A widely tunable dual-wavelength CW Ti:sapphire laser with collinear output

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Abstract: We report a collinear output and tunable dual-wavelength CW Ti:sapphire laser with a simple cavity configuration. The wavelength splitting range is easily tuned from 10 nm to 110 nm, which provides 56 THz bandwidth for terahertz generation. The total output power of two colors with the spatial mode of TEM_{00} is between 700 mW and 300 mW, for small and large wavelength splittings, respectively, under 5 W argon-ion laser pumping.

OCIS codes: (140.3580) Lasers, solid-state; (140.3590) Lasers, titanium; (140.3600) Lasers, tunable

References and links

1. D. H. Auston, "Picosecond optoelectronic switching and gating in silicon, " Appl. Phys. Lett. **26,** 101–103 (1975).
2. A. G. Davies, E. H. Linfield, and M. B. Johnston, "The development of terahertz sources and their applications," Phys. Med. Biol. **47,** 3679–3689 (2002).
3. M. Tani, M. Herrmann, and K. Sakai, "Generation and detection of terahertz pulsed radiation with photoconductive antennas and its application to imaging," Meas. Sci. Technol. **13,** 1739–1745 (2002).
4. G. L. Carr, Michael C. Martin, Wayne R. McKinney, K. Jordan, George R. Neil, and G. P. Williams, "High-power terahertz radiation from relativistic electrons," Nature **420,** 153–156 (2002).
5. R. Koehler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, "Terahertz semiconductor-heterostructure laser," Nature **417,** 156–159 (2002).
6. M. R. X. de Barros and P. C. Becker, "Two-color synchronously mode-locked femtosecond Ti: sapphire laser," Opt. Lett. **18,** 831–833 (1993).
7. J. M. Evans, D. E. Spence, D. Burns, and W. Sibbett, "Dual-wavelength self-mode-locked Ti: sapphire laser," Opt. Lett. **18,** 1074–1076 (1993).
8. D. R. Dykaar, S. B. Darack, and W. H. Knox, "Cross-locking dynamics in a two-color mode-locked Ti: sapphire laser," Opt. Lett. **19,** 1058–1060 (1994).
9. A. Leitenstorfer, C. F?rst, and A. Laubereau, "Widely tunable two-color mode-locked Ti : sapphire laser with pulse litter of less than 2 fs," Opt. Lett. **20,** 916–918 (1995).
10. R. A. Kaindl, D. C. Smith, M. Joschko, M. P. Hasselbeck, M. Woerner, and T. Elsaesser, "Femtosecond infrared pulses tunable from 9 to 18 μm at an 88-MHz repetition rate," Opt. Lett. **23,** 861–863 (1995).
11. M. Hyodo, M. Tani, S. Matsuura, N. Onodera, and K. Sakai, "Generation of millimeter-wave radiation using a dual-longitudinal-mode microchip laser," Electron Lett. **32,** 1589–1591 (1996).
12. M. Tani, S. Matsuura, K. Sakai, and M. Hangyo, "Multiple-frequency generation of sub-terahertz radiation by multimode LD excitation of photoconductive antenna," IEEE Microwave Guid. Wave Lett. **7,** 282–284 (1997).
13. C. L. Pan and C. L. Wang, "A novel tunable dual-wavelength external-cavity laser diode array and its applications," Opt. Quantum Electron. **28,** 1239–1257 (1996).
14. T. Hidaka, S. Matsuura, M. Tani, and K. Sakai, "CW terahertz wave generation by photomixing using a two-longitudinal-mode laser diode," Electron. Lett. **33,** 2039–2040 (1997).

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15. S. Matsuura, M. Tani, and K. Sakai, “Generation of coherent terahertz radiation by photomixing in dipole photoconductive antennas,” Appl. Phys. Lett. **70,** 559–561 (1997).
16. E. R. Brown, K. A. Mclntosh, K. B. Nichols, and C. L. Dennis, “Photomixing up to 3.8 THz in low-temperature-grown GaAs,” Appl. Phys. Lett. **66,** 285–287 (1995).
17. K. A. Mclntosh, E. R. Brown, K. B. Nichols, O. B. McMahon, W. F. DiNatale, and T. M. Lyszczarz, “Terahertz photomixing with diode lasers in low-temperature-grown GaAs,” Appl. Phys. Lett. **67,** 3844–3846 (1995).
18. P. Chen, G. A. Blake, M. C. Gaidis, E. R. Brown, K. A. Mclntosh, S. Y. Chou, M. l. Nathan, and F. Williamson, “Spectroscopic applications and frequency locking of THz photomixing with distributed-Bragg-reflector diode lasers in low-temperature-grown GaAs,” Appl. Phys. Lett. **71,** 1601–1603 (1997).
19. F. Siebe, K. Siebert, R. Leonhardt, and H. G. Roskos, “A fully tunable dual-color CW Ti: Al_2O_3 laser,” IEEE J. Quantum Electron. **35,** 1731–1736 (1999).

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1. Introduction

Recently, there is growing interesting in fields using terahertz (THz) waves, or T-rays, for spectroscopy, imaging, communications, signal processing, and quantum information. By present time one could get THz radiation by dipole antennas [1, 2, 3], free-electron lasers [4], and quantum-cascade lasers [5]. All of these methods have their merits and deficiencies. It is possible to obtain broad-band radiation with microwave lamps, but it is not coherent; free-electron lasers allow to get radiation in wide range and with high output power, but they are not compact and expensive thus being not available for most of research laboratories. A way to create relatively compact and inexpensive coherent terahertz radiation source is heterodyne downconversion, or photomixing of two-wavelength laser beams on a dipole antenna. According to the type of lasers, it could be distinguished into two parts. One is the pulse THz radiation, which could be generated by the mode-locked Ti:sapphire laser with dual-wavelength emission [6, 7, 8, 9] or the ultrabroad spectrum of a single pulse [10]. The other is CW THz radiation generated by the dual-beam laser sources, such as individual lasers with dual- [11] or multi-mode emission [12], coupled-cavity diode lasers [13, 14], two independently operated lasers [15] (Ti:sapphire laser [16], single-mode LD’s [17]), or pairs of actively frequency-locked lasers [18]. Amount of these lasers, diode lasers will be a better candidate for many applications. However, Ti:sapphire lasers should not be forgotten in the exploration of new application areas of THz radiation owing to their high output power, excellent frequency stability, operational robustness, and large continuously tuning range in wavelengths. Siebe, et al., [19] first demonstrated the dual-color CW Ti:sapphire laser in a single laser, which provides two parallel beams at independently tunable wavelengths. For the generation of CW THz, nevertheless, one would prefer to run a single laser with collinear two-color output to simplify the optical alignment and increase the efficiency for THz generation. In the following, we describe the structure of a collinear dual-wavelength CW Ti:sapphire laser and the analysis of its performance.

2. Experimental setup

Figure 1 shows the collinear, tunable dual-wavelength, CW Ti:sapphire laser cavity. It consists of a standard X-configuration resonator and was pumped by an argon-ion laser (Coherent Innova 90) with an output power of 5 W. The 5mm-long Brewster-cut Ti:sapphire crystal was doped with Ti^{+3} ions at the relative concentration of 0.1%. The curvature radius of the focusing mirrors (M1 and M2 in Fig. 1), at the both ends of the Ti:sapphire crystal, was 10 cm. Their tilted angles were 9° and 8.5° respectively. The pump beam (Ar^+ laser) was focused onto the crystal by a lens (L1 in Fig. 1) of 10 cm focal length. The reflectivity of output-coupler (M3 in Fig. 1) was 95%, which was coated at 800 nm with 120 nm spanning.

The prime concept is to expand all wavelengths emitted from a Ti:sapphire crystal in free space by the optical dispersion components. Thus it is possible to select the lasing wavelength inside the cavity through a simple mechanism. In our dual-wavelength CW Ti:sapphire laser,

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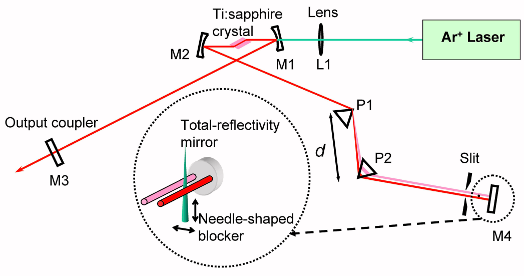

Fig. 1. (Color online) Schematics of the resonator design of the collinear dual-wavelength CW Ti:sapphire laser. M1 and M2 are the curvature mirrors. M3 is the output coupler with 800 nm coating. M4 is the total-reflectivity end mirror. P1 and P2 are the prisms. L1 is the lens for Ar^+ laser. *d* is the distance between P1 and P2.

a needle-shaped blocker was used as the wavelength selector shown in the inset of Fig. 1. One pair of prisms (P1 and P2 in Fig. 1) was inserted into the long arm of X-configuration resonator to introduce spatial dispersion. The first prism (P1 in Fig. 1) spreads all lasing wavelengths in free space. Then, the second prism (P2 in Fig. 1) guides all of these wavelengths to the total-reflectivity end mirror (M4 in Fig. 1).

To begin with, we adjusted all of the optical components in cavity to optimize the output power in single wavelength operation. Afterward the needle-shaped blocker in front of the total-reflectivity end mirror was moved carefully into the laser beam from the underside of the laser beam. It was separated into two beams between the first prism and the end mirror. The difference of two wavelengths can be tuned by varying the distance between the two beams by adjusting the vertical position of needle-shaped blocker. The collinear and dual-wavelength laser was delivered from the other arm including output-coupler in the X-configuration resonator. Its spectrum has been measured directly by a spectrum analyzer (Advantest, model Q8384).

3. Experimental results

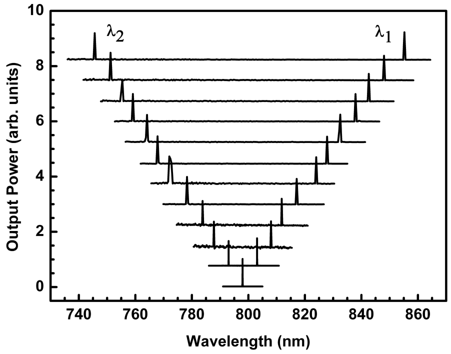

Fig. 2. Spectral separation of the dual-wavelength output of the CW Ti:sapphire laser can be tuned from 10 nm to 110 nm in the case of *d* = 20 cm (the distance between P1 and P2 in Fig. 1).

Figure 2 shows that the difference between two wavelengths ($\Delta\lambda = \lambda_1$-$\lambda_2$) could be continuously tuned from 10 nm to 110 nm by only changing the vertical position of the needle-shaped blocker. Namely, more wavelengths between λ_1 and λ_2 lose as increasing the width of the needle-shaped blocker inside the laser cavity. This wide turning range provides as large bandwidth as 56 THz for the applications of THz generation. Additionally, the two wavelengths could be shifted together with the same separation in wavelength ($\Delta\lambda$) by varying the horizontal position of the needle-shaped blocker. Combining both available operation modes, the different wavelengths with the same separation could properly supply for the THz generation in various types of emitter.

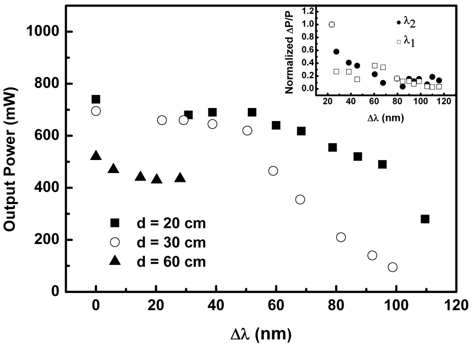

Fig. 3. Total output power of the tunable dual-wavelength CW Ti:sapphire laser as a function of the difference wavelength ($\Delta\lambda$). The solid squares, open circles, and solid triangles represent that the output power in the distance between two prisms (P1 and P2 in Fig. 1) are 20 cm, 30 cm, and 60 cm, respectively. The inset shows $\Delta\lambda$ dependence of the normalized fluctuations of the output power ($\Delta P/P$) for each wavelength.

While the distance (d) between two prisms (P1, P2) is 20 cm, the output power is 740 mW in single wavelength operation as shown in Fig. 3. By increasing the distance between two prisms, however, the output power decreases and the tuning range in $\Delta\lambda$ shrinks. For the case of shorter distance between two prisms, the splitting gap in spectrum between two wavelengths could be as large as 110 nm (solid squares in Fig. 3). On the contrary, the maximum splitting gap in spectrum between two wavelengths is only 30 nm in the case of d = 60 cm (solid triangles in Fig. 3) due to the geometrical restriction of the needle-shaped blocker. The total output power (P, including λ_1 and λ_2) varies slightly below 50 nm in $\Delta\lambda$, but it drops substantially above 50 nm in $\Delta\lambda$. Furthermore, the fluctuations of the output power ($\Delta P/P$, which were estimated from the variation of counts in the spectrometer with 0.2 Hz) in dual-wavelength operation rise clearly especially in smaller $\Delta\lambda$ as shown in the inset of Fig. 3. This indicates that two split wavelengths can independently be amplified by the gain provided in laser cavity in case of larger $\Delta\lambda$ ($>$ 50 nm). On the other hand, two split wavelength modes with smaller $\Delta\lambda$ ($<$ 50 nm) are competing with each other, resulting in the larger fluctuations in the output power. Due to the strong competition of modes around 800 nm, especially, it is hard to achieve dual-wavelength operation under the condition of extremely small splitting ($<$ 10 nm) of two wavelengths. Therefore, the mode competition is concluded to be taking place over ±25 nm in the laser gain bandwidth of Ti:sapphire. Moreover, the fluctuations of output powers of 845 nm and 760 nm with 85 nm splitting were 11 % and 6 %, respectively, over 2.5 hours.

The inset (a) of Fig. 4 shows that the spatial mode of the tunable dual-wavelength CW

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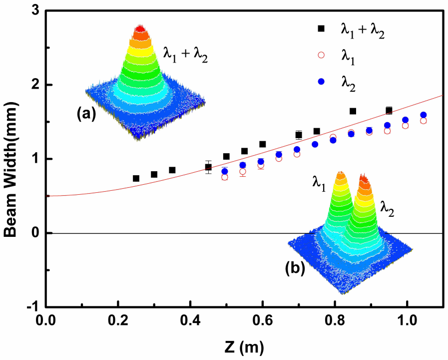

Fig. 4. (Color online) The beam width as function of the distance (z) from output coupler (M3 in Fig. 1). The solid line represents $w(1+(\lambda z/\pi w^2)^2)^{0.5}$, where w = 0.3 mm and λ = 800 nm. The insets show the spatial mode of the output laser beam from the collinear tunable dual-wavelength CW Ti:sapphire laser. (a) Measured just after the output coupler (M3 in Fig. 1) without additional prisms. (b) Measured after one prism set just after the output coupler for separating two wavelength components in free space.

Ti:sapphire laser cavity is TEM_{00} which was measured by the beam profiler just after the output coupler (M3 in Fig. 1). Its propagation along the normal direction of output coupler is Gaussian (solid squares in Fig. 4) and its beam quality (M^2) is 1.28. Furthermore, the same output laser beam had been guided into a prism and measured by the beam profiler after that prism. The spatial modes are still TEM_{00} for both wavelengths, λ_1 = 840 nm and λ_2 = 760 nm, as shown in the inset (b) of Fig. 4. They also propagate along the normal direction of output coupler with Gaussian (solid and open circles in Fig. 4). Additionally, the beam qualities (M^2) of λ_1 (840 nm) and λ_2 (760 nm) are 1.20 and 1.18, respectively. This strongly indicates that the output laser beams of both wavelengths are absolutely collinear. Thus, the collinear output and tunable dual-wavelength CW Ti:sapphire laser could provide many benefits to the dual-wavelength applications, such as wide tuning range, high output power, and easy alignment.

4. Summary

In summary, we have demonstrated the collinear output and wide tunable CW dual-wavelength Ti:sapphire laser. The tuning range of the separation between two wavelengths is continuous from 10 nm to 110 nm. The tunable CW dual-wavelength laser could be stable operated except the very small spitting of two wavelengths. The output power in dual-wavelength operation was greater than 300 mW, even for larger $\Delta\lambda$ (110 nm for the case of d = 20 cm) case. Through this high output power and wide tuning range in CW dual-wavelength Ti:sapphire laser, the high power and tunable coherent CW-terahertz radiation could be generated from the phase matched difference frequency conversion in nonlinear crystals or the photomixing in a biased photoconductive antenna fabricated on a film of low-temperature-grown GaAs.

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