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Efficient concept generating 3.9 W of diffraction-limited green light with spectrally combined tapered diode lasers

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ABSTRACT

We propose an efficient concept increasing the power of diode laser systems in the visible spectral range. In comparison with second harmonic generation of single emitters, we show that spectral beam combining with subsequent sum-frequency generation enhances the available power significantly. Combining two 1060 nm distributed Bragg reflector tapered diode lasers ($M^2_{4\sigma} \leq 5.2$), we achieve a 2.5-3.2 fold increase of green light with a maximum power of 3.9 Watts in a diffraction-limited beam ($M^2_{4\sigma} \leq 1.3$). Without any further stabilization the obtained power stability is within ± 2.6 %. The electro-optical and nonlinear conversion efficiencies at maximum performance are 5.7 % and 2.6 %/W, respectively. Due to the intrinsic wavelength stabilization of the diodes we achieve single-mode emission with a side-mode suppression > 15 dB and a spectral width as narrow as 5 pm. These results increase the application potential of green diode laser systems, for example, within the biomedical field. In order to enhance the power even further, our proposed concept can be expanded combining multiple diode lasers.

Keywords: Diode lasers, Spectral beam combining, Harmonic generation, Sum-frequency generation

1. INTRODUCTION

Green laser systems with high output power and diffraction-limited beam quality are of high importance in many aspects. A major application within the biomedical field is direct pumping of titanium sapphire (Ti:S) lasers. These lasers are capable of emitting high-intensity femtosecond pulses required for applications such as two-photon microscopy [1] or coherent anti-Stokes Raman scattering microscopy [2]. In addition, the broad band emission of Ti:S lasers is ideally suited for optical coherence tomography [3]. Direct pumping of Ti:S lasers requires to overcome high thresholds. With an absorption maximum around 500 nm [4], pump lasers should ideally provide a few watts of blue-green emission at high electro-optical efficiencies without adding to the size of Ti:S laser systems.

Diode lasers represent the most efficient solution towards laser emission [5]. Direct green light emitting diode lasers currently provide up to 170 mW [6], limited by material properties of the diodes. As an alternative, diode pumped $Pr3+$-doped laser crystals provide more than 700 mW at 523 nm [7]. Much higher output power is achieved by nonlinear frequency conversion. For example, multiple tens of watts were obtained by external or intra-cavity frequency conversion of continuous-wave (CW) solid-state lasers [8,9]. Resonant cavity configurations provide high optical conversion efficiencies but become increasingly complex in order to achieve reliable performance. A much simpler solution is a single-pass configuration. Using solid-state lasers, up to 16.1 W (CW) were obtained [10]. A major disadvantage of frequency converted solid-state lasers is the requirement of two conversion processes, reducing the electro-optical efficiency. The question remains, whether diode lasers can overcome these limitations, generating diffraction-limited, mid-power range green light, as required for many biomedical applications, in a more efficient manner?

In addition to their high efficiency, the material compositions of diode lasers offer an emission wavelength tunability that is not limited to certain atomic transitions. Dimensions of only a few mm^3 also allow for compact and cost-efficient laser systems. However, in order to obtain several watts of green laser emission, high-power diode lasers with good spatial and spectral quality are required.

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In this context, 1060 nm distributed Bragg reflector (DBR)-tapered diode lasers with more than 10 W (CW), single-mode emission, and nearly diffraction-limited beam qualities were demonstrated [11]. Single-pass frequency conversion enabled generating a maximum of 1.5 W of green light [12]. In addition, a more compact setup based on these lasers was applied for direct pumping of Ti:S lasers [13], being one of the most critical applications for green laser systems. Unfortunately, the maximum performance of such green diode laser systems is limited by thermal degradation and beam filamentation at high currents. In order to further increase the diffraction-limited power of green diode laser systems we propose spectral beam combining of two DBR-tapered diode lasers in conjunction with sum-frequency generation (SFG). Using two DBR-tapered diode lasers ($M^2_{4\sigma} \leq 5.2$), combining efficiencies above 90% are obtained. Subsequent SFG increases the amount of green light by a factor of 2.5-3.2 compared to SHG of a single emitter. At maximum performance 3.9 W of diffraction-limited green light ($M^2_{4\sigma} \leq 1.3$), with an optical-optical conversion efficiency as high as 24.8%, are achieved, confirming the feasibility of the proposed scheme.

2. SPECTRAL BEAM COMBINING

Beam combining represents a means towards increased output power of moderately operated laser systems [14]. Power scaling is simply obtained by increasing the number of lasers. Coherent beam combining requires a precise control of wavelengths and phase relations between the lasers and becomes increasingly complex the more elements that have to be combined. Incoherent beam combining allows for much simpler setups. The most straightforward technique is polarization coupling [15], combining two orthogonal polarized lasers, e.g., by using a polarizing beam splitter. However, orthogonal polarizations limit the utilization of the highest nonlinear coefficient of typical crystals for green light generation [16]. A solution is spectral beam combining, where two or more lasers at different emission wavelengths are incoherently combined [14]. Despite combining efficiencies as high as 99% obtained with diffraction gratings [17], typical wavelength separations of several nanometers limit the use of comparable diode lasers. For example, the tuning capability of the above mentioned DBR-tapered diode lasers (≈ 0.1 nm/K) requires large changes in laser temperature causing a serious reduction in performance. Based on the grating equation [18],

$$sin\,\theta = m\frac{\lambda}{\Lambda}, \tag{1}$$

with θ being the diffraction angle, m the diffraction order (m = 1, 2, 3, …), λ the incident wavelength and Λ the grating period, shorter wavelength separations require small angular differences, and therefore large source-to-grating distances in order to spatially separate individual emitters. Diode laser arrays potentially overcome this limitation [19] but are limited by mounting induced smiles, negatively affecting the beam quality of the combined beam [20], and the loss in flexibility regarding an optimization of fundamental wavelengths for subsequent nonlinear interactions or an exchange of single emitters in case of failure.

Consequently, the method of choice for spectral beam combining of comparable diode lasers is to use volume Bragg gratings [21]. These gratings written in photo-thermo-refractive (PTR) glass are virtually transparent within a spectral range of 350 nm - 2700 nm and provide excellent thermo-mechanical properties [22]. Using such gratings up to 770 W (CW) were obtained by combining 5 fiber lasers with a combining efficiency > 91 % [22]. The corresponding wavelength separation of 0.5 nm can also be easily obtained with diode lasers by slight laser temperature changes. The underlying principle behind a volume Bragg grating (VBG) is based on Kogelnik's theory of coupled waves [23]. The diffraction efficiency (DE) depends to a large extent on the deviation from the Bragg wavelength and the corresponding Bragg angle. Once the Bragg condition is obtained, the DE of VBGs is close to unity. At multiple points offset from Bragg condition the DE is reduced to zero. Tuning the emission wavelength determines the behavior of the incident beam. Therefore, VBGs are ideally suited for spectral beam combining of comparable, wavelength tunable diode lasers [24]. However, the wavelength separation between the lasers needs to be carefully observed, see below.

3. EXPERIMENTAL SETUP

The setup illustrated in Figure 1 is based on two 6 mm long DBR-tapered diode lasers positioned at the same distance to the grating. Both lasers consist of a 1 mm long, passive DBR-section, a 1 mm long ridge waveguide section and a 4 mm long, 6° tapered amplifier. The ridge waveguide and the tapered amplifier are operated individually. Each laser is mounted p-side up on a CuW heat spreader on a 25 mm x 25 mm conduction cooled package (CCP) mount for efficient heat removal. Both lasers are collimated and corrected for astigmatism using aspheric (f = 3.1 mm, NA = 0.68) and cylindrical lenses (f = 15 mm). This results in circular beams with a diameter of about 2 mm.

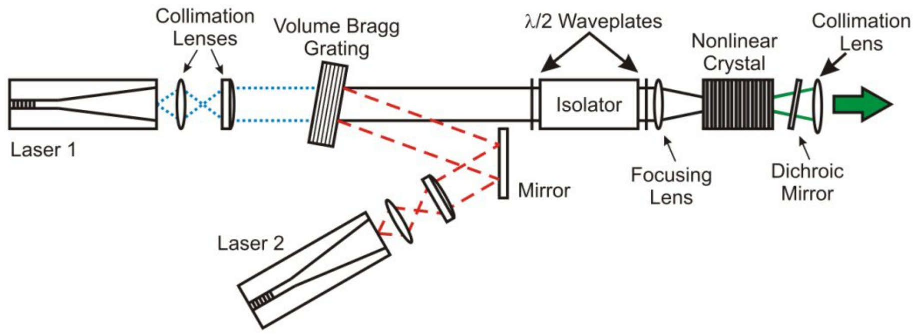

Figure 1. Experimental setup for spectral beam combining of DBR-tapered diode lasers with subsequent SFG.

Spectral beam combining is obtained with a L x W x H = 3.4 mm x 10 mm x 10 mm reflecting VBG (*OptiGrate*). The grating has an average DE of 99.2% at 1062 nm. With a spectral selectivity of $\Delta\lambda_{FWHM}$ = 0.3 nm this grating is ideally suited for beam combining of DBR-tapered diode lasers, providing emission bandwidths as low as 10 pm [11]. The Bragg angles at 1062 nm are 6.4° and -6.7°. Laser 1 not fulfilling the Bragg condition is transmitted by the grating. The diffraction of laser 2 in the same direction as the transmitted beam is achieved by optimizing its angle of incidence and the emission wavelength. Once both lasers are combined, wavelength tuning of laser 1 can be utilized to change the wavelength separation between the two lasers. However, the resulting separation is crucial and needs to be carefully observed. Using a VBG prevents short wavelength separations because of increased diffraction. Therefore, a trade-off has to be made between wavelength separation and combining efficiency.

In order to prevent optical feedback a combination of a 30 dB optical isolator and two half-wave plates is used. An achromat (f = 75 mm) generates a beam waist around 42 µm inside a 30 mm plane cut, periodically poled, MgO-doped lithium niobate crystal (*HCPhotonics*) for efficient SHG and SFG. The poling period is 6.92 µm enabling phase-matching at temperatures around 40 °C. The focus is larger than predicted according to Boyd-Kleinman theory [25], but proved to be optimum value in our experiments. The generated and fundamental emissions are separated using a dichroic mirror. An optional spherical lens is used in order to collimate the generated green emission for further experiments.

4. EXPERIMENTAL RESULTS

In the experiments the ridge waveguides of both lasers are operated at 300 mA. The tapered amplifiers are operated at 6 A, 8.5 A, 11 A, 13.5 A and 16 A. The overlap between both beams is observed using two beam scanners. Figure 2 shows the corresponding beam waist profiles at I_{TA} = 6 A. The far field of the combined beam is shown in Figure 3.

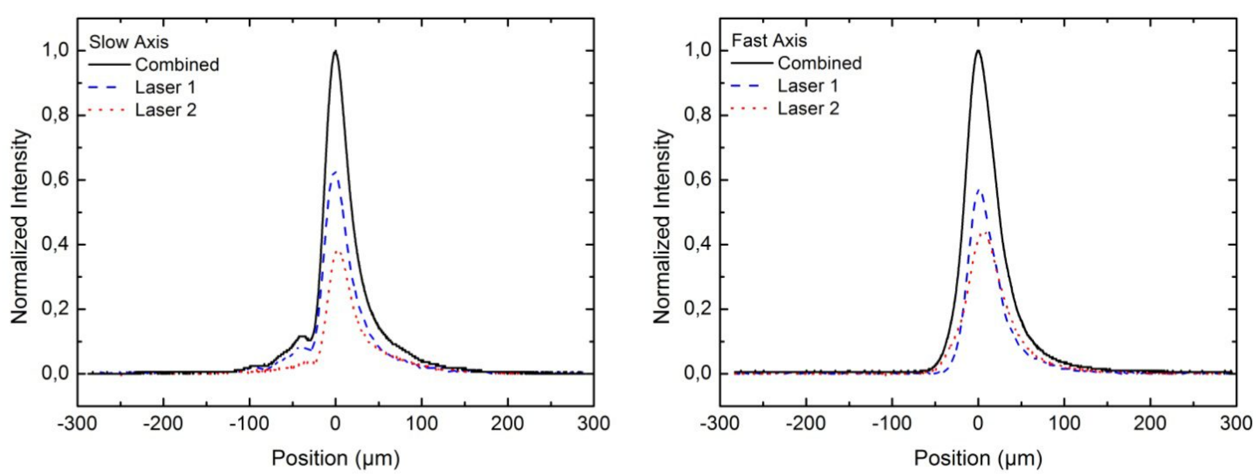

Figure 2: Beam waist profiles of two spectrally combined DBR-tapered diode lasers at injection currents of I_{TA} = 6 A.

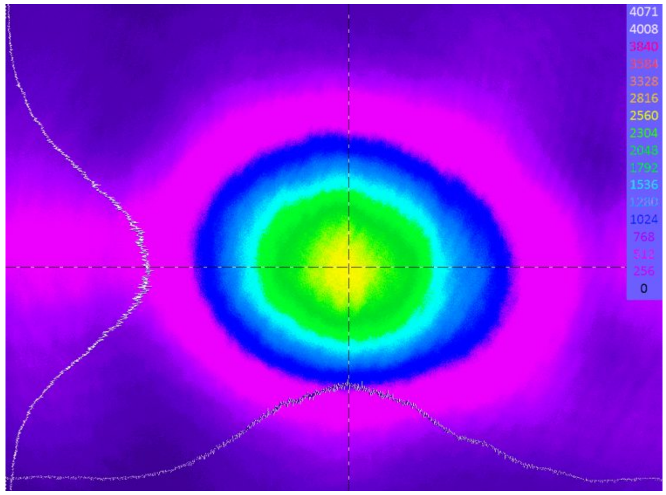

Figure 3: Far field image of two beam combined DBR-tapered diode lasers at injection currents of I_{TA} = 6 A.

Both figures indicate a good overlap obtained by optimizing laser wavelengths and angles of incidence. The intensity contained in the side lobe of the slow axis beam waist profile of laser 1 is also reproduced in the combined beam and the far field image.

The results achieved by spectral beam combining of two DBR-tapered diode lasers are illustrated in Figure 4. At injection currents of I_{TA} = 6 A an output power of 5.1 W is obtained. At I_{TA} = 16 A up to 18.0 W are achieved, which results in a slope efficiency of 1.3 W/A. The inset in Figure 4 illustrates that combining efficiencies up to 90% - 92% are obtained at all settings. The measured beam qualities of the combined beam are $M^2_{4\sigma} \approx 2$ in the fast axis and $M^2_{4\sigma} \approx$ 4-5 in the slow axis, with reduced qualities at higher injection currents.

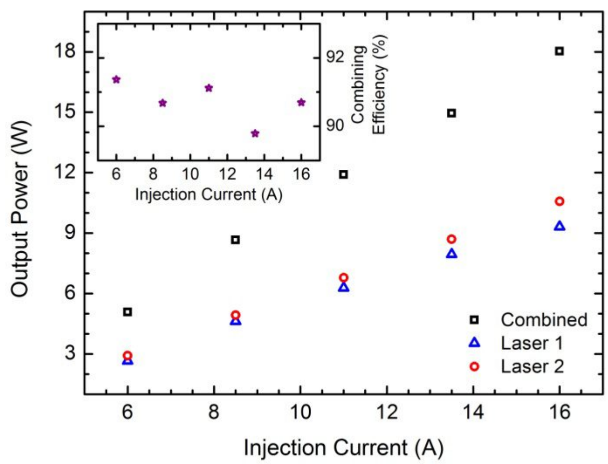

Figure 4: Output power of individual and beam combined DBR-tapered diode lasers at different injection currents. The inset shows the corresponding combining efficiencies.

Regarding frequency conversion three nonlinear interactions can be selected by changing the crystal temperature. Figure 5 shows the output power measured behind the nonlinear crystal as a function of crystal temperature at I_{TA} = 6 A. The three contributions are clearly separated from each other depending on the wavelength separation of the two lasers. Shifting the emission wavelength of laser 1 towards longer wavelengths also shifts the phase-matching temperatures for SFG and SHG. This enables eliminating contributions by SHG in case of SFG. The wavelength separation selected in the experiments is about 1 nm. The measured temperature tolerance in all cases is about 1.4 °C. The distinct side-lobes present next to the individual maxima potentially indicate poling non-uniformities along the crystal length. A rough estimation based on the quasi-phase-matching condition [26] shows that this behavior already results from poling period deviations of less than a few nanometers.

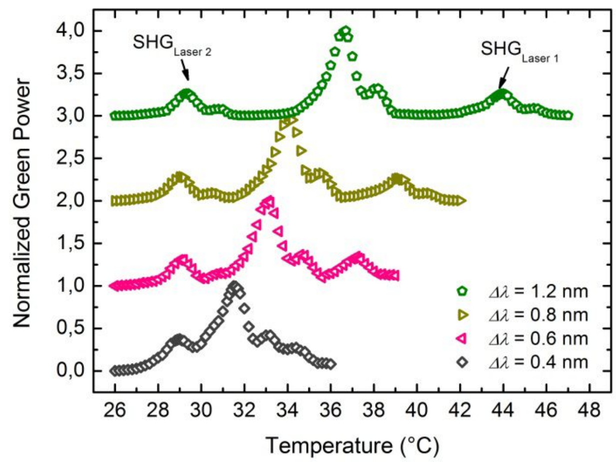

Figure 5: Measured green power as a function of crystal temperature at different wavelength separations.

Figure 6 shows the obtained results for frequency doubling of laser 1 and 2 as well as for SFG of the combined beam. At this setting SHG of the individual lasers results in a maximum of 0.16 W of green light, which corresponds to nonlinear efficiencies of 3.8 %/W and 3.4 %/W for laser 1 and 2, respectively. SFG leads to 0.53 W of green light with an efficiency of 3.2 %/W. Consequently, the amount of green light compared to SHG of a single laser is increased by a factor of 3.2.

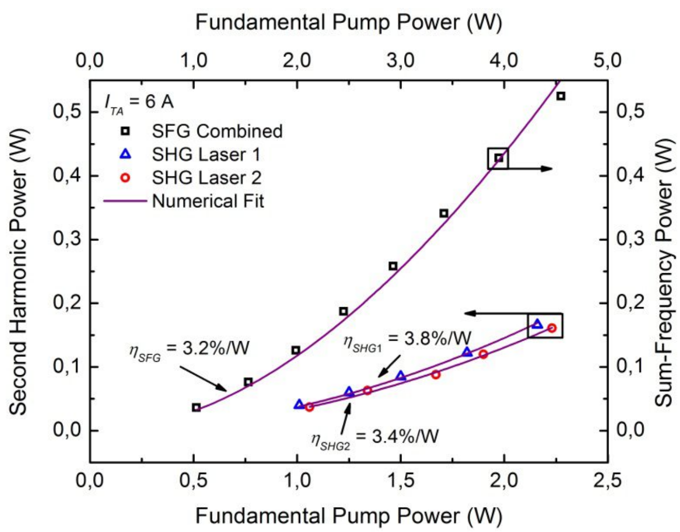

Figure 6: Output power for SHG and SFG versus fundamental pump power at I_{TA} = 6 A. The bottom left axes are used for the case of SHG, the top right axes for the case of SFG

The intensity of second harmonic generation (SHG) at phase-matching condition is given by the following relation [16]

$$I_3 = \frac{2\pi^2 d_{eff}^2}{n_3 n_1^2 \lambda_3^2 \varepsilon_0 c} I_1^2 L^2. \tag{2}$$

In case of SFG the intensity is given by

$$I_3 = \frac{8\pi^2 d_{eff}^2}{n_3 n_2 n_1 \lambda_3^2 \varepsilon_0 c} I_1 I_2 L^2. \tag{3}$$

It becomes obvious that in the ideal case, SFG of comparable lasers increases the amount of green light by a factor of 4 compared to SHG of a single laser. The deviation to the ideal case is affected by the overlap of the two beams, fundamental pump depletion, and intensity outside the central lobe of the beam profile that does not efficiently contribute to the generation of green light.

Regarding the nonlinear efficiencies given above, it should be noted that in the case of SFG the depleted pump approximation [12] is changed towards the following relation in order to express the increase in efficiency by a factor of 4 in comparison to SHG of a single laser

$$P_3 = \frac{P_1 + P_2}{2} tanh^2\left(\sqrt{4\eta\frac{P_1 + P_2}{2}}\right). \quad (4)$$

At increased injection currents (I_{TA} = 16 A) up to 1.6 W are obtained by SHG (Figure 7). In case of SFG a maximum of 3.9 W of green light is achieved [27]. With an available pump power of 15.7 W the optical conversion and nonlinear efficiencies for SFG are 24.8 % and 2.6 %/W, respectively. The reduction to an improvement factor of 2.5 compared to SHG of a single laser is to a high extent caused by reduced beam qualities in conjunction with decreased power content in the central lobe ($1/e^2$) and depletion of the fundamental beams. While the power content in the fast axis remains at 90% at all settings, the values in the slow axis drop from 81 % at 6 A down to 73 % at 16 A. This indicates the increased difficulty to obtain a proper overlap for efficient frequency conversion. The inset in Figure 7 shows an emission spectrum obtained by SFG at maximum performance. Due to the deviation in phase-matching temperatures for all three nonlinear interactions single-mode emission can be obtained. The spectrum shows a side-mode suppression > 15 dB and a spectral width as narrow as $\Delta\lambda_{FWHM}$ = 5 pm.

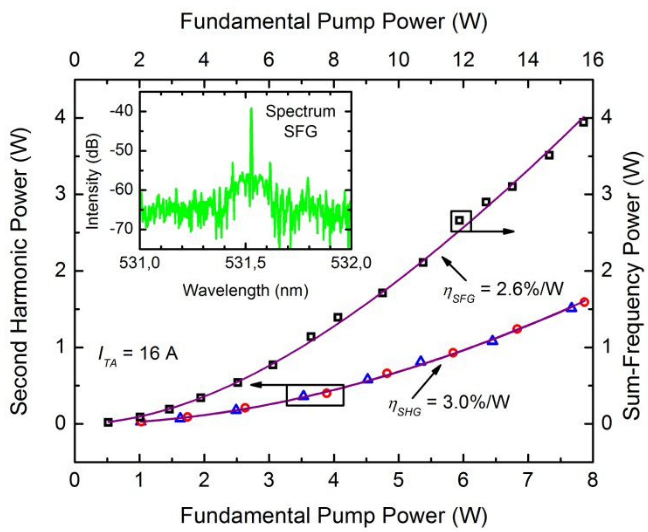

Figure 7: Output power for SHG and SFG versus fundamental pump power at I_{TA} = 16 A.

The power stability measured within one hour is ± 0.7% when excluding outliers (Figure 8). The maximum deviation in that timeframe is 2.6%. Due to direct electric pumping of diode lasers, the obtained stability can be easily improved by additional electronic feedback to the laser.

The spatial properties of the generated green light show diffraction-limited beam qualities with $M^2_{4\sigma}$ = 1.1 in the fast axis and $M^2_{4\sigma}$ = 1.3 in the slow axis, respectively (Figure 9). In conjunction with the obtained stability, this result indicates the absence of potential photorefractive damages at high pump power [28]. The improvement in beam quality with respect to the fundamental emission can be explained by the central lobe contributing most efficiently to the green light generation as well as a spatial nonlinear beam clean-up, affected by the overlap of the involved beams [29].

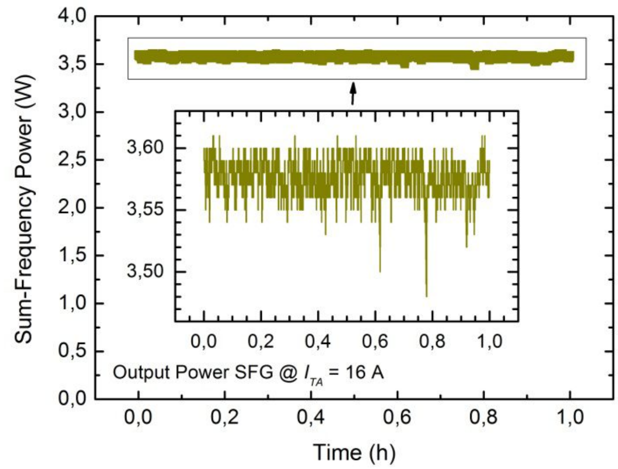

Figure 8: Output power in case of SFG at ITA = 16 A measured over one hour.

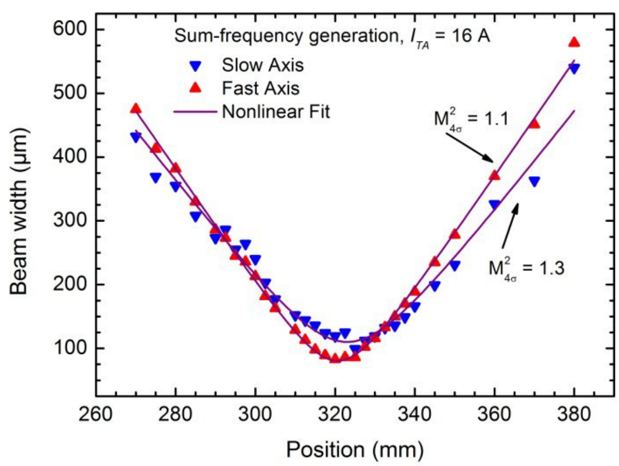

Figure 9: Measured beam width along the beam waist in case of SFG at I_{TA} = 16 A.

In summary, the concept of spectral beam combining with subsequent SFG is an ideal method in order to efficiently increase the output power of visible diode laser systems. Especially the wavelength flexibility of diode lasers adds a spectral flexibility that is not provided by other types of lasers. In order to increase the amount of visible radiation this concept can be easily expanded, combining multiple lasers with additional gratings.

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