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High energy widely tunable narrow-linewidth Ti:sapphire laser using combined-cavity configuration

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Abstract: A high-energy narrow-linewidth Ti:sapphire laser with widely tunable wavelength was investigated. The Littman cavity was seeded by an extended prism cavity, and they were coupled together by sharing a partial reflection mirror. The widely wavelength tunability of the prism cavity and the linewidth compression of Littman cavity were incorporated together, which resulted in a significantly increased tunable wavelength range from 720 nm to 884 nm with linewidth of less than 100 MHz. The coupling effect and the synchronization between the two cavities in temporal and spectral domain were discussed. The narrow-linewidth laser centered at 786 nm was further amplified to 36 mJ and frequency-doubled to 393 nm with pulse energy of 18.8 mJ while maintaining the narrow linewidth at a repetition rate of 10 Hz. This widely tunable narrow-linewidth laser is a promising light source for high-resolution fluorescence spectroscopy.

1. Introduction

The technology of narrow linewidth laser with nanosecond pulse duration and widely tunable wavelength range has been rapidly developed due to increased demand from many scientific research and applications, such as laser spectroscopy [1,2], Light Detection and Ranging (LiDAR) [3], resonance ionization laser ion source for isotope separators or similar [4,5] and laser-induced fluorescence (LIF) [6]. A widely tunable range of laser wavelength can be achieved directly by the laser gain medium possessing a wide emission spectrum. This is an important contributing factor to the widespread use of dye media in narrow linewidth, tunable laser, since it was first demonstrated in 1967 [7]. However, the applications of dye lasers are limited because of the complicate maintenance and potentially toxic chemicals. With the development of solid-state laser crystals, Ti:sapphire crystal became one of the most important laser crystals with ultra-broad bandwidth (from 650 nm to 1100 nm) and excellent physical properties [8,9]. The lasers based on Ti:sapphire crystal can work for generation of femtosecond laser pulses by Kerr-lens mode-locked mechanism [10] and also work as a widely tunable narrow-linewidth laser by the spectral-compressing technique [11]. Typically, spectral compression is achieved by selecting a small part of the whole spectrum to participate in stimulated emission using birefringent filter (BRF), etalon, or diffraction grating. The low cavity loss of the BRF enables high power output. However, the achievement of GHz laser linewidth requires an additional etalon. The correlated tuning of the selected elements makes continuous wavelength scanning beyond 0.2 nm laborious. For grating, the tuning is simplified by changing the grating angle and high spectral compression ratio can be

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achieved with its large dispersion. Littrow configuration [12] and Littman configuration [13] are two typical grating laser configurations, among which Littman configuration can achieve narrower linewidth. Littman configuration with linewidth approximately 330 MHz and wavelength tunable from 760-810 nm in pulsed Ti:sapphire laser oscillator was reported in 1995 [14]. Andrew et al demonstrated the tunable operation of a pulsed Ti:sapphire laser with linewidth of 118 MHz and widely tunable wavelength(735-810 nm) two years later [15]. The system delivered 10 mJ in a 5-ns near-transform-limited single-longitudinal-mode (SLM) pulse with a threshold of 20 mJ and a slope efficiency greater than 40%.Much work has been devoted to compressing the linewidth and extending the wavelength tunable range based on the Littman cavity [16–20], however, the wavelength tunability of classical Littman lasers is limited to 850 nm, which originates principally from the gain competition: the shorter or longer wavelength has smaller gain than that at the gain-peak wavelength with the same pump fluences and the broadband pre-lasing in the standing-wave cavity prevents the further wavelength tuning. A challenging technique is to maintain a narrow linewidth with widely tunable wavelength range. Although a narrow linewidth laser operating at 681 nm was reported [21], the involved configuration made it not suitable for lasing at another wavelength. In addition, a Brewster prism was used to suppress the self-oscillation which reduces the efficiency through additional losses. Also, the simultaneous tuning of prism and grating increases the difficulty in laser alignment. Another technique to achieve widely tunable operation away from the gain maximum is injection seeding, here the need of a master laser and the active stabilization of the cavity increases the complexity and operation difficulty of the system. The tunability is also limited by the injection master laser [22].

In contrast, prism cavity and Littrow cavity lend themselves well to wavelength tuning at the expense of linewidth [12,23,24]. Recent work in dual-cavity designs has ensured the high power and wide tunable wavelength range output from 700 to 950 nm (775 to 980 nm with different mirrors) with a linewidth of 1 GHz [25]. This dual-cavity is constituted with a broadband cavity and a narrowband cavity by inserting a partially reflecting (PR) mirror in the classical Littrow cavity. Despite the wide tunable wavelength range with this configuration, it remains a challenging task to achieve narrow linewidth simultaneously.

In this work, the coupling cavity configuration was adapted and further developed. The combined-cavity consisted of a prism cavity with wide tunable wavelength range and a Littman cavity with narrow linewidth compression. The two resonators were coupled together by sharing a partial reflection mirror. The prism cavity behaves as a ballast which determines the range of the spectrum and the Littman cavity works as a narrow linewidth “band pass filter”. The combined dual-cavity configuration works well with a spectral linewidth of less than 100 MHz spanning the range from 720 to 884 nm, which extended the tunable wavelength range without trading off on the narrow linewidth and provides a new route to generate high-energy, tunable, narrow linewidth laser pulses. The output pulse duration was 13 ns under 10 ns pump pulse due to gain-switching characteristics. For specific applications, the pulse centered at 786 nm was further amplified to 36 mJ in a multi-pass amplifier. The second harmonics generation at 393 nm produced a pulse energy of 18.8 mJ, which gives an efficiency of more than 50%.

2. Experimental setup

The experimental setup of combined-cavity Ti:sapphire laser is shown schematically in Fig. 1. The system can be divided into two main blocks: a prism cavity (light red background) and a Littman cavity (light green background). The Ti:sapphire crystals are $6\times 6 \times 10$ mm^3 and $4 \times 4 \times 4$ mm^3 with >95% absorption at 532 nm in prism cavity and Littman cavity, respectively. Both of them are Brewster angle cut at 800 nm. The two crystals are simultaneously pumped by a frequency-doubled Nd:YAG laser with a pulse duration of 10 ns at a repetition rate of 10 Hz. The pump laser was focused by a plano-convex lens (f=350 mm) and coupled into the oscillator by a triangle reflection mirror, this induced a pump spot size of 800 μm in the Ti:sapphire. The

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prism cavity consists of two SF10 Brewster angle (for 800 nm) prism, a Ti:sapphire crystal, one high reflection(HR) mirror, and a partial reflection (PR) mirror. The two prisms are oriented together according to the apex angle to increase the amount of dispersion, and wavelength tuning is realized by precise adjustment of the end mirror. The Littman cavity is composed of a Ti:sapphire crystal, a diffraction grating, a tuning mirror, a PR mirror and an output coupler (OC). The replicated holographic diffraction grating (Optometrics) has the following specifications: grooves density of 1800 lines/mm, gold coated, blazed for visible light. The grating is oriented at a grazing incidence angle of 87°. The first-order diffraction efficiency is ~5% at this angle. The tuning mirror can be horizontally tuned by a mirror mount with piezo motor actuators to change the oscillating wavelength. The PR mirror and OC have the same reflectivity of 70% for 700-900 nm. All the other mirrors are flat and have high reflectivity of 99.5% for 700-900 nm at an incident angle of zero. The PR mirror is located between the prism cavity and Littman cavity, it is both the output coupler of the prism cavity and the end mirror of the Littman cavity. As a result, the two cavities are combined by the PR mirror, in which the prism cavity provides wide tunable wavelength range and the Littman configuration ensures single longitudinal mode operation with narrow linewidth. With this configuration, the prism cavity sets the central wavelength and the Littman cavity behaves as an "active narrow bandpass filter".

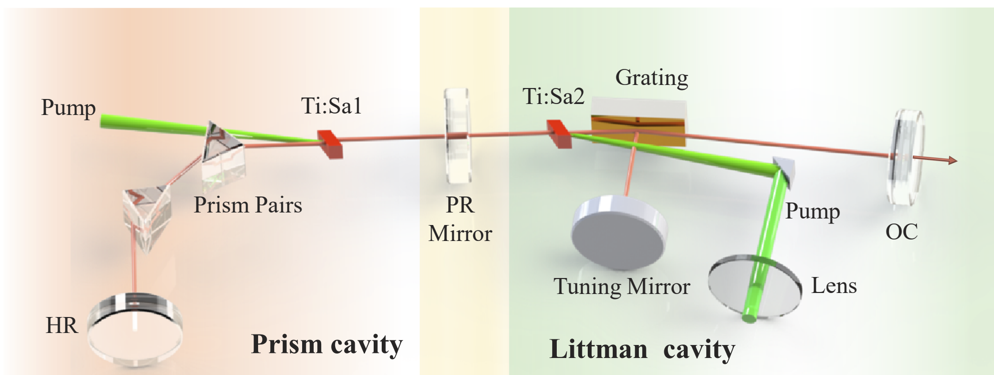

Fig. 1. Schematic diagram of the widely tunable narrow linewidth Ti:sapphire laser with an extended prism cavity. PR mirror: partial reflection mirror, Ti:Sa: Ti:Sapphire, OC: output coupler, HR: High reflection mirror. The HR mirror in the figure has a scale of 25 mm.

In our experiments, the spectrums from prism cavity are monitored by a fiber-optic spectrometer (USB 4000, Ocean Optics Inc.). The pulses with narrow linewidth are measured by a wavelength meter (High Finesse: WS/7). The WS/7 wavelength meter has a set of Fizeau interferometers with a free spectral range (FSR) of 8 GHz in fine mode for infrared light.

3. Experimental results and discussion

With the design described above, both cavities can oscillate and lase independently. Firstly, the performance of the two independent cavities was investigated. As for prism cavity, light leaked from the HR mirror was sent to the USB spectrometer. The wavelength of laser from the prism cavity was tuned by rotation of the HR mirror. As shown in Fig. 2, it covers wavelength tuning range from 720 nm to 904 nm. During the tuning process, the pump energy was kept at 15 mJ for the wavelength shorter than 830 nm and 25 mJ for longer wavelength due to higher threshold. Although the prism cavity shows a large tunable wavelength range, the linewidth is not very narrow.

Similarly, the performance of the Littman cavity was also characterized. In this case, the PR mirror was replaced with a HR mirror. We used a beam sampler to reflect a portion of the

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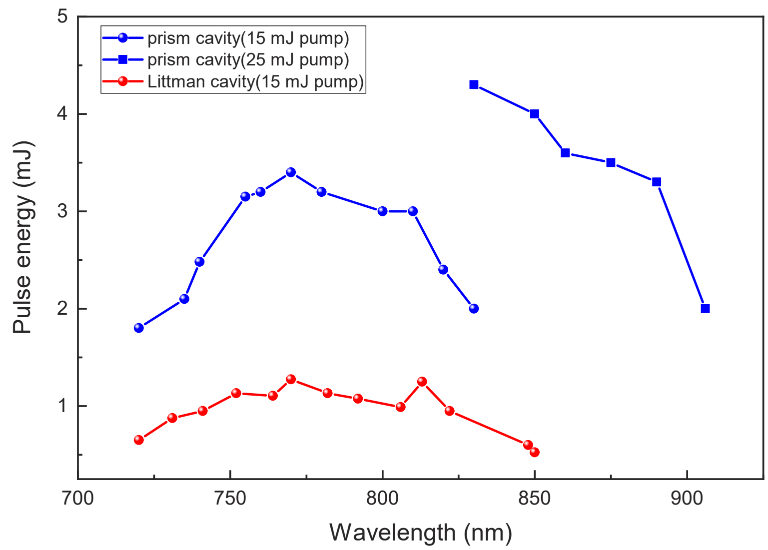

Fig. 2. Tunable wavelength range of laser from the prism cavity and Littman cavity independently.

laser and coupled it into the input fiber of the wavemeter using a focusing lens. The measured linewidth was less than 100 MHz at 786 nm. This linewidth is also less than the nominal accuracy of the wavelength meter, which is estimated by the deconvolution algorithm of the WS7 wavelength meter. The construction and working principle of the WS7 determines the accuracy and resolution, higher linewidth resolution can be achieved using a scanning Fabry–Perot Interferometer. By rotation of the tuning mirror, the Littman cavity was capable of producing continually tunable output wavelengths from 740 nm to 825 nm at pump energy of 15 mJ, as shown in Fig. 2. The linewidth was kept almost the same in the tunable range. Further tuning was limited by the broadband pre-lasing in the standing wave cavity in the classical Littman cavity, which is consistent with other reported results [16]. The output from Littman cavity has narrower linewidth, however, the tunable wavelength range is limited. In our setup, if the tuning angle is outside of 825 nm, the interference fringes of the wavelength meter will be distorted, which indicates the interruption of narrow linewidth output.

By coupling the two cavities, the combined-cavity can inherit the advantages of these two cavities: wide tunable wavelength range and narrow linewidth. A better implementation of coupling requires both temporal and spectral synchronization. Regarding the temporal aspect, it is necessary to synchronize the two laser cavities. The buildup time of the laser depends on the cavity length, the cavity loss, and pump intensity based on the gain-switching dynamic. Through our experiments, in order to get better output performance, the pump energy of 25 mJ and 15 mJ were chosen for the prism cavity and Littman cavity respectively, and the cavity lengths were chosen as 145 mm and 160 mm, corresponding to FSR of 1.03 GHz and 937 MHz respectively. The parameters were adequately chosen to ensure the overlap between the two cavities and the faster buildup of the shorter prism cavity. Moreover, to guarantee high fidelity output, the reflectivity of PR mirror is high enough so that the prism cavity can oscillate, and it also contributes enough energy to the Littman cavity so that the Littman cavity can select small part of the whole spectrum emitted by prism cavity and the pre-lasing in Littman cavity is well suppressed.

Concerning the spectral aspect, reliable operation of coupling requires the spectral overlap of the two cavities. It means that the center wavelength of the two cavities must coincide with each

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other. As shown in Fig. 3, firstly, the correspondence between the angle of the tuning mirror and wavelength in the Littman cavity is calibrated. Then, the center wavelengths of both cavities are roughly set to the same value and the output wavelength of the Littman cavity locates in the range of the prism cavity. As the prism cavity has limited spectral width, the measured interference pattern will be distorted when the tuning wavelength range of the Littman cavity beyond this range. At this point, slightly tuning the wavelength of the prism cavity, the coupling is re-activated. After tuning range of 0.4 nm for Littman cavity, the two cavity spectra were no longer synchronized, thus the linewidth of the prism cavity is estimated about 0.4 nm. This calibration-tuning procedure is repeated to achieve continuous tuning of wavelength.

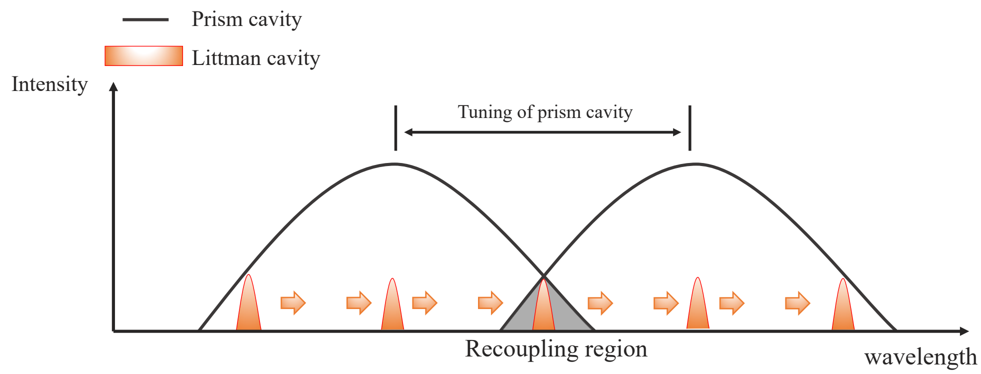

Fig. 3. The schematic of coupling procedure concerning the spectral aspect. The black line indicates the single tuning of prism cavity and the light orange blocks represents the consecutive tuning of Littman cavity.

When the two cavities are coupled through the PR mirror and work simultaneously, the wavelength tunable range with narrow linewidth is extended. Figure 4 shows the tunable wavelength range, it covers from 720 nm to 884 nm. The linewidth is kept less than 100 MHz across the tunable range. This gives clearly better results respect to classical Littman cavity. As shown in Fig. 4, the measured interference fringe pattern shows that the laser is slightly multi-mode in shorter wavelengths. This is related to fine adjustment and stability of the Littman cavity during measurement due to the Littman cavity determines the single mode, moreover, the prism cavity sets the central wavelength. A good feedback of Littman cavity is the key to achieving single mode operation. When the feedback is not strong enough, the double cavity can emit two spectral components-narrow band from the Littman cavity and broad band from the prism cavity at the same time. This phenomenon is obvious from the observation of the laser interference pattern measured by the wavelength meter. In the worst case, the pattern possesses isolated peaks and intensive background. The background indicates the broad band component, and interference peaks indicate the narrow linewidth component. However, slightly tuning the PR mirror, the narrow linewidth can be still achieved only with lower efficiency. For the wavelengths beyond 884 nm, due to the low gain and the higher loss of diffraction grating, the feedback is observed to vanish, which falls into the limitations of the classical Littman configuration.

To prove the effect of the PR mirror and the coupling cavity configuration, we carried out detailed experimental investigation. The pump was blocked for one cavity while the other cavity was firing. When the pump laser was blocked for the prism cavity, the tuning range was the same as the classical Littman cavity. On the contrary, the linewidth was too wide given the situation that the Littman cavity was not pumped. The PR mirror was removed to further verify these experimental results. Without the PR mirror, the configuration is similar as in [21] despite the lack of concave mirrors. The efficiency was improved and the narrow linewidth could be

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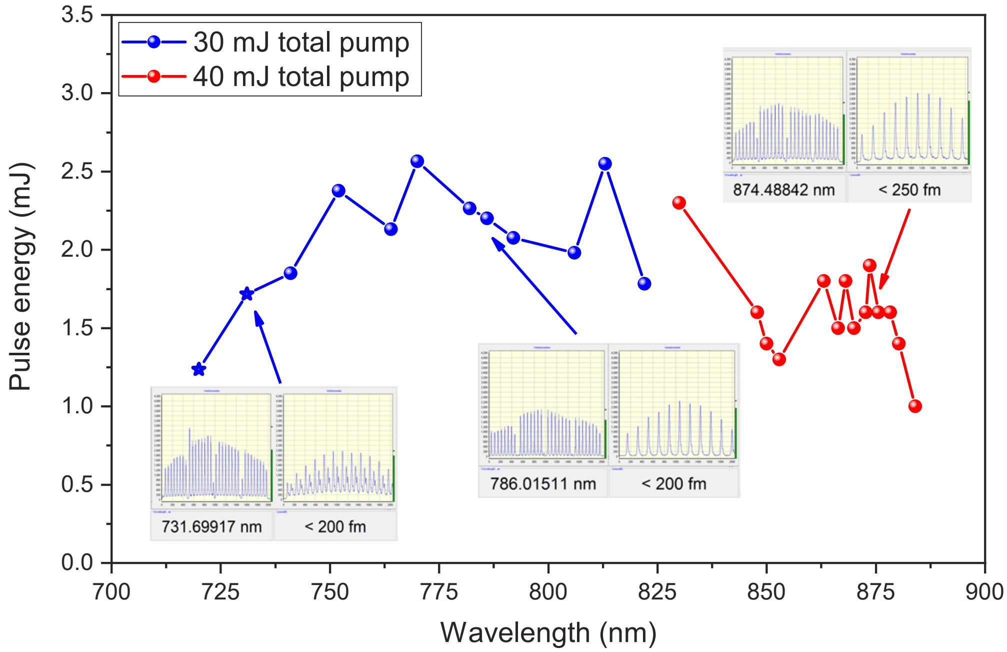

Fig. 4. Tunable wavelength range of laser from the combined-cavity configuration, the interference fringe pattern shows the measured linewidth at the wavelength. Star symbol indicates that slight multi-mode operation occurs.

achieved at specific wavelengths. However, the linewidth could not be maintained consistently across the whole tuning range of 830-884 nm.

From the above results, the performance of the combined-cavity depends on the detailed balance of the two cavity modes and their coupling. The broadband linewidth laser provided by the prism cavity suppresses the oscillation in the Littman cavity. The Littman cavity provides linewidth compression, the compressed laser is amplified by the prism cavity, the iteration of this process during laser build-up achieves a narrow linewidth output. The feedback is essential for the linewidth compression. The reflectivity of the PR mirror and the cavity length can be adapted to the different application. One direction for longer or shorter wavelength is to use mirrors with high reflectivity just at wavelength interested by trading off the tunable range. Moreover, this configuration can be extended to Ti:sapphire lasers working at multi-kHz repetition rate, if the thermal effect in the crystal is well eliminated and the focal spot size is well controlled.

For the application of laser-induced fluorescence velocimetry in a hypersonic flow field wind tunnel test, the delay between the laser and the shock tunnel required the long-term stability of the wavelength. The evaluation of the wavelength stability was characterized, as shown in Fig. 5. The wavelength stability is less than 500 MHz within 15 minutes at 10 Hz repetition rate. The random single-shot measurement gives the same results. For single-shot measurement, once the pump was loaded, the wavelength and the linewidth were recorded. The wavelength drift was less than 0.6 pm (V-V value) within one hour. The combined-cavity laser works well and this is crucial for some experiments where the spectrum needed is only several picometers and no mode-hop is expected.

For specific applications, the seed from the oscillator is further amplified by a four-pass amplifier. The oscillator and amplifier share the same pump laser. Bidirectional pumping is adopted to effectively reduce the energy density under the premise of high gain, thus avoiding the damage of the crystal end face and improving the spatial uniformity of the gain medium.

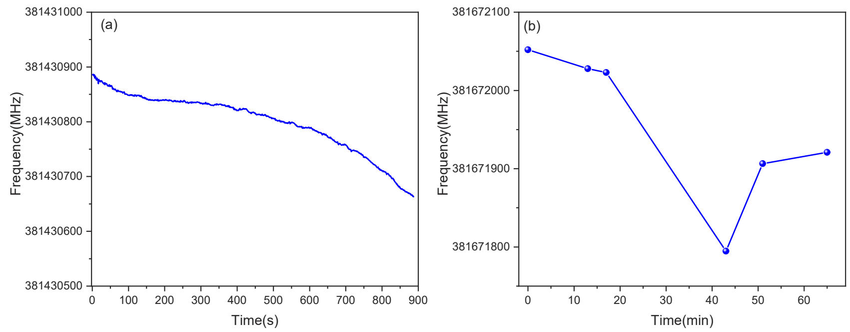

Fig. 5. The wavelength stability (a) at 10 Hz repetition rate and (b) at random single shot.

At the pump energy of 151 mJ and 2.3 mm pump beam width on the crystal surface, after four-pass amplification, the pulse energy of 1mJ from oscillator was amplified to 36 mJ, which gives an extraction efficiency of 23.2%. The M^2 after the amplification was about 1.4. The amplified laser pulse at 786 nm is then frequency-doubled with a type I phase-matched lithium triborate (5 mm×5 mm×20 mm, $\theta = 90°$, $\Phi = 32.9°$) At $40°C$ temperature, a pulse energy of 18.8 mJ at 393 nm was obtained. The efficiency was about 50%. The narrow linewidth is still kept during these processes. Therefore, wavelength tunable ultraviolet (UV) laser through nonlinear frequency conversion will also be narrow linewidth using the combined-cavity, which can extend the application of laser-induced fluorescence molecular tagging velocimetry in hypersonic flow [6].

4. Conclusion

In this work, we reported a combined-cavity based on Ti:sapphire crystal, in which prism cavity and Littman cavity are coupled by sharing a PR mirror, the prism cavity provides wide tunable wavelength range and the Littman cavity ensures single longitudinal mode operation with narrow linewidth. With this configuration, the prism cavity work as the seed and the Littman cavity as an "active narrow bandpass filter". The developed combined cavity not only provides a continuously tunable laser source for 720-884 nm with a linewidth of less than 100 MHz, but also an ideal source for tunable single longitudinal mode UV-DUV (deep ultraviolet) laser through nonlinear frequency conversion. The performance could be further improved by adapting PR mirror with different reflectivity and another cavity mirror set that has a high reflectivity in the desired wavelength region. Such compact high energy ultrashort lasers will be attractive for various applications.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper may be obtained from the authors upon reasonable request.

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