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Dual-wavelength synchronously mode-locked Cr:LiSAF laser with a tunable beating frequency and a central wavelength

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We demonstrate a versatile dual-wavelength synchronous mode-locking of a diode-pumped Cr:LiSAF laser for the first time, to our knowledge. A two-color mode-locked operation is achieved by using intracavity birefringent filters (BRFs) or etalons as frequency-selective elements. Using filters with different thicknesses and hence different free spectral ranges (FSRs), wavelength separation in two-color mode-locking could be selected between 1 and 9 nm, with corresponding beating frequencies in the 0.4–3.5 THz range. Moreover, the central wavelength of the two-color output could be tuned smoothly between 840 and 875 nm, only limited by the bandwidth of the semiconductor saturable absorber mirror (SESAM) used for mode-locking. The method, which enables easy adjustment of the central wavelength and beating frequency of a dual-wavelength operation, is suitable for use in other laser gain media as well.

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Synchronously mode-locked lasers with a two-color or multi-color wavelength output attract the attention of researchers due to their potential usage in dual-color pump–probe experiments [1] as well as for efficient difference frequency generation at the mid-infrared and THz spectral regions [2–4]. Two-color synchronously mode-locked lasers are investigated in various gain media, including Ti:sapphire [5–9], Yb:CALGO [10], Tm:CYA [11], Nd:CNGG [12], Nd:LYSO [13,14], Nd:LGGG [15] Cr:Nd:GSGG [16], and semiconductors [17]. A multitude of different methods are employed for the synchronous multi-color mode-locked operation of lasers. In the case of a broadband Ti:sapphire laser, two-color mode-locking can be achieved by having two independently adjustable cavities that make use of the same gain medium [5,8] or by intracavity shaping of the laser spectrum using a double slit after a prism pair [7]. In Nd-based gain media with close emission lines, especially while using hosts with mixed crystal nature, the two-color mode-locked operation could be achieved via careful alignment of the cavity or via gain balancing using birefringent filters [16]. Overall, when we look at the literature, we see that most of the earlier work only reports lasing at a single wavelength pair and demonstrates rather limited ability in tuning of the central wavelength and beating frequency.

Cr:LiSAF is an attractive alternative to Ti:sapphire due to its higher small signal gain, lower passive losses, almost equivalently broad emission band covering the 780–1110 nm spectral range, and absorption bands in the red spectral region, allowing lower-quantum defect pumping with low-cost diodes [18]. In our earlier work, we have demonstrated broadly a tunable two-color lasing operation of Cr:LiSAF lasers in the continuous-wave (cw) regime [19]. In this follow-up study, we present the first synchronous mode-locked operation of the broadband Cr:LiSAF gain medium.

Figure 1 shows a schematic of the experimental setup. Two linearly polarized 665 nm single-emitter multi-mode diodes (MMD-1 and MMD-2) with 1.8 W of output power are used as the pump source. An astigmatically compensated *X*-folded laser cavity consisting of two curved dichroic mirrors (M-1 and M-2, $R = 100$ mm), a high reflective mirror (HR), and a flat output coupler (OC) is employed in lasing experiments. As the gain medium, a 10-mm-long Brewster–Brewster cut, a 1.5% Cr-doped LiSAF crystal is utilized [20]. For mode-locking experiments, a SESAM with a central wavelength designed at 850 nm [21] is inserted at the second focus generated by a 75 mm radius of curvature (RoC) curved mirror (M-3). The SESAM has a modulation depth of 0.8 ± 0.2% and a reflectivity higher than 99% between 830 and 890 nm. The synchronously mode-locked two-color lasing operation has been achieved using two different approaches.

In the first approach [Fig. 1(a)], on-surface optical axis crystal quartz birefringent filter plates (BRF-1) with thicknesses of 10 mm or 16 mm are inserted into the cavity to achieve a two-color mode-locking. The FSR of these birefringent filters (in the area of reasonable modulation depth) are around 7.4–9.3 nm

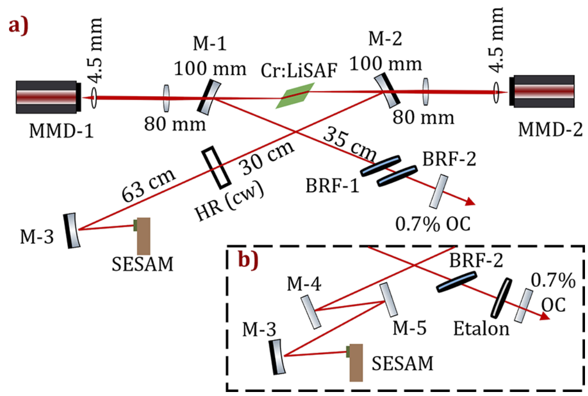

Fig. 1. Schematic of the Cr:LiSAF laser used in the two-color mode-locked laser operation. The dual-wavelength operation is achieved via the usage of (a) birefringent filters or (b) etalons.

and 4.6–5.8 nm, respectively [22]. Hence, considering simultaneous lasing emission at neighboring transmission peaks, these filters enable a dual-wavelength operation with a wavelength separation equivalent to their FSR [19]. As the second approach [Fig. 1 (b)], we have inserted a 200-µm-thick uncoated fused silica etalon to achieve synchronous mode-locking (estimated modulation depth: 12.5%), which enabled two-color lasing with a wavelength separation of around 1 nm. For both approaches, an additional 2-mm-thick off-surface optical axis (25°) birefringent filter plate (BRF-2) with an FSR of around 800 nm is employed for tuning the central wavelength of the two-color lasing pairs [22]. A gain-matched output coupler with a peak transmission of 0.7% is further used to achieve a smoother tuning profile [23]. Additionally, throughout this study, we have chosen to operate the system in a net positive dispersion regime (except in one case using the etalon), as we did not have adequate GTI mirrors at hand to compensate for the large positive dispersion of the thick BRFs used.

We first characterized the system in a single-color mode-locked regime. The Cr:LiSAF laser had a lasing threshold of around 0.5 W. For absorbed pump powers between 0.5 and 1.2 W, the laser operated in the *Q*-switched mode-locked regime, and above the 1.2 W level, stable and self-starting cw mode-locking is achieved. The laser produced up to 180 mW of average power at an absorbed pump power of 2.7 W at a repetition rate of 130 MHz. The corresponding slope efficiency was around 8%, slightly lower than the typical performance due to the relatively high losses of the Cr:LiSAF crystal at hand and the deteriorated brightness of the pump diodes after years of usage [20]. Using the 2-mm-thick BRF, the central wavelength of the pulses could be continuously tuned between 835 and 878 nm (Fig. 2; 43 nm tuning range; data is taken with a 0.5 nm resolution Ocean Optics spectrometer). Within the tuning range, the average power of the mode-locked laser was between 130 and 180 mW, and the measured pulse width varied between 1.5 and 7.5 ps.

As the first approach for the two-color mode-locked operation, we have tried birefringent filters. Figures 3 and 4 summarize the two-color synchronous mode-locking results achieved with the 10-mm-thick and 16-mm-thick BRFs, respectively. In both cases, two-color mode locking was self-starting, and for some wavelength pairs, mode-locking stayed stable for hours despite operating the system without any protective cover. Note that the maximum modulation depth provided by BRF is up to around 38% enabling strong spectral suppression in the low gain Cr:LiSAF cavity (modulation depth due to reflection losses induced on the *s*-polarized intracavity laser beam from the surfaces of BRF-1, BRF-2, and the Cr:LiSAF crystal).

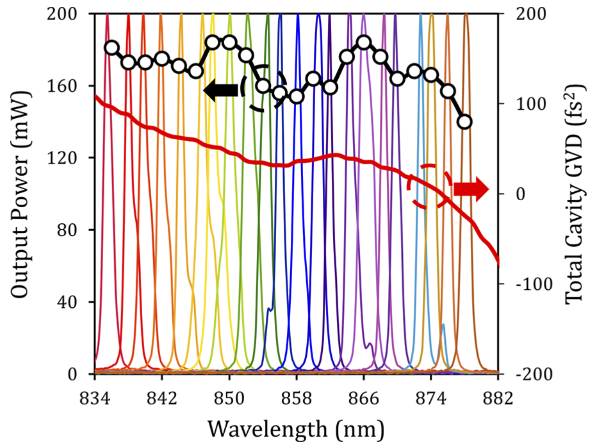

Fig. 2. Sample optical spectra of the Cr:LiSAF laser in the single-color mode-locked regime, showing tunability of the central wavelength from 835 to 878 nm. The calculated total dispersion of the cavity and the obtained average output power levels are also shown.

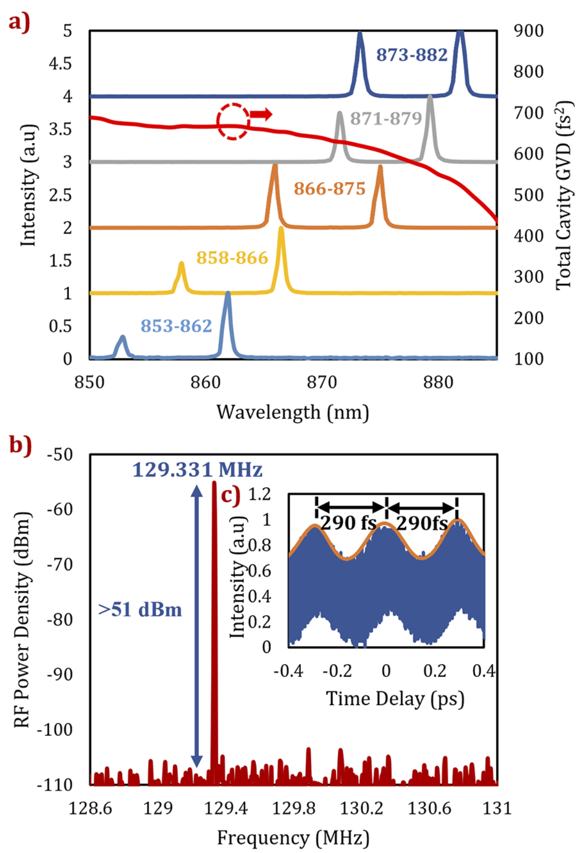

Fig. 3. (a) Measured tuning behavior of the two-color mode-locked Cr:LiSAF laser with the10-mm-thick BRF. (b) Measured microwave spectrum indicating the clean mode-locked operation at 129.3 MHz. (c) Measured pulse beating period (~290 fs) for the 8–9 nm wavelength separation.

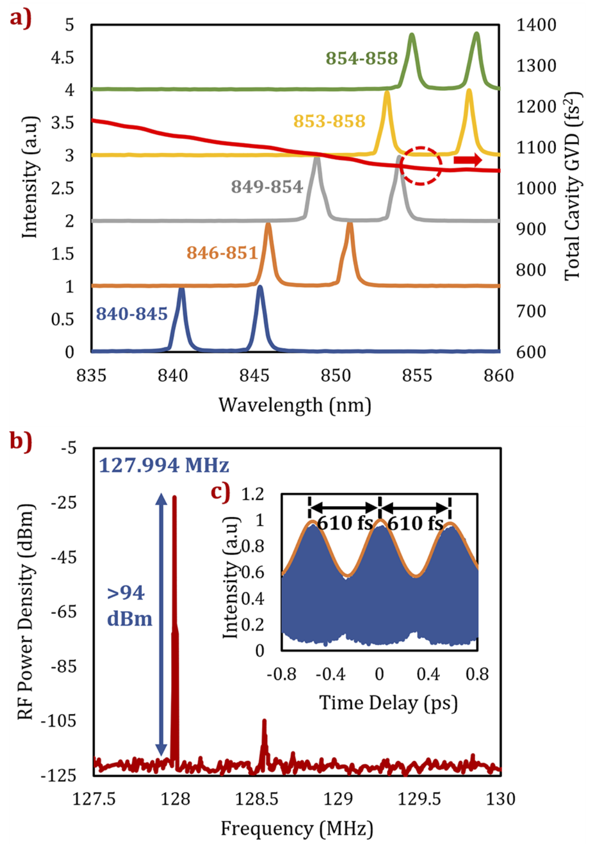

Fig. 4. (a) Measured tuning behavior of the two-color mode-locked Cr:LiSAF laser with the 16-mm-thick birefringent filter. (b) Measured microwave spectrum, indicating the clean mode-locked operation at 127.99 MHz. (c) Measured pulse beating period (~610 fs) for the 4 nm wavelength separation.

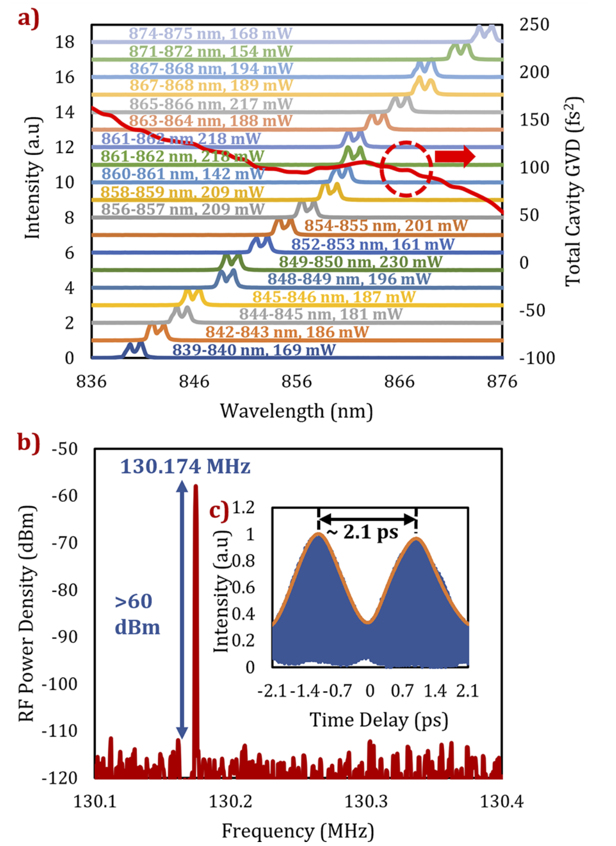

Fig. 5. (a) Measured tuning behavior of the two-color mode-locked Cr:LiSAF laser with the 200-μm-thick etalon (b) Measured microwave spectrum, indicating clean mode-locked operation at 130.17 MHz. (c) Measured pulse beating period (~2.1 ps) for the ~1.2 nm wavelength separation.

Using the 10-mm-thick BRF, two-color tuning is demonstrated at six distinct wavelength pairs (Fig. 3): 853–862 nm, 858–866 nm, 866–875 nm, 871–879 nm, and 873–882 nm. In the case of the 16-mm-thick BRF, two-color mode-locking in five different wavelength pairs is achieved (Fig. 4): 840–845 nm, 846–851 nm, 849–854 nm, 853–858 nm, and 854–858 nm. In accordance with the expectations, the wavelength separation of the two-color lasing pairs is 8–9 nm and 4–5 nm with the 10-mm-thick and 16-mm-thick BRFS, respectively. In both cases, the output power level of the Cr:LiSAF laser varied between 85 and 120 mW, slightly lower than the single-color mode-locking performance.

The measured autocorrelation (AC) traces show strong beating signals and confirm the synchronous mode-locked operation. As an example, Fig. 3(c) shows the measured AC trace for the 873–882 nm pair, where the measured pulse beating period is around 290 fs, which is in very good agreement with the measured spectral data (9 nm wavelength separation around 876 nm, frequency difference around 3.5 THz, and beating period of 286 fs). Similarly, we have measured a beating period of 610 fs for a wavelength separation of around 4 nm around 856 nm while using the 16-mm-thick BRF (frequency difference around 1.63 THz and beating period of 613 fs). As mentioned earlier, the net dispersions of the cavities are kept positive for more flexible two-color mode-locked operation: around 600 fs^2 and 1100 fs^2 for the 10-mm-thick and 16-mm-thick BRF cavities, respectively. Hence, the pulses are chirped in both cases, and the measured pulse widths were within the 10–30 ps range depending on the configuration.

The two-color synchronously mode-locked operation with a wavelength separation of 1 nm requires a BRF with a thickness of around 70 mm. Hence, for such small wavelength separation, using etalons provides a more practical approach. In our second experimental campaign, we used a 200-μm-thick etalon (with an estimated FSR of 1.22 nm), to achieve the two-color mode-locked operation. Figure 5(a) shows the measured tuning behavior of the two-color mode-locked Cr:LiSAF laser while employing the etalon. Tuning of the wavelength pairs is achieved between 839 and 875 nm, and 19 different spectral pairs with an average power between 142 and 230 mW and a pulse width around 10 ps are demonstrated. Note that the tuning range is only limited by the bandwidth of the SESAM used for mode-locking. With the etalon, the wavelength separation of the two-color pairs is around 1.2 nm (0.4–0.5 THz frequency difference). Again, the measured AC trace shows a beating period of around 2.1 ps, confirming the synchronously mode-locked operation [Fig. 5(c)].

While using the etalon, we have also tested the two-color mode-locked operation in the negative dispersion regime [the cavity shown in Fig. 1(b)]. Figure 6 summarizes the mode-locking performance for this case. As the soliton pulse shaping mechanism enables broader bandwidth, the mode-locked laser

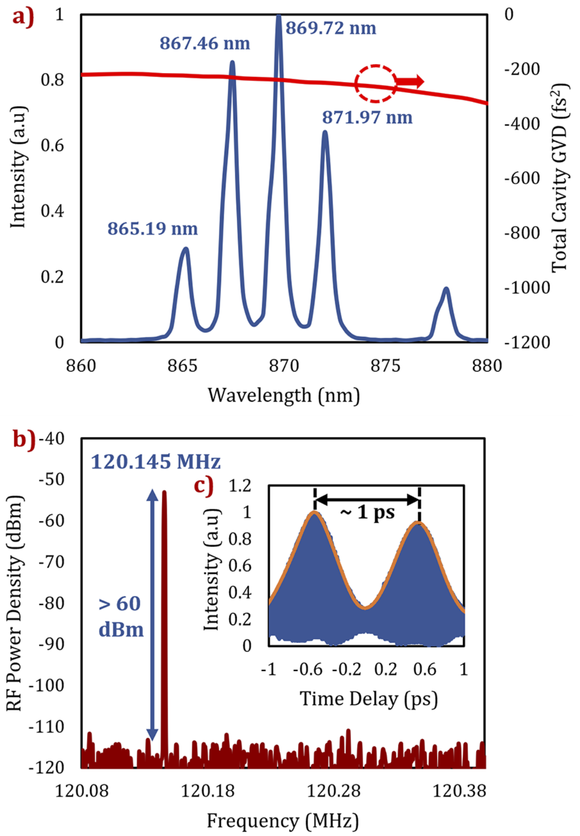

Fig. 6. (a) Measured optical spectrum of the mode-locked Cr:LiSAF laser with the 200-μm-thick etalon in the negative dispersion regime. (b) Measured microwave spectrum, indicating the clean mode-locked operation at 120.14 MHz. (c) Measured pulse beating period (∼1 ps) for the ∼2.2 nm wavelength separation.

switches from the dual-wavelength to multi-color operation. Four different wavelengths contribute to mode-locking, whereas we believe that the small peak around 878 nm is a cw spike due to a design error in the SESAM (see Fig. 3 in [21]). The wavelength separation is around 2.25 nm, which is interestingly two times the FSR of the etalon used. The measured AC trace shows a beating period of around 1 ps [Fig. 6(c)], again confirming the synchronous mode-locked operation.

To summarize, in this work, we have used simple and low-cost intracavity birefringent filters and etalons of different thicknesses to achieve a dual-wavelength mode-locked operation in a Cr:LiSAF laser. The laser was operated in the positive dispersion regime, and a two-color mode-locked operation with chirped pulses is demonstrated at beating frequencies between 0.4 and 3.5 THz. The central wavelength of the two-color mode-locked lines could be smoothly tuned from 840 to 875 nm. The demonstrated beating frequencies and central wavelength tuning ranges are limited by the optics available in this study and could be extended further in the future. Moreover, we believe that these results could be extended to a short pulse regime by employing GTI mirrors with large negative dispersion.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCES

1. X. Zhao, Z. Zheng, L. Liu, *et al.*, Opt. Express **20**, 25584 (2012).
2. D. N. Schimpf, H. T. Olgun, A. Kalaydzhyan, *et al.*, Opt. Express **27**, 11037 (2019).
3. H. T. Olgun, W. Tian, G. Cirmi, *et al.*, Opt. Lett. **47**, 2374 (2022).
4. K. Ravi, D. N. Schimpf, and F. X. Kärtner, Opt. Express **24**, 25582 (2016).
5. A. Leitenstorfer, C. Fürst, and A. Laubereau, Opt. Lett. **20**, 916 (1995).
6. Z. Zhang and T. Yagi, Opt. Lett. **18**, 2126 (1993).
7. M. R. X. de Barros and P. C. Becker, Opt. Lett. **18**, 631 (1993).
8. J. M. Evans, D. E. Spence, D. Burns, *et al.*, Opt. Lett. **18**, 1074 (1993).
9. S. J. White, J. M. Hopkins, M. Mazilu, *et al.*, in *Pacific Rim Conference on Lasers and Electro-Optics, CLEO*, OSA Technical Digest (Optica Publishing Group, 2000), paper CThB5.
10. D. N. Papadopoulos, F. Druon, J. Boudeile, *et al.*, Opt. Lett. **34**, 196 (2009).
11. L. C. Kong, Z. P. Qin, G. Q. Xie, *et al.*, Opt. Lett. **40**, 356 (2015).
12. G. Q. Xie, D. Y. Tang, H. Luo, *et al.*, Opt. Lett. **33**, 1872 (2008).
13. Q. Yang, Y. G. Wang, D. H. Liu, *et al.*, Laser Phys. Lett. **9**, 135 (2012).
14. Z. Cong, D. Tang, W. De Tan, *et al.*, Opt. Express **19**, 3984 (2011).
15. J. Hou, X. W. Fu, J. L. He, *et al.*, IEEE Photonics Technol. Lett. **26**, 40 (2014).
16. T. Yerebakan, U. Demırbas, S. Eggert, *et al.*, J. Opt. Soc. Am. B **34**, 1023 (2017).
17. M. Scheller, C. W. Baker, S. W. Koch, *et al.*, IEEE Photonics Technol. Lett. **28**, 1325 (2016).
18. M. F. Mekteplioglu, Y. Ozturk, M. Pergament, *et al.*, Appl. Phys. B **129**, 22 (2023).
19. U. Demirbas, R. Uecker, J. G. Fujimoto, *et al.*, Opt. Express **25**, 2594 (2017).
20. U. Demirbas and I. Baali, Opt. Lett. **40**, 4615 (2015).
21. U. Demirbas, G. S. Petrich, D. Li, *et al.*, J. Opt. Soc. Am. B **28**, 986 (2011).
22. U. Demırbas, Appl. Opt. **56**, 7815 (2017).
23. C. Cihan, E. Beyatli, F. Canbaz, *et al.*, IEEE J. Sel. Top. Quantum Electron. **21**, 94 (2015).