Blue light generated by intra-cavity frequency doubling of an edge-emitting diode laser with a periodically poled $LiNbO_3$ crystal

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Abstract: We demonstrate for the first time to our knowledge intra-cavity frequency doubling (ICFD) of an edge-emitter diode laser using a 10 mm-long 5.0 µm periodically poled $LiNbO_3$ (PPLN) crystal. An optical output power of 33 mW second harmonic blue light at 490.5 nm is generated at 1.0 A injection current, equivalent to an overall wall-plug efficiency of 1.8%. The measured M^2 values of blue beam are 1.7 and 2.4 along the fast and slow axis.

OCIS codes: (140.2020) Diode lasers; (140.3410) Laser resonators; (190.2620) Frequency conversion; (190.4360) Nonlinear optics, devices.

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1. Introduction

During the past few years high power laser sources in the blue-green frequency range have been attracting increasing interest in various application fields such as displays, optical recording and storage, bio-medical instrumentation, digital imaging and reprographics, space based satellite laser and underwater strategic communication etc [1]. In particular, high-brightness, high-efficiency, low-cost red-green-blue laser sources constitute a large and potentially high margin market opportunity in laser projection display systems that allow scalable screen size, high contrast, and high brightness.

Diode pumped solid state laser (DPSS) [2] and optically-pumped semiconductor laser (OPSL) [3] usually provide a platform as light sources to produce blue and green light by second-harmonic generation (SHG). The DPSS systems can be designed in a compact package with high-quality beam, high power output and low loss. However, they still suffer from low wall-plug efficiency owing to heat management problems. Optically pumped semiconductor disk lasers, which are also known as vertical external cavity surface emitting lasers (VECSEL) [4] combine the benefits of semiconductor lasers with the advantages of DPSS and external cavity flexible application. Recently Coherent Inc. offered the first commercial solid-state laser with CW output up to 2 W at 460 nm and 8 W at 532 nm based on frequency doubling of an optically pumped VECSEL. However, the challenges for laser projection still focus on the scalable greater powers and extremely low cost requirement of the consumer electronics markets.

Direct frequency doubling of electrically pumped diode lasers in the near infrared region is becoming more and more interesting for the blue and green laser markets not only due to the compact size and high reliability but also because it is scalable to high production volumes and modest costs. A new type of continuous-wave (CW) lasers emitting at 460 nm, 488 nm and 532 nm based on intra-cavity frequency doubling (ICFD) of the electrically pumped VECSEL have addressed the low power needs of bio-analytical instruments such as flow cytometers and confocal microscopes [5-7]. Moreover, multi-emitter arrays based on ICFD of electrically pumped VECSEL technology have been demonstrated to be suitable as a platform for projection displays [8,9]. Also, planar-waveguide devices combined with ICFD [10,11] dramatically improves green laser efficiency, power, size and cost. 7.6 W with the record-high electrical efficiency of 20% was demonstrated [11]. Although conventional edge-emitting diode lasers (EEDL) typically suffer from a lack of narrow spectral linewidth and spatial beam quality, the higher output power and higher power-conversion efficiencies achieved with low cost compared with VECSEL and OPSL allow EEDL to transition from specialty scientific items to true industrial tools. Beam-shaping and beam-combining technologies have been developed and paved the way for a new generation of diode lasers with significantly higher brightness. Furthermore, the much more efficient ICFD concept in an extended cavity based on EEDL can also be achieved, which provides a competitive platform for the high power green and blue laser sources, especially, for the next generation projection display markets. In this paper, we exploit for the first time to our knowledge ICFD of an edge emitting diode laser using a PPLN bulk crystal.

2. ICFD model

In order to derive a model for CW frequency doubling efficiency in the laser cavity based on applicable laser rate equations, the diode laser ICFD can be described as in Fig. 1.

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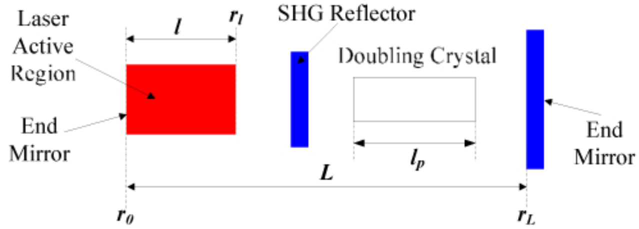

Fig. 1. Simplified diode laser ICFD layout

For an ICFD laser, the harmonic conversion is always considered as a nonlinear loss of the fundamental wave (FW) photons. Therefore the basic laser rate equations which describe the interaction of the photons and electrons in the single-mode diode laser ICFD can be expressed as [12,13]

$$\frac{dn}{dt} = I_e - \beta qn - \frac{n}{\tau} \tag{1}$$

$$\frac{dq}{dt} = \beta qn - \sigma q - Kq^2 \tag{2}$$

where n is the total population inversion between the two laser levels; I_e is the pump injection current divided by the electronic charge; τ is the carrier lifetime (fluorescence mainly); q is the total number of photons in the cavity at the laser frequency; K is the nonlinear coupling coefficient and Kq^2 represents the nonlinear loss due to harmonic conversion.

In Eq. (1, 2), β is related to stimulated emission rate, dimensionless. σ describes loss mechanisms and defines gain threshold, units of s^{-1}. They are given separately as

$$\beta n = \frac{cl}{L} g(\nu) = \frac{cl}{L}\left(\frac{\lambda^2 A}{8\pi n_1^2}\right)\frac{1}{\delta\nu_0 \cdot V_g} \cdot n \tag{3}$$

$$\sigma = \frac{cl}{L} g_t = \frac{cl}{L}\left[\frac{1}{2l}(1 - r_0 r_L) + \alpha_g + \alpha_c\right] \tag{4}$$

where g_t is threshold gain and $g(\nu)$ is determined by the stimulated emission; c is speed of light; l and L are laser active region and cavity lengths respectively as shown in Fig. 1; A is the Einstein coefficient for stimulated emission; n_1 is index of the gain medium; $1/\delta\nu_0$ is a simplified lineshape function; For GaAs $\delta\nu_o$ is ~10^{13} Hz[12] and V_g is the volume of the gain region; r_0, r_l and r_L are the reflectivities of the emitter back facet, output facet and cavity end mirror, respectively; α_g is the distributed loss in the gain media; α_c is the distributed loss in the extended cavity defined as

$$\alpha_c = -\ln(1-\gamma)/L \tag{5}$$

where γ is the extended cavity loss coefficient.

In the steady state, Eq. (1, 2) can be written as

$$I_e - \beta nq - \frac{n}{\tau} = 0 \tag{6}$$

$$\beta qn - \sigma q - Kq^2 = 0 \tag{7}$$

where the nonlinear loss item Kq^2 is related to the second harmonic output power $P_{2\omega}$ and is given by

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$$P_{2\omega} = 2 \cdot K q_0^2 h\nu \tag{8}$$

where the total number of photons q_0 in the steady state can be calculated from Eq. (7,8); the factor of 2 is due to the double pass of the fundamental beam through the PPLN crystal.

For our diode laser ICFD model, the intra-cavity FW optical power, P_{opt}, is related to the photon number q_0 and is given by

$$P_{opt} = \frac{q_0 c}{L} h\nu \tag{9}$$

and $P_{2\omega}$ can also be described by

$$P_{2\omega} = 2 \cdot \chi P_{opt}^2 \tag{10}$$

where the factor of 2 has the same signification in Eq. (8), χ is the SHG normalized conversion efficiency with units of w^{-1} such that[14]

$$\chi = \frac{8\pi^2}{\varepsilon_0 c \lambda^2} \frac{d_{eff}^2}{n_{2\omega} n_\omega^2} \frac{2n_\omega}{\lambda} l_p \exp\left(-\alpha_+ l_p\right) h\left(\alpha, \beta, \kappa, \xi, \mu\right) \tag{11}$$

where ε_0 is the vacuum permittivity; c is speed of light; λ is the fundamental wavelength; d_{eff} is the nonlinear-optic coefficient; n_ω and $n_{2\omega}$ are the refractive index of fundamental and second-harmonic wave respectively; l_p is the length of the PPLN crystal; α_+ is the absorption parameter; h $(\alpha,\beta,\kappa,\mu)$ is defined in [15,Eq. (2.23)].

By using the Eq. (6-11), the second harmonic power for our system is described by:

$$P_{2\omega} = 2 \cdot \frac{h\nu}{4\beta^2\tau^2} \left[\frac{\left(K + \sigma\beta\tau\right)}{\sqrt{K}} - \sqrt{\frac{\left(K + \sigma\beta\tau\right)^2}{K} - 4\beta\tau\left(\sigma - \beta I_e \tau\right)} \right]^2 \tag{12}$$

where K is the nonlinear coefficient; and can be calculated from Eq. (8-11) using:

$$K = \frac{\chi c^2 h\nu}{L^2} \tag{13}$$

3. Experimental setup and results

Figure 2 shows the scheme of ICFD based on an edge emitting diode laser using a PPLN bulk crystal. The cavity consists of a single edge emitter as gain medium, microlens in fast and slow axes L_1, focus lens L_2 and L_3, infrared filter P_1, half-wave plate P_2, PPLN and output coupling mirror. The single edge emitter is 3.6 mm long and 0.4 mm wide. The beam size from the single emitter is 0.5 µm in fast axis and 3 µm in slow axis with lateral far field divergence of 5-9 degrees and vertical far field of 18.5-23.5 degrees. Ultra-low coating reflectivity on the front facet is less than 0.1% in a wavelength range around 976 nm. This high performance facet AR coating must inhibit the original diode laser cavity, allowing the extended longer laser cavity to dominate. In addition, this AR coating must not perturb the laser to cause detrimental spectral and intensity effects through the coupled cavity mechanism.

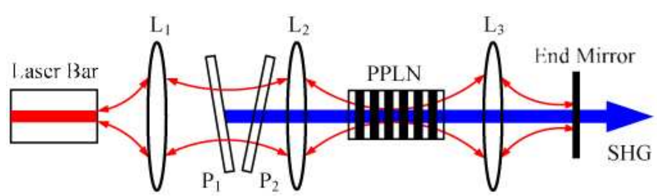

Fig. 2. Optical set-up of ICFD based on an edge emitting diode laser using a PPLN bulk crystal

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The microlens L_1 is a commercially available product for single emitters with standard AR coating at 790-990 nm from LIMO Lissotschenko Mikrooptik GmbH. The output light is collimated in the fast and slow axes to produce a near symmetrical focus by only the microlens element, which is composed of a monolithic glass block with two opposite crossed cylindrical surfaces and passive alignment edges. The beam waist on the focus is imaged through a 5 mm focal length lens L_2 such that it gives a near symmetrical 30 µm beam radius focused to the midpoint of a 10 mm-long 0.5 mm-thick 5.0 µm period PPLN crystal supplied by Covesion. The PPLN temperature is stabilized using an oven in order to achieve phase matching at the laser wavelength. A thin film narrow bandwidth IR filter is inserted in the cavity before the PPLN to restrict the spectral laser bandwidth to <0.1 nm so that optimal frequency conversion can be obtained. A half-wave plate is inserted in the beam path for accurate control of the pump polarization. The beam waists are positioned at the input focal plane of the focusing lens L_3 while the output focal plane is positioned at the end mirror. P_2, L_2, L_3, and PPLN have the AR coating both at 488 nm and 976 nm. Retro-reflection of the IR light is achieved at end mirror coated for high reflectivity in the near-infrared range and transparency for blue light. P_1 AR coated at 976 nm has a reflectivity >95% for unpolarized light at wavelengths of 488 nm. In order to extract the counter propagation SHG beam, a tilt from filter P_1 in the cavity will provide a near collinear but translated beam output. This level of translation would ensure no interference between the beams and allows this beam to be losslessly coupled out. The position of the beam waist is very important. If the position is shifted, it will cause a defocusing loss in the cavity, especially when coupling the light back into the laser emitter.

We aligned all the components to the optimum position. A maximum of 33 mW blue laser output is obtained and the SHG power characteristics are shown in Fig. 3. Here the solid lines are theoretical curves based on Eq. (12) for SHG conversion with different cavity (coupling) losses. The asterisks are the experimental data, which indicate a real cavity loss of around 70% in the experiments. Table 1 shows the parameters used for the laser diode ICFD model. Clearly, the coupling and reflection loss of the laser light into the laser chip is a key driver of the performance. The coupling efficiency quoted depends on a number of key parameters but the main one is the optical specification and alignment of the key micro-lens in the system. In addition, losses may be incurred by unwanted reflections and insertion loss.

Table 1. Parameters in laser diode ICFD model

h	6.626×10^{-34} J.s	L	33×10^{-3} m	α_g	0.8 cm^{-1}
λ	976×10^{-9} m	l_p	10 mm	r_0	0.99
c	2.99×10^{8} m/s	χ	2% w^{-1}	r_L	0.99
e	1.602×10^{-19} c	δv_o	10^{13} Hz	n_1	3.6
l	3.6×10^{-3} m	V_g	0.54×10^{-14} m^3		

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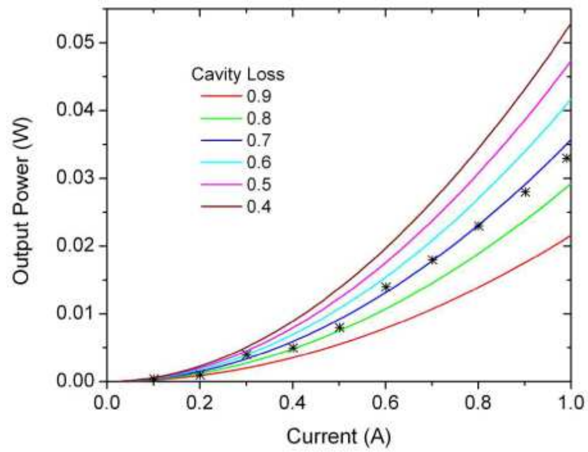

Fig. 3. SHG conversion for different cavity (coupling) losses.

The spectrum of the blue laser emission at an injection current of 1.0 A is shown in Fig. 4, which is measured using an Ocean Optics USB2000 miniature fiber optic spectrometer. A narrow peak at an emission wavelength of 490.5 nm was observed. The bandwidth of 0.65 nm is dominated by the resolution limit of the spectrometer.

Figure 5 shows the caustic for both axes at an injection current of 1.0 A. The output blue beam was focused by a 100 mm focal length lens and the beam profiles were recorded using Thorlabs BP109 Beam Profiler. The M^2 values of the output blue beam at an injection current of 1.0 A were measured to be 1.7 and 2.4 along the fast and slow axis, respectively. The asymmetrical blue beam profiles are due to the asymmetrical IR beam profiles along the fast and slow axis at the beam waist. The M^2 value of the infrared beam of the diode laser was measured to be approximately 1.9 along the slow axis and the beam along the fast axis was found to be nearly diffraction limited.

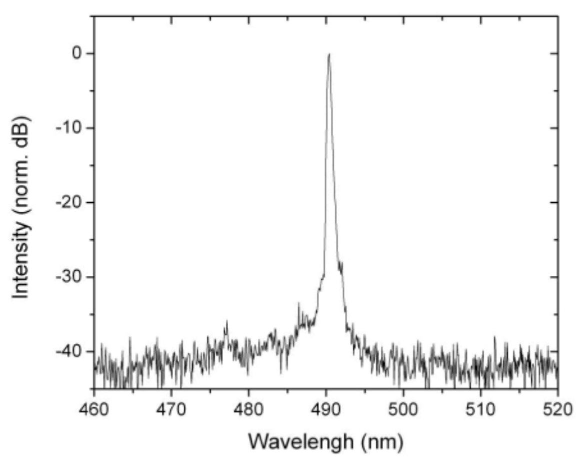

Fig. 4. Spectrum of a generated blue light at an injection current of 1.0 A with an output power of 33 mW.

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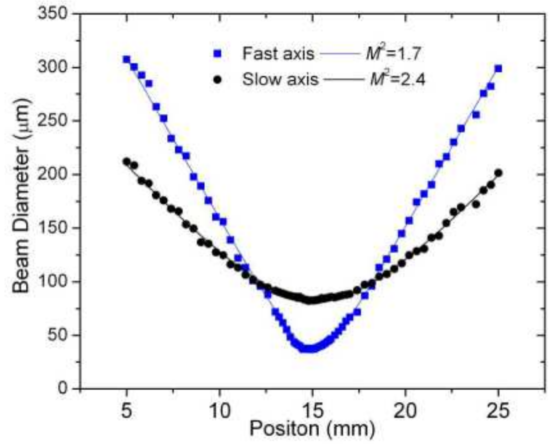

Fig. 5. Caustic of the blue beam for both axes at an optical output power of 33 mW. The hyperbolic fit corresponds to a beam quality of M^2=1.7 in the fast axis (blue squares) and M^2=2.4 in the slow axis (black dots).

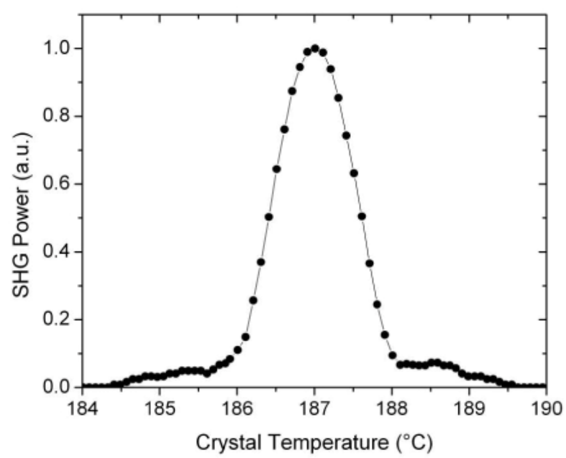

Fig. 6. PPLN crystal temperature dependence of blue light outputs.

In the experiments the crystal is temperature stabilized using an oven in order to achieve phase matching at the laser wavelength. Figure 6 shows the dependence of blue light output on crystal temperature. The optimal phase-matching temperature at a blue output power of 33 mW is around 187 °C. This shows that the acceptance bandwidth of the PPLN crystal used in our work is less than around one degree.

4. Summary and Conclusion

We have demonstrated for the first time to our knowledge that stable ICFD is possible using telecom high power diode lasers with PPLN and that our model correlates with the experimental data. A blue output optical power of 33 mW was achieved at an injection current of 1.0 A with an optimal phase-matching PPLN temperature of 187 °C. The M^2 values of the output blue beam were measured to be 1.7 and 2.4 along the fast and slow axis, respectively. To increase the efficiency further, careful design of the lens used for the fast and slow axis beam shaping and use of lower-temperature MgO-doped PPLN can be considered.

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