Research Article | Vol. 26, No. 8 | 16 Apr 2018 | OPTICS EXPRESS 10000

Optics EXPRESS

7.5 W blue light generation at 452 nm by internal frequency doubling of a continuous-wave Nd-doped fiber laser

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Abstract: We present the first frequency-doubled neodymium-doped fiber laser generating multi-watt CW power near 450 nm. A bow-tie resonator incorporating a LBO nonlinear crystal is integrated within a Nd-doped fiber laser emitting near 900 nm. This scheme achieves an IR to blue conversion efficiency close to 55% without any active control of the internal resonant cavity. As a result, up to 7.5 W of linearly-polarized blue power is generated, with beam quality factors M_x^2 ~1.0 and M_y^2 ~1.5. A simple numerical model has been developed to optimize and analyse the IR to blue conversion efficiency in the resonant cavity. Performance limitations and prospects for further improvements are discussed.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.3530) Lasers, neodymium.

References and links

1. J. Baghdady, K. Miller, K. Morgan, M. Byrd, S. Osler, R. Ragusa, W. Li, B. M. Cochenour, and E. G. Johnson, "Multi-gigabit/s underwater optical communication link using orbital angular momentum multiplexing," Opt. Express **24**(9), 9794–9805 (2016).
2. W. G. Telford, T. Hawley, F. Subach, V. Verkhusha, and R. G. Hawley, "Flow cytometry of fluorescent proteins," Methods **57**(3), 318–330 (2012).
3. H. Sparks, S. Warren, J. Guedes, N. Yoshida, T. C. Charn, N. Guerra, T. Tatla, C. Dunsby, and P. French, "A flexible wide-field FLIM endoscope utilising blue excitation light for label-free contrast of tissue," J. Biophotonics **8**(1-2), 168–178 (2015).
4. N.-O. Hansen, A.-R. Bellancourt, U. Weichmann, and G. Huber, "Efficient green continuous-wave lasing of blue-diode-pumped solid-state lasers based on praseodymium-doped $LiYF_{4}$.," Appl. Opt. **49**(20), 3864–3868 (2010).
5. I. Courtillot, A. Quessada, R. P. Kovacich, J.-J. Zondy, A. Landragin, A. Clairon, and P. Lemonde, "Efficient cooling and trapping of strontium atoms," Opt. Lett. **28**(6), 468–470 (2003).
6. Z. Quan, Y. Yi, L. Bin, Q. Dapeng, and Z. Ling, "13.2 W laser-diode-pumped Nd:YVO_4/LBO blue laser at 457 nm," J. Opt. Soc. Am. B **26**(6), 1238–1242 (2009).
7. J. Rothhardt, T. Eidam, S. Hädrich, F. Jansen, F. Stutzki, T. Gottschall, T. V. Andersen, J. Limpert, and A. Tünnermann, "135 W average-power femtosecond pulses at 520 nm from a frequency-doubled fiber laser system," Opt. Lett. **36**(3), 316–318 (2011).
8. J. Boullet, R. Bello-Doua, R. Dubrasquet, N. Traynor, C. Lecaplain, A. Hideur, J. Lhermite, G. Machinet, C. Médina, and E. Cormier, "Visible and infrared sources based on three-level ytterbium-doped fiber lasers," in Advances in Optical Materials, OSA Technical Digest (CD) (Optical Society of America, 2011), paper FThC5.
9. B. Leconte, B. Cadier, H. Gilles, S. Girard, T. Robin, and M. Laroche, "Extended tunability of Nd-doped fiber lasers operating at 872-936 nm," Opt. Lett. **40**(17), 4098–4101 (2015).
10. P. H. Pax, V. V. Khitrov, D. R. Drachenberg, G. S. Allen, B. Ward, M. Dubinskii, M. J. Messerly, and J. W. Dawson, "Scalable waveguide design for three-level operation in Neodymium doped fiber laser," Opt. Express **24**(25), 28633–28647 (2016).
11. C. Bartolacci, M. Laroche, H. Gilles, S. Girard, T. Robin, and B. Cadier, "Generation of picosecond blue light pulses at 464 nm by frequency doubling an Nd-doped fiber based Master Oscillator Power Amplifier," Opt. Express **18**(5), 5100–5105 (2010).
12. P. Dupriez, J. K. Sahu, A. Malinowski, Y. Jeong, D. J. Richard, and J. Nilsson, "80 W green laser based on a frequency-doubled picosecond, single-mode, linearly-polarized fiber laser," Conference on Lasers and Electro-Optics 2006 Technical Digests (Optical Society of America, Washington, D.C., 2006) CThJ1.

#320644 https://doi.org/10.1364/OE.26.010000
Journal © 2018 Received 25 Jan 2018; revised 9 Mar 2018; accepted 27 Mar 2018; published 6 Apr 2018

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13. G. K. Samanta, S. C. Kumar, K. Devi, and M. Ebrahim-Zadeh, “Multicrystal, continuous-wave, single-pass second-harmonic generation with 56% efficiency,” Opt. Lett. **35**(20), 3513–3515 (2010).
14. J. Hirohashi, V. Pasiskevicius, S. Wang, and F. Laurell, “Picosecond blue-light-induced infrared absorption in single-domain and periodically poled ferroelectrics,” J. Appl. Phys. **101**(3), 033105 (2007).
15. Z. Y. Ou, S. F. Pereira, E. S. Polzik, and H. J. Kimble, “85% efficiency for cw frequency doubling from 1.08 to 0.54, µm,” Opt. Lett. **17**(9), 640–642 (1992).
16. R. Cieslak and W. A. Clarkson, “Internal resonantly enhanced frequency doubling of continuous-wave fiber lasers,” Opt. Lett. **36**(10), 1896–1898 (2011).
17. G. D. Boyd and D. A. Kleinman, “Parametric interaction of focused gaussian light beams,” J. Appl. Phys. **39**(8), 3597–3639 (1968).
18. B. Leconte, H. Gilles, T. Robin, B. Cadier, and M. Laroche, “Transverse mode selection in a Nd-doped fiber amplifier at 910 nm,” Opt. Express **25**(15), 18314–18319 (2017).
19. X. Wang, F. Kallmeyer, S. Wang, A. Ding, and H.-J. Eichler, “Frequency doubling of focused laser beams for high pulse energy at 471nm,” Proc. SPIE **7194**, 71940M (2009).

1. Introduction

High-power, high-brightness continuous-wave (CW) lasers in the blue spectral domain have a number of application areas including laser underwater communications [1], flow cytometry [2], biomedical imaging [3] and optical pumping [4, 5]. But to date there are only a few laser sources that can operate in the 450 nm wavelength region. Single-mode InGaN-based lasers are already available for direct emission near 445 nm but, so far, do not provide more than a few hundreds of mW. Wavelengths generation near 450 nm using a frequency-doubled Nd-doped solid-state laser was also reported in the literature. 13.2 W at 457 nm has been demonstrated by intracavity frequency doubling of a Nd:YVO_4 laser emitting at 914 nm [6]. Hence, the development of high-brightness laser sources in the visible domain mainly relies on the frequency doubling of solid-state lasers emitting in the near infrared (IR) spectral domain. For this purpose, fiber lasers have many advantages over other laser technologies, in particular in terms of output power, spatial beam quality and wavelength agility. While green and blue-green laser source based on Yb-doped fibers are now well developed and have shown high power emissions near 530 nm [6] and 490 nm [8], frequency doubling in the pure blue would require a fiber laser source emitting at wavelengths shorter than 920 nm. In this perspective, Nd-doped fiber (NDF) lasers can be operated on the 3-level $^4F_{3/2}$ - $^4I_{9/2}$ transition and have recently enabled a continuous laser emission from 872 nm to 936 nm [9]. In addition, 27 W of output power near 925 nm has been recently demonstrated using a Nd-doped photonic crystal fiber, which paves the way for further power scaling [10]. Nonetheless, no more than 300 mW of blue power has been reported so far from second-harmonic generation (SHG) of a Nd-doped fiber laser system [11], which tends to show that the frequency doubling scheme needs to be specifically improved for these systems. One of the simplest schemes for the second harmonic generation is a direct conversion of the IR laser beam after a single-pass in a non-linear crystal. However, this process requires very high incident power to achieve a reasonable efficiency, which generally implies that the IR source be operated in pulsed regime (ns, ps or fs) in order to reach multi-kW peak powers. The frequency doubling of Yb-doped fiber lasers has, for example, permitted to generate very high powers near 530 nm in various pulsed regimes [7, 12]. The frequency doubling of a CW fiber laser is even more challenging. Efficient SHG in a single-pass generally requires both a high power laser (P>20W) and the use of a periodically poled crystal which has a relatively high non-linear coefficient [13]. However, for a conversion in the visible, especially in the green or blue domain, the power of the second harmonic is limited by photo-refractive damage, thermal effects as well as blue-light-induced infrared absorption (BLIIRA) [14]. Frequency doubling in an external resonant cavity is another approach which has been proven highly effective to achieve conversion efficiencies as high as 85% [15]. This technique, however, is complex as it requires a single-frequency fiber laser source and an active control of the external cavity length. To overcome these two constraints, another attractive approach consists in using a frequency-doubling resonator integrated within the cavity of the fiber laser.

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This conversion scheme was first applied to a Yb-doped fiber laser and up to 19 W of CW power was demonstrated at 540 nm [16].

In this paper, we report the generation of multiwatt blue light near 450 nm from a frequency-doubled continuous-wave Nd-doped fiber laser operated on the $^4F_{3/2}$ - $^4I_{9/2}$ transition near 900 nm. IR-to-blue conversion was carried out in an internal bow-tie SHG resonator enclosing a LBO crystal. A record power of 7.5 W at 450 nm is obtained, which corresponds to a conversion efficiency of 55% with respect to the power at 900 nm coupled into the resonant cavity.

2. Experimental set-up

The configuration of the experimental set-up is depicted in Fig. 1. The main cavity of the fiber laser is formed by two mirrors with high reflectivity at 900 nm. The gain fiber is a 10 m long Nd-doped double-clad silica glass fiber with a 20 µm core diameter (~0.07 NA) and a 60 µm cladding diameter (0.45 NA). The core-to-cladding area ratio was optimized to increase the gain of the three-level transition and reduce spurious laser or amplified stimulated emission near 1060 nm [9]. Since the gain at 1060 nm is still sufficient to trigger parasitic lasing, both fiber end-facets are cleaved with an angle of ~15° and 1060 nm emission is filtered out at each side of the laser cavity to suppress broadband feedback. The Nd-doped fiber laser is pumped by a 60 W fiber-coupled laser diode (100 µm core diameter, NA 0.22) emitting at 808 nm. As the gain fiber was not designed to maintain the polarization, a quarter-wave plate and a Glan-Taylor polarizer are inserted in the cavity to partially compensate the depolarization in the fiber and align the polarization state of the beam to the vertical or horizontal axis of the SHG resonator. The internal resonator is a Bow-tie cavity with a LBO crystal enclosed at the primary beam waist between the two spherical concave mirrors M_3 and M_4. Compared to other resonator schemes, the bow-tie geometry has the advantage to be unidirectional and to avoid back-reflections from plane mirrors into the fiber laser. Hence, this resonator can be directly inserted in the linear cavity of a fiber laser and acts both as a longitudinal and transverse mode filter. Considering the small free spectral range (FSR) of the fiber laser cavity, we can assume that many longitudinal modes can be transmitted through the SHG resonator, as long as the finesse of this resonator is not too high.

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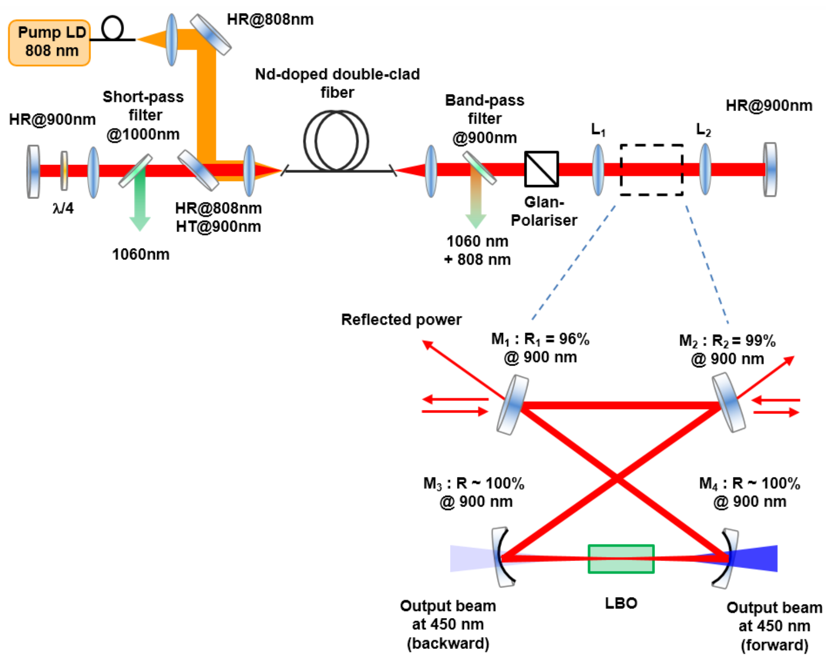

Fig. 1. Schematic diagram of the blue laser using a neodymium-doped fiber and a SHG resonator. M_1 to M_2 distance is 108 mm and M_3 to M_4 distance is 105 mm.

Two lenses, L_1 and L_2 with respective focal lengths 250 mm and 150 mm, were placed on each side of the bow-tie cavity to ensure optimal spatial adaptation of the fiber laser beam to the TEM_{00} mode of the cavity. The LBO crystal is cut for type-I (oo→e) critical phase matching at 905 nm ($\theta = 90°$, $\varphi = 22.5°$, $d_{eff} = 0.8$ pm/V), has a length of 1 cm and both facets are anti-reflection coated near 900 nm and 450 nm (R<0.5%). Using a radius of curvature of 100 mm for the two concave mirrors M_3 and M_4, the beam waist radius at 900 nm in the LBO crystal is estimated to ~40 µm for the experimental cavity geometry. In addition, the angle of incidence on the two concave mirrors is reduced to 7° to minimize the astigmatism aberration. The reflection coefficient of M_3 / M_4 mirrors is experimentally measured equal to 99.97% at 900 nm and 9% at 450 nm. By analyzing the beam transmitted through a concave mirror, it is possible to verify that the intracavity spatial mode at 900 nm is diffraction-limited (M^2<1.05) and shows no visible astigmatism. This power leak at 900 nm is also used to evaluate the intracavity power during experiments.

The fiber laser configuration including a bandpass filter at 900 nm proved to be the most adapted in terms of SHG conversion efficiency and self-pulsing instabilities. The filter has a bandwidth of 10 nm and induces a laser spectral width of ~4 nm [Fig. 4(a)]. Against all expectations, it turned out that the reduction of the laser spectral width by the use of a volume Bragg grating mirror or a diffraction grating was detrimental to the intracavity power and generated temporal instabilities such as transient Q-switching. As this effect is also observed without non-linear crystal, we believe that these instabilities are related to a number of longitudinal modes that is not sufficient to ensure a temporally stable transmission though the resonant cavity. In the absence of active cavity stabilization, the overlap between the two cavity frequency combs can therefore vary, which may induce loss modulation within the fiber laser cavity.

3. Theoretical analysis and resonant cavity optimization

Prior to the experiments, the reflection coefficients R_1 and R_2 of plane mirrors M_1 and M_2 have to be carefully determined in order to ensure both efficient frequency doubling and

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optimal fiber laser operation. The theoretical blue power generated in the LBO crystal can be calculated from the intra-cavity power at 900 nm by using the classical Boyd–Kleinman theory [17] for the actual optical arrangement and non-linear crystal. On this basis, we estimated the single-pass conversion efficiency $\gamma_{2\omega}$ to be 4.7×10^{-5} W^{-1} for a beam waist radius of 40 µm in the LBO crystal. For a fundamental power P_{inc} incident on the mirror M_1, the intracavity power P_ω is the solution of the equation:

$$P_\omega = \frac{(1-R_1)R_2P_{inc}}{\left(1-\sqrt{R_1R_2(1-\alpha)(1-P_\omega\,\gamma_{2\omega})}\right)^2}, \tag{1}$$

where α is the intracavity linear loss. The optimization of R_1 and R_2 values was first performed with the assumptions of an incident power of 15 W at 900 nm and no intracavity losses (α = 0). However, it is important to note that the resonant cavity has to support a few percent of losses induced by SHG in the nonlinear crystal. Consequently, maximum intracavity power is achieved for a moderate value of cavity finesse. From these calculations, it appears that maximum SH power is obtained for R_2 values close to 100%, whatever the value of R_1. For example, Fig. 2(a) shows the evolution of calculated SH power with respect to M_2 reflectivity in the case of R_1 set to 96%. However, feedback for lasing is provided by the backward propagating IR beam reinjected into the fiber after a double-pass in the bow-tie cavity (see Fig. 1). As can be seen from Fig. 2(a), the calculated double-pass transmission decreases rapidly for values of R_2 greater than 94%. In practice, this means that second-harmonic generation has to be mitigated to avoid a strong impact on the NDF laser efficiency. We estimate that the minimum feedback for stable laser operation is ~10%, which implies $R_2 \leq 99\%$. With R_2 set at 99%, Fig. 2(b) shows that maximum SH power (10 W) is reached for R_1 = 96-97%, corresponding to a conversion efficiency of 75%.

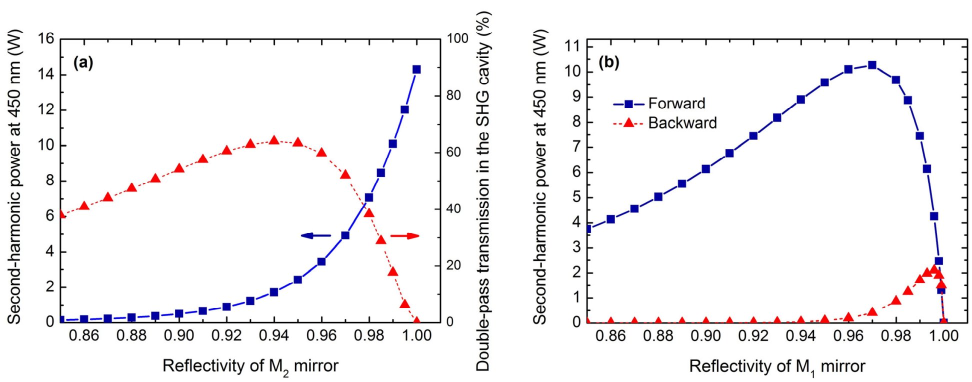

Fig. 2. Output power and transmission characteristics of a simulated SHG resonator based on bow-tie cavity design, (a) as a function of M_2 reflectivity (R_1 = 96%) and (b) as a function of M_1 reflectivity (R_2 = 99%). Incident fundamental power is 15 W, $R_3 = R_4$ = 100%, $\gamma_{2\omega} = 4.7 \times 10^{-5}$ W^{-1}, α = 0.

It is also verified that the blue power generated in the reverse direction (transmitted through mirror M_3) would be less than 0.2 W in that configuration (Fig. 2(b)), hence confirming that asymmetrical bow-tie cavity with $R_1 < R_2$ is well adapted to unidirectional SHG. As a result, M_1 and M_2 reflectivities of 96% and 99%, respectively, were used during the experiments.

4. Experimental result

Figure 3(a) shows the generated second-harmonic output power in the internal cavity as a function of the intracavity fundamental power. A maximum blue output power of 6.8 W at

452 nm is measured through mirror M_4. Taking into account the 9% loss from mirror M_4, the generated blue power corresponds to $P_{2\omega} = 7.5$ W for $P_\omega = 354$ W of intracavity fundamental power. Experimental frequency-doubled power shows a quadratic dependence on the intracavity fundamental power and, from a fitting procedure, the single-pass conversion efficiency in the LBO crystal is calculated to be 6×10^{-5} W^{-1}. Hence, this value is slightly above the theoretical coefficient predicted on the basis of Boyd–Kleinman theory.

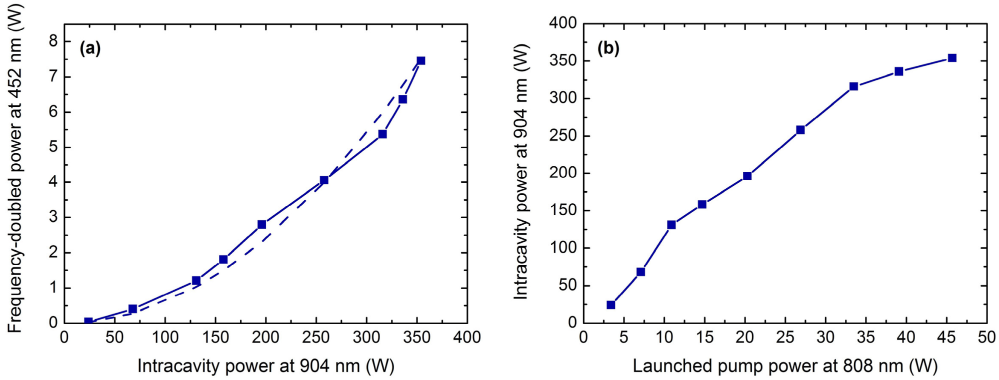

Fig. 3. (a) Blue power generated at 452 nm as a function of fundamental intracavity power at 904 nm (solid line) and corresponding best-fit quadratic curve (dash line), (b) Intracavity power at 904 nm as a function of launched pump power at 808 nm.

By measuring the reflected power in a beam separator placed before the M_1 mirror, we can estimate that the maximum fundamental power incident on the resonant cavity is 18 W [Fig. 3(b)]. The internal slope efficiency of the fiber laser is ~50% for an incident pump power less than 20 W. For higher pump powers, the transmission of internal resonator decreases due to efficient SHG and consequently the laser slope efficiency is reduced to ~35%. We also observed that about 25% of the incident IR power is reflected on the mirror M_1 whereas the theoretical reflection coefficient on the bow-tie cavity in these experimental conditions would be less than 1%. Thus, only 13.5 W of fundamental power can be coupled into the SHG resonator. As the internal resonant cavity only support a gaussian transverse mode, we can assume that the reflected power observed during experiments corresponds to the higher order modes (HOM) guided in the LMA core of the NDF. Indeed, with a V parameter close to 5, the amplification of up to three HOM was previously observed in a very similar NDF [18]. The nonlinear conversion efficiency of the SHG resonator is 55% with respect to the fundamental power coupled into the resonator, whereas the optical-to-optical efficiency is ~16%.

The linear intracavity loss α can be estimated using Eq. (1) for an intracavity power of 354 W and $\gamma_{2\omega} = 6 \times 10^{-5}$ W^{-1}. Considering that only 13.5 W can be coupled into the resonant cavity, the linear intracavity loss is calculated to be 0.7%. Consequently, it can be calculated that the reduction of intracavity losses by the use of a nonlinear crystal with better anti-reflection coatings or at Brewster incidence may improve the SH output power up to ~10 W.

The spectra of the IR intracavity power and blue power, measured using an optical spectrum analyzer, are shown in Fig. 4(a) and 4(b), respectively. The IR emission spectrum of the fiber laser spans a total spectral range of 4.2 nm and consists of five discrete peaks spaced 0.84 nm apart. The reason of this wavelength selection is not clearly identified. Each peak has a linewidth of ~0.06 nm (FWHM, resolution 0.01 nm) and may therefore contain a few tens of internal resonator longitudinal modes. The spectrum of the blue output power consists of the frequency-doubled peaks of the fiber laser as well as others wavelengths corresponding to sum-frequency generation of two consecutive peaks. The total spectral width of the blue laser emission is 1.2 nm. This value seems to indicate that SHG is slightly limited by the acceptance bandwidth of the LBO crystal, which is calculated to be 3.1 nm. As a consequence, the most extreme peaks (i.e. near 903 nm and 906.5 nm) are not converted. However, unlike the case of single-pass frequency doubling, the IR wavelengths being not converted are likely recycled in the fiber laser. Therefore, we can assume that this bandwidth limitation does not reduce the second-harmonic conversion efficiency.

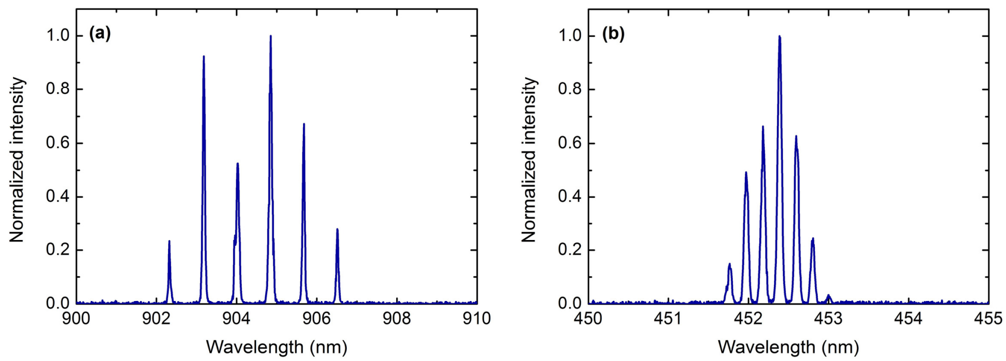

Fig. 4. Measured spectra of the fundamental intracavity power (a) and SH power (b) at the maximum output power.

The M^2 factor of the output beam at 452 nm is equal to 1 and 1.5 along the x and y axes. The blue beam shows a slightly elliptical spatial profile, which is possibly due to the walk-off in the LBO crystal. This effect is indeed commonly observed in the case of SHG operated in a critical phase matching condition [19].

5. Conclusions

In conclusion, we have demonstrated efficient internal SHG of a CW Nd-doped fiber laser with a record output power of 7.5 W at 452 nm. Internal conversion efficiency of 55% has been achieved by using a simple resonator including a LBO crystal cut for type I critical phase matching. To the best of our knowledge this is by far the highest CW "pure blue" power generated from a frequency-doubled fiber laser. Further power scaling should be possible by using a polarization-maintaining Nd-doped fiber with a nearly single-mode core. In addition, due to the large tuning range of a NDF fiber laser [9], other blue wavelengths around 452 nm could be easily generated. Preliminary results show that wavelength tunablility between 445 nm and 462 nm can be achieved using the same LBO crystal.