Evaluation Kit Picosecond Fiber Laser PSFL1030

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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)
- dispersion control using a fiber Bragg grating (FBG)
- ps oscillator + fiber amplifier combination
- continuous wave fiber laser at 1030 nm wavelength
- amplified spontaneous emission (ASE) broadband emitter.

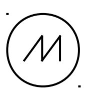
Your comments

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		Fiber scope for visual inspection of connector end face, for instance Thorlabs FS200
6	OSA	***Optional equipment:*** OSA – optical spectrum analyzer
7		***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:

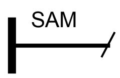
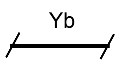
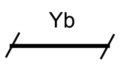
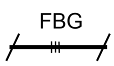
Protector 008.T0004.0 (OD4+ for 960 – 1400 nm) from LaserVision

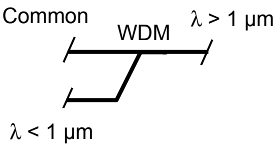
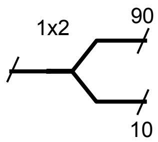
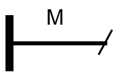
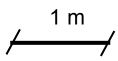
Be aware of hazardous and invisible laser light which can escape from fiber ends.

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 	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 	Panda-Type Yb-doped PM fiber, 20 cm long, FC/APC connectors
4	1	PM-YSF-HI-30-FC/APC 	Panda-Type Yb-doped PM fiber, 30 cm long, FC/APC connectors
5	1	FBG-1030-0.8-87-PM980-XP-100-FC/APC 	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 reflection wavelength 940 – 990 nm, 50 cm fiber length common, 25 cm fiber length FC/APC connector
7	1	LD-980-100 LD980	Laser diode 980 nm wavelength maximum output power 100 mW fiber coupled with FBG FC/APC connector NA = 0.21
8	1	LDC202C from Thorlabs LDC	Laser diode controller Output: 0 to ± 200 mA/ > 10 V, Resolution: 10 µA Accuracy: ± 100 µA
9	1	1x2 SM-coupler 10/90 	Single mode fiber coupler 1x2, ratio 10% : 90%
10	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
11	1	PM980-XP-100-FC/APC 	100 cm passive fiber PM980-XP, FC/APC connector
12	6	Mating Sleeve	ADAFC2 FC/PC to FC/PC Mating Sleeve, Wide Key (2.2 mm), Square Flange
13	1	FCC	Fiber connector cleaner, 20' spool
14	1	FCS3	Precision fiber cleaning fluid
15	1	MC-5	Lens tissues, 25 sheets per booklet

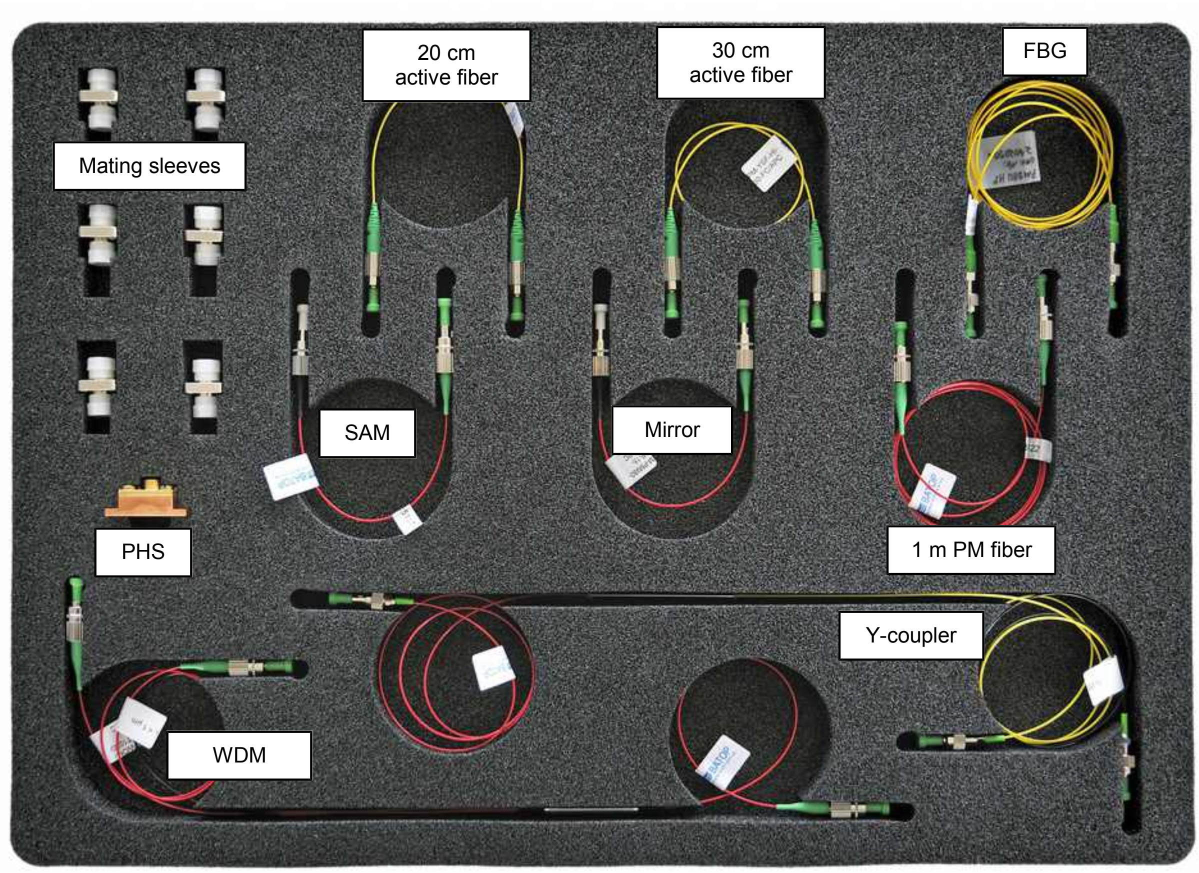


Fig. 4.1.1 Parts on the top plate

Fig. 4.1.2
Parts on the bottom plate

4.2 *Information on operation laser diode controller LDC202C*

Laser diode LD-980-100

Emission wavelength λ = 980 nm
Threshold current I_{th} ~ 20 mA
Maximum pump current $I_{P,max}$ = 215 mA

Laser diode controller LDC202C

Operation

Warning	Before starting operation, please make sure to have switched the laser diode polarity (LD POL) to cathode grounded (CG) [11] by pressing the polarity switch [13]. **Do not start laser operation while polarity is set to anode grounded (AG) as it will lead to damages and in worst case the destruction of the laser diode!**

Attention	To avoid possible damages of parts of the set up by turning on the laser at a high pump power, it is recommended that the potentiometer of the diode driver [6] has to be turned to 0 after operation (by turning it counter clockwise). This is important due to the reason that the value of current is not shown before turning on laser operation.

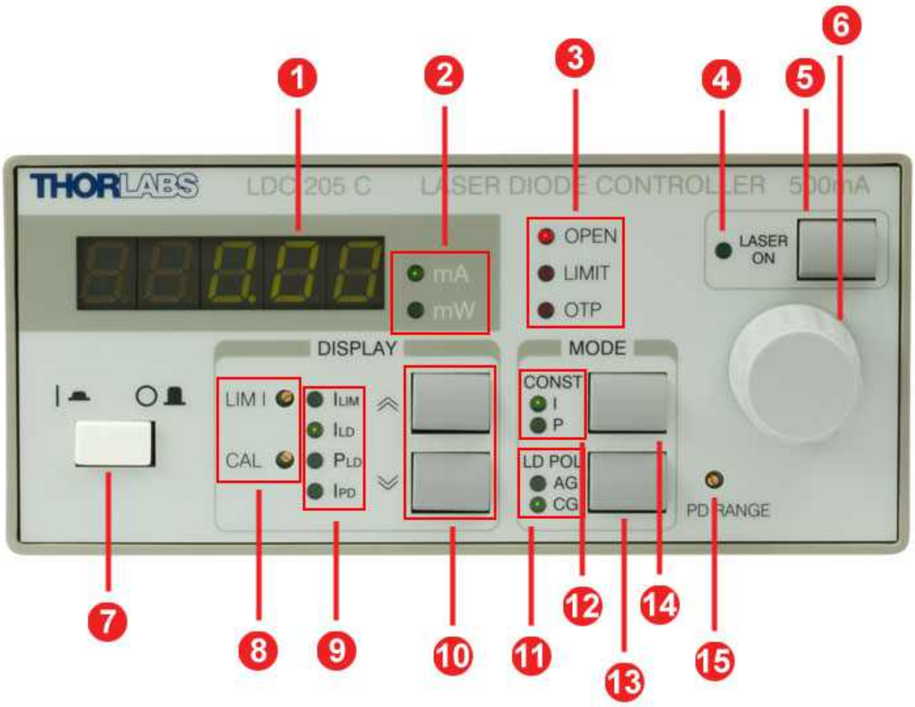


Figure 4.2.1: Laser diode controller front panel
(https://www.thorlabs.de/images/TabImages/Current_Controller_A1-780.jpg)

No	Description	No	Description
1	Display	9	Display mode indicators
2	Unit indicators	10	Up/ down selector
3	Warning indicators	11	Laser diode polarity indicators
4	Interlock indicator	12	Operation mode indicators
5	Laser operation on/ off - switch	13	Laser diode polarity switch
6	Laser current/ power adjust knob	14	Operation mode switch
7	Device on/ off switch	15	Photo diode current range potentiometer
8	Current limit- and photo diode calibration potentiometer		

Note	Before starting operation it is recommended to set current limit either to a desired value or to 200 mA. (see chapter “setting current limit” down below)

At first please turn on device by pressing the on/ off switch [7]. Before starting laser operation, you have to choose an operation mode (either constant current or constant power). This can be done by pressing the operation mode switch [14] until desired operation mode is being indicated [12]. After that choose desired display mode (display showing current or power value) [9] by pressing up/ down selector nearby [10]. Now, you can operate the laser by pressing the laser operation on/ off switch [5].

Indicator LEDs at the front of the laser diode driver [4] as well as at the front of the laser diode case are indicating operation of laser diode. By turning the current/ power adjust knob [6] you can set the desired current or power value (depending on operation mode, see above).

Setting current limit

To set current limit for operation you need to set display indicators [9] by pushing up/ down selector [10] until current limit indicator is on. Afterwards you can adjust current limit by turning the current limit potentiometer [8] with the enclosed screw driver.

Warning indicators

If the **“open”** indicator lights up, the interlock is open. In this case, the laser will immediately turn off. Reasons can be an additional installed safety equipment, like a connected interlock door or a problem within the laser diode and/ or its connection to the laser diode driver. Please check, if the cable is connected firm to both the laser diode case and the laser diode driver and try to restart the laser diode driver and the laser diode. If the problem occurs again please contact us.

If the **“limit”** indicator lights up, the set current limit is reached. The laser is still in operation. It is not possible to increase the current or power with the current/ power adjust knob. If the current limit is set below 200 mA you can handle the problem by turning off laser operation and setting a new current limit (see chapter above “setting current limit”).

If the **“OTP”** indicator lights up, the device will turn off in consequence of thermal overrun and therefore thermal protection of the driver. In this case, you have to wait, until the indicator turns off, that is, when the current temperature has decreased by 10 Kelvin. After the indicator turns off, you can restart the laser and go on operating it.

Adjusting photo diode

First of all, select constant current mode by using the operation mode switch [14]. Afterwards, set a current value, for which the optical output power is well known (e.g. with the help of a power meter) and select “P_{LD}” by using the up or down selector/ button [10]. If the now shown range of output power is sufficient, adjust it by turning the calibration potentiometer [8, “CAL”]. When the shown range is not sufficient, then change the range by keeping the operation mode key [14] pressed while pressing the up or down selector [10]. Then you can adjust it by turning calibration potentiometer as mentioned above.

Disabling the beeper

You can simply turn off the beeper signals, which emerge when pressing the buttons or if the warning indicators light up, by holding the up selector [10] and simultaneously pressing the down selector [10]. Use the same principle for turning it on again.

Note	For further information please see original manual by Thorlabs for LDC202C available in the service/ download section on the Thorlabs homepage.

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

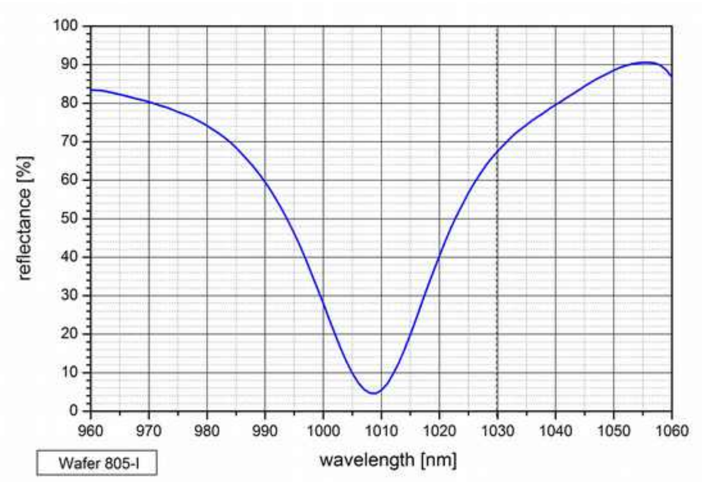
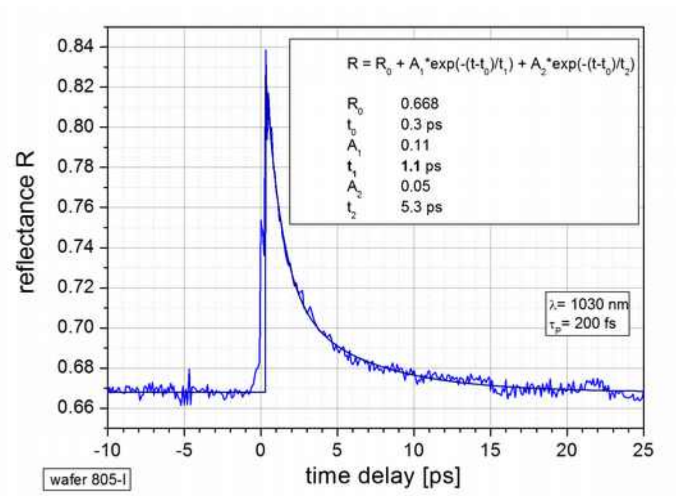


Figure 4.3.2

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.

Two effects are important to get continuous wave mode-locking (cw ML): saturation and heating.

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 as follows:

$$R = 1 - A_0 \cdot \frac{F_{sat}}{F} \cdot \ln\left(1 + \frac{F}{F_{sat}}\right) \tag{4.3.1}$$

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.

Heating

To get stable lasing also the amplitude condition must be fulfilled, which means, that the product of gain G and loss L in a round trip for the pulse must be unity.

The laser will be started at first by moderate pumping of the active Yb-doped fiber. With increasing pump power the saturated length of the active fiber increases and also the fiber gain G. If enough energy is stored in the fiber the gain can compensate the round trip loss L, which is mainly determined by the SAM absorption and the transmission of the output coupler. Then a pulse develops during some round trips. Because the SAM reflectance increases due to the absorber saturation also the pulse energy increases step by step. This process is called ***q-switch mode locking***. With increasing number of round trips of the pulse the stored energy in the pumped fiber decreases because of the low pump power level. Therefore the fiber gain decreases and lasing stops. After some pump time the same q-switch pulse develops again.

The number and amplitude of the pulses during one q-switch increases with increasing pump power. But to get a stable ***continuous wave mode-locking*** a second nonlinear process is needed, which decreases the round trip gain of a pulse at a certain power level. The known effects *gain saturation*, *nonlinear polarization rotation in combination with a polarization filter* and *nonlinear spectral broadening in combination with a spectral filter* are not appropriate for an all normal dispersion fiber laser with ps pulses and a SAM as mode locker.

Therefore a loss increasing nonlinear effect is needed, which is efficient at a pulse fluence not significant higher then the SAM saturation fluence. *Heating of the SAM absorber layer* can be used as pulse energy limiter in the laser cavity. As a result of absorption a part of the pulse energy is converted into heat during the optical pulse hits the SAM. The result is an increase of absorption and hence the cavity loss. The temperature dependent absorption A(T) can be described as

$$A(T) = A_0\left(1 + \left[\frac{\partial A}{\partial T} + \frac{\partial A}{\partial \lambda} \cdot \frac{\partial \lambda}{\partial T}\right] \cdot \frac{\partial T}{\partial F} \cdot F\right) \tag{4.3.2}$$

The differential quotients in this equation can be measured and calculated.

From measurements the following values are available for a typical SAM at 1030 nm wavelength:

$$\beta = \frac{1}{A} \cdot \frac{\partial A}{\partial T} \approx \frac{0.004}{K}$$ temperature coefficient of absorption (4.3.3)

$$\gamma = \frac{1}{A} \cdot \frac{\partial A}{\partial \lambda} = -\frac{1}{1-R} \cdot \frac{\partial R}{\partial \lambda} \approx \frac{-10^8 \,..\, +10^8}{m}$$ slope of spectral absorptance (4.3.4)

$$\beta_\lambda = \frac{1}{\lambda_0} \cdot \frac{\partial \lambda}{\partial T} \approx -\frac{1.6 \cdot 10^{-4}}{K}$$ temperature coefficient of the spectral curve (4.3.5)

The coefficient β is determined by the temperature dependent semiconductor gap of the absorber material. The coefficient γ is a result of the SAM interference layer system. Here the relation R = 1 – A is used. The coefficient β_λ is determined by the temperature coefficients of the interference layer thickness and the refractive indices of the interference layers, which works together in the same direction. β_λ describes the spectral shift to longer wavelengths with increasing temperature.

The temperature dependence on the pulse fluence T(F) can be estimated using the thermal diffusion equation resulting in

$$\frac{\partial T}{\partial F} \approx \frac{A_0}{\lambda_{th}} \left(\sqrt{\frac{a}{\tau \cdot (1 + \tau / t_P)}} + 2 \cdot r \cdot f \right) \qquad (4.3.6)$$

with

with	$\lambda_{th} \approx 40$ W/(m·K)	thermal conductivity of the InGaAs absorber layer
	$a \approx 2.5 \cdot 10^{-5} m^2/s$	thermal diffusivity of InGaAs
	τ = 0.5 .. 10 ps	relaxation time of the absorber
	$t_p \approx 3$ ps	pulse duration in cw mode-locking regime
	r ≈ 3.2 µm	radius of the mode field on the SAM, given by the fiber
	f_{rep} = 50 .. 100 MHz	repetition frequency in cw mode-locking regime.

Here the first summand in the brackets describes the temperature rise during the pulse, which goes back to zero until the next pulse hits the absorber, whereas the second summand describes the average temperature rise of the absorber after an integration time of some hundreds of milliseconds. If we restrict ourselves on the fast dynamic of the temperature dependency T(F), then equation (1) can be extended by considering the temperature influence to

$$R = 1 - A_0 \cdot \left(\frac{1}{F} + \frac{A_0^2}{\lambda_{th}} \cdot \left\{ \sqrt{\frac{a}{\tau \cdot (1 + \tau / t_P)}} + 2 \cdot r \cdot f_{rep} \right\} \left[\beta + \gamma \cdot \lambda_0 \cdot \beta_\lambda \right] \right) \cdot F_{sat} \cdot \ln \left(1 + \frac{F}{F_{sat}} \right) \qquad (4.3.7)$$

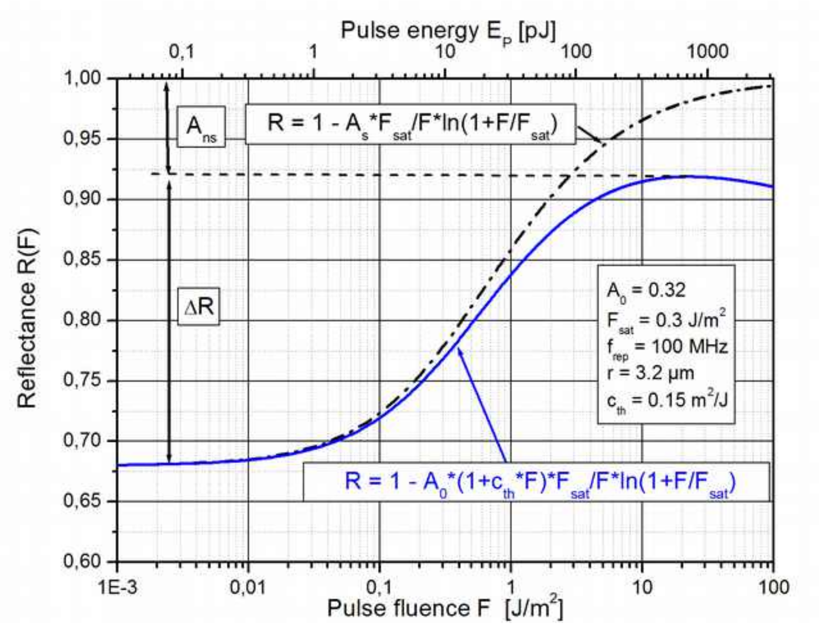
The spectral reflectance inclination dR/dλ = $-\gamma \cdot A_0$ at the laser wavelength λ_0 = 1030 nm is an important SAM parameter. For stable mode-locking a large positive value of dR/dλ is appropriate. From the measured low intensity spectral reflectance of the SAM-1030-32-1ps in figure 2 we can deduce the value dR/dλ = $1.7 \cdot 10^7$/m and with A_0 = 0.32 the parameter γ = $-5.3 \cdot 10^7$/m. With relaxation time of τ = 1.1 ps, pulse duration t_P ~ 3 ps, a repetition rate f_{rep} = 100 MHz and the other parameters given above the nonlinear dependence of the reflectance R on the pulse fluence F can be described for the SAM-1030-32-1ps as

$$R = 1 - A_0 \cdot (1 + c_{th} \cdot F) \cdot \frac{F_{sat}}{F} \cdot \ln \left(1 + \frac{F}{F_{sat}} \right)$$ with c_{th} = 0.15 m^2/J and A_0 = 0.32 (4.3.8)

The saturation parameter S = F/F_{sat} governs the nonlinear fluence dependent SAM reflectance. The temperature determined decrease of the reflectance for higher pulse fluences serves for pulse amplitude limitation and hence for stable cw mode-locking. The saturation curve of SAM-1030-32-1ps according to equation (8) is shown in figure 4 below together with the theoretical saturation curve without temperature effect according to equation (1).

Figure 4.3.4

Saturation curve R(F) for SAM-1030-32-1ps according to equations (1) and (8). 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 thermal effect causes the 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:

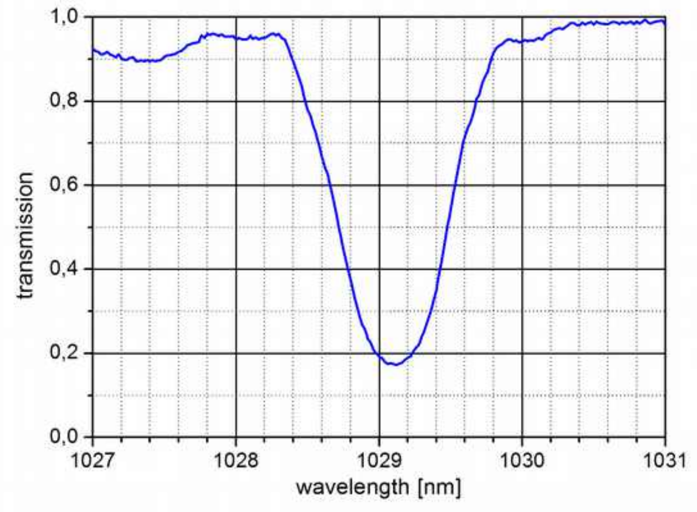
Maximum reflectance wavelength	λ_0 = 1030 nm
Reflectance at λ_0	R_0 = 0.87
Reflectance spectral width	$\Delta\lambda_{FBG}$ = 0.8 nm (Full width at half maximum)

FBG dispersion:

The writing process of the fiber Bragg grating results also in an unintentional chirp of about 500 fs/nm. The silica fiber shows at 1030 nm wavelength a normal dispersion of - 44 fs/(nm·m). This results in a 1 m long laser cavity in a total normal dispersion of 88 fs/nm for a complete round trip of the pulse. This normal fiber dispersion increases or decreases the FBG dispersion dependent on the direction of the FBG in the cavity. Therefore the FBG label is attached on one site. If this marked site is oriented in the cavity direction, then the fiber dispersion is over-compensated and the laser cavity has an anormal dispersion resulting in a negative chirp of the pulse, which supports pulse shortening.

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

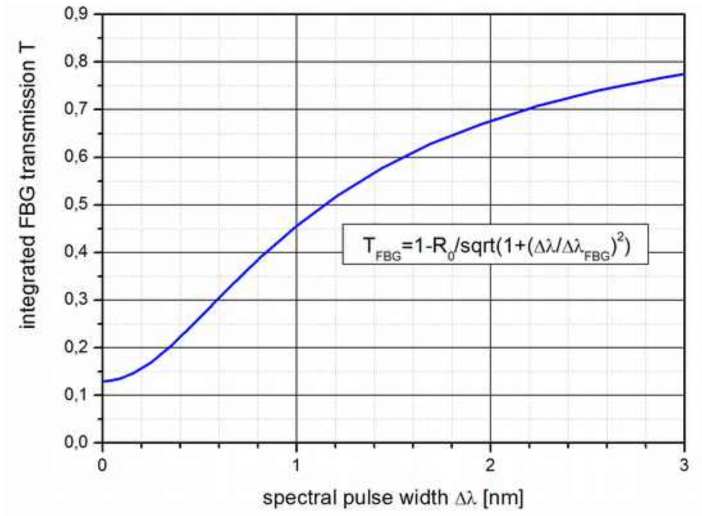
$$I(\lambda)=I_0\cdot e^{-\frac{4\cdot\ln 2\cdot(\lambda-\lambda_0)^2}{\Delta\lambda^2}} \qquad (4.4.2)$$

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

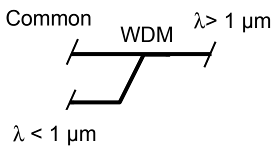
$$T(\Delta\lambda)=\frac{\int_0^\infty I(\lambda)\cdot(1-R(\lambda))\cdot d\lambda}{\int_0^\infty I(\lambda)\cdot d\lambda}=1-\frac{R_0}{\sqrt{1+\left(\frac{\Delta\lambda}{\Delta\lambda_{FBG}}\right)^2}} \qquad (4.4.3)$$

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.

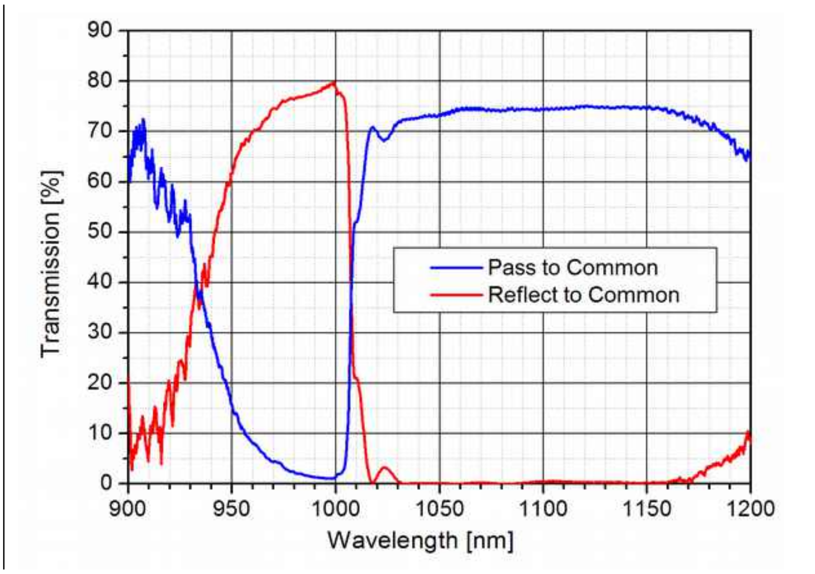
The “Reflect” fiber is marked with a black line.

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

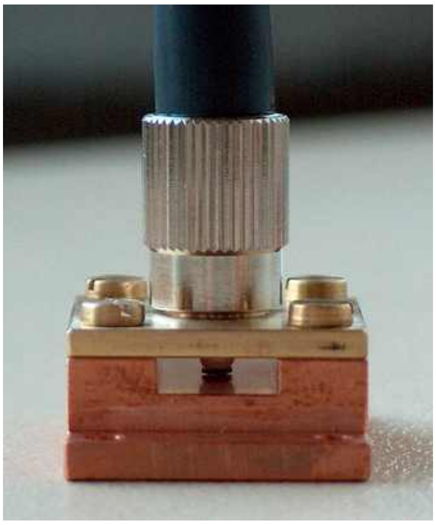
Measured spectral transmittance of the wavelength division multiplexer PMFWDM-1x2-T1030/R980



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 baseplate. Do not overtighten the connector, this may damage the chip!

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

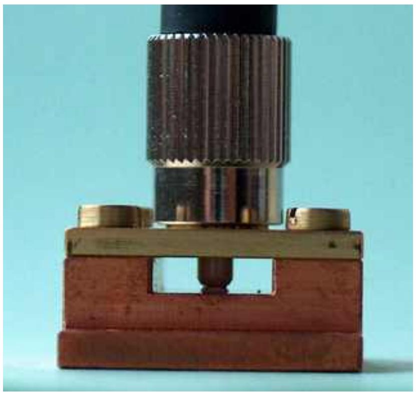


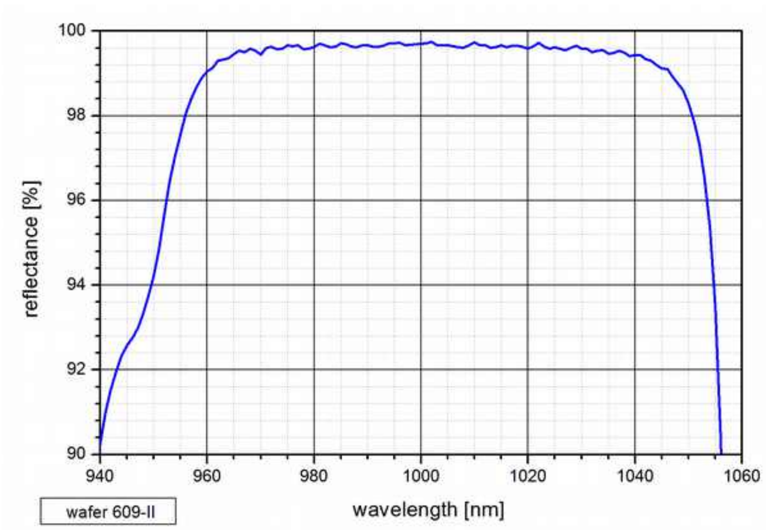
Figure 4.6.5: the SAM chip is in contact with the baseplate, stop tighten the coupling ring

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.

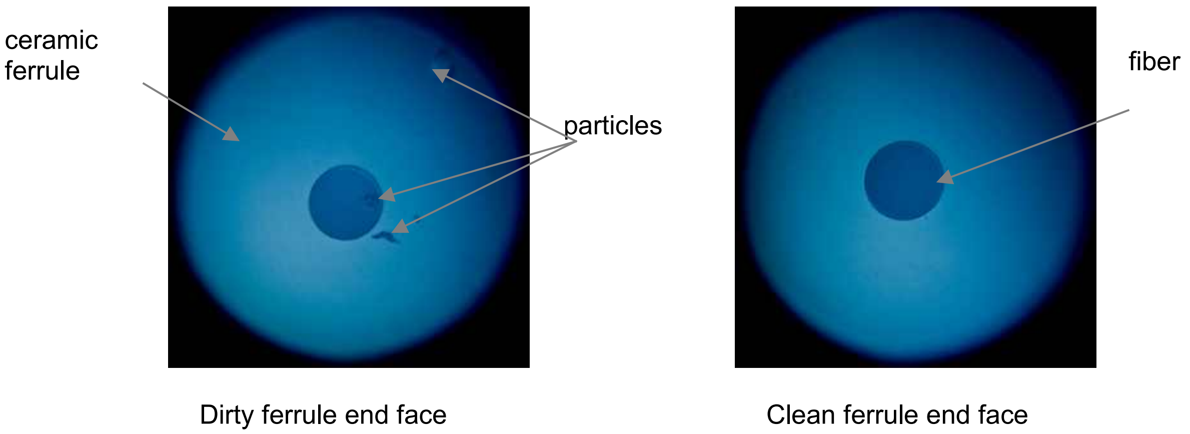


Figure 5.1.1: Microscope images of a dirty (left) and a clean (rifgt) fiber end

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 980 nm pump laser diode LD-980-100. Optional the laser emission wavelength can be measured.

Needed parts from PSFL130 evaluation kit:

LDC	LD980	1 m

Additional equipment needed:

PM	Optional OSA

Schematic

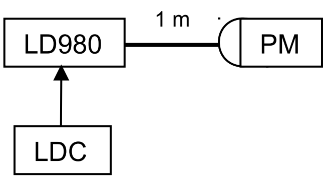


Figure 5.2.1

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 laser diode controller (LDC) and Increase step by step the drive current of the 980 nm laser diode above the threshold current of ~ 20 mA.

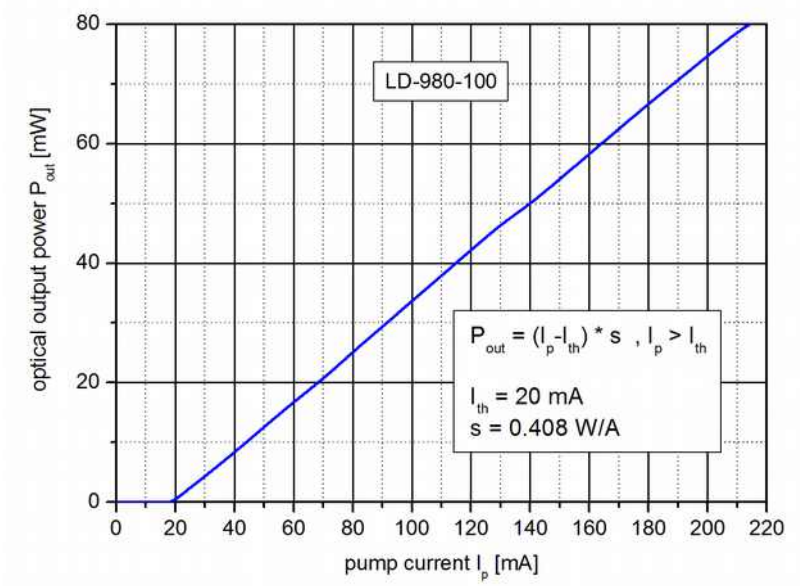
The laser threshold and the differential laser efficiency can be deduced from the measured laser output power as a function of the pump power.

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·s²

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

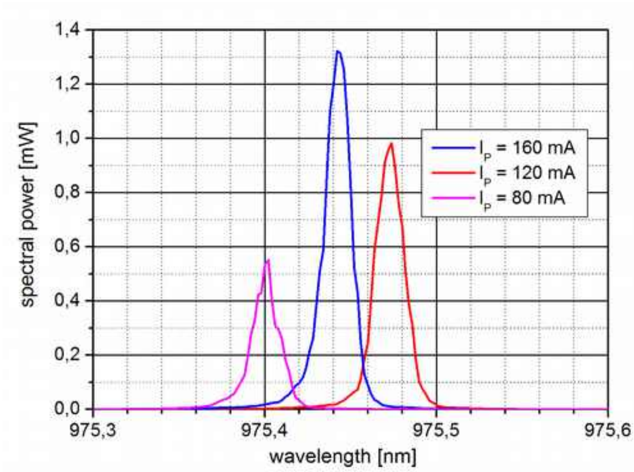
ν = c/λ - laser frequency ~ $3 \cdot 10^{14}$ Hz

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 Yb	C WDM λ > 1 µm λ < 1 µm	LD980	LDC	2 x Mating Sleeve

Additional equipment needed

PM	***Optional:*** OSA

Schematic

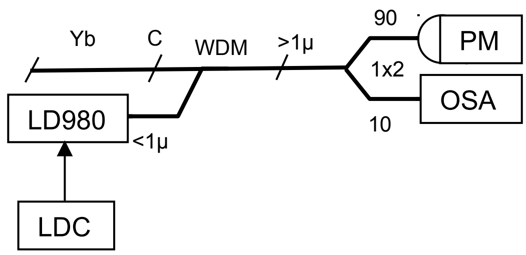
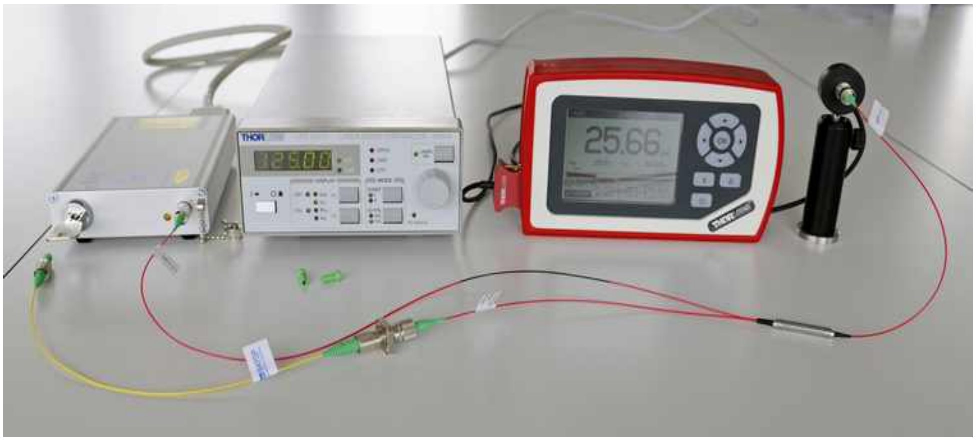


Figure 5.3.1

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 5.6 to

$P_P = s*(I_P - I_{th})$ 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.

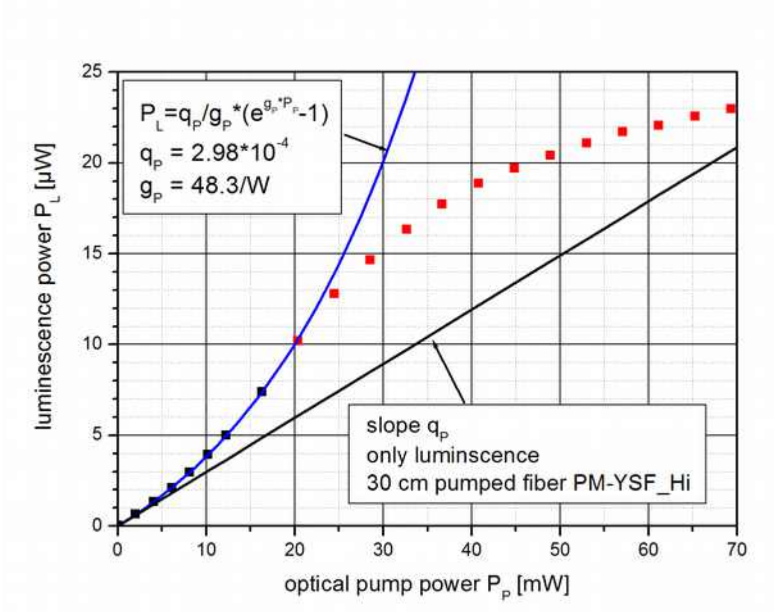


Fig. 5.3.3

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

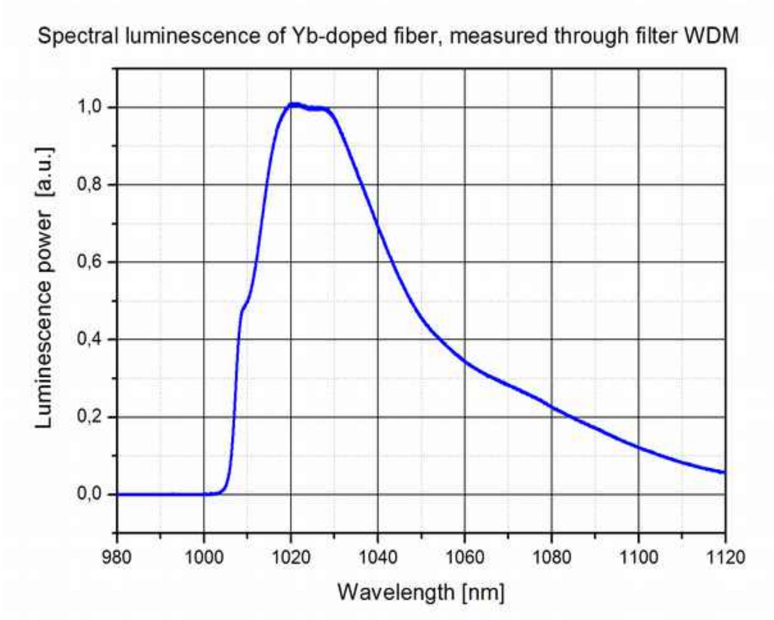
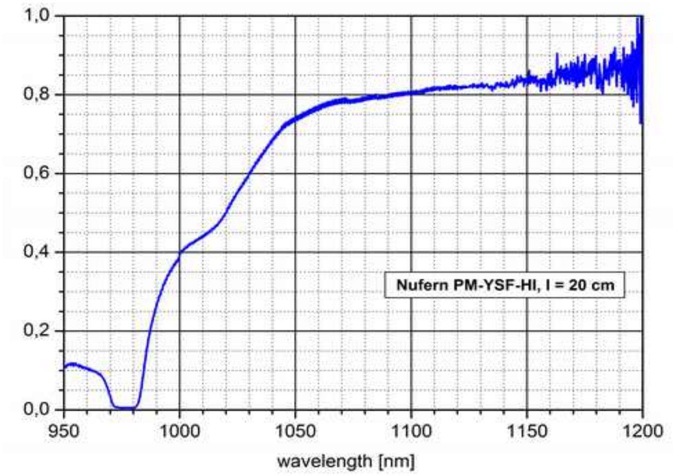


Fig. 5.3.4

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 if 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:

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

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_L with a factor c and can be written as $L = c \cdot P_P$. Using this relation the above equation can be rewritten to

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

with

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

From the measurement in figure 5.4.2 above 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·sinα. 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

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

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.

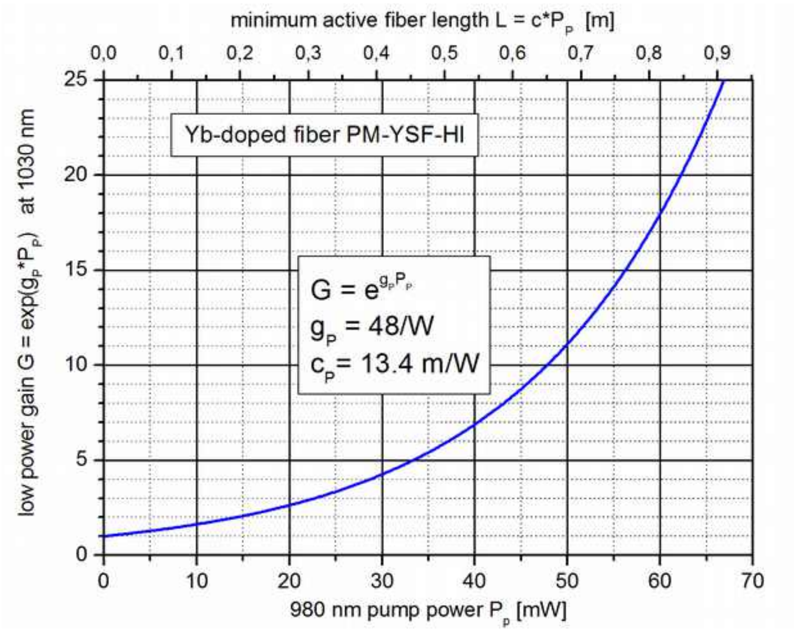
The gain coefficient of the pumped fiber is then $g=g_P/c_P$= 3.5/m = 0.035/cm. With this value the gain of the pumped fiber can be calculated by

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

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

Fig. 5.3.4

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



Spectral transmission

In figure 5.3.4 can be seen, that the absorption of the Yb-doped fiber decreases with increasing wavelengths in the spectral region above 980 nm. This means, that a 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.

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:

M	Yb	FBG	C WDM $\lambda > 1$ µm, $\lambda < 1$ µm	LD980
3 x Mating Sleeve	LDC			

Additional equipment needed:

PM	Optional : OSA

Schematic

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

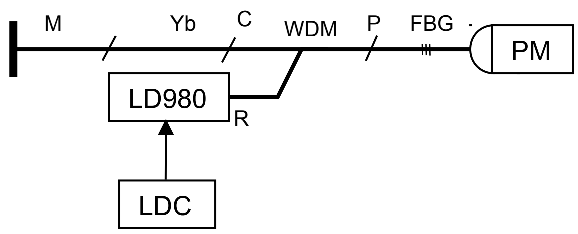
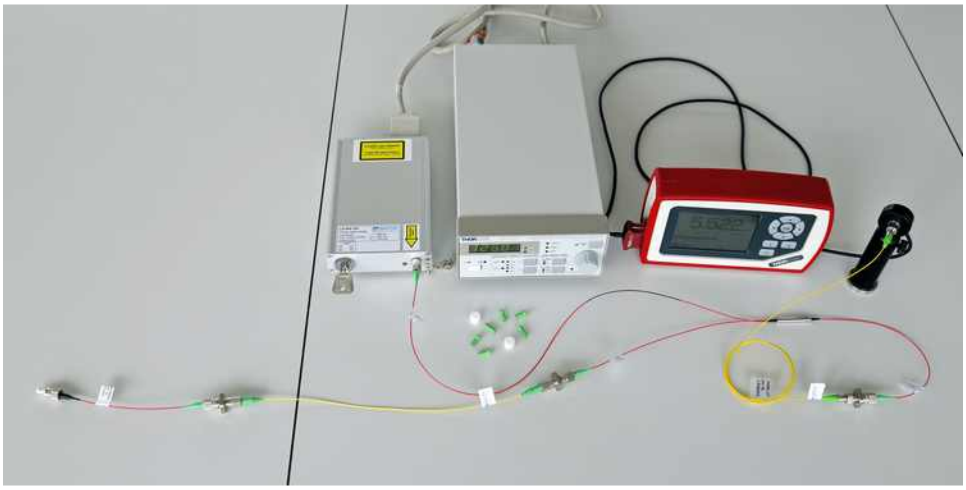


Figure 5.4.1

Photo of the continuous wave laser setup



Measurement:

Switch on the laser diode controller (LDC) and Increase step by step the drive current of the 980 nm laser diode (LD980) 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.

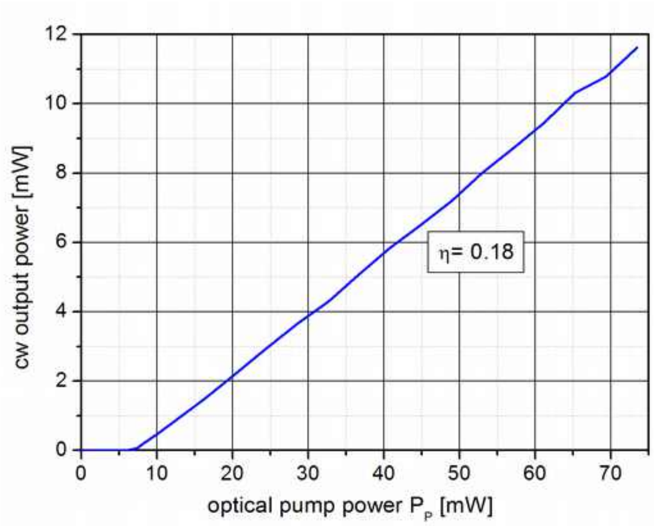
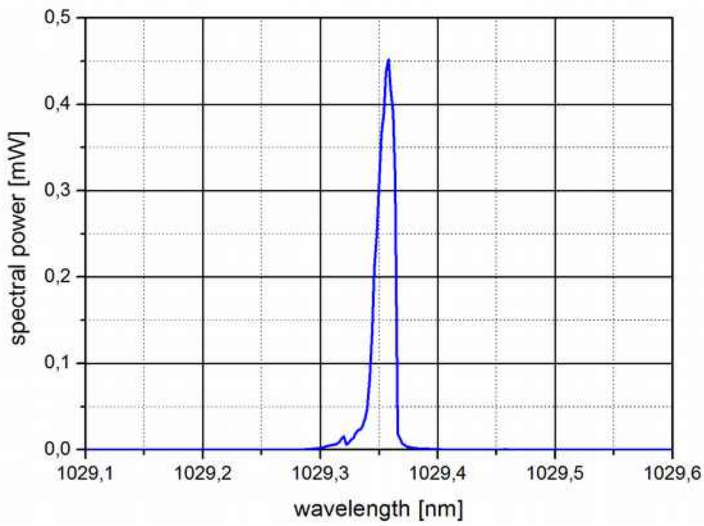


Figure 5.4.3

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 λ > 1 µm λ < 1 µm	LD980
1x2 90 10	Optional 1 m	PHS	5 x Mating Sleeve	LDC

Additional equipment needed:

PD	PM	Optional: OSA	M	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.

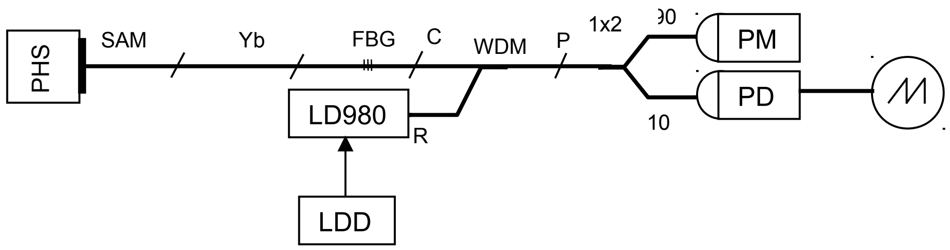
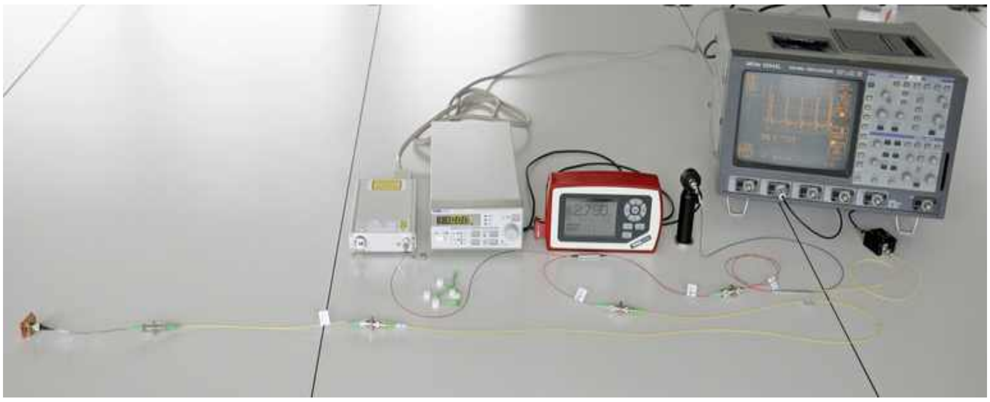


Figure 5.5.1:

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 laser diode controller (LDC) and Increase step by step the drive current of the 980 nm laser diode (LD980) 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 √2.

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

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

with Δν - spectral pulse width in the frequency range

Δλ - 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. The two curves are for different orientation of the FBG in the laser cavity.

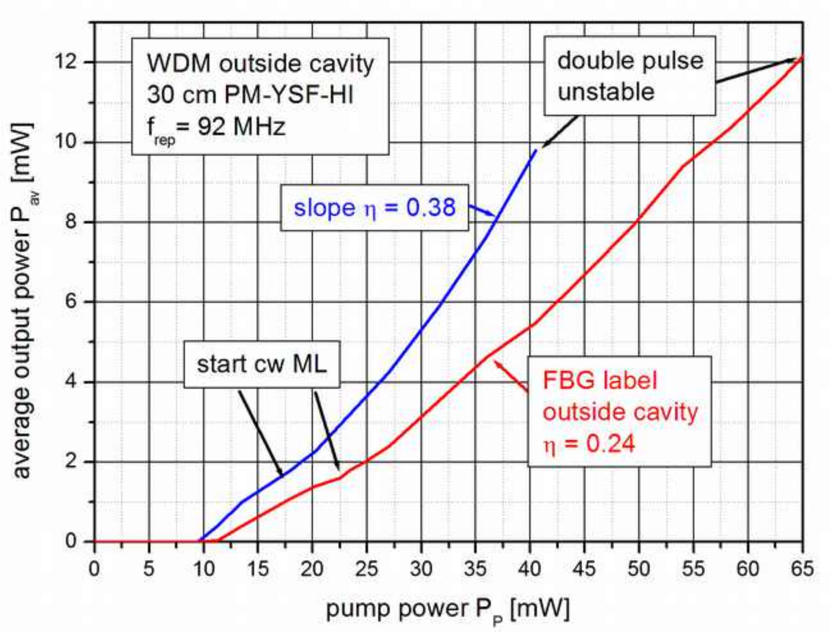


Figure 5.5.3

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.

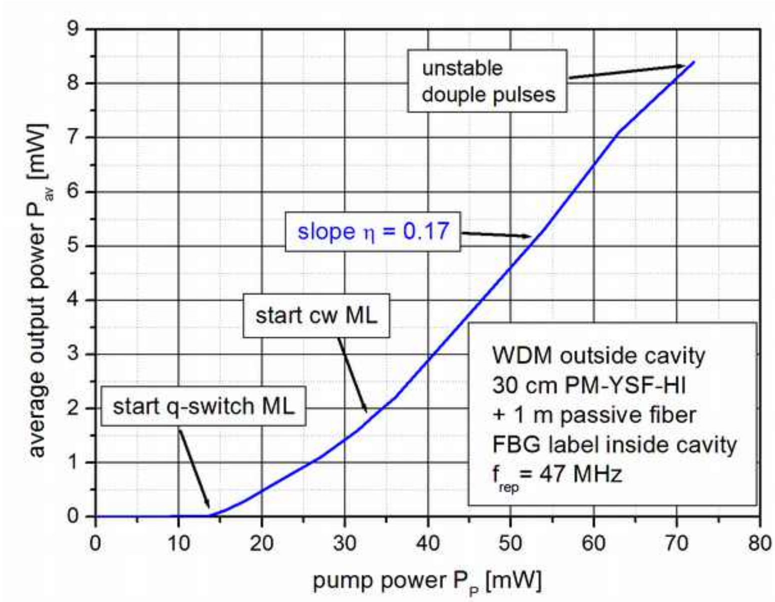


Figure 5.5.4

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.

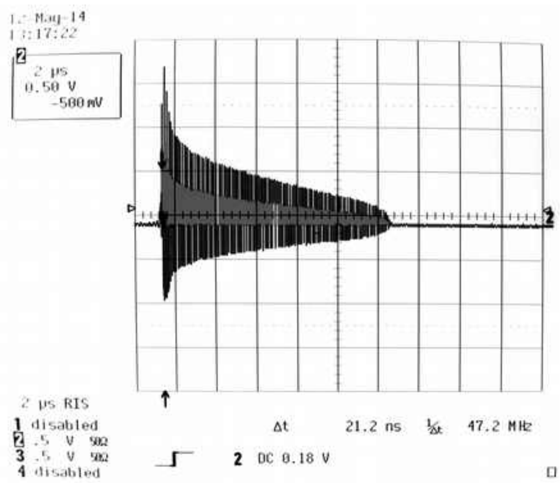


Figure 5.5.5

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

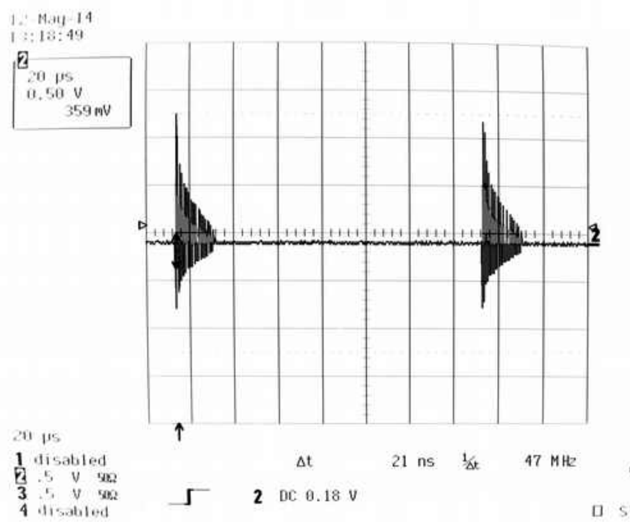


Figure 5.5.6

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

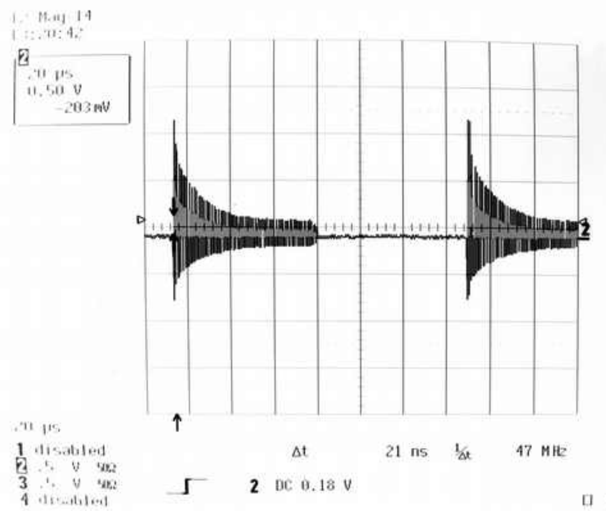


Figure 5.5.7

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

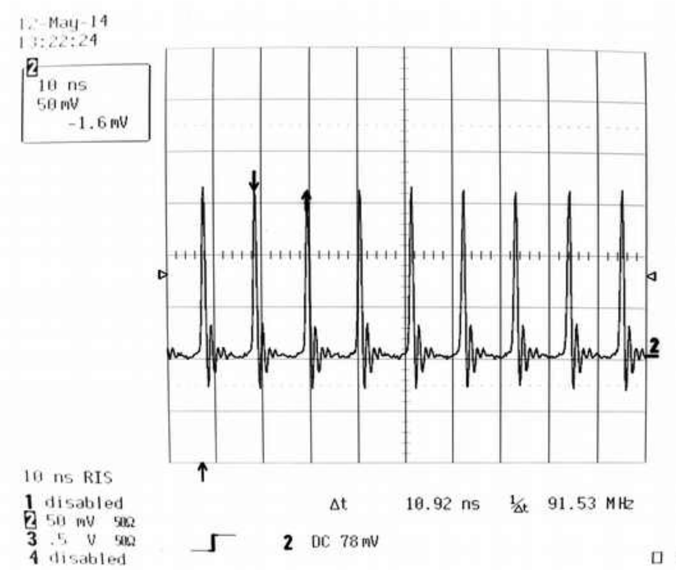


Figure 5.5.8

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.

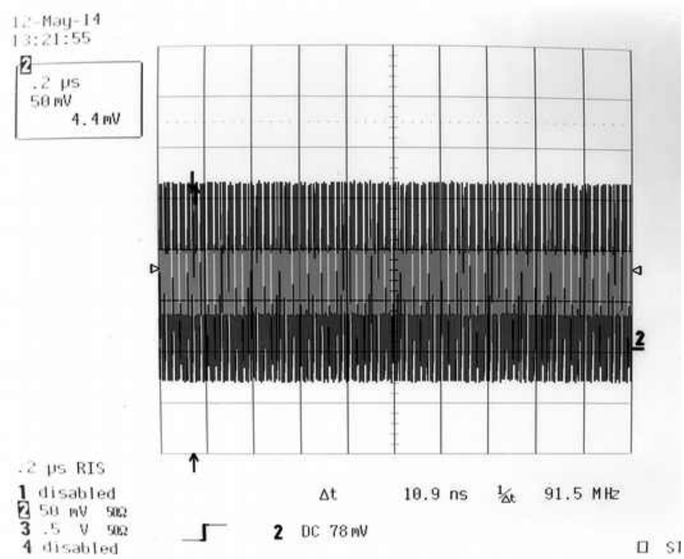


Figure 5.5.9

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

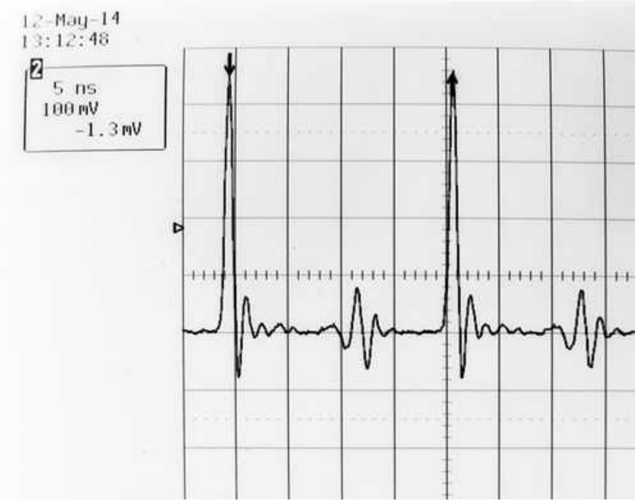


Figure 5.5.10

Spectral laser emission, measured with an OSA at different pump power levels P_P. The label of the FBG is outside the cavity.

The pulse is positive chirped. The long wavelength leading edge of the pulse is attenuated by the absorption in the SAM.

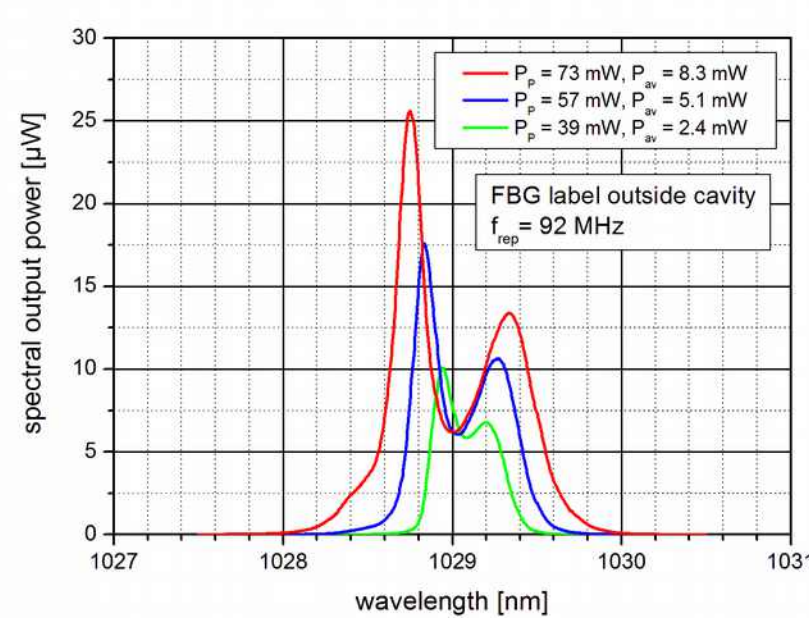


Figure 5.5.11

Spectral laser emission, measured with an OSA at different pump power levels P_P. The label of the FBG is inside the cavity.

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

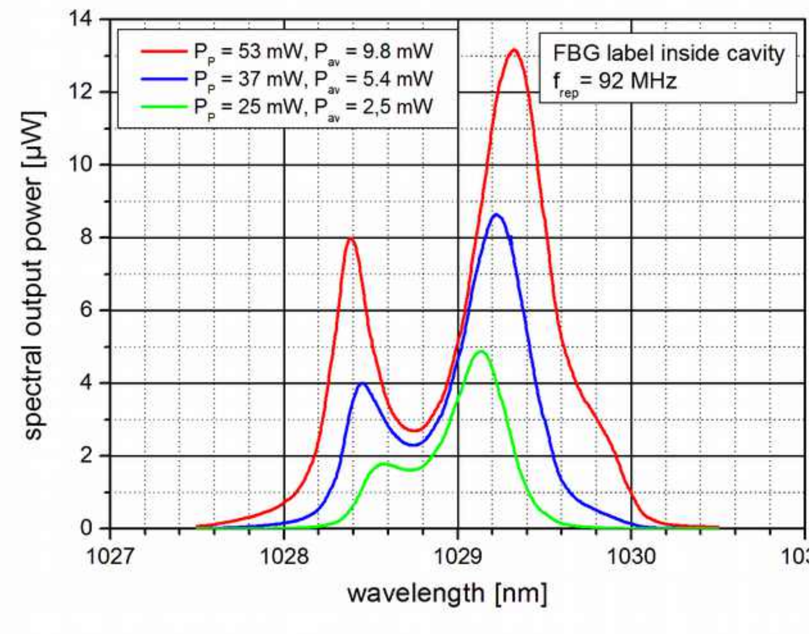


Figure 5.5.12

Spectral laser emission, measured with an OSA at different pump power levels P_P. The label of the FBG is inside the cavity.
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.

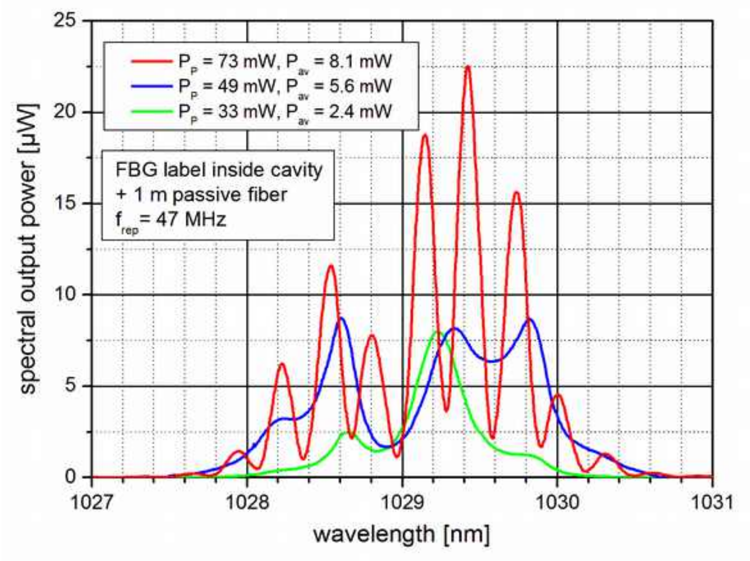
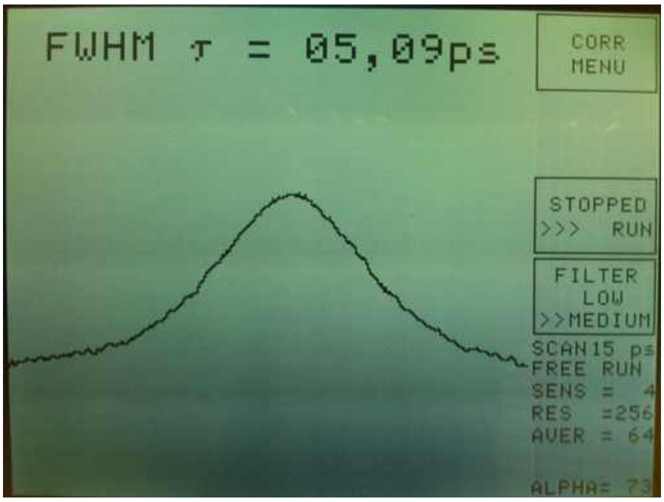


Figure 5.5.13

Pulse duration measurement using an autocorrelator. The mark “N” of the FBG is outside the cavity and the pump power is xxx mW.
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
- Both, the average output power P_{av} and the pulse duration t_P depend on the FBG direction in the cavity.
- If the FBG is inserted with end “N” in the cavity, then the slope efficiency is higher and the output power increases nonlinear with increasing pump power and no saturation effect can be seen.
- 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.

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:

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

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 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.

With increasing pulse amplitude the SAM saturation will be limited because of the roll-over of the saturation curve (see figure 4.3.4) and also the decrease of the excited states in the pumped active fiber due to stimulated emission increases. Therefore the available fiber gain decreases. These effects result in decreasing pulse amplitude and the pulse vanishes after some round trips. From this discussion the maximum pulse fluence in the vicinity of the SAM roll-over fluence in the q-switch ML regime can be expected. This is for the used SAM-1030-32-1ps about F_{max} = 20 J/m^2 (see figure 4.3.4).

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.

Conclusions

- Q-switch mode-locking starts, if the gain compensates the losses in the cavity according to the amplitude condition for an oscillator.
- Because of decreasing loss in the SAM with increasing pulse fluence the pulse amplitude increases during a few round trips very fast before the fiber gain is substantial decreased. The reason for this behavior is, that the saturation fluence of the SAM is substantially lower then that of the active fiber. Therefore high pulse amplitude is possible for a few cycles. Then the fiber gain decreases because the pump power is too low to compensate the loss of gain due to stimulated emission in the active fiber. With decreasing pulse fluence increases the absorption loss in the SAM 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.
- The average output power in the q-switch ML regime is proportional to the pump power as in the cw ML region.

Continuous wave mode-locking (cw ML)

After further increase of pump power to a certain threshold q-switching changes into stable cw mode-locking with regular pulses and a fixed repetition rate f_{rep}. This is a result of the following processes:

- SAM saturation
- Gain limitation due to stimulated emission
- Nonlinear transmission loss in the FBG.

The SAM with its nonlinear response to pulse fluence F serves for locking of all modes in the laser, so that only one pulse is supported in the laser cavity. The pulse travels around the laser cavity with a speed c/n. The repetition frequency f_{rep} can be determined from the measured pulse period T_P on the oscilloscope. Because the pulse period is equal to a full round-trip time in the laser cavity with the length L_C the repetition frequency f_{rep} can be calculated using the relation

$$f_{rep}=\frac{1}{T}=\frac{c}{n\cdot 2\cdot L_C} \qquad (5.5.4)$$

with $c \sim 3\cdot 10^8$ m/s speed of light in the vacuum
$n \sim 1.46$ refractive index of the fiber core
L_C cavity length

Equation (5.5.4) is equivalent to the phase condition of a continuous wave laser. With a cavity length $L_C \sim 1$ m a repetition rate $f_{rep} \sim 100$ MHz and a pulse period $T_P \sim 10$ ns can be expected.

To understand what happens in the cw ML regime, the laser amplitude condition over a full pulse round trip must be considered. As in equation (5.5.2) the gain in the active fiber must be equal to the loss in the laser cavity

$$G \cdot (1 - T) \cdot R \cdot (1 - c_L) = 1 \qquad (\textbf{\textit{first cw ML condition}}) \qquad (5.5.5)$$

Here G is the round trip gain in the active fiber, T the transmittance of the output coupler and R the SAM reflectance. This means, that the cavity losses can be compensated by the fiber gain. This is the well known laser amplitude condition, which holds for any oscillator.

But because of the nonlinear response of the SAM reflectance R(F) and the fiber gain G(F) on a change of the pulse fluence F an additional, second condition must be fulfilled. For a round trip of a pulse in the laser cavity the amplitude change must be zero:

$$\frac{d}{dF}\left(G\cdot(1-T)\cdot R\cdot(1-c_L)\right)=0 \qquad (\textbf{\textit{second cw ML condition}}) \qquad (5.5.6)$$

The dependency R(F) is described with equation (4.3.8) above. The gain G of the active fiber can be written as

$$G=e^{g\cdot L}=e^{g\cdot c_P\cdot(P_P-P_{av}/\eta)}=e^{g\cdot c_P\cdot(P_P-T_{FBG}\cdot F\cdot f_{rep}\cdot\pi\cdot r^2/\eta)} \qquad (5.5.7)$$

with $L = c_P\cdot P_P$ and T_{FBG} according to equations (5.3.2) and (4.4.3) respectively.

The low signal gain coefficient g of the active fiber can be deduced from measured amplified luminescence light to g = 3.5/m (see chapter 5.3.). From the same experiment also the ratio of pumped fiber length L to the corresponding pump power P_P is calculated to $c_P = L/P_P = 13.6$ m/W.

Whereas the fiber gain reacts on increasing pulse fluence with decreasing gain dG/dF < 0, the reflection loss of the SAM reacts on a pulse fluence change dF with a variable loss dR/dF > 0, which depends on the actual pulse fluence. A stable cw ML lasing is only possible, if the negative change of the active fiber gain with increasing pulse fluence is compensated by the positive change of the SAM.

Q-switch mode-locking starts, if dR/dF > - dG/dF.

To evaluate the condition (5.5.6) in a first step, we do not consider a possible dependency of T and c_L on the pulse fluence. This means, we assume dT/dF = 0 and $d(c_L)/dF = 0$. In this case from (5.5.6) we can deduce

$$\frac{1}{R}\cdot\frac{dR}{dF}=-\frac{1}{G}\cdot\frac{dG}{dF} \qquad (5.5.8)$$

Using R(F) according to equation (4.3.8) and considering the fact, that the SAM reflectance is $1-A_0$ at F = 0, then we can write

$$\frac{1}{R}\cdot\frac{dR}{dF}=\frac{1}{1-A_0}\cdot\frac{\Delta R}{F}=\frac{1}{F}\cdot\left(\frac{R(F)}{1-A_0}-1\right) \qquad (5.5.9)$$

With (5.5.7) we get

$$\frac{1}{G}\cdot\frac{dG}{dF}=-\frac{g\cdot c_P\cdot T_{FBG}\cdot f_{rep}\cdot\pi\cdot r^2}{\eta} \qquad (5.5.10)$$

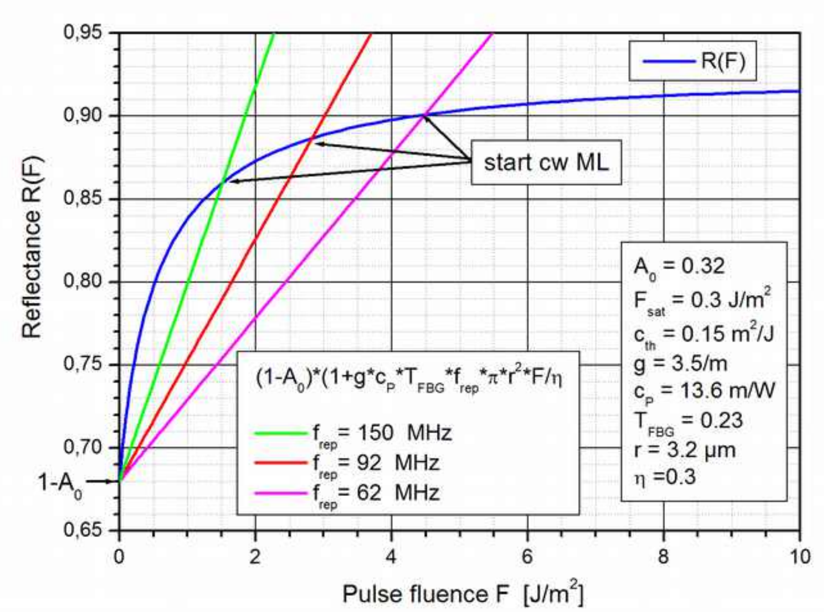
With these findings we can write the second condition for cw ML in a first approximation as

$$R(F)=(1-A_0)\cdot\left(1+\frac{g\cdot c_P\cdot T_{FBG}\cdot f_{rep}\cdot\pi\cdot r^2\cdot F}{\eta}\right) \qquad (5.5.11)$$

The solution of this condition is the minimum pulse fluence for stable mode-locking. A graphical solution is shown in figure (5.5.6).

Figure 5.5.13

Graph of the second mode-locking condition (5.5.11). The intersection points define the minimum pulse fluence F for stable continuous wave mode-locking.



If the minimum pulse fluence F is known, then the corresponding average output power P_{av} can be calculated using the following relation:

$$P_{av}=T_{FBG}\cdot F\cdot f_{rep}\cdot\pi\cdot r^2 \qquad \text{with} \quad r - \text{mode field radius in the fiber} \qquad (5.5.12)$$

Here T_{FBG} is the transmittance of the output coupler.

Conclusions

- For stable mode-locking besides the well known amplitude condition for a round trip of a pulse an additional second condition must be fulfilled. This second condition contains the demand, that the loss of gain in the active fiber due to stimulated emission is not smaller then the decrease of the loss in the saturable absorber mirror due to its saturation. In a laser cavity without a SAM this second stability condition is automatically fulfilled because a decreasing cavity loss with increasing pulse fluence does not exist.
- With increasing cavity length L_C and decreasing repetition rate f_{rep} the minimum pulse fluence for cw ML increases. This results in a smaller range for stable mode-locking.
- A lower slope efficiency η decreases the minimum pulse fluence for cw ML according to equation (5.5.11)

Spectral pulse broadening and FBG transmittance

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

$$\Delta\lambda_0 = \frac{0.44 \cdot \lambda_0^2}{c \cdot t_P} \qquad (5.5.13)$$

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 $n_2 = 2.6 \cdot 10^{-20}$ m²/W and the cavity length L_C. This additional spectral bandwidth $\Delta\lambda_{SPM}$ can be estimated to

$$\Delta\lambda_{SPM} = \frac{2 \cdot L_C \cdot n_2 \cdot \lambda_0 \cdot F}{c \cdot t_P^2} \qquad (5.5.14)$$

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

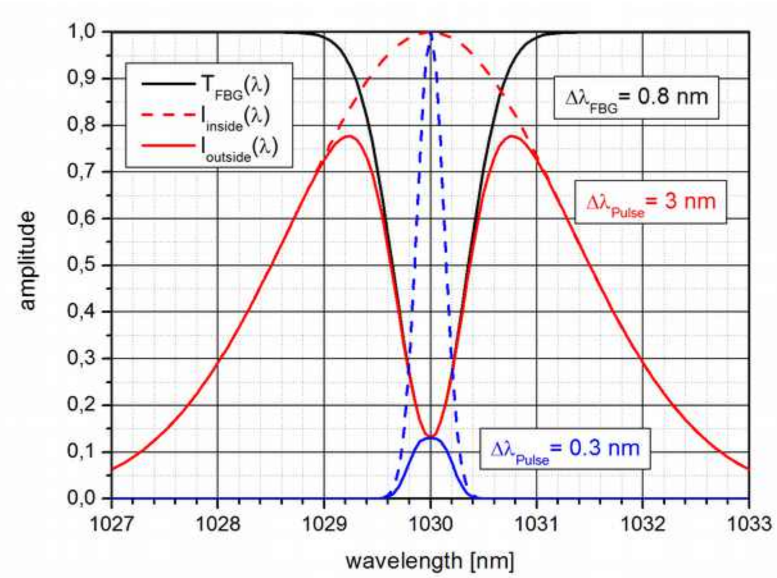
For the total fluence dependent spectral pulse width $\Delta\lambda$ we can write

$$\Delta\lambda = \sqrt{\Delta\lambda_0^2 + \Delta\lambda_{SPM}^2} \qquad (5.5.15)$$

The spectral pulse shape outside the laser cavity after the transmission through the FBG is changed depending on the pulse fluence and the corresponding pulse spectral width $\Delta\lambda$. If the pulse width $\Delta\lambda$ is larger then the spectral width $\Delta\lambda_{FBG}$ of the FBG, then the spectral intensity distribution changes to a two peak curve. This is shown for two different spectral pulse widths in figure (5.5.14).

Figure 5.5.14

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 pulses.



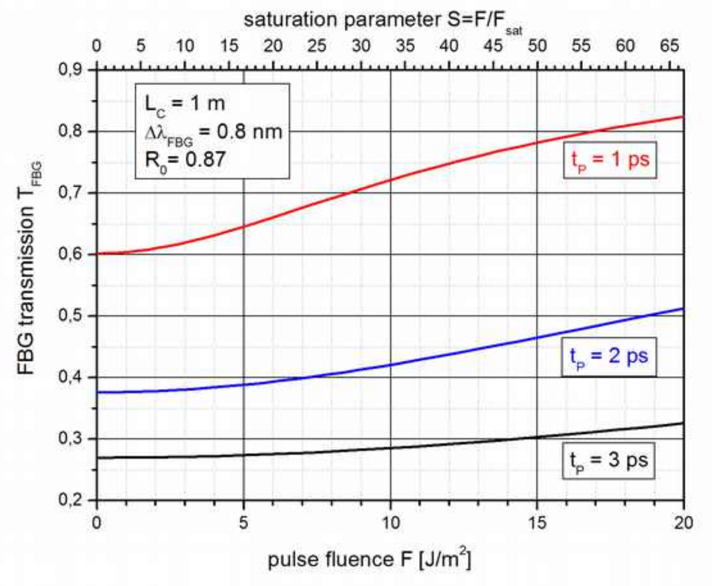
According to equation (4.4.3) the FBG transmittance is not a fixed value, but increases with increasing spectral pulse width $\Delta\lambda$. The fluence dependent spectral integrated transmittance of the FBG can be calculated using equation (4.4.3) to

$$T_{FBG}(F) = 1 - \frac{R_0}{\sqrt{1 + \frac{\Delta\lambda_0^2 + \Delta\lambda_{SPM}^2}{\Delta\lambda_{FBG}^2}}} = 1 - \frac{R_0}{\sqrt{1 + \left(\frac{0.44 \cdot \lambda_0^2}{c \cdot t_P \cdot \Delta\lambda_{FBG}}\right)^2 + \left(\frac{2 \cdot L_C \cdot n_2 \cdot \lambda_0 \cdot F}{c \cdot t_P^2 \cdot \Delta\lambda_{FBG}}\right)^2}} \qquad (5.5.16)$$

The calculated FBG transmission and the connection between the measured average pulse power P_{av} outside the cavity with pulse fluence F inside the laser according to equations (5.5.14) and (5.5.16) are shown in figures 5.5.8 and 5.5.9, respectively

Fig. 5.5.15

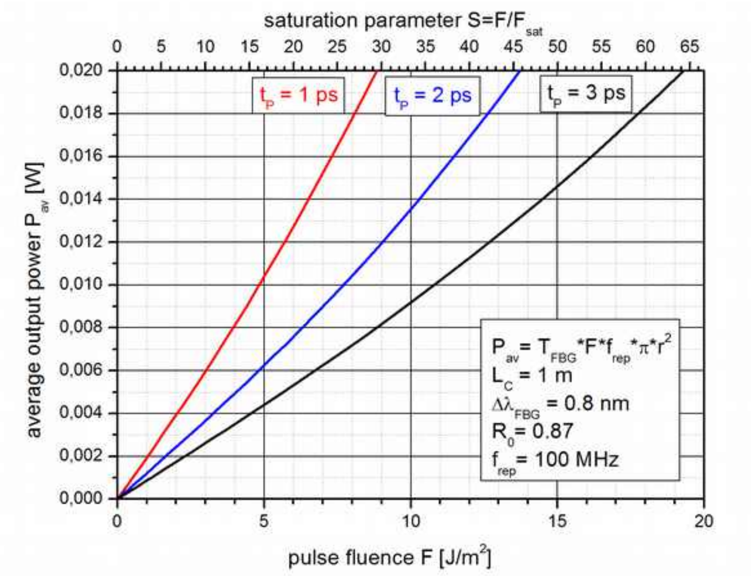
FBG transmission calculated using equation (5.5.16) for three different pulse durations t_P. The spetral width of the FBG is assumed as $\Delta\lambda_{FBG}$ = 0.8 nm.



It can be seen in this graph that for reasonable pulse fluences up to 20 J/m² the nonlinear self phase modulation has only a remarkable effect for short pulses on the FBG transmission.

Fig. 5.5.16

Relation between pulse fluence F inside the laser cavity and the average output power calculated using equation (5.5.12) and (5.5.16) for three different pulse durations t_P.



Conclusions:

- With increasing pulse fluence F and decreasing pulse duration t_P the spectral width $\Delta\lambda$ of the pulse increases as a result of self phase modulation in the fiber core.
- With increasing $\Delta\lambda$ increases the transmission T_{FBG} through the fiber Bragg grating.
- A Gaussian pulse with a larger bandwidth then the spectral width of the FBG inside the laser cavity will be deformed after transmission through the FBG.

Influence of the FBG transmission on the second cw ML condition

Equation (5.5.14) above contains the dependency of the FBG transmission T_{FBG} on the pulse fluence. We consider now the influence of this dependency on the second cw ML condition (5.5.6). In case of $dT/dF \neq 0$ the condition (5.5.6) can be rewritten as

$$\frac{1}{R}\cdot\frac{dR}{dF}=\frac{1}{1-T_{FBG}}\cdot\frac{dT_{FBG}}{dF}-\frac{1}{G}\cdot\frac{dG}{dF} \qquad (5.5.17)$$

With (5.5.16) we can calculate

$$\frac{1}{1-T_{FBG}}\cdot\frac{dT_{FBG}}{dF}=\frac{\left(\frac{L_C\cdot n_2\cdot\lambda_0}{c\cdot t_P^2\cdot\Delta\lambda_{FBG}}\right)^2\cdot F}{1+\left(\frac{0.44\cdot\lambda_0^2}{c\cdot t_P\cdot\Delta\lambda_{FBG}}\right)^2+\left(\frac{2\cdot L_C\cdot n_2\cdot\lambda_0\cdot F}{c\cdot t_P^2\cdot\Delta\lambda_{FBG}}\right)^2} \qquad (5.5.18)$$

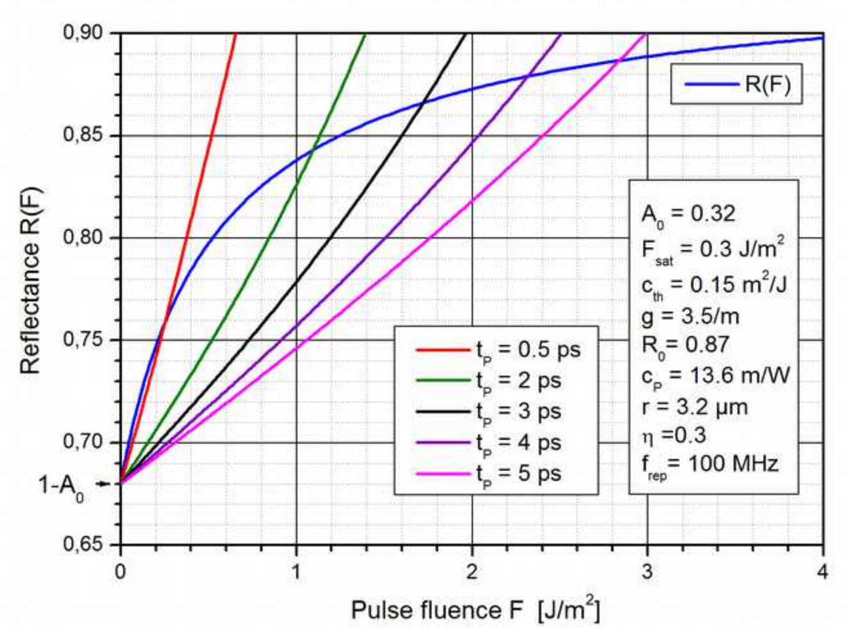
Using equations (5.5.9), (5.5.10) and (5.5.18) we get instead of equation (5.5.11) the following condition for the onset of cw ML:

$$R(F)=(1-A_0)\cdot\left(1+\frac{g\cdot c_P\cdot T_{FBG}(F)\cdot f_{rep}\cdot\pi\cdot r^2\cdot F}{\eta}+\frac{\left(\frac{2\cdot L_C\cdot n_2\cdot\lambda_0}{c\cdot t_P^2\cdot\Delta\lambda_{FBG}}\right)^2\cdot F}{1+\left(\frac{0.44\cdot\lambda_0^2}{c\cdot t_P\cdot\Delta\lambda_{FBG}}\right)^2+\left(\frac{2\cdot L_C\cdot n_2\cdot\lambda_0\cdot F}{c\cdot t_P^2\cdot\Delta\lambda_{FBG}}\right)^2}\right)$$

(5.5.19)

Figure 5.5.17

Second cw ML condition (5.5.6) including the fluence dependent transmittance $T_{FBG}(F)$ of the FBG after equation (5.5.19). The intersection points define the minimum pulse fluence F for stable continuous wave mode-locking



Conclusions

- It can be seen in figure 5.5.17, that the FBG supports stable mode-locking at low pulse fluencies F, especially in case of short pulses with corresponding large spectral pulse width $\Delta\lambda$.
- The most important influence of the FBG on mode-locking is the simple fact, that it fixes the lasing wavelength. Without the FBG the lasing wavelength would be shifted to a value, where the first lasing condition is fulfilled at the lowest gain. But at this wavelength the SAM saturation curve R(F) would be not optimal for cw ML because of lower value of the parameter A_0 and a larger value of the parameter γ.

Pulse duration and spectral width

The influence of the FBG direction on the laser behavior is visible in the experiments. To understand the laser behavior the following effects must be considered:

- Pulse shortening by the SAM
- Pulse prolongation in the fiber as a result of fiber dispersion and non-zero spectral pulse width

- Spectral pulse broadening by self-phase modulation in the fiber
- Chirp of the fiber Bragg grating.

Pulse shortening by SAM reflection

If the optical pulse hits the SAM, then the photons of the leading edge of the pulse are absorbed to saturate the absorber material. Therefore the front side of the pulse is truncated and the pulse shortened.

The time dependent density n(t) of the excited electrons in the absorber material can be calculated using the rate equation for the excited electrons with their density n:

$$\frac{dn(t)}{dt}=\frac{A\cdot I(t)}{h\cdot\nu\cdot d}-\frac{n(t)}{\tau} \quad \text{with} \quad I(t)=I_0\cdot e^{-\frac{4\cdot\ln(2)\cdot t^2}{t_P^2}} \tag{5.5.20}$$

The excited electron density increase per time dn/dt is proportional to the absorption A and the pulse intensity I(t). The product $h\cdot\nu=h\cdot c/\lambda_0$ is the photon energy and d the thickness of the absorber layer. The Gaussian pulse I(t) has a pulse duration t_P.

The differential equation (5.5.20) can be solved under the assumption, that the absorption A is constant. In this case the solution is

$$n(t)=\frac{A\cdot I_0\cdot t_P\cdot\sqrt{\pi}}{h\cdot\nu\cdot d\cdot 4\cdot\sqrt{\ln 2}}\cdot e^{\frac{t_P^2}{16\cdot\ln 2\cdot\tau^2}}\cdot e^{-\frac{t}{\tau}}\text{¿}\left(1-erf\frac{t_P^2-8\cdot\ln 2\cdot t\cdot\tau}{4\cdot\sqrt{\ln 2}\cdot\tau\cdot t_P}\right) \tag{5.5.21}$$

The relation between the pulse fluence F and the maximum intensity I_0 is

$$F=\int_{-\infty}^{\infty} I(t)\cdot dt=\frac{I_0\cdot t_P\cdot\sqrt{\pi}}{2\cdot\sqrt{\ln 2}} \tag{5.5.22}$$

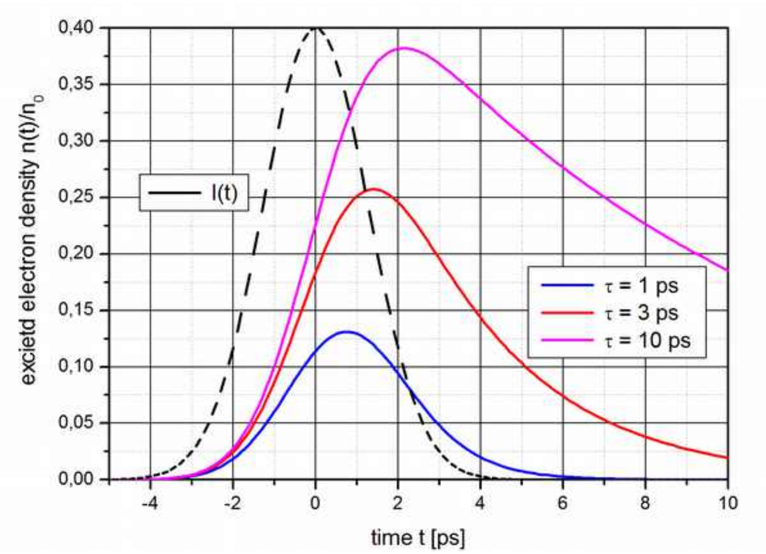
In figure 5.5.11 the time dependent density n(t) of the excited electrons is shown according to equation (5.5.21) with A = 0.5 for 1030 nm photons. The density n(t) is normalized to the value n_0

$$n_0=\frac{F}{h\cdot\nu\cdot d} \tag{5.5.23}$$

For a pulse fluence F = 1 J/m^2, an absorber thickness d = 150 nm and wavelength λ = 1030 nm we get $n_0 = 3.5\cdot10^{25}/m^3$.

Figure 5.5.18

Time dependent density n(t) of the excited electrons in the absorber for a pulse duration of t_P = 3 ps and three different absorber relaxation times τ according to equation (5.5. 21). The pulse intensity I(t) is shown as dashed line.



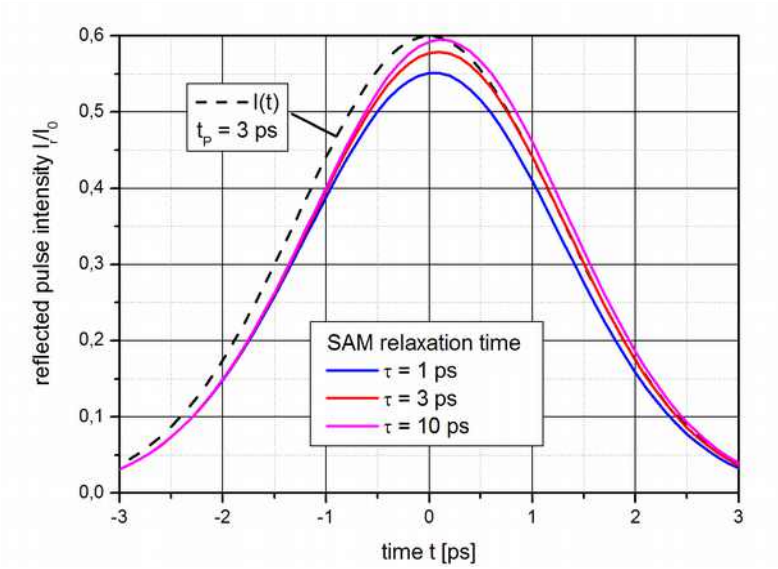
In a saturable absorber the excited electrons cause the saturation effect. The time dependence of the reflected pulse $I_r(t)$ on a SAM can be calculated as

$$I_r(t)=I(t)\cdot R=I(t)\cdot\left(1-\frac{A_0}{1+n(t)/n_0}\right) \tag{5.5.24}$$

The reflected pulse intensity $I_r(t)$ calculated with equations (5.5.21), (5.5.23) and (5.5.24) is shown in figure 5.5.19.

Figure 5.5.19

Time dependency of the reflected pulse I_r after equation (5.5.24) for three relaxation times τ of the SAM. The incident pulse I(t) is downscaled by a factor 0.6 to allow an easier comparison with the reflected pulse.



The pulse shortening on the leading edge of the reflected pulse can be seen. It does not depend on the SAM relaxation time. If the relaxation time of the excited electrons in the absorber material is shorter then the pulse duration, then also the rear side of the pulse is absorbed and truncated.

Therefore each reflection of the pulse on the SAM results in pulse shortening, so that a Gaussian pulse is shaped.

Pulse prolongation or shortening in the fiber

A pulse has a finite spectral width $\Delta\nu$ or $\Delta\lambda$. The correlation between the pulse duration and the spectral width for a transform limited Gaussian pulse is given in equation (5.5.13). In a silica fiber with normal dispersion at 1030 nm wavelength the high-frequency components have a lower group velocity then the low-frequency components. An unchirped pulse changes into a positive chirped pulse. The group velocity dispersion (GVD) prolongs therefore the pulse during its traveling through the fiber.

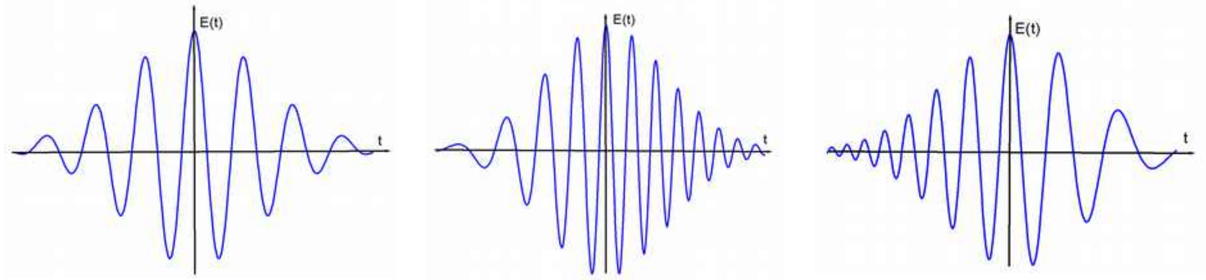
For an unchirped Gaussian pulse with initial duration $t_{P,0}$ the second order group delay dispersion D_2 broadens the pulse duration to the value t_P.

$$t_P=t_{P,0}\cdot\sqrt{1+\left(4\cdot\ln 2\cdot\frac{D_2}{t_{P,0}^2}\right)^2} \tag{5.5.25}$$

At 1030 nm wavelength a standard silica fiber has a second order group delay dispersion D_2 per fiber length of 24 fs^2/mm. This results for a full round trip in a 1 m long cavity to D_2 = 48000 fs^2. The prolongation of a 1 ps pulse per round trip is about 1 %. With increasing pulse duration decreases this effect rapidly and a balance is reached between this pulse prolongation effect and the shortening during the SAM reflection.

If the starting pulse contains already a negative chirp, then it will be shortened on his way along the fiber until it is zero chirped.

In figure 5.5.20 three Gaussian pulses with different chirp are shown. Drawn is the time dependent oscillation of the electric field strength E(t).



Unchirped pulse, GVD = 0 | Positive chirped, GVD > 0 | Negative chirped, GVD < 0

Figure 5.5.20 Spectral components of a Gaussian pulse

Spectral pulse broadening by self-phase modulation in the fiber

As mentioned above with increasing pulse intensity self-phase-modulation adds new frequencies at the wings of the pulse because of the second order refractive index n_2 of the fiber. The resulting spectral pulse broadening can be estimated using equation (5.5.14). An important result of this spectral broadening is the increasing influence of the fiber dispersion with increasing pulse fluence.

Chirp of fiber Bragg grating

The fiber Bragg grating is prepared by illumination of the fiber core with periodic laser intensity along the fiber using fs laser pulses and a phase mask. The result is a periodic variation of the refractive index. A small deviation of the index grating from the periodicity causes a spectral chirp of reflected pulses on the FBG. This chirp can be larger then the material dispersion induced chirp in the fiber and has therefore a significant effect on the resulting chirp in the laser cavity.

The sign of the chirp can be changed by changing the direction of the FBG in the laser cavity. In case of a positive FBG chirp the pulse prolongation due to the fiber dispersion is enhanced by the FBG. In the opposite case the negative FBG chirp can be larger then the positive fiber chirp and a negative chirped pulse travel in the cavity. In this case the pulse duration is shortened and the peak intensity is increased. Therefore the spectral pulse width is increased by self-phase modulation.

The negative chirped pulse shortens outside the laser cavity due to positive fiber dispersion. After a certain fiber length the pulse duration reaches its shortest value, which corresponds to its spectral width according to equation (5.5.13). At this point the pulse is unchirped. After that the pulse prolongs again as a result of the chromatic dispersion in the fiber.

Conclusions

- The SAM shortens the pulse at each reflection.
- The positive fiber dispersion prolongs the pulse.
- Both effects, the pulse shortening by the SAM and the pulse prolongation in the fiber result in an equilibrium pulse width.
- If the FBG is inserted into the laser cavity with a negative chirp, then the pulse is shortened and vice versa.
- A shorter pulse results in higher peak pulse intensity and broader spectral bandwidth.
- Because the different influences on the pulse are distributed over the whole laser cavity there does not exist a fixed pulse duration and spectral width. Instead the pulse changes his parameters during its travel in the laser cavity periodically. A calculation of this complex pulse behavior is not in the scope of this discussion.

Average output power versus pump power

To understand the measured results in figures 5.5.3 and 5.5.4 the average output power P_{av} versus pump power P_P must be calculated. We can use for this calculation the laser amplitude condition (5.5.5) together with equation (5.5.7) for the Gain G.

$$e^{g\cdot c_P\cdot\left(P_P-T_{FBG}\cdot F\cdot f_{rep}\cdot\pi\cdot r^2/\eta\right)}\cdot\left(1-A_0\text{¿}\left(1+c_{th}\text{¿}F\right)\cdot\frac{F_{sat}}{F}\text{¿}\ln\left(1+\frac{F}{F_{sat}}\right)\right)\text{¿}\left(1-T_{FBG}\right)\cdot\left(1-c_L\right)=1 \qquad (5.5.26)$$

This equation can be solved to

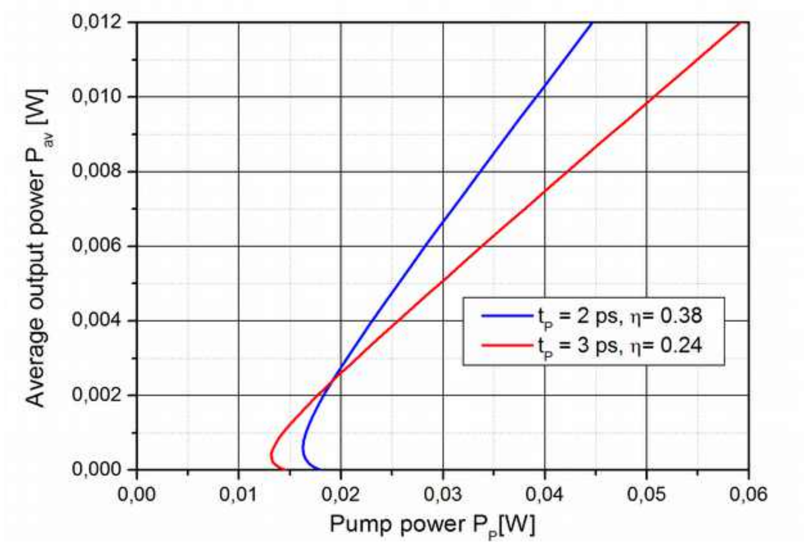
$$P_P(F)=\frac{T_{FBG}\cdot F\cdot f_{rep}\cdot\pi\cdot r^2}{\eta}-\frac{\ln\left(1-A_0\cdot\left(1+c_{th}\cdot F\right)\cdot\frac{F_{sat}}{F}\cdot\ln\left(1+\frac{F}{F_{sat}}\right)\right)+\ln\left(1-T_{FBG}\right)+\ln\left(1-c_L\right)}{g\cdot c_P}$$

(5.5.27)

Also the dependency of the FBG transmission T_{FBG} on the pulse fluence F and the related average output power P_{av} according to equation (5.5.16) must be taken into account. As mentioned above, the connection between dispersion, pulse duration and spectral pulse width is not included in the equation.

Figure 5.5.21

Calculated average output power P_{av} versus pump power P_P using equation (5.5.27) and equation (5.5.12). The parameters are the same as in the previous calculations. The cavity loss c_L is assumed to be zero.



The calculated ambiguity at low pump power is a result of the SAM saturation and the resulting decrease in the cavity loss.

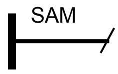
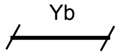
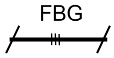
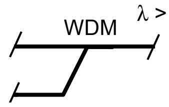
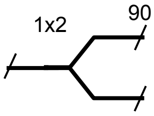
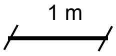
A comparison of the calculated curves in figure 5.5.21 with the measured curves in figure 5.5.3 shows, that the region of q-switching is not described with equation (5.5.2). But this is not surprising because in the q-switch regime the average output power is not a fixed value.

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:

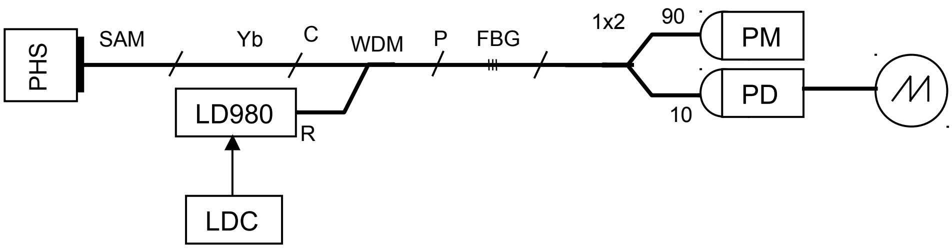
SAM 	Yb 	FBG 	C WDM $\lambda > 1$ µm  $\lambda < 1$ µm	LD980
1x2 90  10	Optional 1 m 	PHS	5 x Mating Sleeve	LDC

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.

Photo of the laser setup

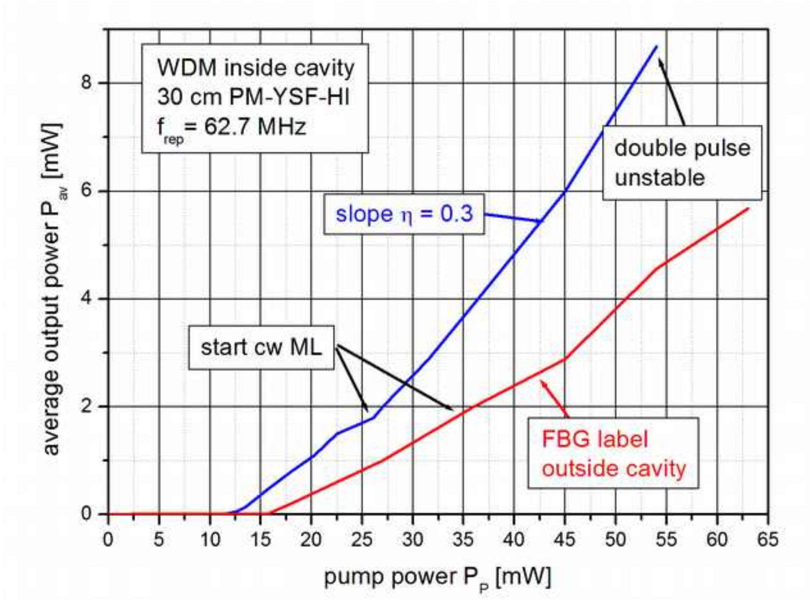
Measurement:

Switch on the laser diode driver (LDD) and Increase step by step the drive current of the 980 nm laser diode (LD980) 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. The two curves are for different orientation of the FBG in the laser cavity.



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 influence of the FBG direction in the laser cavity is the same as in the experiment 5.5 before. 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 insight 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 and mark “1” of the FBG insight 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

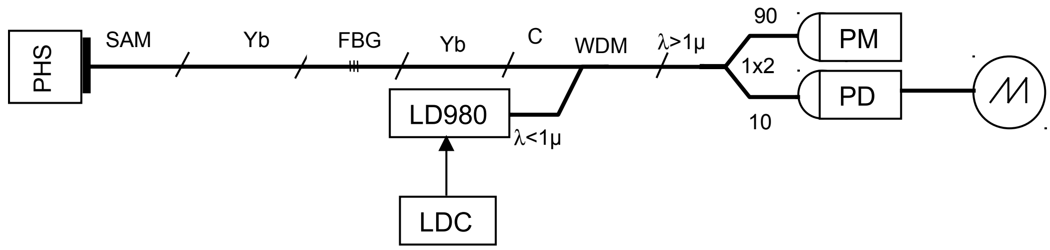
Needed parts from PSFL130 evaluation kit:

SAM	2 x Yb	FBG	C WDM $\lambda > 1$ µm $\lambda < 1$ µm	LD980
1x2 90 10	Optional 1 m	PHS	5 x Mating Sleeve	LDC

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.

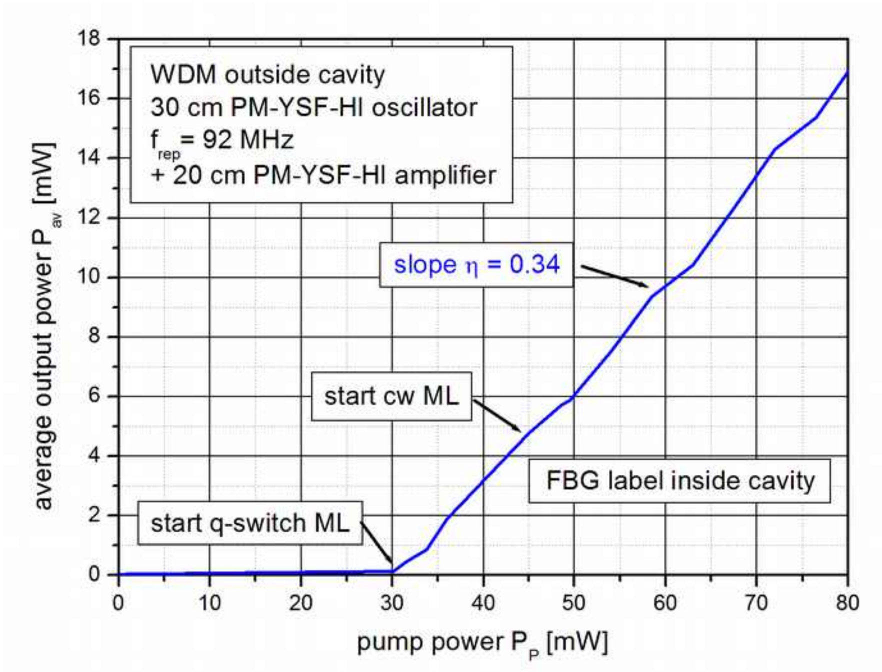
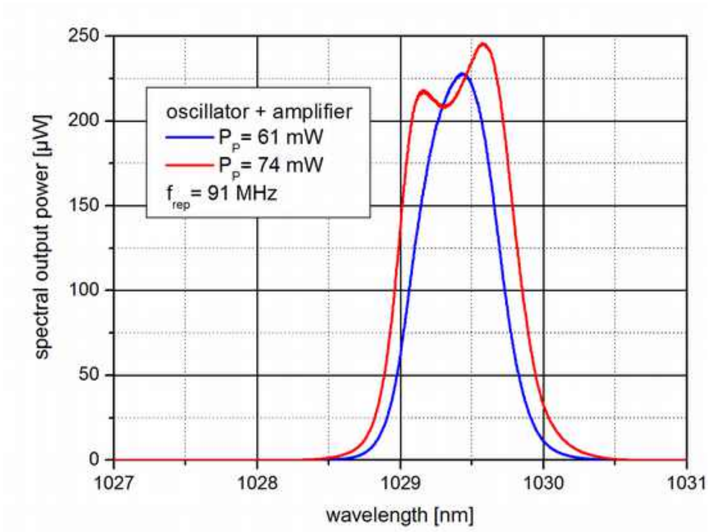


Figure 5.7.3

Spectral laser + amplifier emission, measured with an OSA at two pump power levels P_P. The label of the FBG is insight the cavity.

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.

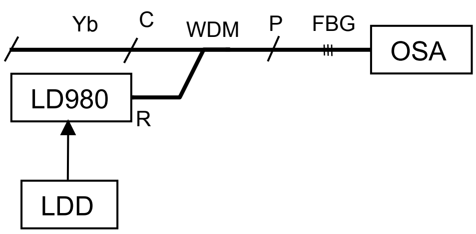
Needed parts from PSFL130 evaluation kit:

FBG	Yb	C WDM P R	LD980	1 m
2 x Mating Sleeve	LDC			

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 laser diode driver (LDD) and Increase step by step the drive current of the 980 nm laser diode (LD980) 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.

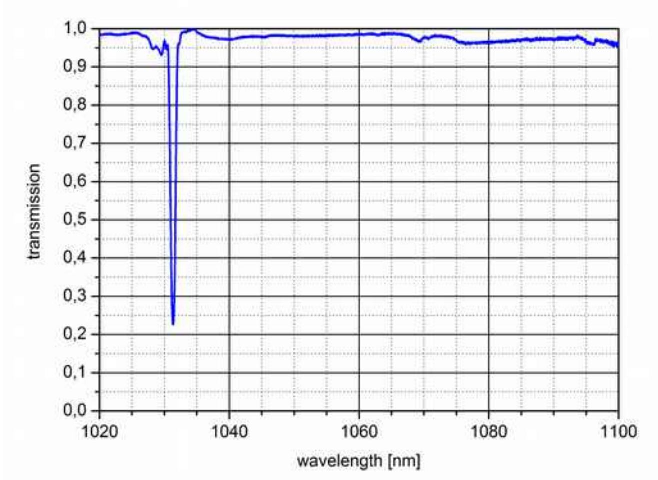
The spectral transmittance T of the FBG results from the transmitted spectral power through the FBG divided by the measured spectral power trough the passive fiber PM980-XP-100-FC/APC

.
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 – 15) 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

Producer: BATOP GmbH
Address: Wildenbruchstr. 15, 07745 Jena, Germany
Tel: +49 (0)3641 6340090
Email: info@batop.de
Website: http://www.batop.de