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# Single-frequency blue light generation by single-pass sum-frequency generation in a coupled ring cavity tapered laser

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A generic approach for generation of tunable single frequency light is presented. 340 mW of near diffraction limited, single-frequency, and tunable blue light around 459 nm is generated by sum-frequency generation (SFG) between two tunable tapered diode lasers. One diode laser is operated in a ring cavity and another tapered diode laser is single-passed through a nonlinear crystal which is contained in the coupled ring cavity. Using this method, the single-pass conversion efficiency is more than 25%. In contrast to SFG in an external cavity, the system is entirely self-stabilized with no electronic locking. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4823821>]

Visible laser sources with the possibility of selecting the desired wavelength are interesting to a number of applications including spectroscopy and bio-photonics. Visible diode lasers have appeared in various spectral regions including the blue, green, and red. Single-mode visible diode lasers, however, are limited to output powers of about 100 mW with multi-longitudinal mode operation while multi-spatial mode lasers are available with watt-level output powers. Visible external cavity single-mode diode lasers emit single-frequency light with even lower output power and the tuning is limited to a few nanometers. Second harmonic generation (SHG) is often used to generate light in this spectral region but due to the lack of gain media at various wavelengths, the spectral coverage is limited. Optical parametric oscillators are very flexible sources for generation of almost any wavelength but they are complicated to operate and they require both high power and high quality pump sources. Sum-frequency generation (SFG) has proven to be very agile in terms of the generated wavelengths. Simple single-pass SFG has been implemented and have generated tens and hundreds of mW at the Sodium D2 resonance at 589 nm using diode pumped solid state lasers (DPSSL) as the pump source.<sup>1,2</sup> Blue light generation at 492 nm was demonstrated by SFG of a DPSSL and a diode laser<sup>3</sup> and recently almost 4 W of green light was obtained by SFG of two beam combined distributed Bragg reflector (DBR) tapered diode lasers.<sup>4</sup> Increased conversion efficiency can be obtained by enhancing the power in the nonlinear crystal. Singly resonant systems have been demonstrated with the nonlinear crystal placed either inside the cavity of a laser<sup>5–9</sup> or in an external enhancement cavity.<sup>10</sup> A conversion efficiency of more than 41% of the single-pass laser power has been demonstrated.<sup>6</sup> Even higher conversion efficiencies can be obtained in doubly resonant systems, where both interacting fundamental wavelengths are resonated in either a laser cavity<sup>11</sup> or an enhancement cavity.<sup>12</sup> These systems tend to become unstable and require electronic locking for stable operation. Coupled cavity operation of tapered amplifiers has recently been demonstrated to provide

high output power in the visible range by SHG.<sup>13,14</sup> In the present paper, we expand this approach to include SFG.

We present a generic method for efficient generation of visible light by SFG between light emitted by two tapered diode lasers. The power of one laser is enhanced using a coupled cavity approach and the single-pass conversion efficiency is increased to more than 25%. This results in the generation of more than 300 mW single-frequency light at 459 nm. The method can easily be expanded to cover the full visible spectrum. The frequency of the resonated laser is passively locked to the resonance frequency of the enhancement cavity by use of optical feedback.

The experimental setup is shown in Fig. 1. In the coupled ring cavity similar to the one used by Jensen *et al.*,<sup>14</sup> a tapered amplifier designed for operation around 1060 nm and tunable in the 1049–1093 nm range is used. The fast axis of the tapered amplifier is collimated using an aspherical lens (L1) with 3.1 mm focal length and a numerical aperture of 0.68. This lens focuses the light in the slow axis due to astigmatism in the tapered amplifier. A cylindrical lens (L2)

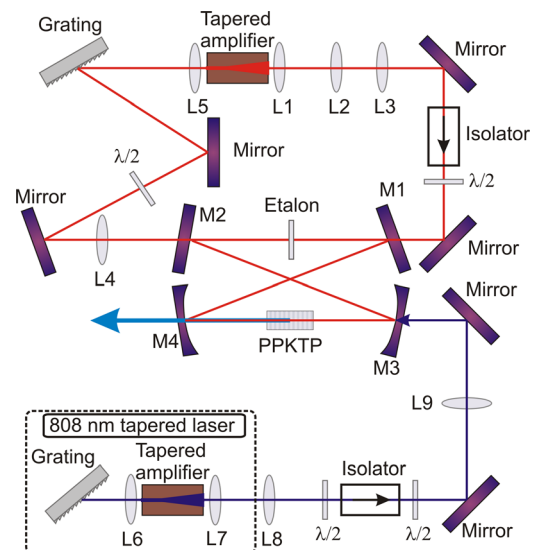


FIG. 1. Schematic layout of the experimental setup for tunable SFG around 459 nm.

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with 30 mm focal length is used to correct for astigmatism and collimate the beam in the slow axis. A spherical lens (L3) with 250 mm focal length is used to couple the beam from the tapered amplifier to the enhancement cavity. An optical isolator with  $>30$  dB isolation is inserted to ensure unidirectional operation and a half wave plate is used to rotate the polarization to horizontal which fits with the phase matching conditions of the nonlinear crystal. The enhancement cavity is designed as a four mirror bow-tie cavity with two plane mirrors (M1 and M2) and two mirrors with 50 mm radius of curvature (M3 and M4). Mirror M1 is coated for 95% reflectivity at 1064 nm and M2 has 98% reflectivity at 1064 nm. These reflectivities proved to be a good compromise between obtaining high circulating power in the cavity and still permitting enough leakage power to saturate the tapered amplifier. Mirror M3 is coated for high reflectivity at 1064 nm and highly transmitting at 808 nm while mirror M4 is coated for high reflectivity at 1064 nm and highly transmitting at 532 nm. M4 has a residual reflectivity of about 10% at 459 nm. The distance between M3 and M4 is about 67 mm and the remaining distance is about 207 mm. This cavity supports a mode with a beam diameter of approximately  $60 \mu\text{m}$  by  $70 \mu\text{m}$  between the curved mirrors. Here, a 10 mm long periodically poled potassium titanyl phosphate (PPKTP) crystal (*Raicol*) is placed. The PPKTP crystal has a poling period of  $5.6 \mu\text{m}$  for SFG between light at 1064 nm and 808 nm and anti-reflection (AR) coated at interacting wavelengths. An un-coated un-doped YAG etalon with a thickness of  $125 \mu\text{m}$  is included in the cavity to increase stability. The light exiting the cavity through M2 is collimated using a spherical lens (L4) with a focal length of 100 mm. A diffraction grating with 1200 grooves per mm is used to select the operating wavelength and a half wave plate is inserted in the beam path to control the polarization incident on the grating. The power coupled to the ridge section of the tapered amplifier can be controlled by rotation of the polarization as the grating diffraction efficiency is polarization dependent. The light is coupled into the ridge section using an aspherical lens (L5) with 3.1 mm focal length.

The 808 nm tapered laser consists of an 808 nm tapered amplifier operated in the Littrow geometry.<sup>15</sup> It is collimated using a combination of an aspherical lens (L7) with 3.1 mm focal length and a cylindrical lens (L8) with 40 mm focal length. The light passes an optical isolator with  $>30$  dB

isolation and two half-wave plates, which are used to control the power and the polarization incident on the PPKTP crystal. A 60 mm focal length lens (L9) is used to focus the light into the PPKTP crystal. The 808 nm tapered laser provides up to 1.28 W of output power after the optical isolator and the beam propagation factor is  $M^2 = 1.3 \times 1.9$  (vertical  $\times$  horizontal). The laser is tunable in the 792–819 nm spectral region (FWHM).

The wavelength of the 1060 nm tapered amplifier operated in the coupled cavity is tuned to 1063.5 nm to facilitate phase matching with the incoming 807.5 nm light at a temperature of  $34^\circ\text{C}$  in the PPKTP crystal. The power in the enhancement cavity can be monitored by the power leaking through the cavity mirrors M3 or M4, when their reflectivities are known.

The power characteristics are shown in Fig. 2. An output power of 340 mW at 459 nm is obtained with 14 W circulating power in the cavity and 1.28 W of single-pass power at 807.5 nm. In Figure 2, it is also seen that the cavity power is decreased due to the extra induced losses by the SFG process. The losses due to SFG are linear in terms of the incident power allowing for higher circulating power compared to SHG where the losses are quadratic.<sup>14</sup> The increased losses at high single-pass power will increase the coupling into the cavity as the input mirror M1 transmission ideally should match the losses in the cavity. Taking into account the losses in the measurement of the generated power through dichroic mirrors and the transmission of M4, more than 400 mW are generated at 459 nm. This corresponds to a single-pass power conversion efficiency of 31.3% and a conversion efficiency in the PPKTP crystal of 2.2%/W.

The spectrum of the generated blue light is determined by the spectrum of the two mixing lasers. The spectra of all three interacting waves are shown in Fig. 3. Here, the measured linewidth at 459 nm is 2 pm, limited by the resolution of the optical spectrum analyser (Advantest Corp. Q8347). The linewidth of the 459 nm light could not be measured directly due to lack of suitable mirrors for a scanning Fabry Perot Interferometer (FPI). The linewidths of the two mixing lasers were measured and the scanning FPI traces are shown in Fig. 4. In both cases the measured linewidth was limited by the resolution of the FPI which was 12 MHz at 808 nm and 10 MHz at 1064 nm, respectively. This indicates that the light at 459 nm is also single-frequency.

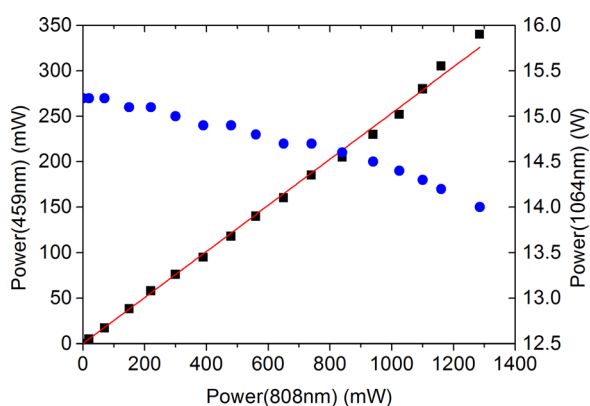


FIG. 2. Output power at 459 nm (squares) and circulating power at 1063.5 nm (dots) versus power at 808 nm.

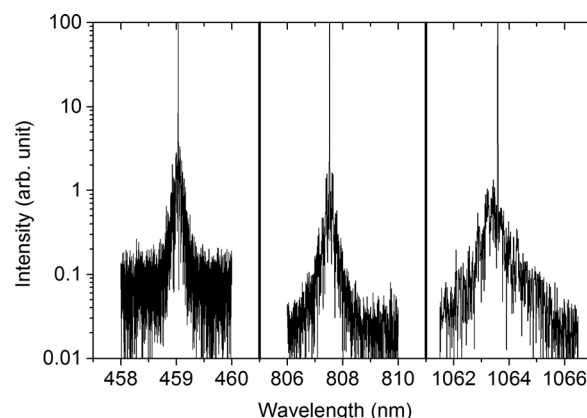


FIG. 3. Spectra of the three waves at 459 nm, 807.5 nm, and 1063.5 nm.

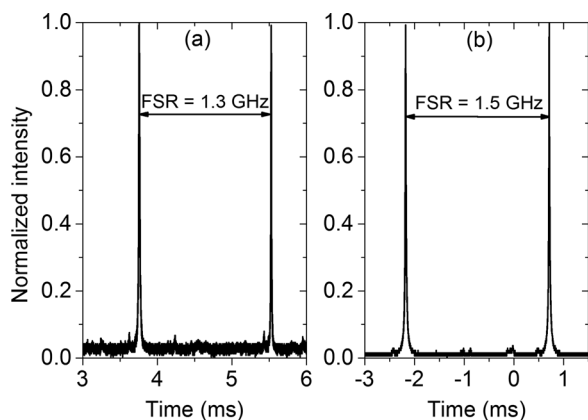


FIG. 4. Scanning FPI traces of the 807.5 nm laser (a) and the 1063.5 nm laser (b) showing single-frequency operation.

The wavelength of the blue light can be tuned by changing the wavelength of either of the two infrared lasers and simultaneously changing the PPKTP temperature to assure phase matching. By tuning the 808 nm laser from 806 nm to 810.5 nm, we have tuned the blue light in the 458.5–460 nm range. If the entire tuning ranges of the tapered amplifiers could be phase matched in the nonlinear crystal, a tuning range of 451–468 nm could be reached. A different selection of tapered amplifier wavelengths and nonlinear crystal can expand this wavelength range to cover most of the visible spectral range and also parts of the UV region are accessible.

The beam quality of the generated blue light is determined partly by the beam circulating in the enhancement cavity, partly by the beam quality of the single-pass beam, and partly by the focusing of the single-pass beam. As shown by Karamehmedović *et al.*,<sup>16</sup> it is possible to use the SFG process with a Gaussian beam to clean up a non-Gaussian incoming beam by properly choosing the overlap between the two beams. In our case, we have the Gaussian beam from the cavity and the near-Gaussian beam from the tapered laser and the resulting generated beam is nearly diffraction limited with  $M^2 < 1.15$  in both directions. The beam caustic through the focus region is shown in Fig. 5 where the beam profiles in the vertical and horizontal directions are included.

The power stability of the current setup is limited by the nonlinear crystal. On short time scales, the power is stable to within  $\pm 4\%$ . This power stability is obtained in an entirely passively locked system with no precautions taken to minimize temperature fluctuations caused by air flows and with all components placed separately on an optical table. Without the intracavity YAG etalon, the power fluctuations were significantly larger in the range of  $\pm 25\%$ . This is attributed to resonance peak mismatch between the two cavities. On long time scales, we see a slow power drop, which is attributed to losses in the PPKTP crystal. The power drop could be an indication of either blue-induced infrared absorption or grey tracking in the PPKTP crystal.

In summary, we have demonstrated a generic approach for generation of single-frequency tunable light in the visible spectral range. The method includes a tapered amplifier operated in a coupled cavity to boost the circulating power

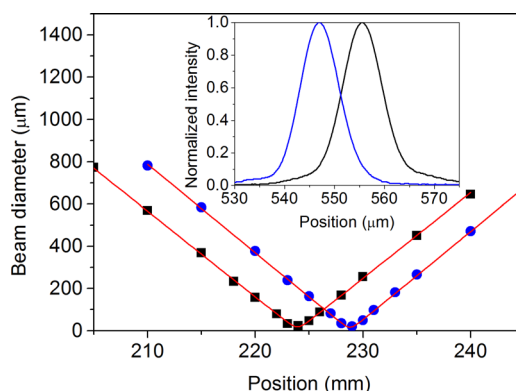


FIG. 5. Beam caustics through a focus for the vertical (dots) and horizontal (squares) direction. The lines are hyperbolic fits. The inset shows the beam profiles in the focus in the two axes. The plots are off-set for clarity.

in a SFG crystal and a single-pass laser. The method presented in this paper is a generic approach to SFG since it allows efficient generation of tunable light at almost any visible wavelength. We applied this approach to a tapered amplifier in a coupled ring cavity setup using SFG with a single-pass tapered diode laser in a nonlinear PPKTP crystal. In this demonstration, we extracted 340 mW of single-frequency light around 459 nm with nearly diffraction limited beam quality. We have demonstrated a tuning range of 1.5 nm and significantly larger tuning is possible by using a different nonlinear crystal. This approach can easily be expanded to cover other spectral regions.

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