Single-frequency, high-power, continuous-wave fiber-laser-pumped Ti:sapphire laser

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We demonstrate a high-power, continuous-wave (cw), single-frequency green source based on single-pass second-harmonic generation of a Yb-fiber laser in MgO:sPPLT as a viable pump source for a cw single-frequency Ti:sapphire ring laser. By careful design and optimization, the Ti:sapphire laser can provide as much as 2.3 W of cw single-frequency output across a 47 nm tuning range, limited by the reflectivity of the cavity mirrors. By implementing active stabilization of the laser frequency to an external reference, an ultrastable Fabry–Perot interferometer, we obtain a frequency stability better than 12 MHz over 10 min and continuous tunability greater than 180 MHz. Stable output power with peak-to-peak fluctuation of 5.4% over 75 min, in high spatial beam quality with $M^2 < 1.34$, is achieved.

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1. Introduction

Titanium-doped sapphire (Ti:sapphire, Ti:Al_2O_3) laser has been a remarkable addition to the class of tunable solid-state lasers, and today is the most reliable source of single-frequency continuous-wave (cw) radiation, as well as ultrashort femtosecond and picosecond pulses, in the near-infrared spectral range [1–8]. Its broad emission spectrum spanning over 680–1100 nm, with peak around 800 nm, has led to diverse applications in spectroscopy, imaging of biological tissues, high-intensity physics, and frequency metrology, among many. Since the absorption bands of Ti:sapphire are located in the blue–green region of the visible spectrum, the pump sources for this laser have relied mainly on argon-ion lasers and frequency-doubled Nd-based solid-state lasers. Soon after the first demonstration of the Ti:sapphire laser pumped by the argon-ion laser [1,2], cw single-frequency operation was realized by employing a ring cavity [3], and frequency stabilization resulted in a linewidth as narrow as 1 kHz rms [4]. Although the argon-ion laser proved a viable pump source in the early development of the Ti:sapphire laser, its low efficiency, large size, and high cost led to rapid takeover by frequency-doubled solid-state lasers in the green. The first cw single-frequency all-solid-state Ti:sapphire laser was pumped by a diode-pumped intracavity-doubled Nd:YAG laser and operated with a threshold as low as 119 mW, generating 3.1 mW of output power at 800 nm for a pump power of 173 mW [5]. Since then, intracavity-doubled solid-state lasers have become universally established as the most viable pump source for the Ti:sapphire laser. Recently, a cw Ti:sapphire laser pumped directly by a GaN diode laser in the blue was reported [6], but much progress is yet needed in this direction to achieve practical output powers. With advances in optically pumped semiconductor lasers, such sources in the

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green can also be potentially used to pump Ti:sapphire lasers [7], but progress in this area still remains limited. This leaves open the need for the development of yet more powerful alternative green sources in simple, practical, all-solid-state design, with high spatial quality and power scaling capability, to pump high-power Ti:sapphire lasers. Although Ti:sapphire laser technology is now relatively mature, further progress toward higher powers is principally limited by the advances in solid-state pump lasers in the green [8], and so it would be prudent to search for new alternative green sources capable of providing increased pump powers in the future.

In recent years, fiber lasers have proved to be highly attractive coherent light sources due to their high-power capability, compact and portable design, robustness, output stability, turnkey operation, cost effectiveness, and power scalability. The combination of a cw infrared fiber laser and a simple single-pass second-harmonic-generation (SHG) scheme based on periodically poled nonlinear crystals can be a potentially attractive approach for high-power cw generation in the green, not only because of a compact and practical architecture, but also due to the power scaling capability of the fiber laser, as well as the narrow linewidth and high spatial beam quality that are inherently transferable from the fiber pump to the green output. We have developed such a source based on single-pass SHG of a Yb-fiber laser in 30-mm-long MgO:sPPLT nonlinear crystal, generating as much as 9.6 W of single-frequency green power [9,10]. Further efforts have been directed to scale the single-pass SHG efficiency up to 56% by using a novel multicrystal scheme [11]. This fiber-laser-based green source has already demonstrated its potential as a successful pump source for a cw optical parametric oscillator [12] and a cw Ti:sapphire laser [13]. Here, we report the successful deployment of this cw fiber-laser-based green source as pump for a high-power, single-frequency Ti:sapphire ring laser, with active frequency stabilization, generating as much as 2.3 W of output power at 812 nm for an incident green pump power of 11.3 W with a slope efficiency as high as 33.7%. The laser is coarsely tunable over 47 nm, while maintaining single-frequency output over the entire tuning range, and is continuously tunable over 181 MHz in 5 s.

2. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. The fundamental pump source is a cw, single-frequency Yb-fiber laser (IPG Photonics, YLR-30-1064-LP-SF) at 1064 nm, providing a linearly polarized output beam with $M^2 < 1.01$ and a nominal linewidth of 89 kHz. A 30-mm-long MgO:sPPLT crystal [9,10], containing a single grating period $\Lambda = 7.97\ \mu\text{m}$, is used for single-pass SHG into the green at 532 nm. At the highest available fundamental power of ~33 W, our SHG source provides as much as 11.3 W of green power in a TEM_{00} spatial profile ($M^2 < 1.3$) with a frequency stability better than 32 MHz over 1 h. However, since our earlier reports [9,10], we have improved the output power stability of the green source from 7.9% to better than 3.3% peak to peak, measured over 1 h. This improvement has been obtained by using a novel uniform crystal heating configuration, where the crystal is placed at the center of a large-area oven used to heat the 50-mm-long crystal. As compared to the small-area oven used previously [9,10], the central part of the new oven provides higher temperature uniformity and is less sensitive to the instability (±0.1 °C) of the temperature controller. As a result, it maintains improved temperature stability over the full crystal length, resulting in higher green output power stability. The fiber green source is so robust that it takes only 30 min to reach stable output power during the fiber laser warm-up time. We have operated the source reliably and regularly on a daily basis for over two years, without any degradation in output power or stability, making it an ideal source for pumping a Ti:sapphire laser. Recently, we have also further improved the

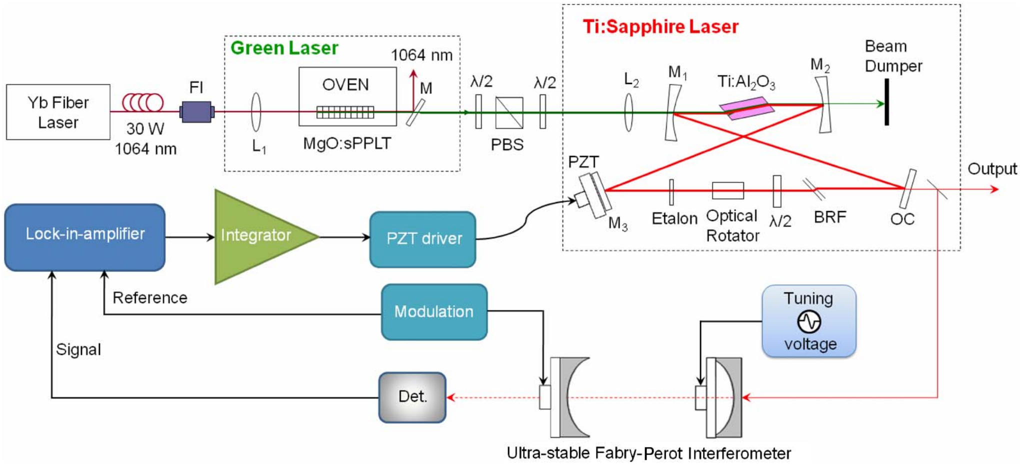

Fig. 1. (Color online) Schematic of the fiber-laser-based green-pumped cw Ti:sapphire ring laser. FI, Faraday isolator; $\lambda/2$, half-wave plate; PBS, polarizing beam splitter; L, lenses; M, mirrors; OC, output coupler; PZT, piezoelectric transducer; BRF, birefringent filter; Det., detector.

single-pass SHG efficiency to 56% for 10 W of fundamental power at 1064 nm, by employing a novel multicrystal scheme based on three MgO:sPPLT crystals in a cascade, making the fiber-laser-based green source even more attractive [12]. In the current experiment, we deployed only the single-crystal SHG scheme to demonstrate the viability of the approach. To maintain stable output characteristics, we operated the fiber-laser-based green source at maximum output power. A combination of a half-wave plate ($\lambda/2$) and a polarizing beam splitter (PBS) was used as an attenuator to vary the input power to the Ti:sapphire ring laser. A second half-wave plate ($\lambda/2$) was used to provide the correct pump polarization relative to the Ti:sapphire crystal orientation. Using a suitable plano–convex lens (L_2), we focused the green pump beam to different waists at the center of the 10-mm-long, Brewster-cut Ti:sapphire crystal (0.15 wt. % doping, figure of merit, FOM > 270). The laser crystal was glued onto a brass slab and water cooled on the lower side. The green beam was polarized along the c axis of the crystal in order to maximize absorption [3], which we measured to be $>80\%$. The laser was configured in an astigmatic-compensated, four-mirror ring cavity, comprising two plano–concave mirrors, M_1 and M_2 ($r = 10$ cm), a plane mirror, M_3, mounted on a piezoelectric transducer (PZT), and a plane output coupler (OC). All mirrors were broadband antireflection coated with high transmission ($T > 97\%$) at 532 nm and high reflectivity ($R > 99.5\%$) across 760–840 nm. The output coupler transmission varied from 24% at 773 nm to 18% at 822 nm. The total length of the cavity was 109 cm (free spectral range, FSR ~ 275 MHz). A birefringent filter (BRF) was used to control and tune the laser wavelength. An intracavity optical diode comprising a Faraday rotator in combination with a half-wave plate ensured unidirectional operation of the ring laser, and a 500-μm-thick uncoated intracavity solid etalon (FSR ~ 206 GHz, finesse ~ 0.6) made of fused silica provided frequency selection and single-mode operation. A homemade ultrastable Fabry–Perot interferometer was used as an external reference to maintain long-term frequency stability of the Ti:sapphire ring laser, by employing the usual lock-in techniques, as described in detail in Subsection 3.C. We will see that the reference can be easily tuned and this feature allows continuous tuning of the stabilized laser.

3. Results

A. Beam Waist Optimization and Power Scaling

To characterize the Ti:sapphire ring laser for optimum performance, we initially operated the laser in standing-wave, X-cavity configuration. Under free-running condition, with an experimentally determined optimum output coupling of ~20% at 812 nm for a pump beam waist ~30 μm [13], we investigated for the optimum pump beam waist at the center of the Ti:sapphire crystal. Using four different plano–convex lenses of focal length $f = 50$, 75, 100, and 125 mm, we focused the pump beam to waist radii, $w_p = 24$, 27, 30, and 40 μm, respectively, in the Ti:sapphire crystal. The laser was optimized in each case to achieve maximum output power, which was recorded as a function of the pump beam waist, as shown in Fig. 2(a). The solid curve corresponds to the theoretically calculated achievable output power as a function of the pump beam waist [2]. As evident from Fig. 2(a), a maximum output power of 2.8 W was achieved for a pump beam waist of 24 μm, which dropped down to 2 W at a beam waist of 40 μm for a maximum available pump power of 11.3 W. Further increase in the maximum output power can, in principle, be possible with reduced pump beam waists. However, the crystal damage at high pump power density due to the lower pump beam waist is an important issue to overcome. Therefore, as a good compromise between the maximum power and crystal damage issue, we used optimum pump beam waist and output coupling of 24 μm and 20%, respectively, to operate the laser in astigmatic-compensated four-mirror ring cavity.

The power scaling results of the Ti:sapphire ring laser, with and without (free-running condition) intracavity elements, such as BRF, optical diode, and etalon, are shown in Fig. 2(b). In free-running condition, the bidirectional ring laser operated at a threshold pump power of 3.6 W, generating a total output

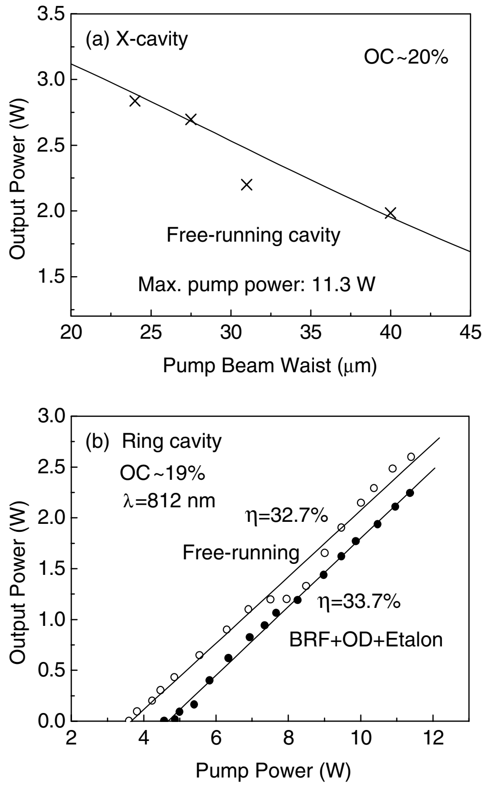

Fig. 2. (a) Ti:sapphire laser output power as a function of pump beam waist in X-cavity configuration. (b) Power scaling characteristics of Ti:sapphire ring laser in free-running operation, as well as with the intracavity elements (BRF, optical diode, and etalon).

power of 2.6 W for a pump power of 11.3 W, with a slope efficiency of 32.7%. Unidirectional operation of the ring laser was achieved by introducing an optical diode. The inclusion of all the intracavity elements led to an increase in the threshold pump power to 4.5 W and a 16% reduction in the output power as compared to the free-running condition, generating a maximum single-frequency output as high as 2.3 W for the same incident pump power of 11.3 W at a slope efficiency of 33.7%. This nominal increase in the slope efficiency could be attributed to the alleviation of the spatial hole burning effect in unidirectional ring laser operation. The corresponding optical-to-optical efficiencies in the two cases with respect to the incident and absorbed pump power were thus 20% and 25%, respectively. No sign of saturation was observed while pumping up to the maximum available pump power.

B. Tuning and Single-Frequency Operation

Owing to the broad emission bandwidth of the Ti:sapphire laser, tuning of the output wavelength over 47 nm, from 774 to 821 nm, was achieved by using the BRF. The obtained tuning range of the ring laser was limited only by the reflectivity of the available cavity mirrors, and so could be readily extended to cover the full gain bandwidth of the Ti:sapphire using more suitable mirrors. The output power across the tuning range, for a constant pump power of 11.3 W, along with the transmission curve of the output coupler, varying from 24% at 773 nm to 18.2% at 822 nm, is shown in Fig. 3(a). As can be seen, despite the drop in output coupling, the output power of the Ti:sapphire ring laser is found to increase, reaching a maximum of 2.3 W at 812 nm. This is expected, given that the Ti:sapphire has a gain peak near 800 nm, resulting in higher output power despite the low output coupling. The corresponding output coupling is ~19%, which is close to the optimum for the wavelength of 812 nm. Further, the spectral characteristics of the Ti:sapphire laser were studied using a commercial scanning Fabry–Perot interferometer (FSR = 1 GHz, finesse = 400). The typical fringe pattern corresponding to a wavelength of 812 nm, recorded at the maximum output power, is shown in Fig. 3(b). The measured instantaneous linewidth is 5.4 MHz, confirming single-mode nature of the output. This instantaneous linewidth is comparable to commercially available Ti:sapphire lasers. The main reason for the relatively large linewidth compared to the previous work [4] could be attributed to the lower finesse of the BRF and etalon used in our experiment. Further reduction in linewidth can be achieved by deploying an etalon with higher finesse. We found the single-frequency operation of the laser to be maintained at different wavelengths across the entire tuning range.

C. Frequency Stability and Continuous Tuning

To improve the performance of the Ti:sapphire ring laser in terms of frequency stability, we set up a stabilization system. The external reference for the laser frequency was provided by a homemade Fabry–Perot interferometer, carefully designed for maximum stability. The main structure, which supports the mirror holders, is a thick super-Invar cylinder. All parts of the interferometer (except PZTs and mirrors) are made of this ultralow-thermal-expansion material, with the intention of minimizing the dependence of the reference on temperature. Two identical PZTs drive the position of the cavity mirrors and provide two independent fine adjustments for the resonator length. Again, with the aim of reducing thermal instabilities, our PZTs are only 3 mm long, and they are placed in the same direction (both glued on the left side of each mirror, as shown in Fig. 1), in order to compensate the effect of their thermal expansion on the cavity length. The mirror spacing can be adjusted at any value between 2 and 12 cm. In the present work, we operated in a confocal geometry with a 10 cm resonator length, corresponding to a FSR = 750 MHz. A small part of the Ti:sapphire beam is sent into the interferometer and a feedback loop stabilizes the laser frequency to the maximum of a transmission peak. In practice, one PZT of the interferometer is modulated at a frequency of about 10 kHz, and the signal from the detector is demodulated by a lock-in amplifier, thus providing an error

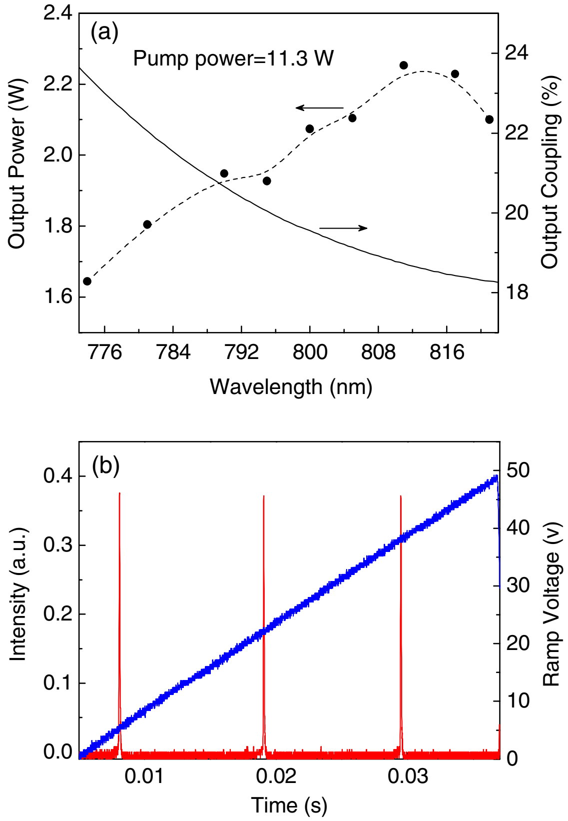

Fig. 3. (Color online) (a) Extracted power and output coupler transmission of the Ti:sapphire ring laser across the tuning range. (b) Single-frequency spectrum of the Ti:sapphire ring laser output recorded by a scanning Fabry–Perot interferometer (FSR = 1 GHz, finesse = 400) at 812 nm.

signal. After integration, this signal drives the PZT on which the plane cavity mirror (M_3) is mounted, in such a way that the laser frequency is maintained to the maximum of the transmission peak. The output wavelength of the stabilized Ti:sapphire laser was recorded using a high-resolution wavemeter (High Finesse, WS-U30). The observed stability was better than 12 MHz over 10 min [Fig. 4(a)] at an output power of 2.2 W around 817 nm. To compare the performance of our homemade ultrastable Fabry–Perot reference cavity, we locked the Ti:sapphire laser using a commercial Fabry–Perot reference cavity (FSR = 1 GHz, finesse 400, Toptica FPI 100) made of aluminum mechanical structure and measured frequency drift, with the results shown in Fig. 4(b). As evident from Fig. 4(b), the frequency drift of the Ti:sapphire laser locked using a commercial reference cavity is measured to be within 30 MHz at mean wavelength of 810.99 nm over 7 min, with no evidence of mode hopping. The better frequency drift obtained with the homemade Fabry–Perot can be attributed to the superior performance of the super-Invar in terms of higher mechanical stability and lower thermal expansion as compared to aluminum. We have considered two different wavelengths, 817 and 811 nm, in this current study, on purpose, to show the frequency stability of our laser at different wavelengths.

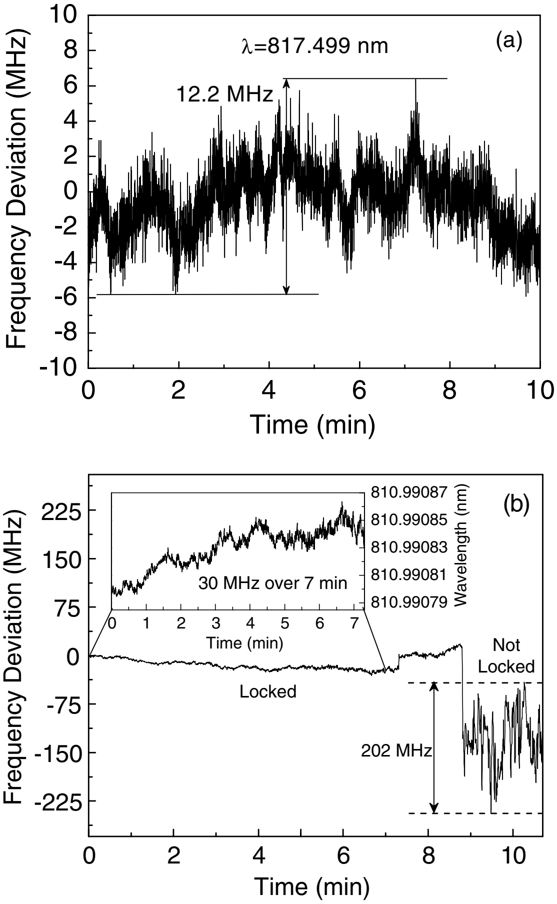

Fig. 4. Frequency stability of the Ti:sapphire ring laser with stabilization to (a) the homemade super-Invar Fabry–Perot cavity, and (b) the commercial Fabry–Perot interferometer, and without stabilization.

In addition to frequency stability, many applications, such as spectroscopy, require continuous tunability about a certain wavelength. By applying a voltage to the second PZT of our Fabry–Perot interferometer, we obtained a fine-tuning of the mirror spacing that allowed us to smoothly adjust the frequency corresponding to the maximum of a transmission peak, hence the frequency of the stabilized laser. To demonstrate the potential of the fiber-based green source pumped Ti:sapphire ring laser for such practical applications, we applied a sinusoidal signal to the second PZT of the interferometer and recorded the output wavelength of the stabilized Ti:sapphire laser with the wavemeter. We then verified continuous tuning of the output wavelength over 181 MHz (corresponding to mode-hop-free tuning of our laser) in 5 s, yet maintaining frequency stable operation (Fig. 5). Even though we have used a solid etalon of FSR ~ 206 GHz, due to its low finesse, the effective FSR of the Ti:sapphire laser is restricted to the FSR determined by the optical cavity length of the laser. Similar frequency locking and tuning was observed across the tuning range of the Ti:sapphire laser. The fine-tuning range of 181 MHz can be further extended with more stringent isolation of the laser, which will help preserve the lock for longer time, and also by increasing the finesse of the etalon. However, the increase of etalon finesse will result in the increase of laser threshold. Additionally, we investigated the effect of different signal waveforms on the fine tuning of our Ti:sapphire laser. For example, using a high-amplitude sawtooth signal to sweep the cavity, we found that the frequency lock of the cavity was disturbed due to abrupt change in the voltage of the sawtooth signal. Smooth transition of the sawtooth signal can make extended fine tuning possible. On the other hand, using a relatively low-amplitude triangular signal, and a reduced sweeping rate, we were able to continuously tune the Ti:sapphire laser over 80 MHz in 1.6 min.

D. Power Stability and Beam Quality

To completely characterize the Ti:sapphire ring laser, we investigated the power stability of the output by

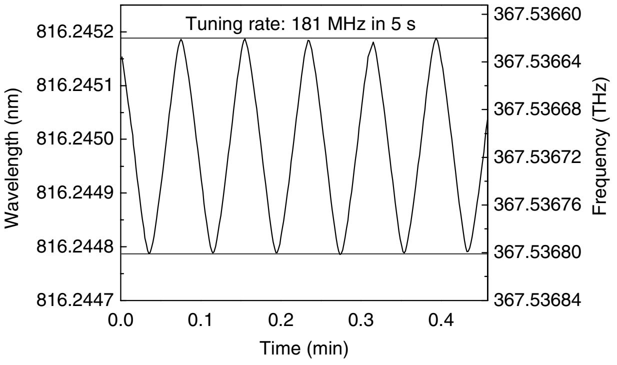

Fig. 5. Continuous tuning of the Ti:sapphire ring laser at 816 nm at a rate of 181 MHz in 5 s.

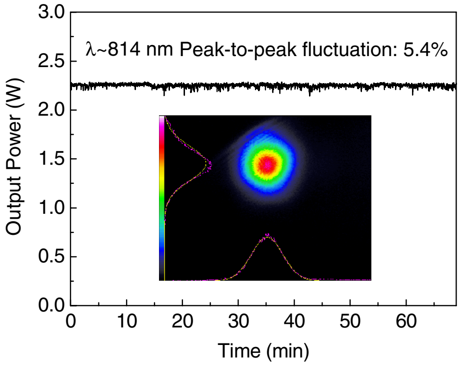

Fig. 6. (Color online) Power stability of the Ti:sapphire output at 2.25 W recorded over a period of 70 min. Inset: far-field energy distribution of the Ti:sapphire ring laser output beam at 812 nm.

recording the variation of output power with time. Figure 6 shows the long-term power stability of the Ti:sapphire output at a wavelength of 814 nm, recorded at a maximum output power of 2.2 W. The peak-to-peak power fluctuation is measured to be 5.4% over more than 1 h, which compares to that of the fiber-based green source (3.3% over 1 h). The power stability can be further improved by providing proper isolation from the mechanical vibrations and air turbulence in the laboratory environment. Also shown in the inset of Fig. 6 is the far-field energy distribution of the Ti:sapphire output at 812 nm, recorded at a distance of >2 m, together with the intensity profiles and the Gaussian fits at the maximum output power. Using a scanning beam profiler and a focusing lens, we measured the beam quality M^2 factor of the output beam. The measurement resulted in a value of $M_x^2 \sim 1.22$ and ${M_y}^2 \sim 1.34$, confirming the Gaussian nature of the output beam.

4. Conclusions

In conclusion, we have demonstrated that a high-power, cw, single-frequency green source based on single-pass SHG of a Yb-fiber laser in MgO:sPPLT nonlinear crystal is a viable pump source for a cw single-frequency Ti:sapphire ring laser. Careful design and optimization of the ring laser provided as much as 2.3 W of single-mode output power at 812 nm for an incident green pump power of 11.3 W, with a slope efficiency of 33.7% and an instantaneous linewidth of 5.4 MHz. The laser is coarsely tunable over 47 nm, from 774 to 821 nm, limited by the reflectivity of the cavity mirrors, and maintains single-frequency operation over the entire obtained tuning range. Active stabilization of the Ti:sapphire ring laser to an external reference provided by a specially designed ultrastable Fabry–Perot interferometer resulted in a frequency stability better than 12 MHz over 10 min and continuous tuning of the laser frequency over 181 MHz in 5 s. Moreover, a measured peak-to-peak power fluctuation of 5.4% over more than 1 h at maximum power and a high spatial beam quality with $M^2 < 1.34$ further confirm the viability of the fiber-laser-based green source as a robust, reliable, power-scalable, and competitive pump source for single-frequency Ti:sapphire lasers.

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