therefore the reflectance R of the FBG is simply R = 1 –T.

Measurement results

Figure 5.8.2

Spectral transmission T of the FBG-1030-0.8-87-FC/APC-PM980-XP. The minimum transmission at ~ 1030 nm wavelength corresponds to the maximum reflection at this wavelength. An extended view of the transmission is shown in figure 4.4.1.



Discussion of the result

The transmittance T of the FBG is almost 1 besides the small spectral region around the reflection wavelength of ~ 1030 nm. To measure the exact spectral bandwidth and the minimum transmission the wavelength step of the OSA scan must be chosen appropriate small.

6. Ordering information

All parts of the evaluation kit PSFL1030 (items 1 – 14) can be ordered as replacement pieces. Please use the Part No. for ordering.
Besides the parts of the evaluation kit the following additional equipment can be ordered from BATOP if needed:

Laser safety goggles
Fast photo diode to trace the time dependent laser output signal from ALPHALS ?
Digital optical power and energy meter from Thorlabs with sensor head S120C and FC adapter S120-FC or: Fiber Optic JW3216C handheld Optical Power Meter Tester -50 ~ +26dBm USB for < 300 €
Fiber inspection scope FS200 from Thorlabs Optical magnification: 200 x field of view: 600 µm diameter LED illumination

7. Support

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