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Singly-resonant sum frequency generation of visible light in a semiconductor disk laser

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Abstract: In this paper a generic approach for visible light generation is presented. It is based on sum frequency generation between a semiconductor disk laser and a solid-state laser, where the frequency mixing is achieved within the cavity of the semiconductor disk laser using a single-pass of the solid-state laser light. This exploits the good beam quality and high intra-cavity power present in the semiconductor disk laser to achieve high conversion efficiency. Combining sum frequency mixing and semiconductor disk lasers in this manner allows in principle for generation of any wavelength within the visible spectrum, by appropriate choice of semiconductor material and single-pass laser wavelength.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.5960) Semiconductor lasers; (140.7300) Visible lasers; (190.0190) Nonlinear optics.

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1. Introduction

The development of efficient, compact and robust laser sources in the visible and UV spectral range is the subject of intensive research, for applications in areas as diverse as optical spectroscopy, projection displays, bio- and chemical sensing, and biomedical diagnostics. The generation of visible light from optically-pumped solid-state and semiconductor lasers is usually achieved via second harmonic generation (SHG), as the transition lines of most conventional doped dielectric laser crystals and the semiconductor bandgaps of the most common III-V semiconductor alloys are in the near infrared (NIR). SHG has been demonstrated for numerous diode-pumped solid-state (DPSS) lasers, both in continuous wave (CW) and pulsed [1, 2] operation, fiber lasers [3], and external cavity diode lasers (ECDL) [4]. One of the main limitations to the SHG-based visible light sources is that these devices are limited by the available NIR laser lines. One approach to reach spectral ranges difficult to access via SHG is through sum frequency generation (SFG), either combining two solid-state lasers [5], a solid-state and a semiconductor laser [6, 7] or an ECDL [8]. The latter allows for some tuning of the generated light, provided that the nonlinear process can accommodate phase-matching over the tuning range of the ECDL. The generated wavelength is calculated from the photon energy of the two mixed laser lines.

SHG has provided the main route to visible and UV light emission from semiconductor disk lasers (SDLs) also referred to as vertical-external-cavity surface-emitting-lasers (VECSELs) [9]. These devices have been developed into commercially available products, delivering Watt-level output power at specific wavelengths in the visible, as replacements for DPSS lasers and argon ion lasers. Despite broad tuneability in the NIR, gaps and regions of low efficiency remain in the spectral coverage of SDLs at the compositional and strain extremes of available semiconductor quantum well alloys, with corresponding gaps in the second harmonic spectrum [9].

SFG has also been demonstrated within SDLs where both fundamental wavelengths are generated within the laser cavity. Härkönen et al. mixed both fundamental wavelengths of a dual-wavelength infrared SDL in an intra-cavity LBO crystal for conversion to a single visible wavelength [10], and more recently Chilla demonstrated frequency tripling between the intra-cavity second harmonic and fundamental beams of an infrared SDL containing two nonlinear crystals (both LBO), providing access to the near UV [11].

In this work a generic ‘hybrid’ approach based on SFG between a single-pass NIR laser source and the intra-cavity field of a SDL is suggested. The approach is experimentally demonstrated through sum frequency mixing of a single-pass Nd:YVO_4 solid-state laser at 1342 nm and an InGaAs-based SDL with peak emission at 1064 nm to generate light at 593 nm. In the following the experimental setup is described, including the fundamental performance of each of the two laser sources, followed by analysis of the nonlinear frequency conversion and the measured parameters of the generated light. We conclude with a brief discussion on the prospects for broad wavelength tuning of this type of device.

2. Experimental configuration

Figure 1 depicts the experimental configuration. The SDL was designed as a 4-mirror, z-fold cavity with an InGaAs SDL gain structure, similar in design and structure to that reported earlier [12], acting as a planar end mirror. The cavity mirrors M1, M2 and M3 were high reflectivity (HR) coated at 1064 nm and high transmittance (HT) at 808 nm, all mirrors had a radius of curvature of -100 mm. In order to match the cavity mode to a pump spot size of ~80 μm at the SDL, the cavity arm lengths were set to be: 53 mm, 457 mm, and 156 mm, respectively. An additional beam waist (~53 μm) was located in one cavity arm, where the nonlinear crystal was positioned. For this experiment a 10 mm Brewster-cut periodically-poled $KTiOPO_4$ (PPKTP) crystal with an effective nonlinear coefficient of $d_{\mathrm{eff}} = 10$ pm/V was used. The middle arm contained a three-plate birefringent filter (BRF) for wavelength tuning of around 30 nm, centered at an emission wavelength of 1055 nm.

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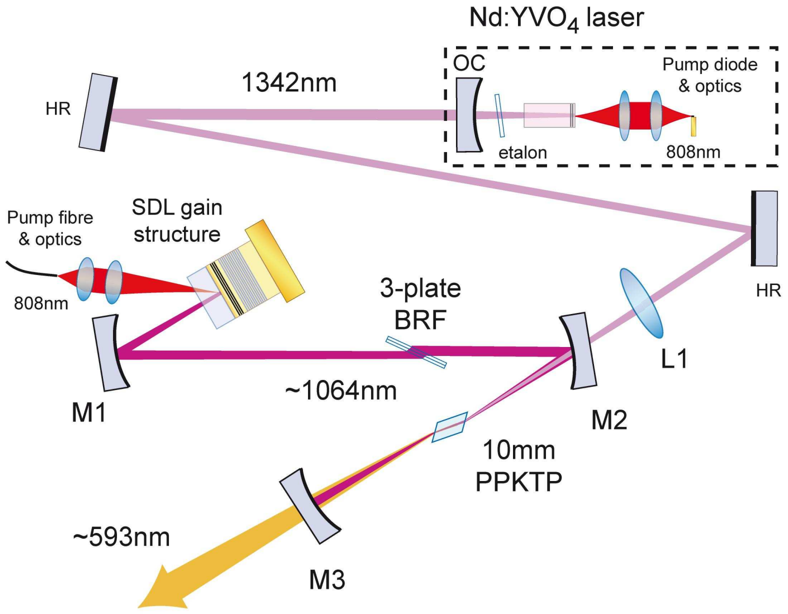

Fig. 1. Experimental setup for generation of 593 nm yellow-orange light within a high finesse SDL cavity, including PPKTP at an intra-cavity focus and a single-pass of the output beam of a diode-pumped Nd:YVO$_4$ solid-state laser. HR: high reflector; OC: output coupler; BRF: birefringent filter.

13 W of optical pump power were incident at the SDL structure applied by an 808 nm fiber-coupled diode laser. At this power level a high heat load is introduced into the semiconductor structure and therefore a 500-µm-thick diamond heatspreader was liquid capillary bonded to the intra-cavity surface of the semiconductor for thermal management and the structure kept at a temperature of 0 °C via a water/glycol cooled brass mount.

The single-pass 1342 nm beam was generated by an 8 mm long *a*-cut Nd:YVO$_4$ crystal (0.5 atm% Nd-doped), pumped by an 808 nm 4 W broad area laser diode. The pump-side facet of the crystal was coated for HR and HT at 1342 nm and 808 nm respectively, whereas the intra-cavity facet was anti-reflection (AR) coated at 1342 nm. The cavity was established between the HR coated facet and a 2% output coupler (OC) of -200 mm radius of curvature. A 0.3-mm-thick intra-cavity etalon enabled wavelength tuning and line shape narrowing. The beam was aligned and focused into the PPKTP-crystal by two plane steering mirrors and a lens L1 (f = 120 mm, measured power transmittance at 1342 nm ~93 %). The 1342 nm beam was coupled into the PPKTP crystal through mirror M2, having a measured power transmittance of ~87 % at this wavelength.

The sum frequency generated beam at ~593 nm was coupled out through the end mirror M3 with a measured power transmittance of ~85 %.

3. Laser characterization

In order to achieve efficient sum frequency conversion, three conditions must be met: the fundamental power levels reaching the nonlinear crystal must be maximized; the spectrum of the fundamental fields must be within the spectral acceptance bandwidth of the nonlinear material; and the state of polarization of the fields must align with the highest possible second order susceptibility of the nonlinear material.

SDLs have a significant gain bandwidth, allowing for broad tuning around their design wavelength, which typically leads to broadband emission. It is therefore necessary to

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introduce intra-cavity spectral filters to narrow and tune the emission spectrum. This was done by placing the three-plate quartz BRF (also known as a Lyot filter) within the SDL cavity, plate thicknesses 4-, 2-, and 1-mm where the thickest BRF determines the filter resolution and the thinnest the free spectral range [13]. Figure 3(a) illustrates the measured SDL spectrum using the three-plate BRF. The linewidth was measured to be less than 0.1 nm (corresponding to 125 longitudinal cavity mode spacings), which is comparable to the linewidth achievable by a single 4 mm BRF. The benefit of the three-plate filter in this case is to suppress the additional peaks allowed by the single BRF, Fig. 3(b), which broaden the emission spectrum, thus lowering the conversion efficiency. The separation of the additional peaks corresponds to the free spectral range (~0.4 nm) of the 500-μm-thick diamond heatspreader. By monitoring the fundamental power leakage through mirror M1 (measured transmission 0.017 %), the circulating power within the SDL was estimated to be approx. 40 W.

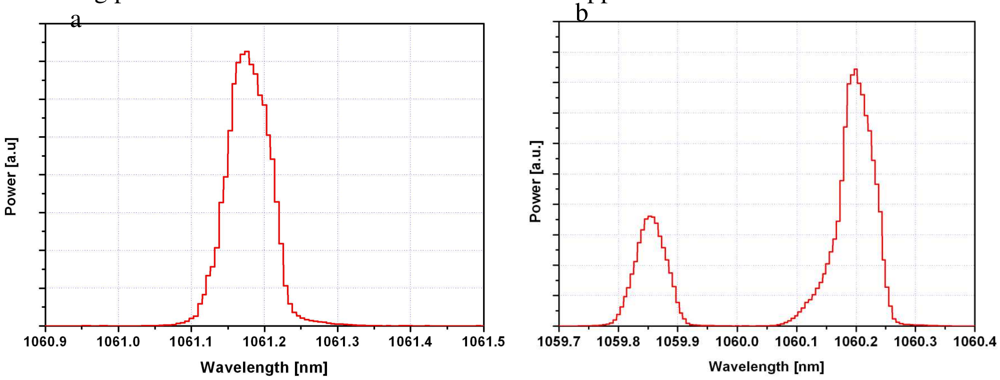

Fig. 3. Spectrum of the SDL: (a) using a three-plate BRF. The spectral line width is <0.1 nm, no additional peaks were seen using the three-plate filter. (b) using a simple 4mm BRF.

The 1342 nm transition line of Nd:YVO_4 has a narrow gain bandwidth compared to the SDL and therefore a thin intra-cavity etalon, in this case 0.3 mm thick, is sufficient to ensure a spectral emission of less then 0.2 nm (corresponding to 30 longitudinal mode spacings). The corresponding spectra and tuning range obtained by tilting the etalon are shown in Fig. 4(a). The measured power performance is shown in Fig. 4(b), for an emission wavelength of 1342.4 nm, corresponding to the red line spectrum of Fig. 4(a). The maximum output power of the Nd:YVO_4 laser was 900 mW at 1342.4 nm. Approximately 20 % is lost via the two steering mirrors, the mode matching lens L1 and mirror M2, lowering the maximum input power at the nonlinear material to less than 700 mW.

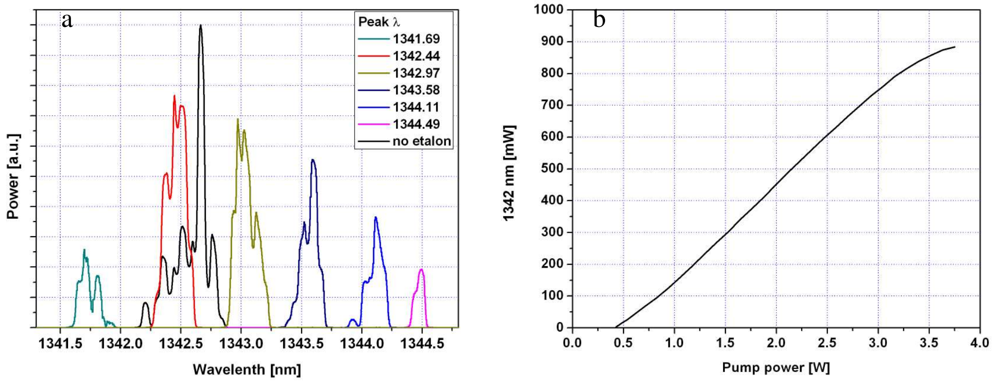

Fig. 4. Characteristics of the 1342 nm laser with intra-cavity 0.3 mm-thick etalon. (a) Output spectra obtained over the tuning range of the laser by means of tilting the etalon, and (b) slope efficiency at 1342.4 nm.

4. Sum frequency generation

For efficient phase-matching, the temperature of the PPKTP crystal could be regulated within the range 22 to 52 ºC. In order to generate the data plotted in Fig. 5, the wavelengths of the SDL and single-pass laser were kept fixed at 1063 nm and 1342.4 nm respectively, while the temperature of the PPKTP crystal was scanned through this temperature range. Optimum phase-matching was found for a PPKTP temperature of 42 °C, which is in close agreement with that predicted theoretically using the Sellmeier equations for KTP (PPKTP poling period 12.65 μm).

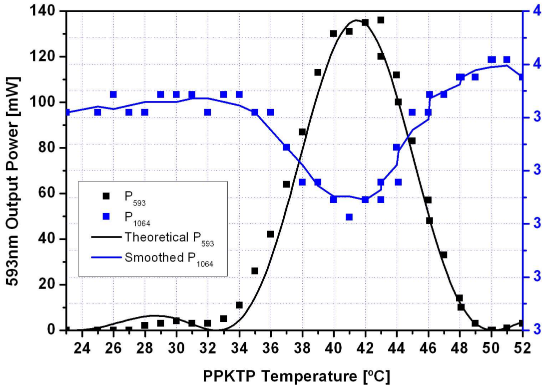

Fig. 5. Measured phase-matching temperature acceptance bandwidth of the PPKTP crystal shown as the generated output power at 593 nm as a function of crystal temperature. Close agreement with the theoretical curve is seen. Also shown is the simultaneous measurement of circulating intra-cavity power at 1064 nm. The data is averaged over 5 points using adjacent-averaging. The underlying decrease in intra-cavity power going from 50 to 24 degrees relates to alignment drift of the system during the course of the measurement.

A maximum generated power of 136 mW at 593 nm was obtained, corresponding to a conversion efficiency of ~20 % of the single-pass 1342 nm power. It is expected that the conversion efficiency of the system can be improved to more than 30 % by optimization of the polarization extinction ratio of the intra-cavity 1064 nm power. The extinction ratio was measured to be approx 1/65, see Fig. 6. The limited extinction ratio is due to the intrinsic unpolarized nature of the vertically-emitting semiconductor gain region, and imperfections in the alignment of the many intra-cavity Brewster's surfaces, which also adds to the intra-cavity losses limiting the circulating power in the 1064 nm cavity.

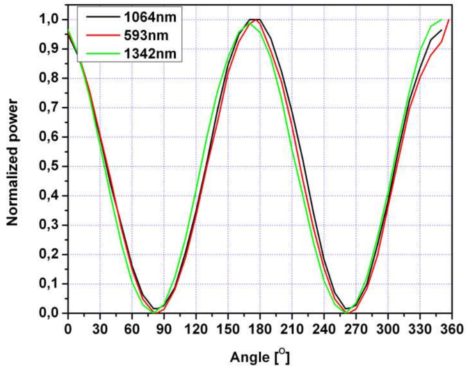

Fig. 6. Polarization characteristics of the fundamental and generated beams: measured power transmitted through a polarizing beamsplitter cube as it is rotated 360°.

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The generated power is shown as a function of single-pass power in Fig. 7. It is worth noting the linear slope, even at low power levels, which is in strong contrast to second harmonic generation, as the up-conversion efficiency is independent of the power of the single-pass laser. This means that even very weak single-pass signals can be up-converted to a new wavelength with high efficiency.

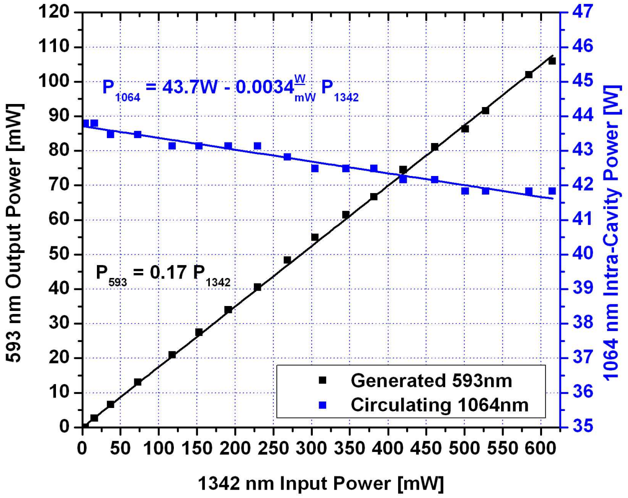

Fig. 7. Generated output power at 593 nm and intra-cavity circulating power at 1064 nm as a function of single-pass 1342 nm power.

5. Wavelength tuning

As mentioned in the introduction, and demonstrated in [9], one of the interesting features of using semiconductor materials as gain media is the significant gain bandwidth of these devices. To investigate the potential tuning range of the frequency-mixed system, a numerical model based on the Sellmeier equations for KTP and the available tuning range of the SDL was written and the results are shown in Fig. 8.

In Fig. 8(a) and (b) the dotted lines are iso-wavelength lines for the generated field; the line in the upper right corner corresponds to 600 nm and the lower left line corresponds to 582 nm. The blue crosses in Fig. 8(a) and (c) indicate phase-matching curves for PPKTP maintained at a fixed temperature of 18, 43 and 52 ^{o}C, respectively, and the solid blue lines indicate the possible tuning range of the 1342 nm laser. In order for the nonlinear PPKTP crystal to accommodate phase-matching over the entire tuning range available from the SDL, a temperature scan of more than 250 ^{o}C is needed. As shown, a wavelength tuning of less than 2 nm / 34 ^{o}C was achieved using PPKTP. Using type I phase-matched LBO a numerical calculation shows that a wavelength tuning of almost 10 nm in the generated field can be achieved by changing the LBO temperature 10 ^{o}C, see Fig. 8(b), however, using LBO compared to PPKTP reduces the nonlinear coefficient by almost one order of magnitude, thus reducing the overall conversion efficiency of the system. A magnified view of the indicated range in Fig. 8(a) is shown in Fig. 8(c) with experimentally measured points that are seen to agree closely with theoretically predicted values.

It is clearly seen that dual wavelength tuning to allow fixed temperature operation of the nonlinear material is not possible at the wavelengths investigated in the present setup. However, other wavelength ranges or alternative nonlinear materials with different dispersion relations would perhaps make dual wavelength tuning possible. Alternatively, chirped or fanned poling structures could enable significant tuning of such devices.

Another important consideration when making broadly tunable devices is to keep losses low over the entire tuning range. Using Brewster-cut nonlinear materials, as opposed to plane-cut AR coated crystals, ensures very low losses over a broad tuning range of the mixing

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wavelengths. The use of the Brewster-cut also allows true single-pass configurations as the refraction angle is different for the different wavelengths, therefore there is no residual feedback for the single-pass laser. Finally the cost of Brewster-cut crystals in low quantities are significantly lower than for coated crystals.

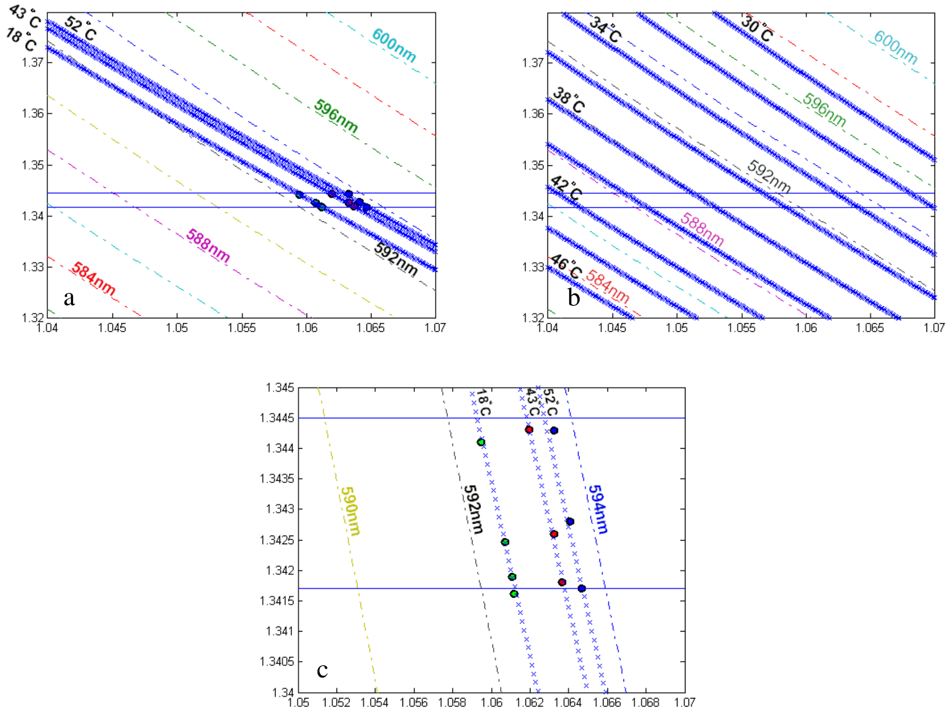

Fig. 8. Phase-matching diagrams for sum-frequency mixing between wavelengths centered around 1055 nm and 1342 nm for the full tuning ranges available from the lasers used. Dotted lines indicate iso-wavelength curves for the generated light, and blue crosses indicate phase-matching curves for the nonlinear crystal at different temperatures. (a) for PPKTP at three different temperatures, from left to right 18, 43 and 52 °C, (b) for type-I phase-matched LBO, (c) green, red and blue points show measured data for PPKTP at 18, 43 and 52 °C.

6. Conclusion

A generic approach to visible light generation has been presented, using a semiconductor disk laser as one of two mixing lasers, allowing for generation of high power single-frequency intra-cavity fields tunable over a broad range of wavelengths in the NIR (depending on the composition of the gain structure). Combining these devices with efficient quasi phase-matched nonlinear crystals and single-pass lasers delivering Watt levels of power, it is in principle possible to generate hundreds of mW of power anywhere in the visible spectrum with the possibility for tuning of the generated wavelength. However, if the full tuning potential of the SDL is to be transferred to the visible spectral region, tuning of the phase-match condition is needed, either using a fanned structure combined with mechanical movement or using a chirped structure at the expense of reduced efficiency.

As demonstrated in this experimental realization, 136 mW of output power in the orange spectral range has been reached. Although this first demonstration has a lower efficiency compared to more mature systems based on two solid-state lasers, the potential of using semiconductor disk lasers in combination with intra-cavity sum-frequency mixing has been demonstrated.

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