Optics Communications 405 (2017) 233–237

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High-efficiency tunable dual-wavelength Cr:LiSAF laser with external grating feedback

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A R T I C L E   I N F O

MSC:
00-01
99-00

Keywords:
Cr:LiSAF
Dual-wavelength laser
Tunable laser
Coupled cavity

A B S T R A C T

A high-efficiency tunable all-solid-state dual-wavelength Cr:LiSAF laser is demonstrated. A V-folded main cavity combined with an external grating feedback was used to improve the efficiency and tunability. With one wavelength fixed at 862 nm, the other wavelength could be tuned from 840 nm to 882 nm. The output power in dual-wavelength operation mode reaches 195 mW with a pump power of 735 mW, indicating an optical–optical efficiency of 26.5%.

1. Introduction

In recent years, dual-wavelength lasers have attracted considerable attentions because of their potential applications in terahertz (THz) wave generation [1,2], communication [3], remote sensing [4], and digital holography [5]. For example, in THz radiation technique, two laser beams of close wavelength are focused to a photomixer such as low-temperature-grown GaAs (LT-GaAs) to generate electric current at THz beat frequency and subsequently radiate into free space [6]. Lasers that oscillate at two wavelengths simultaneously are appealing and have considerable advantages over the simple combination of two separated lasers. The main advantage is that, the dual-wavelength beams from one laser cavity, are naturally optimized in spatial mode matching and with same polarizations, which eases the alignment, focusing and polarization control in applications such as continuous wave (CW) THz radiation generation [1,2,6].

To date, dual-wavelength oscillations have been demonstrated in semiconductor lasers [1,2], fiber lasers [7], solid-state lasers [8–10], dye lasers [11], etc. Among these lasers, Cr^{3+}-doped colquiriites oscillators have several outstanding features. First, the gain bandwidth extends to wider than 300 nm with peak emission at around 850 nm [12], so that the wavelength gap could be continuously tuned from 0 to over 100 nm [13], which cannot be achieved in semiconductor lasers, fiber lasers and Nd^{3+}-doped solid-state lasers. Second, comparing to other tunable near-infrared lasers such as Ti:Sapphire lasers, Cr^{3+}-doped colquiriites lasers have advantages of much lower pumping threshold, higher efficiency and direct red laser diode (LD) pumping [12,14]. Furthermore, the anisotropic character of the Cr^{3+}-doped colquiriites readily allows for linearly polarized oscillation without the need of any active polarizing control [15]. In 2010, H. Maestre et al. reported a dual-wavelength Cr:LiCAF laser with a line-shaped main cavity and coupled-cavity feedback [16]. The maximum output power was only 20 mW, with a 665 nm LD pump of maximum power of 1.8 W and pump threshold of 600 mW. Then they improved the output power to 60 mW with an absorbed pump power of 1.5 W under the configuration of a V-folded main cavity and two grating feedbacks [9]. Reference [13] demonstrated a dual-wavelength Cr:LiSAF laser in which the wavelength difference extended to over 120 nm with 20 mW output as the pump power reached 325 mW. However, all these studies showed relatively low optical–optical efficiencies of less than 10%, instead of the high efficiency of Cr^{3+}-doped colquiriites oscillators [12].

In this paper, a high-efficiency tunable dual-wavelength Cr:LiSAF laser with a V-shaped main cavity and grating-controlled coupled cavity is demonstrated. In this dual-wavelength laser, one wavelength is set as 862 nm, the other wavelength is tunable between 840–882 nm, owing to the grating feedback from the coupled cavity. The linewidths of both wavelengths are narrowed to less than 0.15 nm. The output power reaches 195 mW at a pump power of 735 mW, indicating an optical–optical efficiency of 26.5%.

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http://dx.doi.org/10.1016/j.optcom.2017.08.028
Received 6 June 2017; Received in revised form 28 July 2017; Accepted 14 August 2017
Available online 30 August 2017
0030-4018/

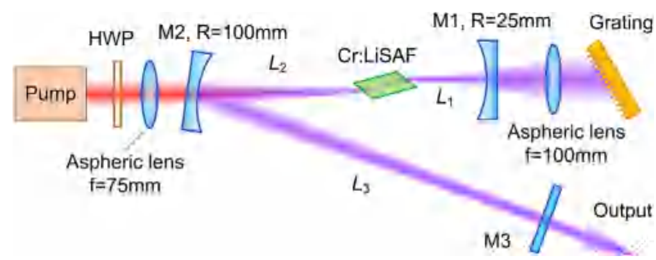

Fig. 1. Schematic of the dual-wavelength Cr:LiSAF laser with external grating feedback. HWP: half wave plate. L_1 ~20 mm is the distance between M1 and the crystal, L_2 ~60 mm is the distance between M2 and the crystal, L_3 ~200 mm is the distance between M2 and M3.

2. Experimental setup

Fig. 1 shows the schematic diagram of the dual-wavelength Cr:LiSAF laser with a grating-controlled coupled-cavity of Littrow configuration. A 671 nm Nd:YVO_4 /LBO laser with a maximum power of approximately 1 W and M^2 approximately 1.5 was used as pump source. Polarization ratio of the pump was larger than 100:1. A half-wave plate was used to adjust the polarization direction parallel to the incidence plane as well as the *c*-axis of the crystal. The divergence angle of the pump beam was 1.5 mrad and an aspheric lens with a focal length of 75 mm was used to focus the pump beam to a waist of 70 μm in the crystal. The main cavity consisted of a Cr:LiSAF crystal and three cavity mirrors (M1, M2 and M3), which were further coated to obtain high reflectivities within the lasing tuning range of 800–900 nm. In addition, M2 had a high transparency at the pumping wavelength of 671 nm. The radii of curvature of M1, M2 were 25 mm and 100 mm, respectively. The flat mirror M3 was used as an output coupler. A 5 mm long, Brewster-cut, 3% Cr^{3+}-doped LiSAF crystal mounted with indium foil in a copper holder was used as the gain medium. It has different absorption and emission cross-sections for π and σ polarizations. In particular, the absorption ratio was measured as 86.3% for the π-polarized pump power. Both the anisotropic character and Brewster-cut setting contributed to the perfect linear polarization of the laser beam. To improve the laser efficiency, the positions of the crystal and mirrors, e.g. L_1, L_2 and L_3, were carefully adjusted to ensure optimum spatial overlapping between the pump and oscillating beams with their beam waists near the middle of the crystal. The coupled cavity consisted of a collimating mirror and a diffraction grating. The emitted light from M1 was firstly collimated by an aspheric mirror with focal length of 100 mm, and then diffracted by the grating mounted in a Littrow configuration. In such configuration, the first-order diffraction component returned to the main cavity from the coupled cavity. The grating was 1800 grooves/mm with a blaze wavelength of 500 nm, and the first-order diffraction efficiency varied from 67% to 80% in perpendicular polarization in the 800–1000 nm region. In this type of configuration, the output coupler (OC) is separated from the external cavity, so that the OC allows for a relatively high transmission ratio to improve the laser efficiency, while the external feedback enable a free control of the oscillations for a wide tunable range.

The V-folded main cavity allows for oscillating independently even without feedback from any external cavity. While with an external feedback, the lasing wavelength is controlled by the grating, as a result pump thresholds decrease. This is because the effective reflectivity R_{eff} with the coupled-cavity is higher than the reflectivity of M1. The lasing wavelength could be tuned by rotating the grating.

There are intense mode competitions between the oscillations in the main-cavity free running and under coupled-cavity control. The lasing mode depends on the feedback ratio of the coupled cavity. If the feedback from the external cavity is forceful and the free-running oscillation suffers heavier passive loss, the feedback laser will control the oscillation wavelength and the free-running lasing mode will disappear. However, by weakening the feedback from the coupled cavity though tilting the grating, free-running and coupled-cavity controlled oscillations can occur simultaneously, while the passive losses of the two types of oscillations are similar.

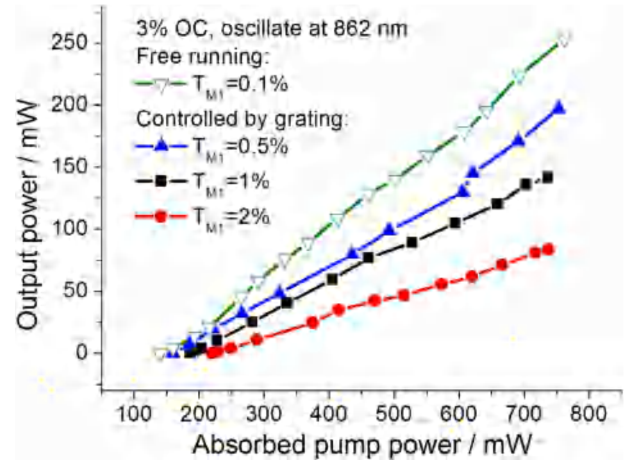

Fig. 2. Output power versus absorbed pump power taken in free running and grating-controlled oscillations. T_{M1} is the transmission of M1. The free-running wavelength is 862 nm; hence the grating-controlled oscillating is tuned to 862 nm for comparison.

3. Results and discussion

3.1. Single-wavelength operation

As shown in Fig. 2, the output efficiency in the single-wavelength operation varied with the transmission ratio of M1 (T_{M1}). In situation that T_{M1} was as low as 0.1%, the laser leaking in the coupled cavity was weak and the feedback did not control the oscillations. In this condition, the main-cavity laser would oscillate independently at 862 nm. In particular, the free-running wavelength of 862 nm is mainly determined by two factors. First, the emission cross-section of the Cr:LiSAF has a peak at 850 nm. Second, the coating of the cavity mirrors has a relatively low transmission ratio at 862 nm, which results in low cavity loss of oscillating at 862 nm.

As T_{M1} increased to 0.5%, it was evident that the lasing wavelength was controlled by the coupled-cavity feedback. However, cavity loss increases with the increasing of T_{M1}, which reduces laser efficiency. This explains why the curve of $T_{M1} = 0.5\%$ had a lower pump threshold and a higher slope efficiency compared to the curve of $T_{M1} = 1\%$. Note that we tuned the wavelength of the grating-controlled oscillation to 862 nm in order to compare the efficiencies.

Fig. 3 represents the tuning curves of the single-wavelength operation with grating feedbacks. Within the tuning range, there existed only grating-controlled oscillation. While outside the tunable bandwidth, the grating-controlled oscillation disappeared, and the free-running oscillation occurred. With an absorbed pump power of 735 mW and 1% T_{M1}, we changed the output couplers with transmissions ratio to 1%, 2% and 3%, respectively. The output power increased with the increasing of OC transmission ratio, and reached to its maximum value of 136 mW at 848 nm with 3% OC. The fluctuations in the tuning curves were caused by several factors such as the emission cross-section of the Cr:LiSAF crystal, mirror coatings and the first-order diffraction ratio of the grating. The tuning range decreased slightly while the OC transmissions changed from 1% to 3%.

3.2. Dual-wavelength operation

The dual-wavelength operation can be achieved by tilting the grating to reduce the feedback from the coupled cavity. Fig. 4 shows the

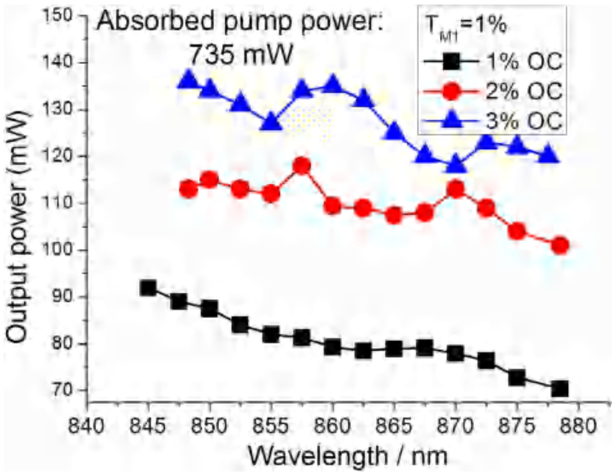

Fig. 3. Tuning curves taken in single-wavelength operation controlled by the grating feedback. OC is the output coupler M3.

tuning characteristics in dual-wavelength operation. One wavelength derived from the free-running oscillation was fixed at 862 nm, and the other wavelength relying on the grating-controlled oscillation could be tuned from 840 nm to 882 nm, while the grating incident angle varied from 49.1° to 52.5°. If the grating feedback is set outside the tunable bandwidth, the feedback in no longer strong enough to control the oscillations, thereby leaving only the free-running oscillations. The maximum wavelength difference was 22 nm as T_{M1} was set to 2%. Since the Cr:LiSAF crystal has a gain band of larger than 300 nm, the wavelength difference has a potential of extending to 100 nm, which is always desired in many applications. A maximum output power of 195 mW was obtained in condition of $T_{M1} = 0.5\%$, indicating an optical–optical efficiency of 26.5%. For comparison, in former studies, the optical–optical efficiencies of dual-wavelength operation were limited to 6% in Cr:LiSAF lasers [13] and 4% in Cr:LiCAF lasers [11]. Nevertheless, the efficiency could be further improved by optimizing the cavity design, such as adopting a grating with higher diffraction efficiency and a M1 with lower transmission.

As shown in Fig. 4(a), increasing T_{M1} can extend the tuning range and reduce the output power. The tunable bandwidth of the dual-wavelength operation is determined by the pump thresholds of the two types of oscillations. Dual-wavelength operation occurs only if the thresholds in free-running and under feedback control are similar. The threshold power of the grating-controlled oscillation increases as the wavelength approaches to the edge of the tuning range. At the point where the threshold power just exceeds that of free running, the oscillation becomes uncontrollable by the grating and in result there remains only free-running oscillation [17]. Tunable bandwidth extends with the increase of T_{M1}, because the pump threshold of free running increases. However, another aspect suggests that, higher T_{M1} causes heavier cavity loss, which decreases the laser efficiency and the output power. Fig. 4(b) represents the power ratio of the two wavelengths taken with the mirror set of 3% OC and 0.5% T_{M1}. We can see that the power ratio of the two wavelengths could be adjusted to almost 1:1 by tilting the grating to control the feedback ratio.

Fig. 5(a) represents the tunable range of 840 to 882 nm and Fig. 5(b) shows the detailed spectra of free-running, grating-controlled, and dual-wavelength oscillations. As shown in Fig. 5(b), the bottom width of the spectrum in free running was approximately 6 nm, and there were several peaks in the spectrum. While under the grating-feedback control, the free-running mode disappeared and the spectrum was extremely narrowed to a full width at half maximum (FWHM) of 0.08 nm. However, in dual-wavelength operation, both the spectra of free-running and grating-controlled components were different from those in the single-wavelength operations. The free-running spectrum is narrowed and laser energy was focused on one main spectrum peak due to the intense mode competition in dual-wavelength operation. In the spectrum of the grating-controlled component, the bottom width extended and several weak peaks appeared on the side of the main peak, because the feedback was suppressed to achieve dual-wavelength oscillation. Nevertheless the main-peak FWHMs of both the wavelengths spectra were less than 0.15 nm. According to Ref. [18], the spectral linewidth could be narrowed further to achieve an even single-frequency oscillation if necessary by extending the laser beam in the coupled cavity.

Fig. 6 shows the power stability for 1 h. The power in the dual-wavelength operation did not decrease significantly during 1 h. However, owing to the forceful mode competition and the instability of the pump, short-term jitters were obvious and the power of free-running component showed high fluctuation. The RMS of the power of tunable and fixed wavelengths were 3.22% and 3.59%, respectively.

Fig. 7 shows the output beam profiles in the dual-wavelength operation. We can see that the beams of the two wavelengths had optimum spatial mode matching. Though the spot sizes in the meridian and sagittal planes were different due to the astigmatic distortions in the cavity, the dual-wavelength output had favorable beam qualities with M^2 values less than 1.2 in both the planes. The collinear dual-wavelength beams with favorable spatial mode matching and M^2 factors would ease the alignment and focusing in applications such as THz wave generation. Note that the dual-wavelength beams have the same polarizations due to the anisotropic emission cross-section and Brewster angle cutting of the Cr:LiSAF crystal.

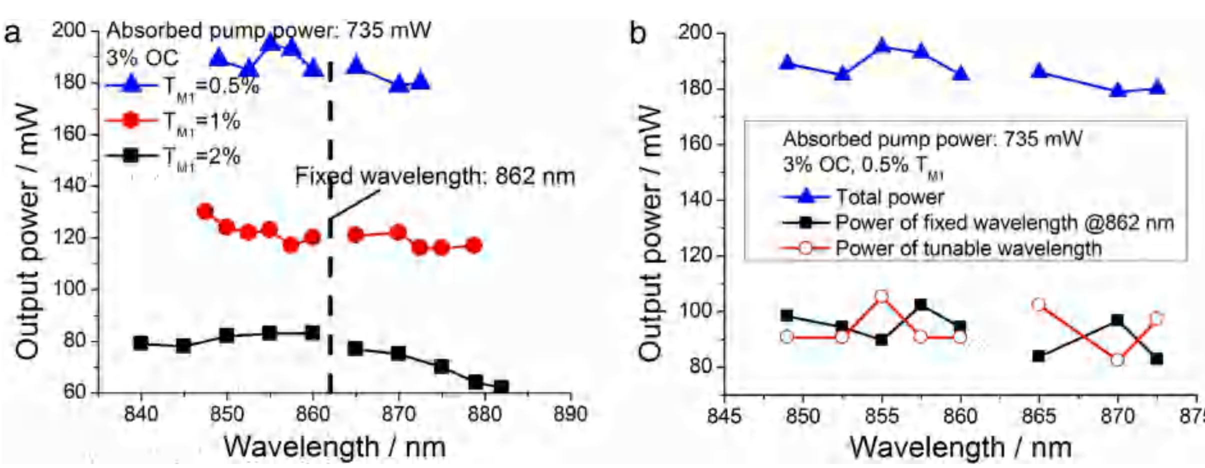

Fig. 4. Tuning curves in dual-wavelength operation. (a) Total power taken with different T_{M1}. (b) Power of each wavelength taken with 0.5% T_{M1}.

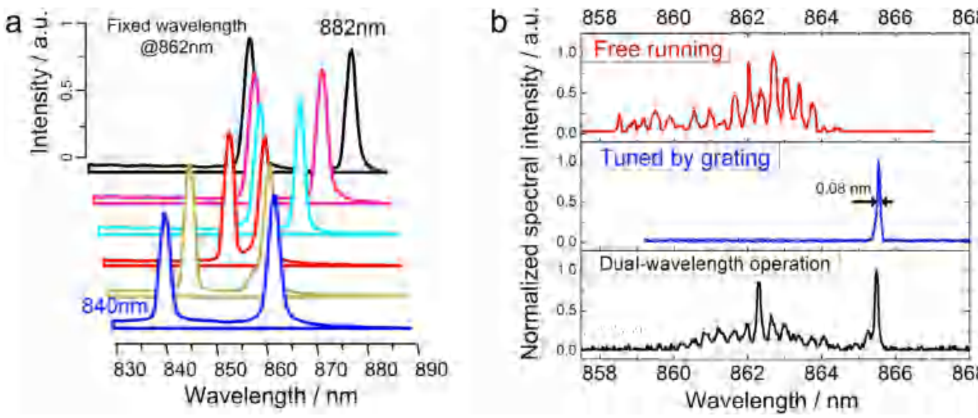

Fig. 5. Tuning range of dual-wavelength operation (a) and spectra of free-running, grating controlled and dual-wavelength operation (b). The spectra is obtained with the mirror set of 3% OC and 2% T_{M1}.

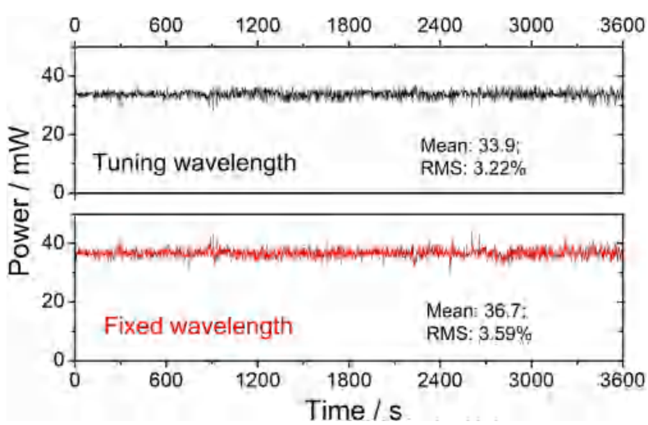

Fig. 6. Power stability in dual-wavelength operation for 1 h. The tunable wavelength is tuned to 845 nm, and the fixed wavelength is 862 nm; T_{M1} = 2%; the absorbed pump power is 735 mW.

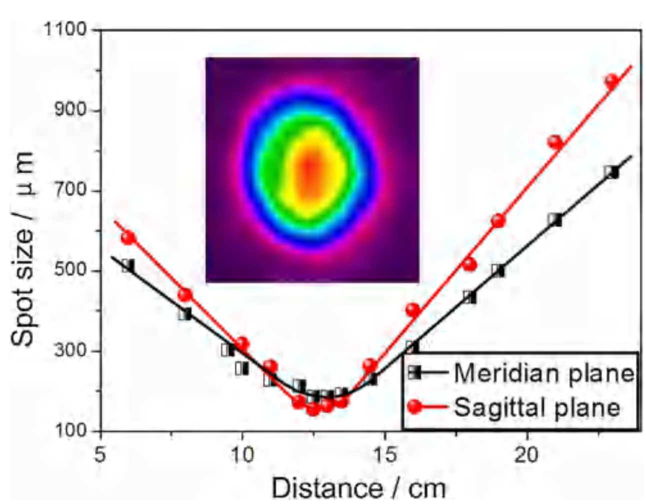

Fig. 7. Measured output beam profiles in dual-wavelength operation. M^2 values in meridian and sagittal plane are 1.19 and 1.16, respectively.

4. Conclusion

In conclusion, we demonstrated a dual-wavelength tunable all-solid-state Cr:LiSAF laser with a grating-controlled coupled-cavity. The laser design is optimum for achieving a high efficiency and a wide tunable range. With one wavelength fixed at 862 nm, the other wavelength can be tuned from 840 to 882 nm. The maximum output power of 195 mW is obtained with an absorbed pump power of 735 mW, revealing an optical–optical efficiency of 26.5%. We believe the efficiency could be improved further by optimizing the cavity design. The beams of the two wavelengths have narrow linewidths of less than 0.15 nm and optimum spatial mode matching. The results indicate that the high-efficiency dual-wavelength Cr:LiSAF lasers with an external grating feedback is potentially applicable for THz wave generation by photomixing.

Acknowledgments

The authors thank Prof. Zhang Yongsheng and Wang Zhenbao (State Key Laboratory of Laser Interaction with Matter, Northwest Institute of Nuclear Technology, China) for helpful discussions.

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