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High-power ps InGaAs diode laser MOPA system for efficient frequency doubling in periodically poled KTP

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ABSTRACT This paper reports on a mode-locked InGaAs master oscillator power amplifier (MOPA) system that generates at 920 nm 14-ps-long pulses with a repetition rate of 4.3 GHz and an average power of 2.7 W. Single-pass frequency doubling in a periodically poled KTP crystal provides 550 mW of blue 460-nm radiation. The power of the blue output, which corresponds to a conversion efficiency of more than 20%, was optimized by a detailed investigation of the influence of various system parameters like injection current and repetition rate on pulse power, pulse duration, and spectral shape of the infrared laser pulses.

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1 Introduction

Compact blue laser sources are of interest for many applications such as optical data storage, medical diagnostics, lithography, and display technology. Although the operation of blue semiconductor diode lasers has been demonstrated [1], the development of reliable high-power devices required for most applications still remains a challenge. Today, the highest achievable output power of commercially available blue diode lasers is about 60 mW (Sanyo). An alternative concept for blue light sources based on diode lasers is the frequency doubling of near-infrared diode laser radiation [2]. Appropriate diode laser sources are master oscillator power amplifier (MOPA) systems based on amplifiers with a tapered lateral geometry of the active area. Such devices provide an output power of more than 5 W in a near-diffraction-limited beam [3]. Suitable techniques for increasing the conversion efficiency are the use of mode-locked ps pulses [4] or second harmonic generation (SHG) in external high-finesse optical cavities [5].

Due to the high peak power, high SHG efficiencies are achievable with ps pulses in a single pass through periodically poled nonlinear crystals. This concept is simple and should provide superior long-term stability in comparison to the conversion with a nonlinear crystal in an external enhancement cavity. A crucial prerequisite for efficient SHG of picosecond pulses is, however, an optimum temporal and spectral profile, since both parameters strongly influence the achievable conversion efficiency.

In this paper, we report on the realization of a mode-locked 920-nm InGaAs MOPA system and its optimization for efficient SHG of the infrared output. For optimum SHG, it has to be considered that the amplification of picosecond pulses in semiconductor optical amplifiers changes both the temporal as well as the spectral pulse shape. This is due to the strong coupling of the charge carrier density and the refractive index, which causes a nonlinear change of the phase of the pulse during the amplification process, which results in a transient variation of the frequency. For efficient SHG of picosecond light pulses, it is thus essential to identify and minimize the influence of this effect on the temporal and spectral shape of the amplified optical pulses by an appropriate choice of the system components and the operating parameters.

A powerful method to characterize the temporal and spectral properties of ultrashort pulses is the method of "frequency resolved optical gating" (FROG) [6]. Using this method, the influence of the operating parameters of the oscillator, preamplifier, and the tapered power amplifier (TA) on the temporal and spectral shape of the amplified pulse has been investigated and optimized with respect to high output power and SHG conversion efficiency.

The paper is divided into the following sections: Sect. 2 describes the experimental setup. Section 3 presents the properties of the MOPA system for continuous-wave (cw) operation. The following Sect. 4 describes the MOPA performance for mode-locked operation and the method used for measuring the pulse duration and spectral properties of the generated ps pulses. In the last Sect. 5, the generation of blue laser radiation by SHG in PPKTP is described for cw as well as mode-locked MOPA-radiation.

2 Experimental setup

The scheme of the experimental setup is shown in Fig. 1, which consists of the InGaAs diode laser MOPA system and a periodically poled KTP (PPKTP) crystal. The MOPA oscillator is a single-stripe diode laser (SDL, prototype) with an HR/AR coating operated in an external cavity with a grating of (1600 lines/mm) in Littrow configuration

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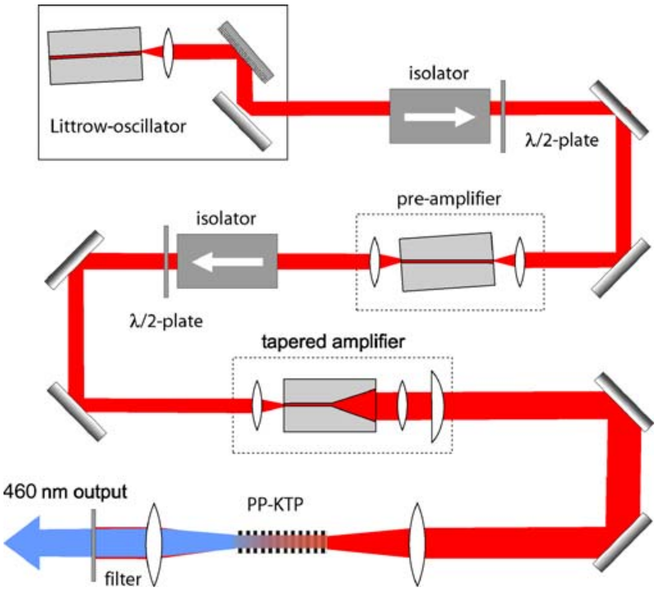

FIGURE 1 Scheme of the experimental setup of the diode laser MOPA system with subsequent single-pass frequency doubling in a PPKTP crystal. The MOPA system consists of a Littrow oscillator, a single-stripe pre-amplifier, and a tapered amplifier. The laser-active components are optically separated by appropriate optical isolators

tuned for laser operation at 920 nm. To saturate the tapered amplifier, the oscillator output is preamplified in a single-stripe diode laser (SDL, prototype) with AR-coated ($R < 10^{-3}$) facets. The oscillator output is injected into the waveguide at an angle of 17° in order to prevent any residual retroreflection into the active laser area. The amplified laser light is emitted from the output facet at the same angle of 17°. The 2.75-mm-long tapered amplifier (manufactured by the Ferdinand Braun Institut für Höchstfrequenztechnik, based in Berlin) contains two sections: a 0.75-mm-long single-stripe waveguide and a 2-mm tapered laser region with a taper angle of 6°. This geometry is optimized for high gain in a single pass. Optical isolators (Linos SR 920/5 TS, isolation: 60 dB) positioned between the oscillator, preamplifier and TA avoid back-reflections from the subsequent optical components.

3 Continuous-wave cw operation of the MOPA system

For cw operation, a DC current of 20 mA is injected into the oscillator diode. At this current, the single frequency output is about 1 mW. The oscillator's output is amplified in the single-stripe amplifier. With an injection current of 95 mA, the output power is typically 50 mW. With this input, the TA generates an output power of 3.4 W when driven by an injection current of 6 A. Under these operating conditions, 75% of the optical output are contained in a beam with an M^2- value of less than 1.1. The spatial quality of the TA emission was analyzed using the method described in [7].

4 Picosecond operation of the MOPA system

In the following section, the ps operation of the MOPA system as well as the diagnostics used for measuring the properties of the generated ps pulses are described.

4.1 *Diagnostic tools*

The temporal and spectral properties of the generated ps pulses were analyzed using an autocorrelator (Model, APE 150 ps), a spectrometer (ANDO, Modell AQ-6317 B) and a high-resolution (home build [8]) SHG FROG system. The high spectral resolution of 2 GHz (14 pm) at 460 nm and the high detection sensitivity of the SHG-FROG system was crucial for optimizing the performance of the ps MOPA system.

4.2 *Mode-locked oscillator*

To generate ps pulses, the oscillator was actively mode-locked by driving the diode laser with a DC current of 10 mA and a sinusoidal radio frequency (rf) signal. The applied rf power was typically 24 dBm, the frequency 1.7–5.1 GHz, corresponding to the round-trip time in the used optical Littrow cavities.

Figure 2a shows the measured FROG trace of an oscillator pulse when the oscillator is operated at a repetition rate of 4.3 GHz. In this case, the DC current was 10 mA, the average optical output 0.7 mW. The wavelength range of the FROG-trace is 0.18 nm, the time delay 60 ps and the FROG-error [9], which is an indicator of the accuracy of the reconstruction of the FROG trace is 6×10^{-3}. From this measurement, the temporal and spectral pulse shape as well as the phase of the optical pulse are reconstructed. Figure 2b displays the spectral shape of the ps pulses. The width of the reconstructed spectrum is 0.14 nm (FWHM). This value agrees well with the one obtained from the spectrum recorded with the Ando spectrometer. Figure 2c shows the temporal pulse shape and its phase. As seen from this figure, the temporal profile is almost symmetric, and the width is 13.4 ps (FWHM). Figure 2b and c also show the spectral and temporal phase. The dependance of the phase on time and wavelength is almost parabolic, which indicates that the wavelength of the pulses are linearly chirped, which causes an increase of the time-bandwidth product to a value of 0.67. A typical intensity autocorrelation of the generated pulses is shown in Fig. 2d. The measured autocorrelation trace with a width of 18.1 ps (FWHM) is also in good agreement with the trace reconstructed from the FROG measurement. With these measurements, the temporal and spectral characteristics of the pulses are fully characterized, which is beneficial for a systematic optimization of the following amplification process in order to obtain pulses with optimum power and lowest distortion of the temporal and spectral shape.

4.3 *Amplification in the pre-amplifier*

The amplification of picosecond pulses in optical semiconductor amplifiers changes the temporal and spectral pulse properties. The strong coupling between the charge carrier density and the refractive index causes non-linear phase changes during the amplification process, which results in dynamic changes of the light frequency. In the experiment it was most important to find operating conditions (with respect to amplifier current and optical input power), which minimize this influence on the shape and phase of the amplified pulses. As a result of these investigations, it was found that

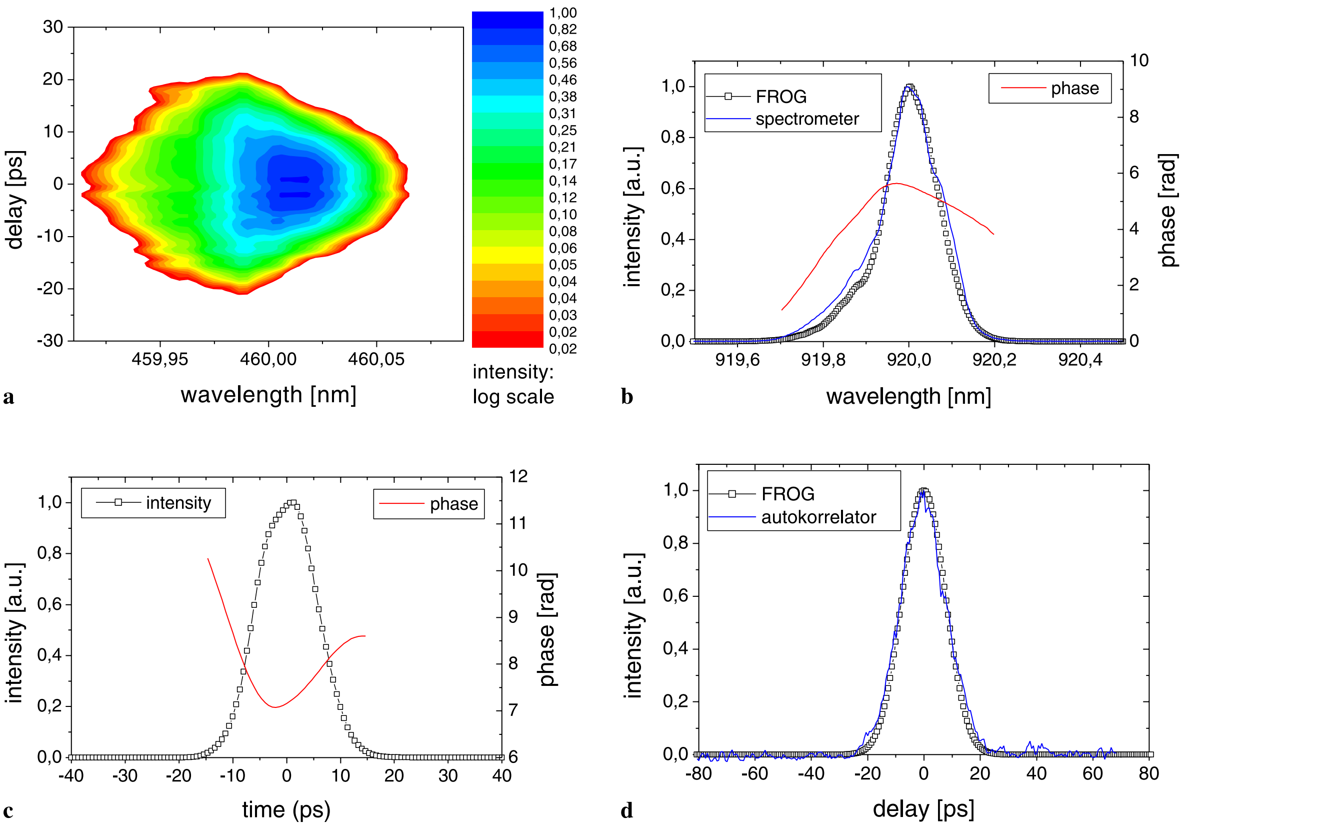

FIGURE 2 (**a**) Measured FROG trace of a typical pulse emitted by the oscillator at a repetition rate of 4.3 GHz. (**b**) Reconstructed and directly measured spectrum (0.14 nm FWHM) and the spectral phase of the pulse. (**c**) Temporal intensity profile (13.4 ps FWHM) and temporal phase. (**d**) Measured and reconstructed intensity autocorrelation (18.1 ps FWHM)

for an injection current of 85 mA (which generates an average optical output of 30 mW) no significant temporal and spectral pulse deformations were observed. For higher currents, the optical output power increased. The FROG measurements indicated, however, a strong change of the spectral and temporal pulse properties. Since a power of 30 mW is sufficient to saturate the amplification in the TA, no further investigations were required for optimizing the pre-amplification process.

4.4 *Amplification in the tapered amplifier*

The output of the pre-amplifier was further amplified in the tapered amplifier (TA). With an injection current of 6 A, the TA generated an output power of 2.7 W. Figure Fig. 3a shows the FROG measurement of the amplified pulses with a FROG error of 3×10^{-3}. The wavelength range of the FROG trace is 0.18 nm and the time delay is 60 ps. The shape of the reconstructed spectrum (with a width of 0.12 nm) is in good agreement with the spectrum recorded with the Ando spectrometer (Fig. 3b).

The temporal intensity profile (shown in Fig. 3c) with a width of 13.7 ps is slightly non-symmetric. This is in good agreement with the profile obtained from independent measurements with a streak camera (Optronis Optoscope) shown in Fig. 4. The sign of the phase of the pulse can be determined from the asymmetry of the pulse shape. The temporal phase shows a cubic dependence, which indicates a parabolic chirp that causes an intensity modulation of the pulse spectrum. The corresponding time-bandwidth product is 0.55. An intensity autocorrelation of the amplified pulses is shown in Fig. 3d.

The measurements shown in Fig. 3 indicate an asymmetry of the temporal pulse shape with a steeper leading edge and a flatter trailing edge. This asymmetry, which increased with output power, can be attributed to substantial gain depletion in the TA. In addition, with increasing saturation of the amplifier, the temporal phase changed from a parabolic to a cubic shape (which is due to self-phase modulation). For optimum operating conditions, the spectral and temporal width of the amplified pulses are close to those of the oscillator. It should be mentioned that higher optical input into the tapered amplifier (which is obtained by increasing the current in the pre-amplifier) enhances the broadening of the pulse spectrum and the temporal width. Because of the saturation effects and the associated self-phase modulation, these pulse distortions are further enhanced by the amplification in the tapered amplifier.

4.5 *Operation at lower repetition rates*

The SHG conversion efficiency depends strongly on the peak power of the pulsed radiation. For the same average output power, a further improvement can usually be achieved at lower repetition rates because of an increase of the pulse peak power.

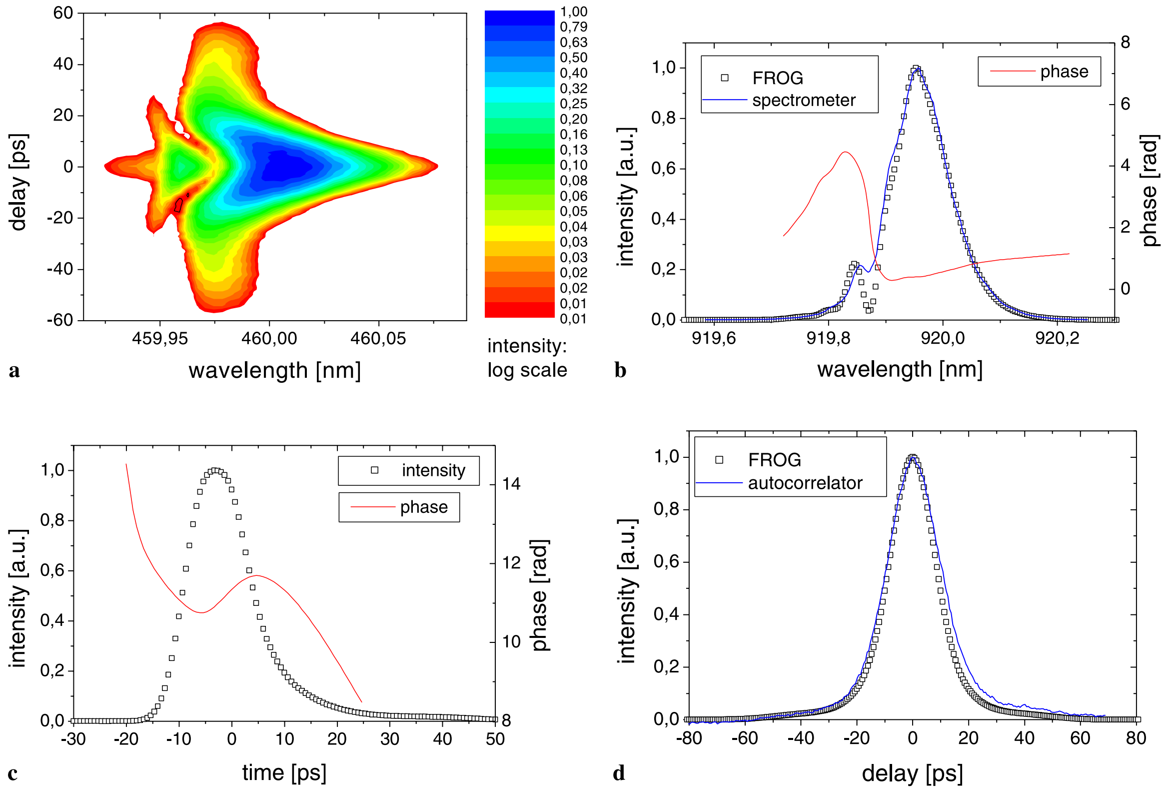

FIGURE 3 (**a**) FROG measurement of the ps pulses amplified in the tapered amplifier. (**b**) Reconstructed and directly measured spectrum with a width of 0.12 nm. (**c**) Temporal phase and intensity profile (13.7 ps FWHM). (**d**) Measured and reconstructed intensity autocorrelation

However, with the same oscillator current of 10 mA and a repetition rate of 1.7 GHz, the pulses split up into two pulses. Because of the higher oscillator intracavity pulse energy, the non-linear effects (self-phase modulation) in the laser active medium are much stronger. The main pulse has a width of 9 ps and the second pulse a width of 10 ps. The temporal spacing between the pulses is 54 ps and depends on the intracavity power and thus on the oscillator current. The average optical output of the oscillator was 0.7 mW. The oscillator DC current had to be reduced from 10 to 7 mA in order to maintain single-pulse emission. Therefore the average optical output of the oscillator decreased to 0.45 mW. Because of the lower average oscillator output, the current of the preamplifier had to be increased to 100 mA in order to generate the same optical power of 30 mW required for gain saturation in the tapered amplifier. The higher current had several disadvantages. First, the amplified spontaneous emission (ASE) between consecutive pulses increases because of the high intrinsic gain. The ASE limits the inversion and thus the amplification of the input pulses. Second, the average optical output power drops as seen from Fig. 5, which shows the average output power in dependence of the repetition rate. For a repetition rate of 1.7 GHz, the average power of the amplified pulses is 80% of the optimum output. With increasing repetition rate the gain is almost saturated by the injected ps pulses, which reduces the amount of ASE radiation with a corresponding increase of the average power of the amplified pulses. These measurements confirm the advantage of higher repetition rates such as 4.3 GHz.

5 Second harmonic generation

The second harmonic of the continuous and mode-locked 920-nm radiation was generated in PPKTP crystals (provided by Raicol Crystals Ltd.) with a grating period of 5.5 μm as calculated from the Sellmeier equations for room temperature (20 °C) [10]. The length of the crystal used for the conversion of cw radiation was 30 mm. Since the bandwidth of the amplified ps pulses (0.12 nm) exceeded the spectral acceptance of the 30-mm-long PPKTP crystal, the crystal length had to be reduced. With a spectral acceptance bandwidth of 0.18 nm cm the calculated optimum crystal length was 15 mm. In the experiment, however, we found that a 20-mm-long PPKTP crystal provided the highest SHG output power.

5.1 *SHG of cw MOPA radiation*

In cw operation, the MOPA system generates an output power of up to 3.4 W. Frequency doubling of this 920-nm radiation in the 30-mm-long PPKTP crystal provided 370 mW of blue 460 nm light. This output power corresponds to a conversion efficiency of 10.9%. The dependence of the power of the 460-nm second harmonic on the infrared input power is shown in Fig. 6. These measurements indicate a slope efficiency of about 3.2%/W.

Recently, Maiwald et al. [11] reported for the same infrared laser power a second harmonic power of 510 mW at 488 nm generated in a 30-mm-long ppMgOLN crystal heated to 70 °C. This output corresponds to an optical conversion of 15%. The reason for the higher conversion can be attributed to the higher nonlinear coefficient of PPMgOLN ($d_{\text{eff}} =$

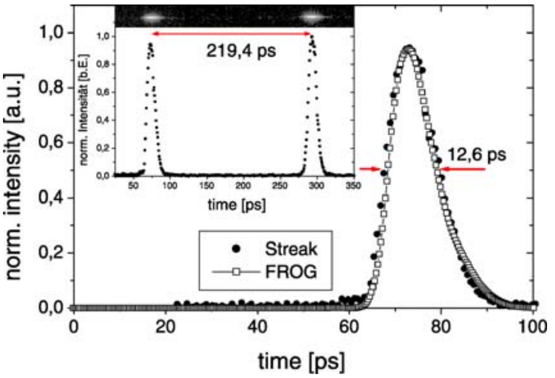

FIGURE 4 Temporal pulse profile measured with a streak camera (Optronis Optoscope) (*closed circles*) and reconstructed from the FROG measurement (*open squares*)

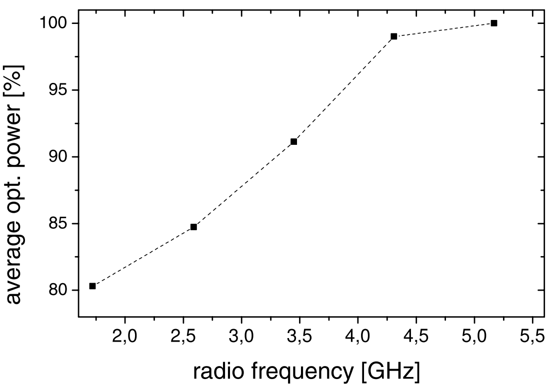

FIGURE 5 Measured average optical output power in dependence of the pulse repetition rate for an optical input power of 30 mW and a TA current of 6 A. The 100% level corresponds to the output power measured for a cw input power of 30 mW. The *dotted line* is drawn as a guide for the eye

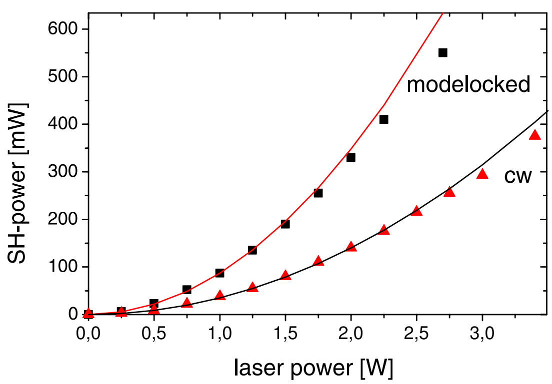

FIGURE 6 Measured dependence of the power of the blue second harmonic (SH) of 920 nm cw and mode-locked MOPA radiation. The length of the PPKTP crystal used was 30 mm for cw and 20 mm for mode-locked radiation. For comparison, the quadratic dependence of the power of the frequency-doubled output on the laser power is shown as a *solid line*. The deviation from the expected quadratic dependence is caused by power depletion of the laser radiation

19 pm/V [12]) compared to the d_{eff} (of 11.8 pm/V [13]) of PPKTP.

PPKTP offers, however, several advantages. It shows no blue-induced infrared absorption (BLIRA), and the manufacturing of crystals with the required short poling periods of about 5.5 μm is well established. PPKTP crystals are thus available in good optical quality and since they show no photo refractivity it is well suited for operation at room temperature.

5.2 *SHG of mode-locked MOPA radiation*

The frequency doubling of the mode-locked output of the optimized MOPA system in a 20-mm-long PPKTP crystal provided a second harmonic power of 550 mW. The measured dependence of the average power of the second harmonic on the power of the infrared MOPA radiation is also shown in Fig. 6.

With a fundamental average power of 2.7 W, the conversion slope efficiency was 7.6%/W and the conversion efficiency was 20.3%. The conversion efficiency of the mode-locked radiation is thus two times higher than the one obtained with cw radiation, although the length of the PPKTP crystal used is only two-thirds the one used for doubling the cw radiation. This result demonstrates the advantage of using mode-locked radiation for the generation of visible radiation by frequency doubling of the infrared output of diode laser MOPA systems.

6 Summary

The MOPA system we have investigated consists of the InGaAs diode laser oscillator with an external Littrow cavity, a single-stripe pre-amplifier, and a high-power tapered amplifier. In cw operation, the system provides an output power of up to 3.4 W at 920 nm. Seventy-five percent of the optical output is contained in a beam with an M^2-value of less than 1.1. For mode-locked operation, the oscillator was actively mode-locked by driving the oscillator with a DC current of 10 mA and a sinusoidal rf power of 24 dBm.

With FROG analysis of the oscillator pulses and the amplified pulses, it was possible to determine the optimum injection current, input power, and pulse repetition rate for the amplification of picosecond pulses in the amplifier stages of the MOPA system with respect to subsequent frequency conversion. With increasing output power, the measurements show an increasing asymmetry in the temporal pulse shape, i.e., a steeper leading edge and a flatter trailing edge. These effects can be attributed to substantial gain depletion in the diode laser amplifiers. In addition, the temporal phase changes with output power from a parabolic to a cubic shape. Frequency doubling of the cw radiation in a 30-mm-long PPKTP crystal provided 370 mW of blue 460-nm light. This output power corresponds to a conversion efficiency of 10.9%. With ps pulses with a repetition rate of 4.3 GHz, a power of 550 mW was generated at 460 nm by single-pass frequency doubling of the 2.7 W of near-infrared pulsed radiation in a 20-mm-long PPKTP crystal. This corresponds to a conversion efficiency of 20.3%.

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