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Generation of single-frequency tunable green light in a coupled ring tapered diode laser cavity

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Abstract: We report the realization of a tapered diode laser operated in a coupled ring cavity that significantly improves the coherence properties of the tapered laser and efficiently generates tunable light at the second harmonic frequency. The tapered diode laser is tunable with single-frequency output in the broad wavelength range from 1049 nm to 1093 nm and the beam propagation factor is improved from $M^2 = 2.8$ to below 1.1. The laser frequency is automatically locked to the cavity resonance frequency using optical feedback. Furthermore, we show that this adaptive external cavity approach leads to efficient frequency doubling. More than 500 mW green output power is obtained by placing a periodically poled $LiNbO_3$ crystal in the external cavity. The single frequency green output from the laser system is tunable in the 530 nm to 533 nm range limited by the $LiNbO_3$ crystal. The optical to optical conversion efficiency exceeds 30%.

OCIS codes: (140.2020) Diode lasers; (140.3515) Lasers, frequency doubled; (140.3560) Lasers, ring; (190.4410) Nonlinear optics, parametric processes.

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1. Introduction

Visible narrowband lasers with high beam quality are required for a number of applications within both science and industry. Several methods exist for the generation of light at the required spectral regions. Direct emission from diode lasers is available in certain wavelength regions. The output power is, however, limited by the narrow ridge waveguide which is necessary to obtain TEM_{00} emission. An extensively used approach is nonlinear frequency conversion such as second harmonic generation (SHG) or sum frequency generation (SFG) of lasers in the near infrared spectral region. The simplest approach is single-pass SHG in which the light from a laser is incident on a nonlinear crystal. When tuning of the generated light is required, for example for laser cooling of atoms, a diode laser is an obvious choice as the pump source due to the wide emission bandwidth of diode lasers. As an example of this approach, a single-mode DFB diode laser was frequency doubled in a periodically poled MgO doped $LiNbO_3$ (PPMgLN) waveguide to produce 107 mW at 530 nm [1]. The output power using this approach is still limited by the power of the diode laser and also the power handling of the waveguide. Using tapered diode lasers, the nearly diffraction-limited output power from the laser can be significantly increased and SHG of tapered diode lasers have produced more than 1.5 W of visible light [2]. SFG of two spectrally combined tapered diode lasers has pushed this power level even further towards 4 W [3]. The beam properties of the tapered lasers, however, typically consist of a powerful central lobe and lower higher order side lobes. This higher order mode content is to some extend transferred to the second harmonic beam. If the used diode laser is tunable, the generated visible emission is also tunable as long as phase matching is achieved in the nonlinear crystal. Tuning over more than 5 nm around 488 nm was achieved with an external cavity diode laser in combination with a PPMgLN crystal [4]. A comprehensive overview of SHG using edge-emitting diode lasers can be found in [5].

Higher conversion efficiency can be achieved using an external cavity for enhancing the fundamental power. Extensive work has been performed on this topic and external cavity SHG has been demonstrated throughout the visible spectral range using different lasers [6,7]. A complication using this method is that the resonance frequency of the cavity must match the laser frequency and thus some sort of active locking is required. Active locking requires additional optical and electronic components and the final setup is typically sensitive to vibrations and acoustic noise. Passive locking of the laser frequency to the cavity resonance frequency can be obtained using feedback from the cavity to the laser in order to obtain optical locking. Kozlovsky et al. presented an elegant approach towards this method using a monolithic potassium niobate ring resonator for SHG and a grating for selecting the laser wavelength [8]. A similar approach was demonstrated using a bow-tie ring resonator as the external cavity [9]. Recently this approach was expanded to include a tapered amplifier as the gain element and in this way the output power was significantly increased to more than 300 mW around 488 nm [10]. However, the tuning was limited by the available temperature range and thus the applicability is somewhat limited. Tuning by more than 2 nm of the output from a passively locked frequency doubled broad area diode laser was demonstrated with a compact quasi-monolithic ring resonator [11].

In this paper we present a coupled ring cavity approach for improvement of the coherence properties of a tapered diode laser and for the generation of tunable visible light. The cavity resonance in combination with a diffraction grating ensures single-frequency emission and the beam propagation factor, M^2, is improved from 2.8 to below 1.1. The laser frequency is passively locked to the cavity resonance frequency by optical feedback providing stable and simple locking. More than 500 mW of diffraction limited green light is generated with optical conversion efficiency exceeding 30%. Furthermore, the single-frequency green light is tunable from 530 nm to 533 nm.

2. Experimental setup

A schematic layout of the experimental setup is shown in Fig. 1. The core of the setup is a tapered amplifier designed for operation around 1060 nm. The output from the tapered

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amplifier is collimated in the fast axis using an aspherical lens with 3.1 mm focal length and a numerical aperture of 0.68. The fast axis collimating lens focuses the beam in the slow axis due to the inherent astigmatism of tapered amplifiers. The slow axis is collimated using a cylindrical lens with 30 mm focal length which provides a nearly circular beam. A focusing lens with 250 mm focal length is used to modematch the beam from the tapered amplifier to the enhancement cavity with a focus diameter of 240 µm by 260 µm in the horizontal and vertical direction, respectively. The beam is passed through an optical isolator with >30 dB isolation to ensure unidirectional operation. A half wave plate is used to rotate the polarization to vertical which fits with the phase matching conditions of the nonlinear crystal. The enhancement cavity is constructed as a four mirror bow-tie cavity with two partly reflecting plane mirrors (M1 and M2) and two highly reflecting curved mirrors with a radius of curvature of 50 mm (M3 and M4). The curved mirror after the nonlinear crystal (M4) is coated for high reflectivity at 1064 nm and highly transmitting at the second harmonic wavelength of 532 nm. The plane input mirror (M1) in the cavity is 90% reflecting and the output mirror (M2) is 95% reflecting. These reflectivities proved to be optimum in terms of the generated second harmonic power. The distance between the two curved mirrors in the cavity is about 67 mm and the remaining distance is about 207 mm resulting in a free spectral range (FSR) of approximately 1.1 GHz. This cavity supports a mode with a beam diameter of approximately 210 µm by 250 µm between the plane mirrors and a diameter of 60 µm by 70 µm between the curved mirrors. In the small beam waist, an 8 mm long PPMgLN crystal (*HC Photonics*) is placed. The crystal is poled with a period of 6.92 µm for SHG of light at 1064 nm and AR coated at both the fundamental and second harmonic wavelengths. A 125 µm thick un-coated YAG etalon with a FSR of approximately 659 GHz is included in the cavity to increase the power and wavelength stability as the laser tended to perform random mode hops without the etalon. The infrared light escaping the enhancement cavity is collimated using a spherical lens with a focal length of 100 mm. A half wave plate is inserted in the beam path to control the polarization incident on the 1200 grooves pr. mm grating. The polarization can be used to optimize the power coupled into the ridge section of the tapered amplifier as the diffraction efficiency of the grating is polarization dependent. An aspherical lens with 3.1 mm focal length is used to couple the light into the ridge section. The laser ring cavity is approximately 910 mm long resulting in a FSR of approximately 330 MHz.

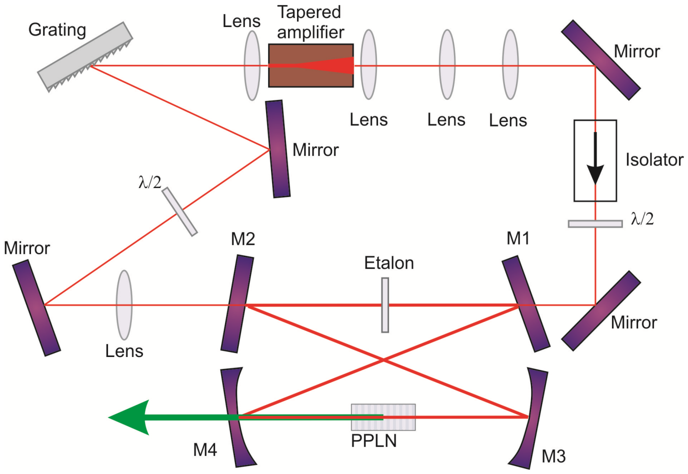

Fig. 1. Schematic layout of the coupled ring cavity setup.

The tapered amplifier used in the experiments has a total length of 4 mm divided between a 1 mm long index guided single-mode ridge waveguide section and a 3 mm long gain guided tapered amplifier section. The taper angle for the amplifier is 4° resulting in an output aperture width of 210 µm. The tapered amplifier is grown by metal-organic vapor phase epitaxy. The active region of the amplifier consists of a double InGaAs quantum well, each 7

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nm thick. The active region is embedded in a 3.6 µm thick $Al_{0.25}Ga_{0.75}As$ waveguide and $Al_{0.5}Ga_{0.5}As$ cladding layers. The layer sequence is completed by a highly doped GaAs contact layer. The vertical far field angle of this super large optical cavity structure (SLOC) [12] is about 22° (FWHM). The facets of the device were passivated and optically coated. The rear facet of the amplifier is antireflection coated with a reflectivity below 0.1% while the front facet is coated to a reflectivity of about 2%. The device was mounted p-side down on a CuW submount using AuSn solder. This subassembly is soldered on a standard C-mount.

3. Results and discussion

The tapered amplifier was first characterized in an external cavity setup using the Littrow geometry. The amplifier current was increased up to 3 A and the output power of the external cavity laser was measured at different operating wavelengths. The wavelength is tunable in the 1049 nm – 1093 nm wavelength range and the output is single-frequency throughout the tuning range. A spectrum of the laser is shown in Fig. 2(A). The output power at four different wavelengths is shown in Fig. 2(B). A maximum power of 1.79 W is reached at 1064 nm and the output power is above 1.6 W in the 1052 nm to 1080 nm wavelength range. The beam propagation factor of the laser is measured at a current of 3 A to $M^2 = 1.3$ and 2.8 in the fast and slow axis direction, respectively. The beam in the slow axis direction exhibits the typical characteristics of a tapered diode laser with a strong central lobe containing about 80% of the power and some smaller higher order lobes.

When the laser is operated in the coupled external cavity, the laser is tunable within the same spectral range as in the Littrow configuration and the laser stays single-frequency throughout the tuning range. The beam profile is pure TEM_{00} and the propagation factor, M^2, is improved significantly to 1.03 in both axes due to the external cavity. In the present setup, the focus was on achieving a high second harmonic output power and thus only very low power was extracted at the fundamental wavelengths. However, it is possible to select mirror combinations to optimize the extracted power in a diffraction limited beam around 1064 nm.

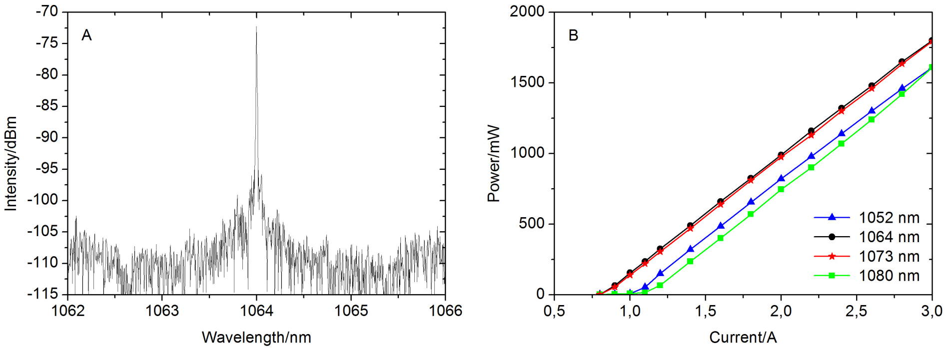

Fig. 2. (A) Example spectrum of the laser at 1064 nm. (B) Power-current characteristics for the external cavity tapered diode laser at different wavelengths within the tuning range.

The PPMgLN crystal is mounted in a temperature controlled oven and the temperature is stable to within 0.1 K. At a PPMgLN temperature of 22.7°C, the corresponding phase matched wavelength is 1061.4 nm. The generated green light is thus at a wavelength of 530.7 nm. The generated power at the second harmonic is shown in Fig. 3.

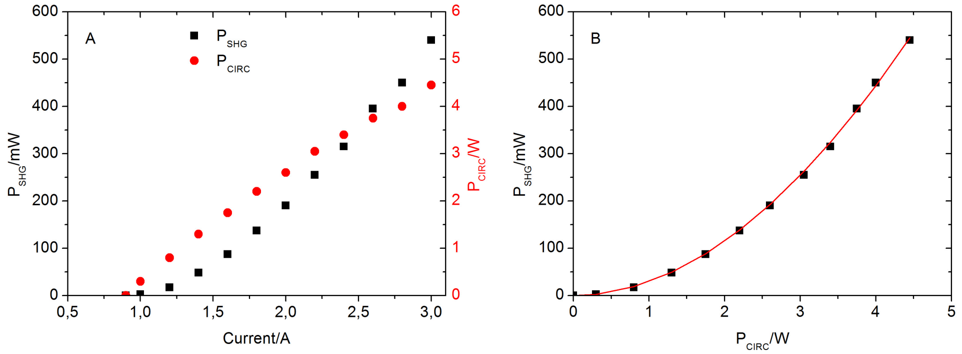

Fig. 3. (a) Generated second harmonic power (squares) as function of injection current to the tapered amplifier. The corresponding circulating fundamental power is also shown (dots). (b) Second harmonic power versus circulating fundamental power. The solid line is a fit to the measured values (squares).

A second harmonic output power of 540 mW is obtained at 3 A injection current to the tapered amplifier. The circulating fundamental power is 4.45 W at this operating point. This corresponds to a nonlinear conversion efficiency of 3%/W when fitting the measured values using the depleted pump approximation [2]. The circulating fundamental power is measured as the leakage through the curved mirror before the PPMgLN crystal (M3). The reflectivity of this mirror has been measured to 99.98% in a separate setup. The optical-to-optical conversion efficiency is 30.2% compared to the maximum power available from the external cavity tapered laser. It is seen in Fig. 3(a) that the circulating power is limited by the high conversion efficiency of the nonlinear crystal. Without the intracavity YAG etalon, the power was fluctuating between 300 and 500 mW. We attribute this behaviour to mismatch between resonance peaks of the two resonant cavities. The spectrum of the green light is measured with an optical spectrum analyzer (OSA) (Advantest Corp. Q8347) and a typical spectrum is shown in Fig. 4(a). The measured spectral width is 2 pm, limited by the resolution of the OSA. A more detailed analysis was performed with a homemade Fabry Perot interferometer (FPI) with a FSR of 1.5 GHz and a finesse of 160 and the result is shown in the inset of Fig. 4(a). The FPI measurement shows no side peaks and a measured linewidth limited by the 9.4 MHz resolution of the FPI.

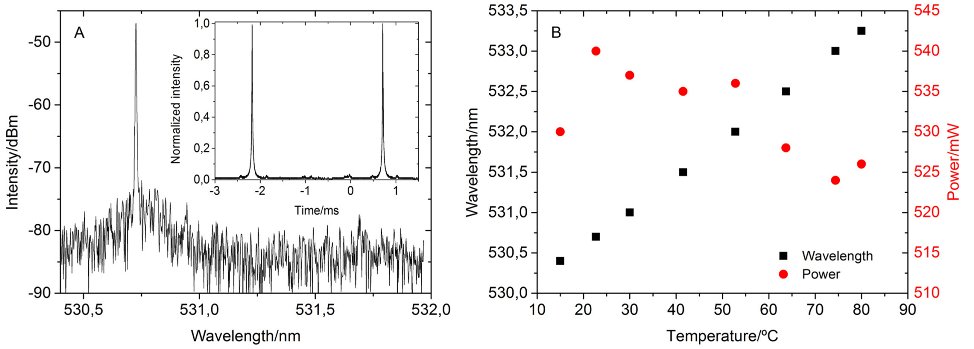

Fig. 4. (a) Measured spectrum of the second harmonic light. The inset shows a FPI trace of the green light. (b) Tuning characteristics of the second harmonic wavelength with PPMgLN temperature. The black squares show wavelength and the red dots show the output power.

With the intracavity etalon in fixed position, the fundamental wavelength of the laser can be tuned with the characteristics of the etalon, i.e. with a free spectral range of approximately 2.5 nm at 1060 nm and the power dropping significantly between the transmission peaks of

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the etalon. The tuning is performed by rotation of the diffraction grating. However, by simultaneous rotation of the grating and the etalon, it is possible to tune the laser at approximately constant intracavity power and by adjusting the temperature of the PPMgLN crystal, the second harmonic light can be tuned. In this way, more than 500 mW is obtained in the wavelength range from 530.4 nm to 533.2 nm with the temperature of the PPMgLN crystal increasing from 15°C to 80°C. The tuning characteristics are shown in Fig. 4(b). The tuning was not continuous and mode hops occurred during the tuning. The tuning range can easily be extended just by exchanging the PPMgLN crystal with another crystal with a period selected for the chosen wavelength range. In this way it is possible to cover the wavelength range from 525 nm to 546 nm with the present tapered amplifier. In [13] a tuning range from 1018 nm to 1093 nm was demonstrated with a single tapered amplifier and such an amplifier used in the present setup would increase the potential second harmonic tuning range to 509 nm to 546 nm. With a proper selection of tapered amplifier and nonlinear crystal, this method can be used to efficiently generate high quality light in large sections of the visible spectrum.

The fundamental beam resonating in the coupled ring cavity was improved to have a pure TEM_{00} beam profile and this profile is transferred to the second harmonic beam. The measured beam propagation factor is M^2 is 1.03 × 1.04 in the horizontal and vertical direction, respectively. The beam cross section is slightly elliptical due to the angled incidence on the two curved mirrors. The beam profiles of the second harmonic are shown in Fig. 5.

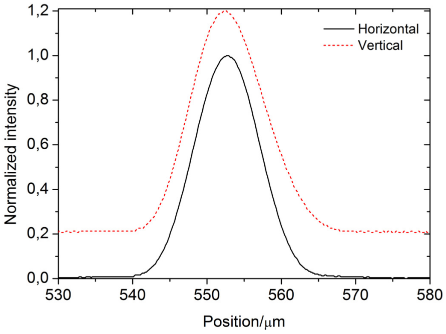

Fig. 5. Beam profiles of the generated second harmonic beam in the horizontal (solid line) and vertical direction (dashed line). The profiles are offset for clarity.

4. Conclusion

We have investigated improvement of the coherence properties of a tapered laser operated in a coupled external cavity and efficiently generated tunable light at the second harmonic frequency. A single-frequency tuning range of the tapered diode laser from 1049 nm to 1093 nm is demonstrated and the diode laser frequency is optically locked to the cavity resonance frequency. We have demonstrated a significant improvement of the beam quality with the beam propagation factor improving from $M^2 = 2.8$ to below 1.1. We have employed this approach to efficient second harmonic generation and have obtained more than 500 mW of diffraction limited output power with a conversion efficiency of more than 30%. Furthermore we have demonstrated tuning of the second harmonic wavelength in the range from 530 nm to 533 nm. With the demonstration of tuning, we have shown that this approach can be extended to cover a very wide range of wavelengths.

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