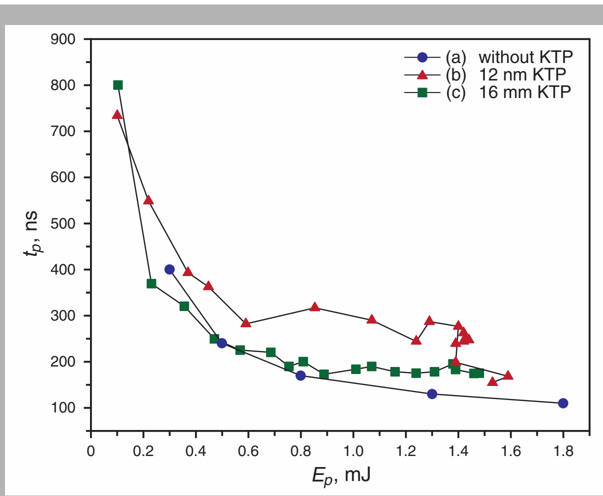
Abstract: A Q-switched Ho:YAG laser, longitudinally in-band pumped by a thulium fiber laser at a wavelength of $\lambda = 1920$ nm was designed in order to temporally stretch the Q-switched pulses at the fundamental wavelength. This was realized by two different methods:

(a) wavelengths with a small cross section for stimulated emission have been selected, which leads to a pulse duration of 162 ns at 2128 nm compared to 32 ns at a wavelength of 2098 nm with energies around 1 mJ,
(b) additionally intracavity second harmonic generation in the overcoupling regime has been used to further increase the pulse duration up to 300 ns at 1 mJ.



Pulse duration *versus* pulse energy at 2106 nm with different KTP crystals

Temporally stretched Q-switched pulses in the 2 μm spectral range

I. Rohde, [1,*] *D. Theisen-Kunde,* [2] *and R. Brinkmann* [1,2]

[1] Institute for Biomedical Optics, University of Lübeck, 23562 Lübeck, Germany
[2] Medical Laser Center Lübeck, 23562 Lübeck, Germany

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1. Introduction

Mid-infrared Q-switched laser radiation around $\lambda \approx 2$ μm, either pumped continuous wave (CW) by laser diodes or pulsed by flashlamps, is well established in medical laser applications, for example laser surgery [1–4]. Transmitted via optical fibers, the use of high repetitive Q-switched laser radiation for laser surgery, however, is limited in pulse energy by the damage threshold of the optical fiber, especially at the distal tip, which gets in contact with tissue [5]. In order to improve the usability, the pulse duration of the Q-switched pulses can be increased in order to allow higher pulse energy transmission. The long term objective of the project is to generate pulse energies of several millijoules at pulse durations of several hundreds of nanoseconds in order to keep the peak fluence below the damage threshold of 30 MW/cm^2 [5] for a low OH – fiber in contact with biological tissue.

It has been shown in previous works, that intracavity second harmonic generation in the overcoupling regime, firstly presented in 1970 by Murray and Harris [6], is suitable to produce Q-switched pulses of several millijoules in the microsecond regime in the green spectral range [7]. The principle of this method is based on the fact that the nonlinear crystal inside the cavity acts as a variable output coupler due to the nonlinear power conversion from

* Corresponding author: e-mail: rohde@bmo.uni-luebeck.de

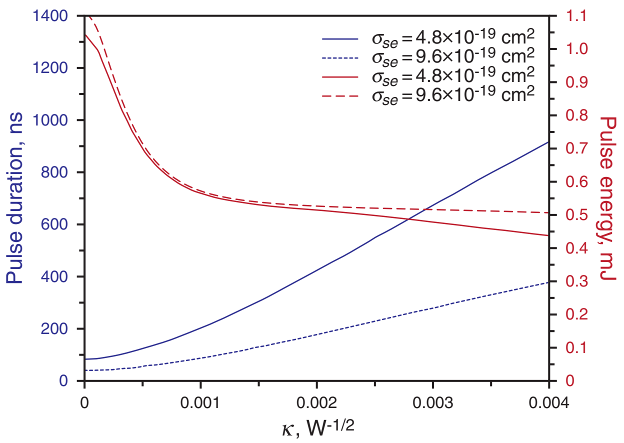

Figure 1 (online color at www.lasphys.com) Calculated fundamental pulse duration and energy for intracavity SHG in dependence of the conversion factor K for cross sections of stimulated emission of 4.8×10^{-19} and 9.6×10^{-19} cm^2

Wavelength, nm	Relative gain, a.u.
2090	1.00
2098	0.90
2106	0.45
2122	0.53
2128	0.42

Table 1 Cross-sections at different wavelengths of Ho:YAG (1% dopant level, values are extracted from Fig. 1 in [11])

the fundamental wave to the second harmonic. The peak power is reached when the losses (linear and nonlinear) equal the gain for the fundamental mode. If the conversion efficiency becomes much higher than that necessary to generate maximum second harmonic peak power, the stored remaining inversion is slowly depleted in an extended pulse.

In this regime the pulse energy decreases slowly with increasing conversion efficiency while the pulse duration increases significantly. The overcoupling effect provides a method to adjust the pulse duration without significant loss of pulse energy [8].

The aim of this work is to show the feasibility of the overcoupling effect to generate stretched pulses at the fundamental wavelength of 2 μm, using the second harmonic for nothing more than nonlinear loss.

2. Method

2.1. Theory

Since the overcoupling effect compensates the gain of the active medium, a low cross section of stimulated emission is favorable. In this special case the linear losses of the output coupler additionally reduce the intracavity power and therefore the second harmonic generation (SHG) conversion efficiency. In the small signal approximation the second harmonic power is given by $P_{2\omega} = P_\omega^2 K^2$, depending on the square of the fundamental power P_ω and the nonlinear conversion factor K, which is given by:

$$K = \frac{\kappa\, l\, d_{eff}}{\gamma\, \omega_c \sqrt{\pi}} \sin c\left(\frac{\pi\, l}{2\, l_c}\right) . \quad (1)$$

The conversion of the fundamental frequency ω to the second harmonic 2ω mainly depends on the length of the nonlinear crystal l, its effective nonlinear coefficient d_{eff}, and the fundamental beam waist ω_c within the nonlinear crystal [9]. The coherence length is described by $l_c = \lambda_\omega/(4\Delta n)$ and the walk off angle ρ of the nonlinear crystal is taken into account by $\gamma = \sqrt{1 + l/l_a}$ with an aperture length $l_a \approx \omega_c/\rho$. The constant factor

$$\kappa = \frac{8\pi^2}{n_{2\omega} n_\omega^2 \lambda_\omega^2 c \varepsilon_0}$$

depends on the fundamental wavelength λ_ω, the indices of refraction n_ω and $n_{2\omega}$ of both wavelengths and the dielectric constant ε_0.

In this case, two $KTiOPO_4$ (KTP) crystals cut in the xz plane at an angle $\Theta = 51°$, thus allowing frequency doubling in a wavelength range between approximately 2000 and 2130 nm with an effective nonlinear coefficient $d_{eff} = 2.7$ pm/V [10]. The crystal lengths were 12 and 16 mm, respectively. With a beam radius of approximately 210 μm, conversion factors K of 1.41×10^{-3} and 1.84×10^{-3} W$^{-1/2}$ are estimated.

For illustration, Fig. 1 shows a plot of fundamental pulse energy and pulse duration in dependence of the conversion factor K for different cross sections of stimulated emission, calculated with a set of rate equations for intracavity SHG in plane-wave, fixed-field approximation according to [7] with an additional 10% output coupler. Thereby, the different gain of different wavelengths of Ho:YAG are taken into account by numerically adjusting the cross section of stimulated emission. The relative gain of some selected fundamental wavelengths is listed in Table 1 and is extracted from the literature of Kwiatkowski et al. [11].

With increasing K, in both cases the fundamental pulse energy decreases rapidly due to the increasing nonlinear losses up to a conversion of $k = 1\times10^{-3}$ W$^{-1/2}$. With further increase of K, the pulse energy remains almost constant, but the pulse duration continues to rise. By reducing the cross section of stimulated emission by a factor of 2 from 9.6×10^{-19} to 4.8×10^{-19} cm^2, the pulse lengthening effect is significantly enhanced, thus a significant increase of pulse duration from some 10 ns to

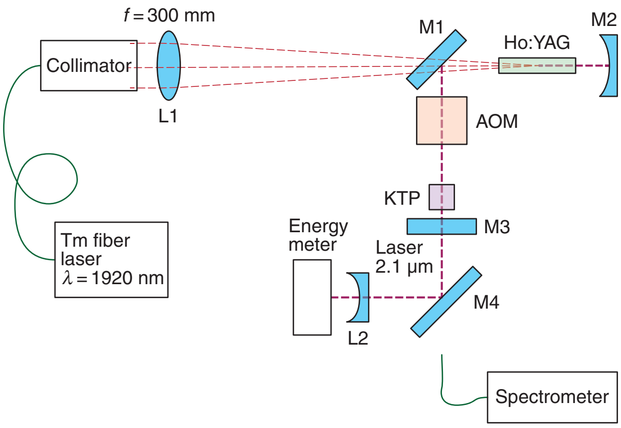

Figure 2 (online color at www.lasphys.com) Sketch of the resonator setup

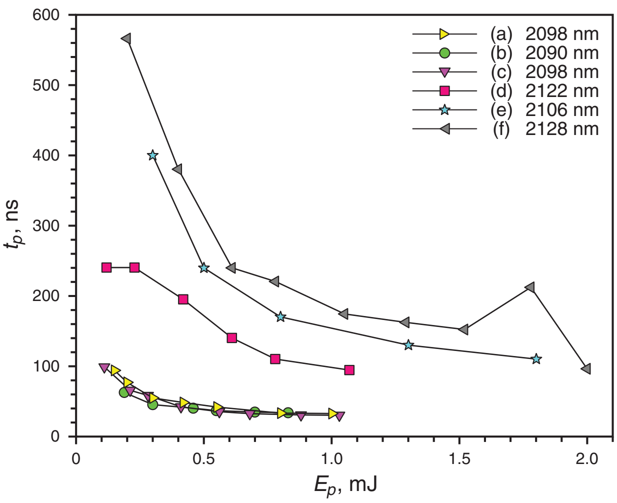

Figure 3 (online color at www.lasphys.com) Pulse durations *versus* pulse energy for different fundamental wavelengths without SHG

some hundred nanoseconds appears reasonable by combining gain reduction *via* wavelength selection in combination with use of the overcoupling effect.

2.2. Laser setup

A Q-switched Ho:YAG laser longitudinally in-band pumped by a thulium fiber laser at a wavelength of 1920 nm (IPG Inc., USA, 60 W) was designed. The experimental setup of the L-shaped laser system is sketched in Fig. 2. The collimated pump radiation is focused by a lens L1 with a focal length of 300 mm and coupled into the resonator by a dichroitic 45° mirror M1 (Layertec, Germany). The outside is AR coated for 1850 to 1950 nm and the resonator side is HR coated for 2115 to 2200 nm with a partial reflectivity of less than 3% between 1850 and 1950 nm. 80% of the pump radiation is absorbed in single pass through the Ho:YAG crystal (FEE, Germany, ∅5×30 mm^3, 0,72%), the transmitted light is back reflected by the broadband HR coated end mirror M2 of the first arm of the resonator. The acoustic-optic modulator (AOM, Googe & Housego, UK, Model IQS027-2s4v6-s5) is placed in the second arm behind the 45° pump mirror, followed by a plane output coupler M3 with a transmission of 10% at a wavelength of 2100 nm.

Due to the curved back mirror (ROC = 500 mm) of the first arm, the focus of the laser radiation is located at the output coupler, where KTP crystals of different lengths were placed for intracavity frequency doubling. One crystal had a length of 12 mm (GWU, Germany), another one was walk-off compensated and had a length of 16 mm (Crystallaser, France). Both are cut in the zx-plane at angles of $\theta = 51°$ and $\varphi = 0°$ for type II phase matching. Because of the wide acceptance range, frequency doubling can be achieved for a wavelength range between 2013 and 2123 nm, the effective nonlinear coefficient is d_{eff}=2.7 pm/V [10]. In this setup, half of the generated second harmonic radiation is coupled out through the pump mirror, the other half through the output coupler.

Behind the resonator, the fundamental radiation is reflected by a dichroitic 45° HR mirror M4 and guided through a lens L2 (f = –25 mm) to an energy meter (Coherent, USA, LabMax). Pulse shapes were measured with a InGaAs-photodiode (Laser Components GmbH, Deutschland, J23-18I-R250U-2.2, 4 ns rise time), and an oscilloscope (Tektronics, USA, Tek 220, 100 MHz).

The second harmonic radiation exiting through the output coupler passes through the 45° mirror, thus acting as a filter and is measured either by an energy meter (Ophir, Israel, LaserStar) or a spectrometer (Avantes, Netherlands, AvaSpec 2048, 586 – 1100 nm) with a spectral resolution of 0.4 nm.

The spectrum was generally measured with an external SHG crystal before entering the spectrometer. Accordingly the spectral wavelengths given here were converted to the 2 μm region by multiplying with a factor of 2.

The repetition rate of the laser system was set to 300 Hz, corresponding to a repetition time of 3.33 ms. The integration time of the spectrometer was set to 2 ms, thus ensuring that a measured spectrum resembles a single pulse. A tunability of the fundamental wavelength over a large regime from 2070 to 2130 nm has been reported for Ho:YAG [11]. Therefore a $Y_3Al_5O_{12}$ (YAG) (uncoated, t = 58 μm) and a glass (uncoated, t = 140 μm) Etalon (Layertec, Germany) were used to stabilize the fundamental laser wavelength.

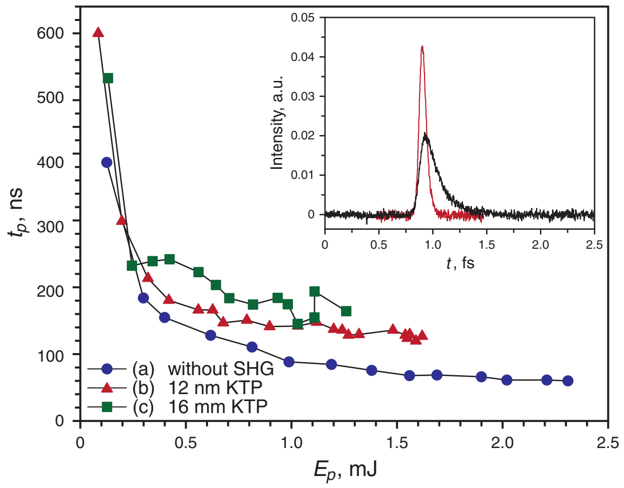

Figure 4 (online color at www.lasphys.com) Pulse duration *versus* pulse energy at 2122 nm with different KTP crystals. The inset shows the comparison of a stretched (black) and a usual pulse (red)

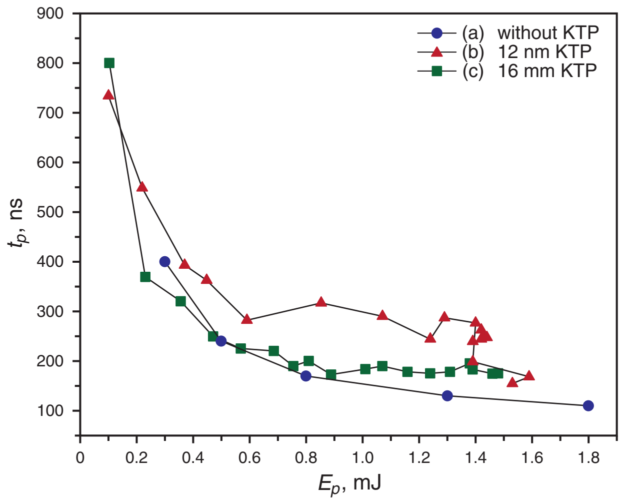

Figure 5 (online color at www.lasphys.com) Pulse duration *versus* pulse energy at 2106 nm with different KTP crystals

3. Results

3.1. Wavelength dependence

Fig. 3 shows the pulse durations in dependence of pulse energy for different fundamental wavelengths without intracavity SHG. The wavelengths were selected with etalons and measured by external SHG and the spectrometer. The pump power was typically varied between 6.3 and 12.3 W.

Curve (a) shows the dependency without spectral control where the pulse duration starts at 94 ns and an energy

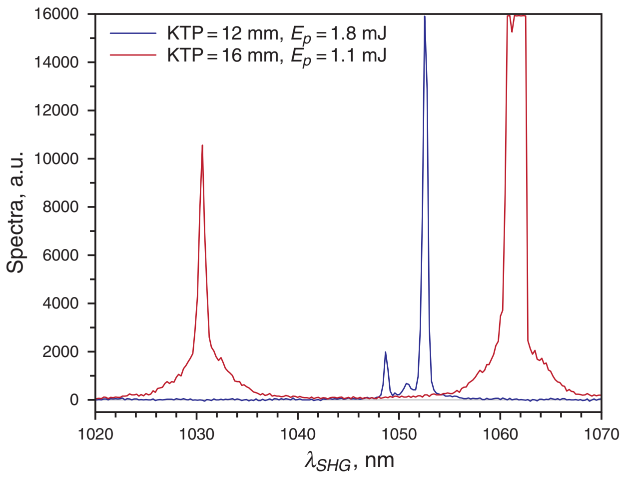

Figure 6 (online color at www.lasphys.com) Example for spectra with different wavelengths in a single pulse

of 150 μJ, decreases to 33 ns at 800 μJ and then remains practically constant with 32 ns at 1 mJ. At a repetition rate of 300 Hz this corresponds to an average power of 300 mW at a pump power of 10.5 W. The fundamental wavelength that is emitted at 2090 nm, which corresponds to the gain maximum of Ho:YAG reported in [11], but occasionally pulses at a wavelength of 2098 nm were observed.

For curves (b) and (c) the laser radiation was spectrally stabilized by the YAG etalon at wavelengths of 2098 and 2090 nm, respectively. All three curves show a similar dependency of pulse duration and energy. Because of the low transmission of the output coupler and the short pulse durations, the pulse energy was not increased above 1 mJ to prevent damage of the optical coatings.

Curve (d) shows an according plot at a fundamental wavelength of 2122 nm, which corresponds to an local maximum of the emission spectrum of Ho:YAG with 48.4% cross section of stimulated emission compared to the laser lines around 2090 nm. Accordingly the pulse durations are higher and start with 240 ns at 120 μJ decreasing to 94 ns at 1.07 mJ.

This effect is increasing at wavelengths of 2106 and 2128 nm, with cross section of stimulated emission of 42.8 and 38.4%. Pulse durations of 130 ns at 1.3 mJ and 110 ns at 1.8 mJ could be realized at 1053 nm as shown by curve (e) and 162 ns at 1.29 mJ and 96 ns at 2 mJ at a wavelength of 2122 nm. Finally, curve (f) shows the highest pulse durations at a wavelength of 2098 nm with 152 ns at pulse energy of 1.52 mJ. At a pulse energy of 1.78 mJ the measured pulse duration was even 213 ns, but the pulse shape was a double pulse, indicating die build up of another wavelength. In these measurements, the maximum pulse energy was increased slightly due to the longer pulse durations, thus reducing the peak intensities of the pulses.

Overall, the pulse duration could be increased significantly by selecting different wavelengths. A factor of 3.5

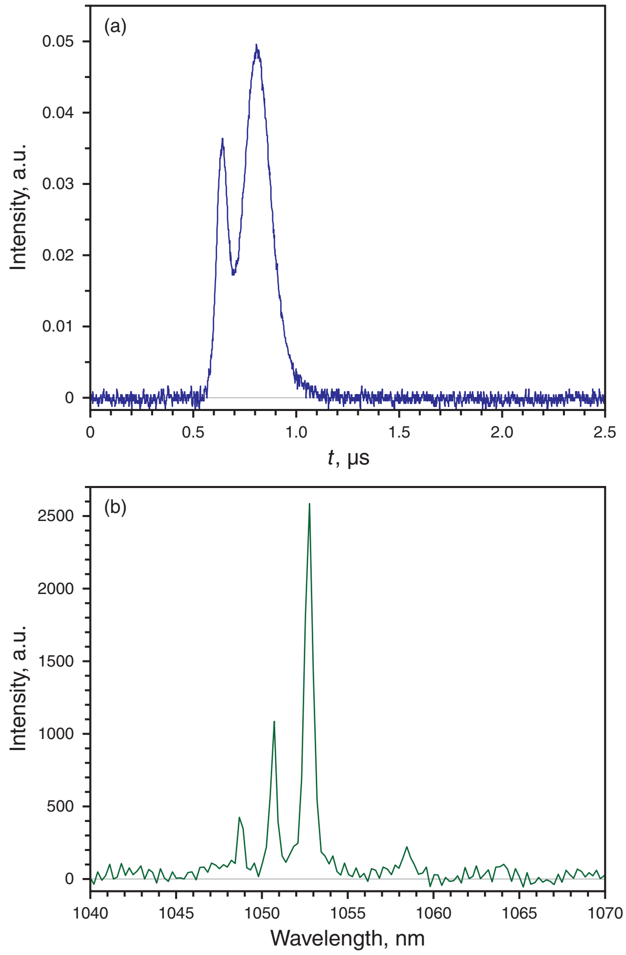

Figure 7 (online color at www.lasphys.com) Example for an instable double pulse shape (a) at a center wavelength at 2106 nm, a pulse duration of 300 ns and a pulse energy of 1.1 mJ. The second harmonic spectrum (b) shows a center wavelength of 1053 nm and satellites at 1050 and 1049 nm

from 32 ns at 2098 nm to 110 ns at 2106 nm and a factor of 5 to 2128 nm could be realized.

3.2. Overcoupling

Fig. 4 shows the pulse duration versus pulse energy with intracavity second harmonic generation at a wavelength of 2122 nm with KTP crystals of 12 and 16 mm length compared to a measurement without SHG. The overall trend with decreasing pulse durations with increasing pulse energy is similar, but with SHG longer pulse durations are realized. At around 1 mJ, e.g. the duration rises from 96 ns without SHG to 147 ns with 12 mm KTP and 180 ns with 16 mm KTP. This fact in combination with the change of pulse shape from a Gaussian shape to a pulse form with a steep rising edge and a slow falling edge is a strong indication, that the overcoupling regime is reached in spite of the intensity loss induced by the output coupler.

It has to be noted however, that the pulses were limited by pulse instabilities associated with additional fundamental wavelengths which could not be suppressed by etalon at higher pump powers between 11 and 14 W. Examples of such second harmonic spectra are given in Fig. 6.

This effect increases with KTP length, and the trend of the curve with the 16 mm KTP is irregular with fluctuating pulse durations. In this case the doubling crystal is suppressing the center line and additional wavelength can be observed even at pulse energies below 1 mJ. This leads to double pulses which can increase the pulse duration because of a temporal overlap of different frequencies. An example is given in Fig. 7.

In Fig. 5 the according measurements at a wavelength of 2106 nm are displayed. In this configuration 298 ns at 1 mJ can be realized with the 12 mm KTP. But the curve also shows an irregular trend because of additional wavelengths and the pulse energy could not be increased beyond 1.4 mJ, with the pulse duration fluctuating between 200 and 300 ns. With the 16 mm KTP crystal, the laser radiation could not be constricted to the central wavelength for significant pulse energies and the pulse lengthening effect is small.

Fig. 6 shows two typical second harmonic spectra of instable pulses. The black curve was generated with the 12 mm KTP and adjusted to a wavelength around 1053 nm. At fundamental pulse energy of 1.8 mJ, satellites at 1051 and 1049 nm were observed as well as strong fluctuations of the fundamental pulse energy and pulse duration. In the same manner, the red line shows the spectrum of a pulse at a center wavelength of 1061 nm, produced with the 16 mm KTP at fundamental pulse energy of 1.1 mJ. The main peak is broadened by saturation and cannot be determined correctly. This was accepted to record the second peak at 1030 nm, which demonstrates the wide gain spectrum of Ho:YAG as well as the difficulty to select a single low gain laser line during Q-switched intracavity second harmonic generation.

In Fig. 7a the example of a pulse shape of a double pulse is shown with a pulse energy of 1.1 mJ at a pulse duration of 300 ns, measured with the 12 mm KTP. The double peak of the pulse shape indicates the temporally shifted build up of additional frequencies in a single pulse. This is validated by the corresponding second harmonic spectrum in Fig. 7b, which shows the frequency doubled center wavelength at 1053 nm, as well as satellites at 1050 and 1049 nm. These competing wavelengths lead to fluctuations in pulse duration and pulse energy, thus destabilizing the pulses.

4. Conclusion

We demonstrated pulse stretching of the fundamental wavelength of a Tm-fiber laser pumped Q-switched

Ho:YAG laser by intracavity second harmonic generation. In this concept the fundamental wavelength shall be used for further applications and the second harmonic only as a nonlinear loss to stretch the fundamental. Because of the linear losses of the output coupler, the fundamental intracavity intensity and therefore the SHG conversion efficiency is limited.

In order to further enhance the conversion efficiency and further stretch the pulses, wavelengths with a smaller cross section for stimulated emission were selected with etalons, already increasing the pulse duration at energies around 1 mJ from 32 ns at a wavelength of 2098 nm to 110 ns at 2122 nm, 130 ns at 2106 nm, and 162 ns at 2128 nm. The overcoupling effect has been used to further increase the pulse duration up to 298 ns at 1 mJ at 2106 nm, which is in good agreement with theoretical considerations.

However, with intracavity second harmonic generation, pulse energies were again limited at around 1.5 mJ by the build up of additional wavelengths, which could not be suppressed. This leads to fluctuations of pulse duration and energy and this effect increases with K and a reduced cross section of stimulated emission.

In the next step of experiments, we intend to enhance the spectral management by a combination of a Lyot filter and a coated etalon to stabilize the frequency with a higher finesse in order to extend the overcoupling effect.

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