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InGaAs diode laser system generating pulses of 580 fs duration and 366 W peak power

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Abstract This paper reports the generation of fs light pulses by a passively mode-locked InGaAs master oscillator power amplifier (MOPA) system. The laser system generates chirped pulses with 6.2 ps duration, a center wavelength of 922 nm and 4 GHz repetition rate. Pulse compression by an external grating compressor reduces the pulse duration to 580 fs. The average power of the compressed pulses of 851 mW corresponds to a peak power of 366 W.

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1 Introduction

Actively [1–4] and passively [5–10] mode-locked semiconductor devices have been used for the generation of ultrashort pulses for more than two decades [1, 5]. Passive mode-locking has been obtained e.g. by saturable absorption in degraded [5–7] or ion implanted facets [8–10] and in multi-contact diodes with a non-uniform current injection or a reversed bias section [11–13]. A more detailed review of the various mode-locking concepts and the amplification and gain dynamics has been published by Delfyett et al. [14].

Despite the successful demonstration of fs diode lasers [15] the generation of ultra-short light pulses is dominated by optically pumped mode-locked solid-state lasers [16] such as the titanium–sapphire laser [17]. The advantage of these lasers is certainly the high output power of several watts emitted in a diffraction-limited beam. Recently, the generation of ps pulses with an average power of several watts was realized by an actively mode-locked InGaAs master oscillator power amplifier (MOPA) system [18]. This system provided 16 ps long pulses at a repetition rate of 4 GHz with an average power of 4 W and with good spatial beam quality.

In this paper we demonstrate a diode laser MOPA system generating 580 fs long pulses with 366 W peak power and 851 mW average power. The short pulse duration is obtained by external pulse compression. Because the oscillator was optimized to generate a strongly chirped pulse the system does not—in contrast to previous concepts [19]—contain any pulse-stretching devices before amplification.

2 Theory

It is well known that the amplification of ultra-short pulses in semiconductor gain media is strongly influenced by gain saturation [20] and self-phase modulation (SPM) [15, 18, 21]. Gain saturation results in low output powers. Furthermore, SPM leads to spectral pulse broadening [22] since the instantaneous light frequency $\omega_{\text{inst}}(t)$ depends on the transient refractive index $n(t)$:

$$\omega_{\text{inst}}(t) = \omega - kz\frac{\partial n(t)}{\partial t} \tag{1}$$

Herein k denotes the vacuum wave vector and z is the propagation direction of the wave.

The transient refractive index $n(t)$ is influenced by the microscopic gain or absorption and by the spectral position relative to the gain or absorption resonance frequency. The

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induced index change δn is [23]

$$\delta n = -\frac{n}{2\epsilon\hbar\gamma V}\sum_k |\mu_k|^2\left[f_k^{\mathrm{e}} + f_k^{\mathrm{h}} - 1\right] \times \mathcal{L}(\omega_k - \omega_{\mathrm{gap}})\frac{\omega_k - \omega_{\mathrm{gap}}}{\gamma}, \qquad (2)$$

with μ_k denoting the transition matrix element for the light frequency ω_k and with ω_{gap} denoting the band-gap frequency ($E_{\mathrm{gap}} = \hbar\omega_{\mathrm{gap}}$). $\mathcal{L}(\omega)$ is the Lorentz line-shape function and γ is the damping constant in the Lorentz oscillator model. f_k^{e} and f_k^{h} are the distributions for the electrons and the holes in the QW, respectively.

For absorbing media the relation $f_k^{\mathrm{e}} + f_k^{\mathrm{h}} < 1$ holds. When carriers are generated by incident radiation the term $f_k^{\mathrm{e}} + f_k^{\mathrm{h}}$ increases. For gain media the relation $f_k^{\mathrm{e}} + f_k^{\mathrm{h}} > 1$ holds and the term decreases, when carriers recombine due to stimulated emission.

In our discussion we exclude spectral hole burning; this means that one of both the relations $f_k^{\mathrm{e}} + f_k^{\mathrm{h}} < 1$ and $f_k^{\mathrm{e}} + f_k^{\mathrm{h}} > 1$ holds for *all* k-vectors. In simple words, there is either gain for all frequencies or absorption for all frequencies. We can exclude spectral hole burning effects because the pulse duration is much longer than the intraband scattering time scale of 0.5 ps [21]. This leads to a fast carrier transfer in the k-space and equalizes carrier density gradients within the bands.

Equation (2) describes the transient index $\delta n(t)$ as a result of the transient carrier density. The effect of the changing density on $\delta n(t)$ depends on the position of the light frequency with respect to the band-gap frequency ω_{gap}, which can be derived from the relation $eU_{\mathrm{gap}} = \hbar\omega_{\mathrm{gap}}$. From a band-gap voltage of $U_{\mathrm{gap}} = 1.329$ V we estimate a band-gap transition wavelength of $\lambda_{\mathrm{gap}} = 931.2$ nm for our diode laser. As our spectra (see Fig. 3) are located at shorter wavelengths, we obtain that $\omega > \omega_{\mathrm{gap}}$.

For this case it is clear from (2) that carrier depletion in the gain section will cause a decreasing refractive index $n(t)$. According to (1) this leads to the increase of $\omega_{\mathrm{inst}}(t)$ and to an up-chirp. In the same way carrier generation in the absorber section will cause a down-chirp.

In this paper we demonstrate that the oscillator can be optimized in order to generate a frequency chirp with a dominating linear term. One further aim of the experiments presented in this paper is to determine whether gain or absorption saturation is dominant in the passively mode-locked laser. For this purpose we use a grating compressor in order to determine the sign and value of the chirp directly from the geometry of the compressor.

3 Experimental set-up

In order to achieve high output powers and to avoid strong SPM effects we use a MOPA system that generates and amplifies spectrally broad ps pulses with a strong frequency chirp. The chirp allows a pulse compression of the amplified pulses to sub-ps pulse durations. Since the used oscillator itself provides strongly chirped ps pulses, no stretcher (commonly used for the *chirped pulse amplification* technique [16]) is required before amplification.

Figure 1 shows the experimental set-up. The master oscillator is a 1300 µm long, passively mode-locked single-stripe

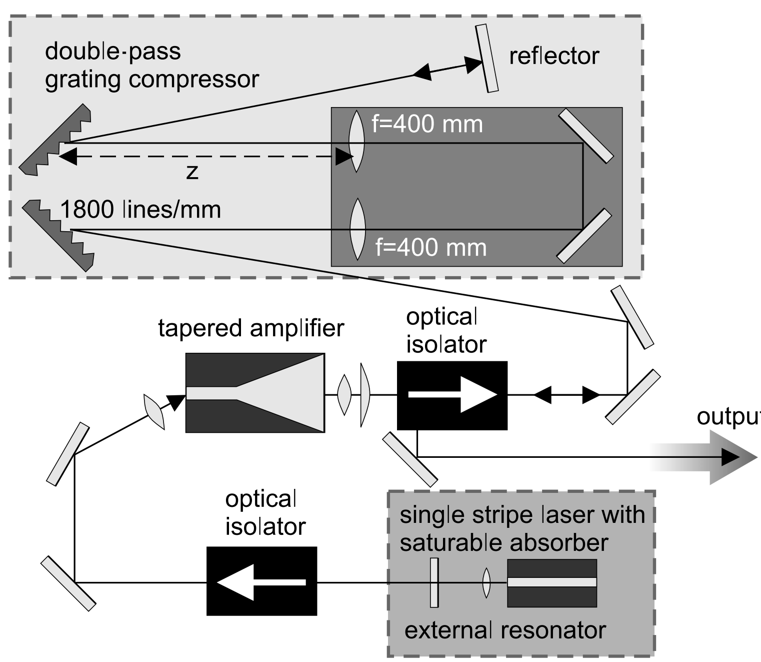

Fig. 1 Experimental set-up. For details see text

InGaAs laser with a 80 µm or 100 µm long saturable absorber section. The losses in the absorber section were controlled by a reverse DC voltage bias. Except for the constant-current source for the gain section and the constant-voltage source for the absorber section no further driver electronics are required for the master oscillator.

Since the generation of fs pulses requires a spectral bandwidth of several nanometers, the waveguide contains neither DBR nor DFB structures. The oscillator is operated in an external resonator formed by the oscillator back facet, an aspherical lens ($f = 4.5$ mm) and an external plane mirror with a reflectivity of 30%. A high repetition rate of 4 GHz is used to avoid ASE [18].

For amplification a 2750 µm long tapered amplifier (TA) was used. The TA has a 750 µm long ridge-waveguide preamplification section, and a 2000 µm long tapered region for high-power amplification. The output facet is 200 µm wide and 1 µm high. A cylindrical lens behind the TA compensates the astigmatism.

The amplifier is followed by a double-pass grating compressor consisting of two gratings with 1800 lines per mm and two lenses of 400 mm focal length. Since the beam is reflected twice at each grating the compressor output power strongly depends on the diffraction efficiency. The used gratings (manufactured by Spectrogon) provided a first order diffraction efficiency of 94%. The compressor is able to provide a negative or positive group delay dispersion (GDD) [24]. The GDD of a double-pass grating compressor is [16, 24]

$$\mathrm{GDD} = -\frac{\lambda^3}{\pi c^2 d^2}\frac{L}{1-(\frac{\lambda}{d}-\sin\vartheta)^2}, \tag{3}$$

where λ denotes the center wavelength of the pulse (922 nm), L the optical path length between the gratings, d the grating groove width (0.56 µm) and ϑ the angle of incidence on the first grating ($\vartheta = 64°$). The amount of dispersion can be adjusted by changing L.

L can be calculated using the distance z between gratings and lenses (see Fig. 1) and the focal length f:

$$L = 2(z - f). \tag{4}$$

The optical path length L between the two gratings can be negative, if the gratings are placed within the focal length of the lenses.

In our experiments we optimized z with respect to the shortest pulse duration after compression. From the optimum value of z the sign and the amount of the GDD can be calculated using (3) and (4). If $z > f$ then L is positive and the compressor has an anormal dispersion, which means that the uncompressed pulse is up-chirped (and vice versa).

4 Results

In order to obtain high peak powers both the average output power as well as the pulse duration have to be optimized. Our previous experiments concerning the amplification of MHz repetition rate ps and fs pulses showed a significantly different amplification behavior for continuous-wave (cw) radiation and mode-locked pulses [20]. Hence, before we focused the investigations on the compression of amplified pulses (see Sect. 4.2), we investigated the amplification of mode-locked ps pulses with repetition rates in the GHz range. The results are compared to the results obtained for the cw regime (see Sect. 4.1).

4.1 Average output power

Figure 2 shows the output power of the MOPA system for an amplifier current of 4 A. The output power P_{out} of the TA consists of ASE and amplified signal radiation. For high input powers P_{in} the signal power saturates and the ASE is suppressed. Therefore, for a given injection current the dependence of the optical output power P_{out} on the optical input power P_{in} (Fig. 2) can be described by

$$P_{out} = P_{max}^{ase}\exp\left(-\frac{P_{in}}{P_{sat}}\right) + P_{max}^{sig}\left[1-\exp\left(-\frac{P_{in}}{P_{sat}}\right)\right], \tag{5}$$

with the saturation power P_{sat} and the maximum ASE and signal output power, P_{max}^{ase} and P_{max}^{sig}.

To measure the achievable output power P_{max}^{sig} mode-locked pulses with different average input powers from the oscillator are amplified in the TA. The TA input power is

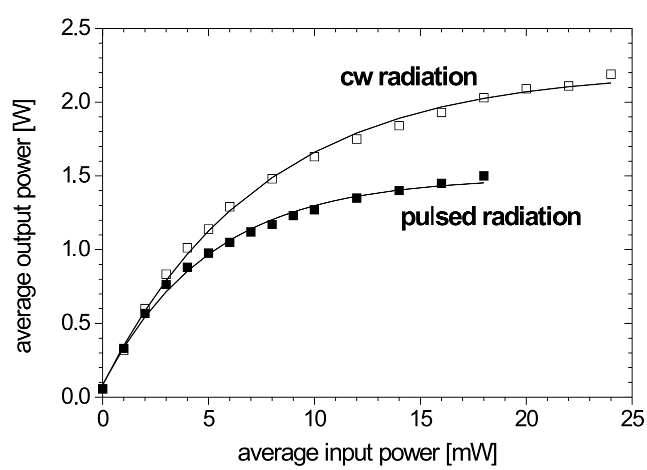

Fig. 2 Output power of the tapered amplifier in dependence on the optical input power measured for an injection current of 4 A with cw and pulsed radiation (*open* and *solid squares*). Equation (5) was used for curve fitting (*solid* and *dashed lines*)

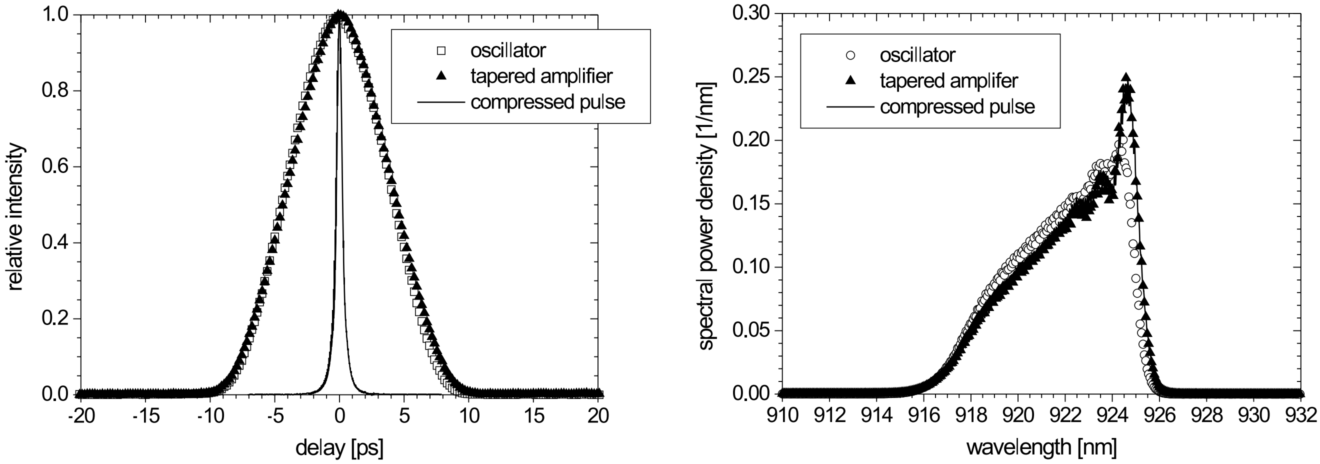

Fig. 3 Autocorrelation (*left*) and spectrum (*right*) of the pulse measured behind the oscillator, the amplifier and the pulse compressor

attenuated by a combination of a half-wave-plate and a polarizing beam splitter. The electrical input into the oscillator diode laser is fixed: $I_{gain} = 120$ mA, $U_{abs} = 4$ V, $I_{abs} = 18$ mA. The absorber length of the oscillator is 100 µm. The oscillator emits Gaussian shaped pulses with a duration of 3.7 ps and an average output power of 22 mW.

Due to delayed gain recovery the value of P_{sat} is smaller for pulsed operation (5.06 ± 0.26 mW at 4 A) if compared to cw operation (7.4 ± 0.3 mW). The pulse duration is 3.6 ps (assuming a Gaussian pulse, which fits very well to the experimental results). The maximum average output power P_{max}^{sig} with pulsed radiation at 4 A gain current is 1.5 W.

4.2 Pulse compression

For the pulse compression experiments an oscillator with an absorber length of 80 µm was used. The gain current was kept at 120 mA. Note that a small reverse voltage leads to an incomplete mode-locking, because the losses in the absorber are small. A large voltage leads to short pulses from the oscillator, but they experience high-order phase changes in the TA and cannot be compressed efficiently. Therefore, the reverse bias voltage at the absorber was set to $U_{abs} = 4.25$ V in order to achieve a minimal pulse duration after compression.

Figure 3 shows the autocorrelation functions (ACFs) and the spectra of the pulses behind the oscillator, the amplifier and the pulse compressor.

The oscillator generates Gaussian shaped pulses with a duration of 6.1 ps and an average power of 19.8 mW. The optical input and output powers of the TA were 16.6 mW and 1.56 W, respectively. The injected current was 4 A. As depicted in Fig. 3 the pulse is neither changed in shape nor broadened significantly (from 6.1 ps to 6.2 ps) by the TA.

As the spectral shape of the pulses is asymmetric we use the *center of gravity* and the *standard deviation* to characterize the spectral power distribution [20]. SPM in the oscillator causes an asymmetric, 4.4 nm wide spectrum (Fig. 3). In the TA the center of gravity of the spectral power distribution is shifted to longer wavelengths by about 0.4 nm from 921.8 nm (oscillator) to 922.2 nm (TA). This shift is caused by SPM [22], but is also a first indication for the up-chirp of the pulse. The long-wavelength components enter the amplifier first and experience a larger gain if compared to the components with shorter wavelength.

The ACF of the compressed pulse (see Fig. 4) cannot be described by a Gaussian or sech^2 function [25]. In order to obtain a value for the real pulse duration from the autocorrelation function $A(\tau)$, we used the following method valid *for all pulse shapes* [26]: the standard deviation

$$\Delta\tau_{ACF}^2 = \frac{\int \tau^2 A(\tau)\,d\tau}{\int A(\tau)\,d\tau} \tag{6}$$

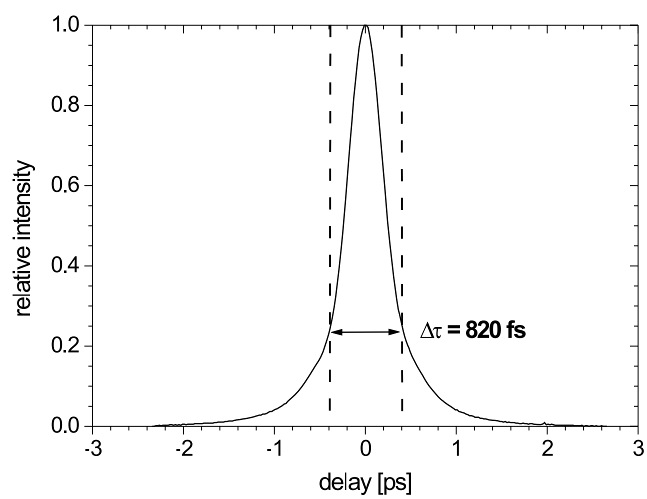

Fig. 4 Autocorrelation trace of the compressed pulse. For details see text

of the ACF is related to the standard deviation $\Delta\tau_p$ of the real temporal intensity function by the equation

$$\frac{\Delta\tau_{ACF}}{\Delta\tau_p} = \sqrt{2}. \quad (7)$$

Using the ACF from Fig. 4 and (6) and (7) we found that the pulse can be compressed to a duration of 580 fs. The average power behind the pulse compressor is 851 mW. This corresponds to a peak power of 366 W.

The shortest pulse duration was obtained for $z = 422$ mm. This means that the gratings of the compressor are placed outside the focal length (400 mm) of the lenses. Hence, we conclude that the uncompressed pulse has an up-chirp. Using (3) and (4) we estimate a GDD of –802 000 fs^2 for the amplified pulse. From the experimental results and from the discussion of the transient refractive index in Sect. 2 we conclude that the SPM is dominated by the carrier depletion in the gain section.

5 Summary

We demonstrated the generation of 580 fs long pulses with a peak power of 366 W in a passively mode-locked InGaAs diode laser MOPA system with external pulse compression. The key concept is to generate spectrally broad, strongly chirped ps pulses directly by a mode-locked oscillator without an additional stretcher and to compress the pulses after amplification. In order to amplify these pulses efficiently and without strong gain saturation their duration has to be long compared to the gain recovery time of 0.5 ps. The experimental results indicate that the carrier depletion in the gain section of the master oscillator results in an up-chirp of the light frequency.

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