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Efficient concept for generation of diffraction-limited green light by sum-frequency generation of spectrally combined tapered diode lasers

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In order to increase the power of visible diode laser systems in an efficient manner, we propose spectral beam combining with subsequent sum-frequency generation. We show that this approach, in comparison with second harmonic generation of single emitters, can enhance the available power significantly. By combining two distributed Bragg reflector tapered diode lasers we achieve a 2.5–3.2 fold increase in power and a maximum of 3.9 W of diffraction-limited green light. At this power level, green diode laser systems have a high application potential, e.g., within the biomedical field. Our concept can be expanded combining multiple diode lasers to increase the power even further. © 2012 Optical Society of America

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High-power, diffraction-limited green lasers are of high importance for many applications. One major application within the field of biomedicine is direct pumping of Ti:sapphire lasers. Such lasers offer high-intensity, ultrashort femtosecond pulses required for, e.g., two-photon microscopy [1] or coherent anti-Stokes Raman scattering microscopy [2]. In order to overcome the high pump thresholds of Ti:sapphire lasers, corresponding pump lasers should ideally provide a few watts of green light at high electro-optical efficiencies without adding to the size of Ti:sapphire systems.

The most obvious way to achieve laser emission in this spectral region is to use direct green-light emitting lasers. Unfortunately, the performance of such InGaN based laser diodes, emitting more than 60 mW [3], is so far limited by the material properties of the lasers. Other promising candidates for generating green light are diode pumped Pr^{3+}-doped laser crystals emitting more than 700 mW at 523 nm [4].

Much higher output powers can be achieved by frequency doubling of high-power infrared lasers. For example, several tens of watts were generated by external [5] or intracavity frequency conversion [6] using continuous-wave (cw) solid-state lasers, respectively. These cavity configurations offer high optical conversion efficiencies, but also require precise control and positioning of optical components in order to achieve reliable performance. In a simpler, single-pass configuration up to 16.1 W (cw) were obtained [7]. One disadvantage of these laser systems is that two frequency conversion processes are required to generate green light, reducing the overall efficiency. Therefore the question remains; can diode lasers be an alternative to generate diffraction-limited, mid-power-range green light, as required for many biomedical applications, in a more efficient manner? One major advantage is that diode lasers show by far the highest electro-optical efficiencies. Compared to lasers based on strict atomic transitions their material composition also offers certain emission wavelength tunability. In addition, their dimensions of only a few mm^3 allow for compact and cost-efficient laser systems. However, achieving several watts of green light requires high-power diode lasers with good spatial and spectral quality. In this context 1060 nm distributed Bragg reflector (DBR)-tapered diode lasers with up to 12 W of output power in a nearly diffraction-limited beam were demonstrated [8]. These lasers enabled generation of more than 1.5 W of green light by single-pass frequency doubling [9]. Later, a more compact setup was applied for direct pumping of mode-locked Ti:sapphire lasers [10]. This was one of the most critical applications for green laser systems. Unfortunately, the green power achieved with these diodes so far is limited by the thermal degradation and beam filamentation at high currents.

In this Letter we propose spectral beam combining (SBC) of DBR-tapered diode lasers [11,12] followed by sum-frequency generation (SFG), in order to further increase the diffraction-limited green power. Unlike coherent beam combining, which requires precise control of wavelengths and phase relations between the lasers, SBC is achieved simply by using a diffraction grating. In our concept, a reflecting volume Bragg grating is chosen, enabling efficient spectral beam combining of lasers with narrow wavelength separations [13]. In order to obtain high combining efficiencies, the wavelength separation between the lasers needs to be carefully observed. Using two DBR-tapered diode lasers ($M^2_{4\sigma} \leq 5.2$) we obtain combining efficiencies above 90% at all settings, indicating no thermal damage to the grating. Subsequent SFG improves the visible output power by a factor of 2.5–3.2 compared to second harmonic generation (SHG) of single emitters. The maximum power achieved with this scheme is 3.9 W in a diffraction-limited beam ($M^2_{4\sigma} \leq 1.3$) with an optical-optical conversion efficiency as high as 24.8%. These results confirm the feasibility of our proposed scheme leading to, to our knowledge, the highest visible power generated with tapered diode lasers.

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Figure 1 illustrates the proposed scheme. The two 6 mm long, high-power DBR-tapered diode lasers are mounted p-side up on a CuW heat spreader on a 25 mm × 25 mm conduction cooled package (CCP) mount. Each laser consists of a 1 mm long, passive DBR section, a 1 mm long ridge waveguide section, and a 4 mm long, 6° tapered amplifier. Both beams are collimated and corrected for astigmatism using pairs of antireflection (AR)-coated aspheric lenses ($f = 3.1$ mm, $\mathrm{NA} = 0.68$) and cylindrical lenses ($f = 15$ mm).

Spectral beam combining is achieved using a reflecting volume Bragg grating (OptiGrate). The grating, written in photothermo-refractive glass, is specified to have an average diffraction efficiency of 99.2% at 1062 nm, with an acceptance bandwidth of 0.3 nm FWHM. The Bragg angles are around ±6.5°. Its dimensions are $L \times W \times H = 3.4\ \mathrm{mm} \times 10\ \mathrm{mm} \times 10\ \mathrm{mm}$. Optimum spectral beam combining is achieved by adjusting the angle of incidence on the grating and the wavelengths of both lasers properly. The tunability of diode lasers allows the latter to be achieved simply by changing the laser temperatures. Then the emission from Laser 1 transmits the grating and the emission from Laser 2, incident on the other side of the grating, is diffracted into the same direction.

In order to prevent optical feedback toward the diodes we use a combination of a 30 dB optical isolator and two half-wave plates. This furthermore allows adjusting the power available for SFG without changing the injection current. An $f = 75$ mm achromat is used to focus the combined beam inside the nonlinear crystal. The generated beam waist radius is around 42 μm. This value is larger than the optimum radius of 29 μm, calculated according to Boyd–Kleinman theory [14], but proved to be optimum value in our experiments. The crystal we use for these experiments is a plane cut, periodically poled MgO-doped lithium niobate crystal (HCPhotonics), AR coated for both the fundamental and the generated green wavelengths. It has a length of 30 mm with a poling period of 6.92 μm and is positioned inside an oven for temperature phase matching. After the crystal, the fundamental and generated beams are separated using a dichroic mirror ($R < 5\%$ at 530 nm, $R > 99.9\%$ at 1060 nm). A spherical lens ($f = 200$ mm) is used to collimate the green beam.

In our experiments the ridge sections of the diode lasers are operated at 300 mA. The injection currents to the tapered sections are set to 6, 8.5, 11, 13.5, and 16 A. At all settings, combining efficiencies above 90% are achieved. The beam propagation parameters of the spectrally combined beams are $M^2_{4\sigma} < 2$ in vertical direction and $M^2_{4\sigma} <$ 3.9–5.2 in lateral direction, with better beam qualities at lower currents. All beam propagation parameters for this work are measured with an Ophir, Spiricon M2-200S beam propagation analyzer. The wavelength separation between the two lasers at all settings is around 1 nm. Shorter separations can be achieved by adjusting the temperature of Laser 1.

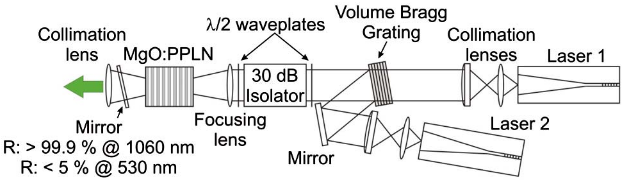

Fig. 1. (Color online) Setup for spectral beam combining of DBR-tapered diode lasers with subsequent sum-frequency generation.

Optimizing the wavelength separation between the lasers is crucial in our concept. Regarding frequency conversion the ideal case would be to have equal wavelengths and phase-matching temperatures. The green light conversion would then be based on contributions from both SHG and SFG, maximizing the overall performance. However, when using a volume Bragg grating with its wavelength-dependent diffraction efficiency, a trade-off has to be made between wavelength separation and combining efficiency. While enabling SBC, the diffraction efficiency also causes the transmitted power of Laser 1 to drop due to increased diffraction at wavelengths within the acceptance bandwidth of the grating.

Figure 2 shows the green power generated at maximum current. It can be seen that 3.9 W of green light are obtained by SFG at a total input power of 15.7 W measured in front of the crystal. The corresponding optical-optical conversion efficiency is 24.8%. The electro-optical and nonlinear conversion efficiencies are 5.7% and 2.6%/W, respectively. The optimum phase-matching temperature is 39.6 °C. The lasers are operated at 23.1 °C (1063.3 nm, Laser 1) and 15.9 °C (1062.3 nm, Laser 2). Regarding SHG of the individual lasers 1.5–1.6 W are achieved. Therefore SFG leads to a 2.5 fold increase in green power compared to SHG of single emitters.

In order to estimate the stability of our setup, the green power generated by SFG is measured once a second over one hour. Without any further stabilization the obtained stability is within ±2.6% at maximum output. We did not observe indications for photorefractive damage.

A spectrum of the green beam is shown in the inset of Fig. 2, measured with an Advantest Q8347 optical spectrum analyzer. Due to the intrinsic wavelength

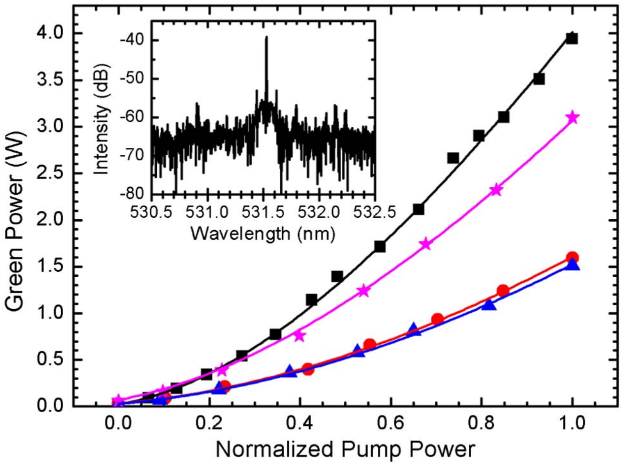

Fig. 2. (Color online) Green power versus normalized pump power at 16 A in the case of SFG (squares) and SHG (Laser 1, triangles; Laser 2, circles). The stars represent the sum of the individual SHG results. For each curve the pump power is normalized with respect to the corresponding maximum pump power. The numerical fits are based on the depleted pump approximation. The inset shows a measured spectrum of the green light generated by SFG at maximum current.

stabilization of the diodes, we achieve single-mode emission with a side-mode suppression >15 dB and a spectral width as narrow as $\Delta\lambda = 5$ pm.

The green light generated by SFG is diffraction limited with beam propagation parameters of $M^2_{4\sigma} < 1.1$ in vertical direction and $M^2_{4\sigma} < 1.3$ in lateral direction. We did not observe changes at higher powers, a typical sign in case of photorefractive damage. The improvement with respect to the individual lasers can be explained by nonlinear beam cleanup [15]. It was shown that the beam propagation parameters of waves generated by SFG highly depend on the overlap of the fundamental beam profiles.

When comparing the results achieved at different injection currents, we note that our concept increases the green power compared to SHG of single emitters by a factor of 2.5–3.2, with larger improvement factors at lower currents (Fig. 3). The reduced values at higher input powers can be explained by a reduced overlap of the fundamental waves, fundamental pump depletion, reduced beam qualities of the lasers, and a reduction in central-lobe power at higher currents. While the central-lobe power along the fast axis remains constant, it drops in the slow axis from 81% at 6 A ($P_{\mathrm{IR}} = 4.6$ W) down to 73% at 16 A ($P_{\mathrm{IR}} = 15.7$ W).

For comparison, Fig. 3 also shows an estimation of the expected improvement factors. It is based on the depleted pump approximation for high-power frequency conversion, under the assumption of equal power and emission wavelengths of the two lasers. Because the power of the generated light scales, with the input power squared, using similar lasers will increase the efficiency compared to SHG [9] by a factor 4, resulting in the following relation:

$$P_{\mathrm{SFG}} = \frac{P_{\mathrm{IR}}}{2} \tanh^2 \sqrt{4\eta_{\mathrm{SHG}} \frac{P_{\mathrm{IR}}}{2}}. \qquad (1)$$

Here P_{IR} represents the fundamental pump power, P_{SFG} the expected green power, and η_{SHG} the nonlinear conversion efficiency. The calculation is carried out with an efficiency of 3%/W, measured for second harmonic generation at 16 A. It can be seen that pump depletion leads to reduction of the improvement factors at higher pump powers. Deviations between measured and calculated values can be explained by unequal and changing nonlinear conversion efficiencies for SHG and SFG at the different pump power levels, ranging between 3.8%/W and 2.3%/W.

In order to increase the power level of visible diode laser systems even further, this setup could be expanded combining multiple diode lasers using additional gratings [13]. In that case, the frequency conversion of the combined beams may be limited by the acceptance bandwidths of the nonlinear crystal, depending on the wavelength spacing between the lasers.

In summary, spectral beam combining with subsequent sum-frequency generation is presented. Using this concept the green power generated by two DBR-tapered diode lasers, compared to second harmonic generation of single emitters, is increased by a factor of 2.5–3.2. At maximum performance we achieve 3.9 W of diffraction-limited green light. These results represent, to our knowledge, the highest visible power generated with tapered diode lasers and show the suitability of the proposed scheme.

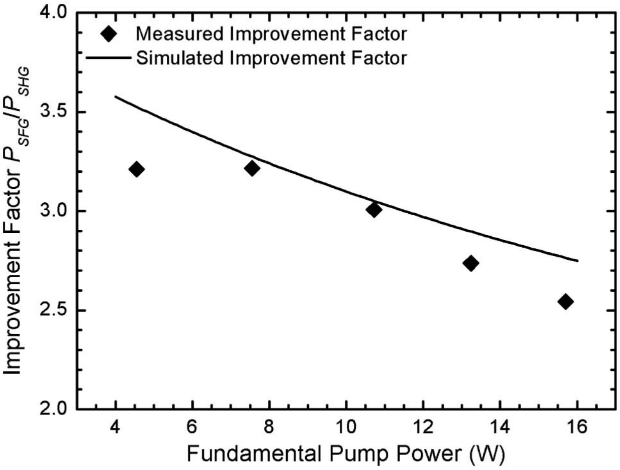

Fig. 3. Achieved improvement in green power compared to second harmonic generation of single emitters. The solid line shows an approximation of the improvement factor based on a nonlinear conversion efficiency of 3%/W.

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