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

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ABSTRACT

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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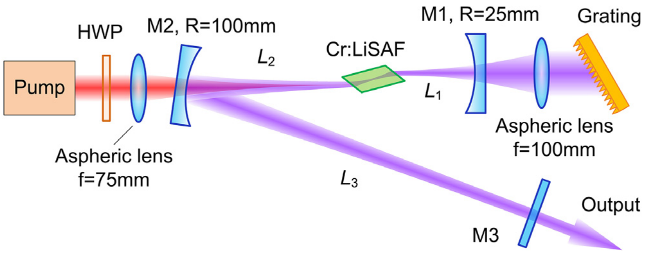

Fig. 1. Schematic of the dual-wavelength Cr:LiSAF laser with external grating feedback. HWP: half wave plate. L_1 ~20 mm is the distance between M1 and the crystal, L_2 ~60 mm is the distance between M2 and the crystal, L_3 ~200 mm is the distance between M2 and M3.

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$_{\text{eff}}$ 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.

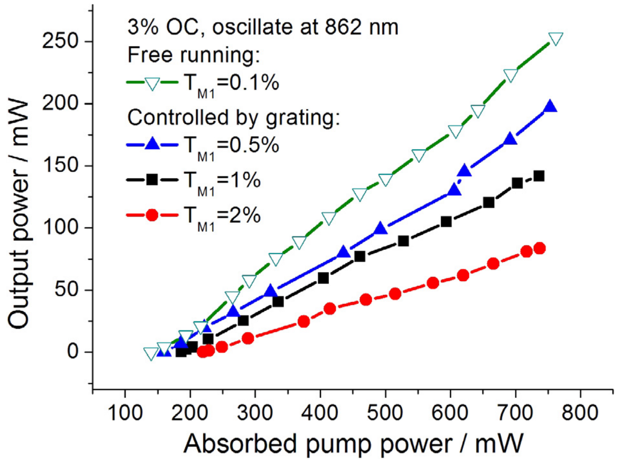

Fig. 2. Output power versus absorbed pump power taken in free running and grating-controlled oscillations. T$_{\text{M1}}$ is the transmission of M1. The free-running wavelength is 862 nm; hence the grating-controlled oscillating is tuned to 862 nm for comparison.

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$_{\text{M1}}$). In situation that T$_{\text{M1}}$ 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$_{\text{M1}}$ 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$_{\text{M1}}$, which reduces laser efficiency. This explains why the curve of $\text{T}_{\text{M1}} = 0.5\%$ had a lower pump threshold and a higher slope efficiency compared to the curve of $\text{T}_{\text{M1}} = 1\%$. 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$_{\text{M1}}$, 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