Recent advances in non-linear frequency conversion of high-power, single-mode diode lasers

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ABSTRACT

Frequency conversion of near-infrared diode lasers provides an efficient method to generate tunable laser radiation in the near-UV, violet and blue-green spectral range. High-power, coherent fundamental laser sources such as master oscillator–power amplifier (MOPA) configurations are now state of the art and commercially available.

A new, highly efficient material for second-harmonic generation (SHG) is Bismuth Triborate ("BiBO", stoichiometry BiB3O6). The material has a high effective non-linearity d_{eff}, is non-hygroscopic and transparent for wavelengths between 286 nm and 2.5 µm. Compared to other non-linear crystals, "walk-off" effects between fundamental laser radiation and frequency-doubled beam are considerably lower. We used a BiBO crystal in a resonant doubling cavity to convert the output of a 780 nm, 900 mW tapered amplifier system. A maximum UV power of 400 mW (conversion efficiency 44%) was attained. This value is 3-4 times higher than previous results obtained with LBO or BBO crystals and, to the best of our knowledge, represents the highest tunable cw power of a frequency-converted diode laser.

Keywords: nonlinear optics, frequency conversion, UV laser radiation

1. INTRODUCTION

Nonlinear frequency conversion extends the spectrum of diode-based laser systems to wavelengths which cannot be reached with a single laser diode. In particular, UV laser radiation is difficult to achieve without nonlinear frequency conversion. Several non-linear optical crystals like $KNbO_3$[1], $LiNbO_3$[2] and KTP[3] are available and have been proven suitable for highly efficient second harmonic generation into the visible spectral range. Unfortunately these crystals are not suitable to generate UV radiation via second harmonic generation, either because they are not transparent for UV light or because phase matching cannot be achieved. Periodically poled nonlinear crystals further extend the range, provided that noncritical phase matching can be realized. Periodically poled $LiNbO_3$ has been employed for efficient frequency conversion into the blue spectral range[4] and even to the UV (360nm)[5]. However, the fabrication of these crystals for SHG to the UV range is difficult; moreover, crystals are not commercially available for non-standard wavelengths.

The commonly used and well-known crystals for generating UV laser light, LBO[6] and BBO[1],have several disadvantages. The effective non-linearity d_{eff} of LBO is between 7.34*10-1 pm/V at 780nm and 8.32*10-1 pm/V at 1060nm, which is an orders of magnitude lower than that of KNbO3 (8.2 pm/V at 1060nm). BBO, on the other hand, has a relatively large d_{eff} , 2.01 pm/V at 1060nm and 1.99 pm/V at 780nm, but also a large walk-off which reduces the conversion efficiency. Furthermore, BBO is hygroscopic, which limits the lifetime of the crystal. Efficient frequency generation into the UV with LBO and BBO has been demonstrated, but only for high fundamental laser power, long crystals and short laser pulses. Therefore, the search for new materials for efficient frequency conversion of low power cw-laser radiation into the UV range is of high practical interest.

In this paper, we report on the use of a BIBO crystal in a resonant enhancement cavity, which is a very sensitive setup to test the performance of the crystal. Due to the high finesse of the cavity, which is needed to achieve an efficient frequency conversion, the cavity is sensitive to different loss mechanisms caused by the crystal, e.g. scattering losses , one and two photon absorption or thermal lensing effects.

2. THEORETICAL BACKGROUND

The power $P_{2\omega}$ of the frequency converted light can be written as

$$P_{2\omega} = \eta P_\omega^2 = K P_\omega^2 l k_1 h(\sigma, B, \xi)$$

with

$$K = \frac{2\omega^2 d_{eff}^2}{\varepsilon_0 n_1^2 n_2 c^3 \pi} .$$

Here, η denotes the conversion efficiency while P_ω is the fundamental power. The conversion efficiency η depends on several parameters: l is the length of the crystal, k_1 the absolute value of the wavevector, n_1 and n_2 the indices of refraction of the fundamental and the second harmonic wave, d_{eff} the effective nonlinearity, ε_0 the dielectric constant and c the vacuum speed of light.

The h-function describes the influence of the focusing parameter $\xi = \frac{l}{b_0}$, the phase mismatch σ and the walk-off parameter B on the conversion efficiency and is defined as

$$h(\sigma, B, \xi) = \frac{1}{4\xi} \int_{-\xi}^{\xi} \int_{-\xi}^{\xi} \frac{e^{i\sigma(\tau-\tau')} e^{-B^2(\tau-\tau')^2/\xi}}{(1+i\tau)(1-i\tau')} d\tau d\tau' .$$

For a given crystal, $h(\sigma, B, \xi)$ can be maximized with respect to ξ and σ, while B is a constant, representing double refraction. With $b_0 = 2\frac{\pi\omega_0^2}{\lambda}$, the optimum beam waist in the crystal is defined.

The value of η is usually a small number in the range from $10^{-4}\ W^{-1}$ to $10^{-2}\ W^{-1}$, depending on the crystal properties and beam parameters. A detailed description of nonlinear frequency conversion can be found elsewhere[7].

The power of the second harmonic radiation generated by single pass frequency doubling is limited by the available power of the fundamental laser source, the crystal length and the effective nonlinearity of the crystal. Thus, higher second-harmonic power can be achieved with significantly higher fundamental power. A promising method to increase the available fundamental power is the resonant enhancement of cw radiation in a high finesse cavity.

The enhancement factor for the incident radiation in a high finesse cavity can be calculated, according to

$$E := \frac{1-R_{ic}}{(1-\sqrt{R_{ic} R_m})^2} .$$

Here, R_{ic} denotes the reflectivity of the incoupling mirror, R_m the reflectivity of the remaining resonator without the incoupling mirror. Thus R_m contains the passive losses of the remaining resonator mirrors as well as passive losses and conversion losses within the crystal.

For a given reflectivity R_m of the cavity, the enhancement reaches a maximum if the transmission of the incoupling mirror T_{ic} equals R_m, as shown in Figure 1.

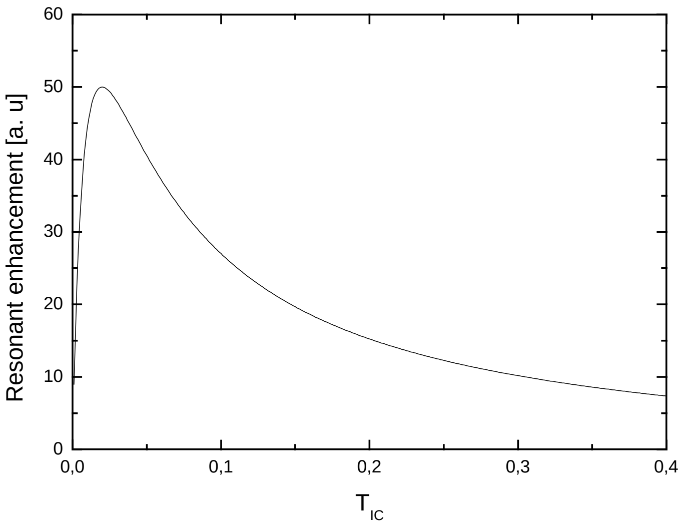

Figure 1: Cavity enhancement as a function of the transmission of the incoupling mirror

Since the second-harmonic power increases quadratically with the intracavity fundamental power, it is of high importance to minimize any passive cavity losses which would otherwise reduce the intracavity power. Thus, the utilized nonlinear crystal ideally shows low absorption and scattering losses. A criterion of equally high importance is proper impedance matching, as shown in Figure 1, to maximize the enhancement of the intracavity power.

3. EXPERIMENTAL SETUP

Our experimental setup is shown in Figure 2:

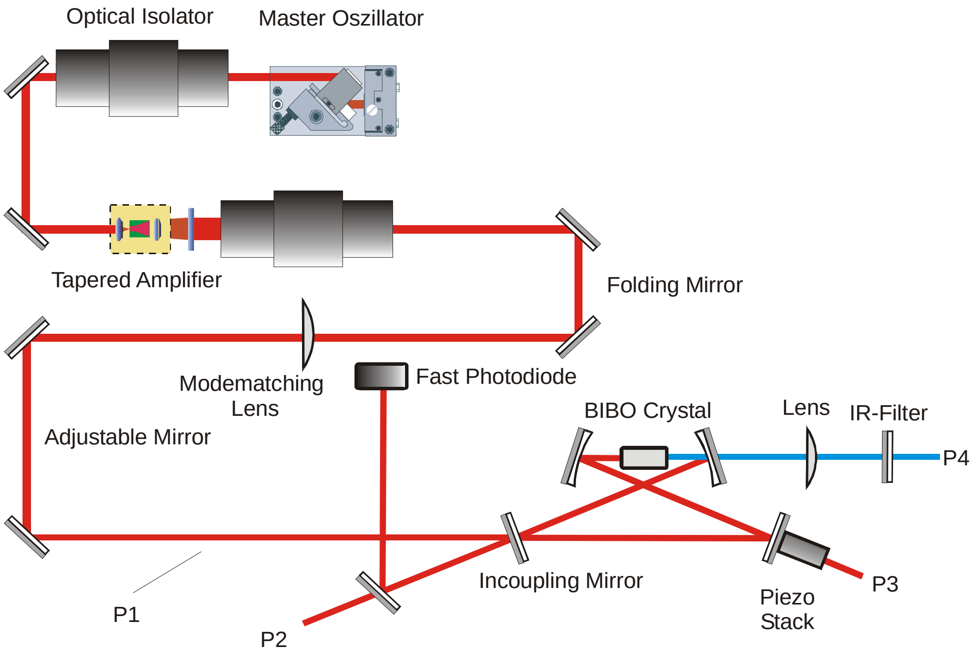

Figure 2: Experimental setup

To test the performance of the BiBO crystal, we used a frequency stabilized external-cavity diode laser in Littrow configuration, operating at 780nm. The emitted laser radiation was single pass amplified in a tapered amplifier, which maintained the spectral properties of the diode laser. A 60 dB isolator between the external-cavity laser and the tapered amplifier was used to avoid optical feedback into the laser diode. A second isolator was placed behind the amplifier to prevent feedback into the amplifier. In this setup a fundamental power up to 900mW was achieved and used as fundamental laser radiation in the enhancement cavity. The output beam of the tapered amplifier passed a spherical lens to match the beam to the mode of the enhancement cavity. The size of the beam waist between the two plane mirrors was 140µm in the tangential and 178µm in the sagittal plane which can be matched with a lens with a focal length of 500mm. We used a 10mm long BiBO crystal, cut for critical phase matching and normal incidence and antireflection coated for 780nm and 390nm. We tested a crystal with coated facets instead of a brewster-cut crystal, in order to examine if the coating would be damaged due to photochemical reactions on the faces of the crystal, as reported previously for BBO[8].

Our enhancement cavity was a four-mirror bow-tie resonator, with two plane and two curved mirrors with a radius of curvature of 38mm. The distance between the curved mirrors was 46mm; the total distance for one complete round trip was 246mm. The angle of incidence on the mirrors was 12°. This setup provided a stable resonator with a beam waist in the crystal center of 22.94µm in the tangential and 22.9µm in the sagittal plane, which is close to the optimum waist of 22.18µm. In order to lock the cavity length to the laser frequency, we employed the Pound-Drever-Hall method, which applies side-band modulation of the laser source to generate a phase sensitive error signal[9]. The error signal was used to control the cavity length by moving one of the plane mirrors, which was attached to a piezo stack. With this setup, stable and reliable laser operation was achieved. After a few minutes warm up time, the UV output power was constant for several hours without any realignment.

To achieve maximum enhancement, the transmission of the incoupling mirrors is calculated to be 1.5% for a fundamental power of 900mW, passive resonator losses of 0.5%, and a conversion efficiency η of 2.51% W^{-1}. Due to the sensitivity of the enhancement cavity to losses it turned out to be advantageous to use a slightly higher transmission of the incoupling mirror. Thus, a mirror reflectivity of 97.6% was chosen. To characterize the system, we measured three relevant power values. First, the fundamental power P1 was measured in front of the incoupling mirror. By measuring the power P2 in the resonant and non-resonant case the coupling efficiency into the cavity could be calculated. To assess the enhanced cavity power the leakage through one of the HR cavity mirrors was measured (P3). As the mirror reflectivity is known, the power in the cavity can be calculated. The UV power (P4) was measured behind a color glass filter (BG38) to block the residual IR light. The power values were corrected for the transmission of the UV light through the filter.

4. MEASUREMENTS AND RESULTS

Figure 3 shows the measured SHG power as function of the power in the enhancement cavity. The internal power was calculated from the power P3 and the measured reflectivity of the HR mirror of R=0.9996. A nonlinear curve fit to the data points yields a conversion efficiency of $\eta = 2.251*10^{-4}W^{-1}$. This value is slightly higher than the value of $\eta = 2.125*10^{-4}W^{-1}$, which can be calculated with d_{eff} = 2.26pm/V, given by SNLO[10].

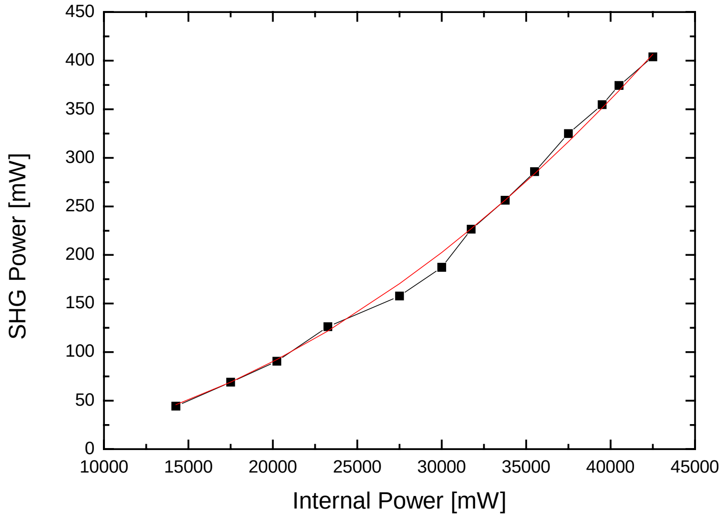

Figure 3: Second harmonic power as function of the intracavity power. Squares: measured data, red line: non-linear least squares fit to determine the conversion efficiency η.

Figure 4 shows the SHG power as function of the tapered amplifier output power. The measured coupling efficiency from the fundamental beam to the enhancement cavity is 74%, the passive cavity losses are estimated to be 0.5%. With the fixed transmission loss of the incoupling mirror of 2.4% and a conversion efficiency of $2.251*10^{-4}W^{-1}$, the theoretical enhancement and thus the estimated SHG power can be calculated. Both the calculation and our measurements show good agreement with literature values.

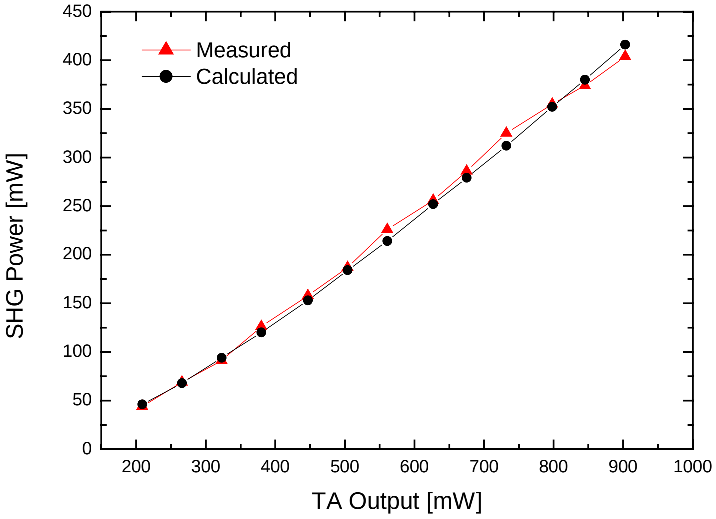

Figure 4: Measured and Calculated SHG power as function of the TA power

Figure 5 shows the second harmonic conversion efficiency as function of the tapered amplifier power. The conversion efficiency is increasing from low to high power, because of the selected transmission of the input coupler, which is optimized for high fundamental power. A maximum conversion efficiency of 44% is obtained for a fundamental power of 900 mW.

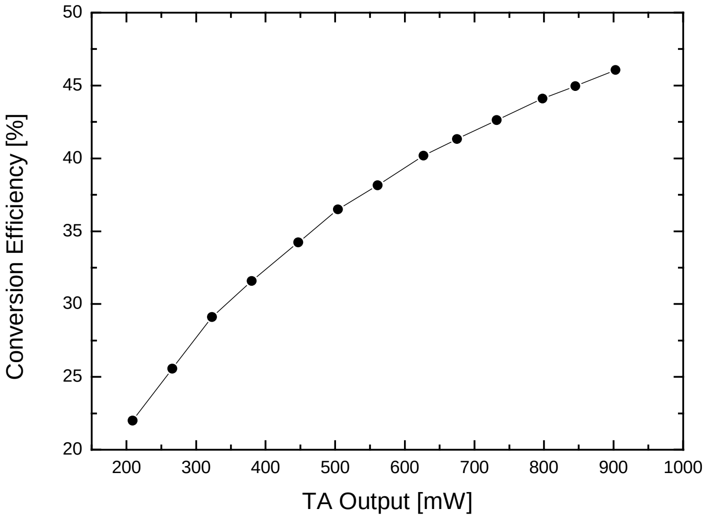

Figure 5: Conversion Efficiency as function of the TA output power

5. CONCLUSION AND OUTLOOK

We presented an all solid state laser system operating at 390nm. The fundamental laser beam from an amplified diode laser was frequency doubled in an enhancement cavity. The nonlinear optical crystal was a BiBO crystal of 10mm length. The crystal facets were cut for normal incidence and antireflection coated. At a fundamental power of 900mW, more than 400mW of UV radiation @ 390 nm were obtained. No damage of the coated crystal surface was observed. The conversion efficiency thus amounted to 44%, which is a factor of 3-4 higher than previous results obtained with LBO. With the locked cavity, stable laser operation could be maintained for several hours. No power losses or stability problems caused by the crystal were detected.

Taking these results into account, BiBO crystals can be used to generate efficiently second harmonic output in the entire range from 286nm to about 500nm, where other nonlinear crystals with higher conversion efficiency are available.

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