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Dual-wavelength operation in all-solid-state Cr:LiSAF lasers with grating-controlled coupled-cavities

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An all-solid-state Cr:LiSAF laser with a grating-controlled coupled-cavity for dual-wavelength operation is demonstrated. One wavelength is decided by the main-cavity oscillation and fixed at 860 nm. The other wavelength can be tuned from 790 nm to 987 nm by the grating in the coupled cavity. The maximum output power is 10 mW and both the linewidths are narrowed to below 0.2 nm.

1. Introduction

Dual-wavelength lasers have been extensively studied for applications such as optical communication devices [1], remote sensing instruments [2], THz wave generation [3] and digital holography [4]. For example, to generate CW THz wave, the dual-wavelength output could be focused on the photoconductive antennas (PCAs), to generate a CW electric current at the beat frequency of the two wavelengths and subsequently radiate it into free space [5]. And in the application of digital holography, the dual-wavelength lasers could increase the maximum height of the features which can be unambiguously imaged [4]. Compared to a dual-laser configuration, a dual-wavelength configuration eases the alignment and focusing, which are strict in applications such as CW THz wave generation and digital holography. Also, a dual-wavelength configuration simplifies and stabilizes the system.

Dual-wavelength emission has been obtained in semiconductor lasers [6,7], fiber lasers [8], dye lasers [9], Ti:Sapphire lasers [10], Cr^{3+} – doped colquiriites lasers [2,11], etc. Among these lasers, Cr^{3+} – doped colquiriites lasers have some attractive properties. Firstly, Cr^{3+} – doped colquiriites have a gain bandwidth of over 300 nm [12], so the dual-wavelength separation has the potential to be continuously tuned from 0 to over 200 nm, which cannot be realized in semiconductor lasers, fiber lasers or dye lasers. In THz generation by photomixing, the separation of the two wavelengths is generally below 20 nm [13]. However in dual-wavelength digital holography, the separation sometimes extends to over 200 nm [14]. Secondly, compared with Ti:Sapphire lasers which are also widely tunable, Cr^{3+} – doped colquiriites lasers have a comparable tuning range with advantages of much lower pumping threshold, higher efficiency and direct red LD pumping [12,15].

Recently, Maestre et al. demonstrated a dual-wavelength Cr:LiCAF laser with coupled-cavity tuned by grating feedback, which was suitable for terahertz continuous wave generation [11,16]. Dual-wavelength operation was controlled by adjusting the feedback ratio from the external cavity. The coupled-cavity configuration is also demonstrated in Cr:LiSAF lasers [17]. The coupled-cavity configuration is suitable for the tuning of such low-gain laser materials, because the tuning elements with optical insertion loss are inserted in external cavity separated from the low-loss main cavity. So the effect of insertion loss of tuning elements can be reduced. Gratings and prims, which have high insertion loss and are barely used in all-solid-state Cr:LiSAF lasers of other configurations, can be used as tuning elements in coupled-cavity lasers. Since Cr:LiSAF crystal has the largest emission cross-section and lifetime product in Cr^{3+} – doped colquiriites, dual-wavelength operation could be achieved in Cr:LiSAF lasers with low threshold and high efficiency.

In this paper, a 786–985 nm tunable Cr:LiSAF laser with external cavity tuned by a grating is demonstrated, and dual-wavelength emission is achieved. In the single-wavelength operation, the maximum output power is 19.7 mW, and the tuning characteristics in Littrow configuration and Littman–Metcalf configuration are compared. In the dual-wavelength operation, the maximum output power is 10 mW, and the dual-wavelength separation extends to 130 nm. Compared to Refs. [11,16], we demonstrate a

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dual-wavelength operation with much lower pump threshold and much wider tunable range. To our knowledge dual-wavelength emission in all-solid-state Cr:LiSAF lasers is first demonstrated.

2. Experimental setup

Figure 1 represents the schematic diagram of the Cr:LiSAF laser with a grating-controlled coupled-cavity of (a) Littrow configuration and (b) Littman–Metcalf configuration. A 671 nm Nd: YVO_4/LBO laser with maximum power of about 400 mW and $M^2 \approx 1.5$ is used as the pump source. The polarization ratio of the pump is above 100:1. A half wave plate is used to adjust polarization direction parallel to the incidence plane and *c*-axis of the crystal. The angle of divergence of the pump beam is 1.5 mrad and an aspheric lens of a focal length of 50 mm focuses the pump beam to a waist of ~60 μm in the crystal. The main cavity consists of two concave mirrors (M1 and M2) and a Cr:LiSAF crystal. M1 is coated to have a high transparency at pumping wavelength of 670 nm and high reflectivity in the lasing tuning range of 760–960 nm. The coupling mirror M2 has a high transparency at 670 nm and a reflectivity of over 93% in the 760–960 nm region. The radius of curvature of M1 and M2 is 50 mm and the main-cavity length is 96 mm, accordingly the radius of oscillation beam waist in the crystal is 56 μm and 84 μm in sagittal plane and meridian plane, respectively. The gain medium is a 6-mm-long, Brewster-cut, 3% Cr-doped LiSAF crystal mounted with indium foil in a copper holder and exhibits different pump absorption cross-section for π and σ polarizations [18]. In particular, an absorption ratio of 91% for the π-polarized pump power is measured. The emitted light from M2 is collimated by the aspheric mirror of focal length of 50 mm, and then diffracted by the grating. The grating has 1800 grooves/mm with the blazed wavelength of 500 nm, and the first-order diffraction efficiency varies between 67% and 80% in perpendicular polarization in 800–1000 nm region (Thorlabs Corporation). In Littrow configuration (see Fig. 1(a)), the first-order diffraction component as the feedback returns to the main cavity directly from the grating. While in Littman configuration (see Fig. 1 (b)), the light emitted from the main cavity is diffracted by the grating and subsequently reflected by the tuning mirror. The main cavity can oscillate independently without the external cavity, while with the external feedback, the lasing threshold is reduced and the lasing wavelength is controlled by the grating. Pump thresholds extremely decrease with the coupled-cavity, because the effective reflectivity R_{eff} with coupled-cavity is higher than the reflectivity of M2. So using the external feedback is equivalent to raising the reflectivity of M2. The lasing wavelength varies with the rotation of the grating or the tuning mirror because the wavelength of the feedback light to the main cavity varies.

The feedback ratio in Littrow configuration is higher than that in Littman–Metcalf configuration, mainly because the feedback light is diffracted twice by the grating in Littman–Metcalf configuration. However in Littrow configuration, the direction of the output beam changes while rotating the grating, which increases the complexity of measuring the output power and using the laser in practice.

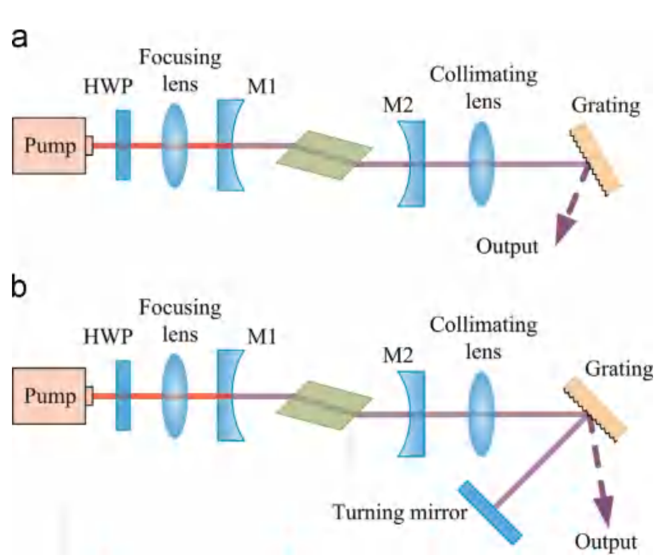

Fig. 1. Schematic diagram of the tunable Cr:LiSAF laser with grating-controlled coupled-cavity of (a) Littrow configuration and (b) Littman–Metcalf configuration. HWP, half wave plate.

3. Results and discussion

3.1. Single-wavelength operation

Figure 2 shows the pump threshold and output power curves of the coupled-cavity Cr:LiSAF lasers of Littrow configuration. The results obtained in Littman–Metcalf configuration will be discussed later for comparison. The pump thresholds of the main-cavity free running are 137 mW and 188 mW with the transparency of M2 (T_2) of 3.4% and 4.5% at 860 nm, respectively. The pump thresholds extremely decrease with the coupled-cavity. The tuning range is 199 nm from 786 to 985 nm. Pump thresholds increase as the lasing wavelength approaches to tunable band edges. When pump thresholds with external feedback exceed those of free running, the main cavity will oscillate independently of the coupled-cavity control. So the tuning range is decided by competition of thresholds under coupled-cavity control and in free running. In general, by using M2 with low reflectivity, threshold in free running can be increased and the tuning range with external feedback can be expanded. However in our experiments, since T_2 change little from 3.4% to 4.5%, the tuning range

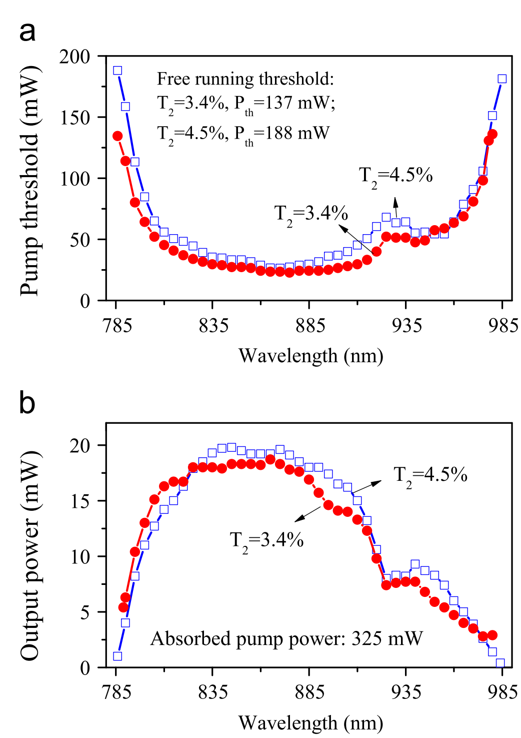

Fig. 2. Tuning characteristics in Littrow configuration. T_2 is the transparency coefficient of M2. Tuning range: T_2=3.4%, 786–980 nm; T_2=4.5%, 786–985 nm.

does not change obviously. Note that self-absorption loss prevents lasing below 780 nm [12] and the relatively low reflectivity over 980 nm of cavity mirrors limits lasing at longer wavelength. Thus, by changing the mirrors with high reflectivity optimized at longer wavelength, the tuning range might extend to over 1000 nm [12].

As shown in Fig. 2(b), the output power achieves its maximum value of 19.7 mW and is always above 15 mW in the tuning range of 820–910 nm with a output coupler of $T_2=4.5\%$ when absorbed pump power is 325 mW. The output power depends on the pump threshold and slope efficiency. In general, high transparency of the output coupler results in high threshold and slope efficiency [19], so the threshold and slope efficiency in lasers with $T_2=4.5\%$ are higher than those in lasers with $T_2=3.4\%$. If the threshold with $T_2=4.5\%$ is close to that with $T_2=3.4\%$, the output power with $T_2=4.5\%$ will be higher, due to the higher slope efficiency. And this situation happens in the most part of the tuning range. Otherwise, if there is a wide gap between the threshold curves, the output power with $T_2=4.5\%$ will be similar to or lower than that with $T_2=3.4\%$, and this situation can be seen in the region below 820 nm and 910–935 nm. Note that the concave in output power curve and convexity in pump threshold curve at 925 nm are caused by the convexity in transparency curve of M1. Both the tunability of 786–985 nm and the output power of 15–20 mW in 90 nm region of 820–910 nm are improved compared to former results in Cr:LiSAF lasers with external cavities [17,20,21].

Figure 3 shows the spectra measured by an optical spectrum analyzer (Agilent 86140B) with a RBW (resolution bandwidth) of 0.06 nm. Linewidth is narrowed evidently with grating feedback compared to that in free running. As the wavelength tuned from 786 nm to 985 nm, the grating is rotated and the incident angle to the grating varies from 45° to 62°. However the FWHM (full width at half maximum) of the spectrum is not obviously narrowed and maintains at ~0.12 nm when the incident angle increases.

Figure 4 represents the tuning characteristics in Littman–Metcalf configuration for comparison. The tuning range and output power are worse than those in Littrow configuration, due to the heavier external-cavity loss.

3.2. Dual-wavelength operation

As mentioned before, there is a competition between oscillations in main-cavity free running and under coupled-cavity control. So when the pump thresholds of two kinds of oscillations are similar, the simultaneous emission at two wavelengths can be achieved. One wavelength is fixed at the free-running wavelength of 860 nm, and the other wavelength is tuned by the grating. As shown in Fig. 2, the threshold in free running is fixed and higher than that under the control of external cavity. To achieve dual-wavelength operation, we can weaken the feedback to the main cavity, to raise the threshold under coupled-cavity control, by tilting the grating in external cavity. Rotating the grating controls the wavelength of the feedback, while tilting the grating controls the feedback ratio. Since the pump threshold varies with the wavelength under coupled-cavity control, the feedback ratio or tilt is different for each wavelength pair in dual-wavelength operation. The dual-wavelength operation can be realized in both Littrow configuration and Littman–Metcalf configuration. In order to improve the output power, Littrow configuration is used to achieve dual-wavelength operation.

The spectra of dual-wavelength operation in the full tuning range are shown in Fig. 5(a). With one wavelength fixed at 860 nm, the other wavelength can be tuned from 790 nm to 987 nm. Note that we adjust the external cavity to make the spectral intensity of the two wavelengths similar. Figure 5 (b) shows the spectrum in detail. Compared with Fig. 3, the bottom width of free-running spectrum is narrowed evidently from 5 nm to 2 nm, which can be explained by that the mode-competition is more intense in dual-wavelength operation. The FWHM of both wavelengths are narrowed to below 0.2 nm.

Figure 6 shows the output power of dual-wavelength operation in condition of about 1:1 ratio of power when the absorbed pump power is 325 mW. Compared with the results in single-wavelength operation shown in Fig. 2, the output power falls obviously in the most part of the tuning range. When there is only main-cavity oscillation at 860 nm, the output power of zero-order diffraction is measured to be ~5 mW. The output power in dual-wavelength operation should be between that in free-running and in single-wavelength operation controlled by coupled cavity. The output power is maximum to 10 mW when the tunable wavelength is ~40 nm from the fixed wavelength (860 nm), almost two times the output power of zero-order diffraction in free running. When the tunable wavelength is tuned near to the fixed wavelength, the output power decreases greatly and close to free-running output power, because the gain competition becomes intense when the two wavelengths get close. Note that in our experiments the power of the two wavelengths is

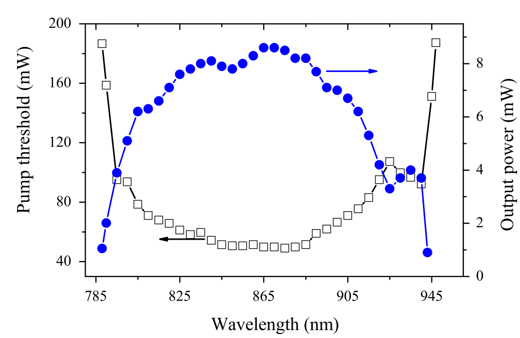

Fig. 4. Tuning characteristics in Littman–Metcalf configuration. Tuning range is 788–943 nm, $T_2=4.5\%$. The output power curve is obtained with incident angle of 65° and absorbed pump power of 325 mW.

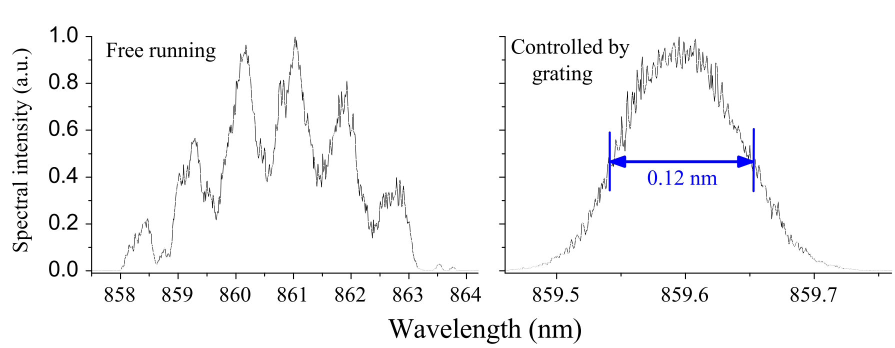

Fig. 3. Spectra in free running (left), and with grating control in the configuration without tuning mirror (right).

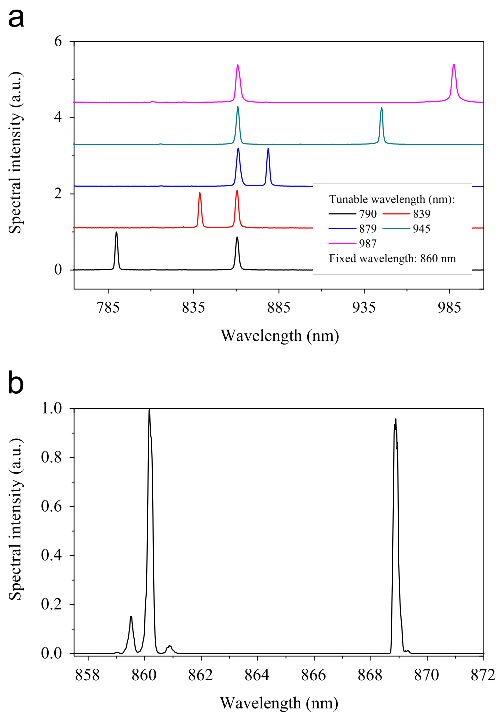

Fig. 5. Spectra of dual-wavelength operation.

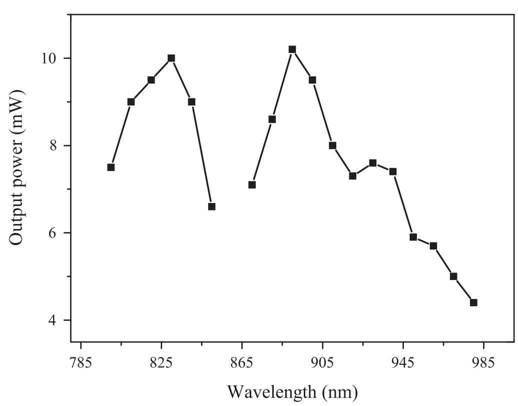

Fig. 6. Output power of dual-wavelength operation.

similar, and if lifting this restriction, the output power in dual-wavelength operation can be improved. In the experiments, when we increase pump power from threshold to max, the powers of the two wavelengths will not increase with 1:1 ratio without adjusting the grating. For each pump power over the threshold, we have to tilt the grating to achieve 1:1 ratio of power. Due to the unstability of 5% of the pump, the dual-wavelength operation is not very stable and the short-term jitter is obvious. Both the output power and power ratio would change if the pump power varies. If we use a pump of high stability, the short-term jitter might weaken.

In Refs. [11,16], Maestre et al. demonstrated dual-wavelength Cr:LiCAF lasers controlled by external grating cavity, with the output power of 20 mW [16] in line-shaped cavity and 60 mW [11] in V-shaped cavity, with the incident pump power of 1.5 W. So the efficiency in our laser is close to that in Ref. [11] with much lower pump power, which simplifies the heat-management. If we use V-shaped cavity Cr:LiSAF lasers with external cavity to achieve dual-wavelength operation, the output power and the efficiency might be improved greatly.

4. Conclusion

In conclusion, we demonstrate a tunable all-solid-state Cr: LiSAF laser with a grating-controlled coupled-cavity, for both single-wavelength and dual-wavelength operation. In single-wavelength operation, the laser could be continuously tuned from 786 to 985 nm, and the output power is over 15 mW tuned from 820 nm to 910 nm with the maximum power of 19.7 mW obtained at 840 nm. In dual-wavelength operation, one wavelength is fixed at 860 nm and the other can be tuned from 790 to 987 nm. The output power is maximum to 10 mW and the FWHM of the two wavelengths are both narrowed to below 0.2 nm. The results indicate that dual-wavelength grating-controlled coupled-cavity Cr:LiSAF lasers have the potential to be applied in digital holography THz generation by photomixing.

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