Optics and Laser Technology 100 (2018) 294–297

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Mode locked Nd^{3+} and Gd^{3+} co-doped calcium fluoride crystal laser at dual gain lines

Feng Zhang [a,b], Yongjing Wu [a,b], Jie Liu [a,b,*], Siyuan Pang [c,d], Fengkai Ma [c,d], Dapeng Jiang [c,d], Qinghui Wu [c,d], Liangbi Su [c,d,*]

[a] Shandong Provincial Key Laboratory of Optics and Photonic Device, School of Physics and Electronics, Shandong Normal University, Jinan 250014, China
[b] Institute of Data Science and Technology, Shandong Normal University, Jinan 250014, China
[c] Synthetic Single Crystal Research Center, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China
[d] Key Laboratory of Transparent and Opto-functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China

ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 6 September 2017
Accepted 21 October 2017

Keywords:
Dual-wavelength
Mode locking
Fluoride disordered crystal

ABSTRACT

Based on a novel disordered fluoride crystal—Nd^{3+} and Gd^{3+} co-doped CaF_2, we demonstrate a dual-wavelength synchronously mode locked laser in a single cavity, for the first time. Two gain lines at 1064.2 nm and 1064.7 nm were synchronously mode locked by gain spectrum splitting method, corresponding to a 0.15 THz repetition rate. The mode locked laser shows a 6.5 ps separated pulse duration.

1. Introduction

Dual-wavelength synchronously mode locked lasers are promising light sources applying in the Terahertz (THz, 10^{-12} Hz) wave generation, differential absorption lidar, fine laser spectra analysis and nonlinear frequency conversion technology. Until now, wide band gain medium----Ti:sappirare, has been employed to realize dual or multi-wavelength operation [1–11] through cross-phase coupling method [11] and gain spectrum splitting method [5]. Besides, rare earth ion doped laser materials are more suitable for several to tens THz waves generation benefiting from their relative narrow spectral bandwidth [12–20]. In 2011, Cong et al. demonstrated dual-wavelenth synchronously mode locked $Nd:LuYSiO_5$ laser with 0.59 THz repetition rate [15]. In 2015, Kong et al. reported a 2-μm wavelength band 0.13 THz dual-wavelength laser on $Tm:CaYAlO_4$ crystal [18].

MeF_2-LnF_3-NdF_3 (Me = Sr^{2+}, Ca^{2+}, Ba^{2+}, Ln = Y^{3+}, Lu^{3+}, La^{3+}, Gd^{3+}) disordered crystals are excellent ultra-fast gain media as wide band structure and high thermal conductivity [21–23]. Their wide absorption and emission spectra are derive from the Nd^{3+} multiple local coordination structure, which resulting in the spectra inhomogeneously broadened and split. Recent years, spectra properties and ultrafast single wavelength laser operation are widely investigated on the crystals [24–28]. The wide and split band structure is beneficial for dual or multi-wavelength laser generation. In 2016, we demonstrated a dual wavelength mode locked operation on a $Nd,Gd:SrF_2$ laser with 1.94 THz optical beating frequency [29].

In this paper, a novel 0.5 at.% Nd^{3+}, 5 at.% Gd^{3+} co-doped CaF_2 disordered crystal was successfully fabricated by temperature gradient technology (TGT). Continuous wave (CW) and dual-wavelength mode locking was experimentally investigated for the first time. By gain spectrum splitting method, dual-wavelength synchronously mode locked pulse was realized at two gain lines of 1064.2 nm and 1064.7 nm, corresponding to a 0.15 THz optical beats frequency. The mode locked laser output 2.3 ps sin-shape beating pulses at a fundamental repetition rate of 81.3 MHz. Maximum average output power of 312 mW was obtained, corresponding to a 11.1% slope efficiency.

2. Experimental setup

CW operation of $Nd,Gd:CaF_2$ laser was investigated priority of the CW mode locking by using a standard plano-concave cavity with total length of 190 mm. The transmittance of the output coupler was 3%. After careful alignment of the cavity, maximum average output power up to 1.335 W was obtained, corresponding to a

* Corresponding authors at: Shandong Provincial Key Laboratory of Optics and Photonic Device, School of Physics and Electronics, Shandong Normal University, Jinan 250014, China (J. Liu). Synthetic Single Crystal Research Center, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201800, China (L. Su).
E-mail addresses: jieliu@sdnu.edu.cn (J. Liu), suliangbi@mail.sic.ac.cn (L. Su).

https://doi.org/10.1016/j.optlastec.2017.10.018
0030-3992/

slope efficiency of 45.0%. The experimental results reveal Nd,Gd: CaF_2 can be applied in high energy laser system.

The mode locked laser setup was schematically shown in Fig. 1. A five-mirror-W-folded resonator was employed to generate and sustain the mode locked pulse. The fiber-coupled laser diode (LD) emissioned ~795 nm pump light. Diameter of the coupled fiber was 105 μm. The pump light was injected into the Nd^{3+},Gd^{3+}:CaF_2 crystal through a 1:2 amplifying coupling focusing system. The gain medium was processed with cross section of 3 × 3 mm^2, and 5 mm in length. We didn't coat antireflection film on the end face of the crystal, as less than 10% pump light reflected by the end face (Fresnel-reflection loss). The cavity mirror M1 was high-transmission coated at ~795 nm, M2 and M3 was high-reflection coated from 1030 nm to 1090 nm. The transmittance of the output coupler M4 was 1% for the output laser. According to the ABCD propagation matrix, and simulated by the Mathcad software, oscillated mode size on the crystal was designed to be 1.5 times as the pump light size, and ~50 μm in radius on the SESAM (BATOP, SAM-1064-0.7-1ps-4.0). The modulation depth and relaxation time of the SESAM were 0.4% and 1 ps, respectively. The small modulation depth was beneficial for restraining the Q-switched mode locking.

3. Results and discussion

Unstable Q-switched mode locking first realized, when the absorbed pump power beyond 1.25 W. The instability remained a range, until the pulse energy reached the threshold of the CW mode locking. To suppress the Q-switched instability, the intra-cavity pulse energy should follow the formula [30]:

$$E_p^2 \triangleright E_{sat,L} E_{sat,A} \Delta R$$

E_p, $E_{sat,L}$, $E_{sat,A}$ are the cavity pulse energy, saturation energy of the crystal, saturation energy of the SESAM, respectively. ΔR is the maximum modulation depth of the SESAM.After precise alignment of the cavity, stable CW mode locking was realized at the two gain lines when the absorbed pump power reached 2.32 W. The two gain lines were synchronously mode locked as proved by the time domain synchronous pulse trains in Fig. 2, which was measured by a fast photo-electric detector (EOT, ET-3000) and a 1 GHz-bandwidth oscilloscope (Tektronix, DPO4104). The pulse trains in the time scale of 20 μs and the detailed view with zoom factor of 2kx were shown in Fig. 2. Obvious CW component was observed in the pulse trains, as a result of the small modulation depth of the employed SESAM (ΔR = 0.4%). The output pulse shows distinct trains without separated structure at a fundamental repetition rate of 81.3 MHz, which correspond to the optical cavity length 1.84 m (see Fig. 3).

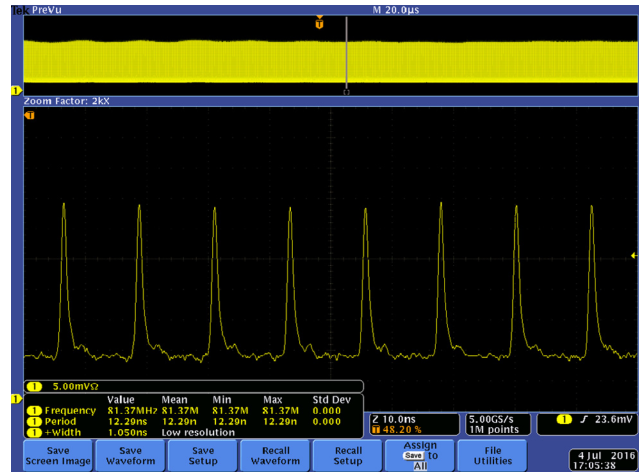

Fig. 2. Pulse train in the time scale of 20 μs and the detailed view with zoom factor of 2kx.

The mode locked spectrum of Nd^{3+},Gd^{3+}:SrF_2 laser was measured by the MS 3504i commercial spectrum analyzer with a resolution of 0.15 nm. Dual peaks at 1064.2 nm and 1064.7 nm was observed. The intensity ratio of the two peaks was about 1:1. FWHM of the envelope spectrum was 1.7 nm. However, it is hard to simulate the FWHM of the two peaks, as the small peaks buried in the envelope.

The autocorrelation trace of the Nd^{3+},Gd^{3+}:CaF_2 synchronously mode locked pulse was measured by a intensity autocorrelator (Femtochrome, FR-103L). By optical beating, the laser output a sin-type beating pulse with 2.3 ps beating duration. The beating frequency was about 0.15 THz, matching with the wavelength difference (see Fig. 4).

To characterize the output beam quality and stability, we measured the radio frequency (RF) spectrum and M^2 factor both in horizontal and vertical directions. A clear peak at 81.3 MHz was recorded by a RF spectrum analyzer (ROHDE&SCHWARZ FSC-SPECTRUM ANALYZER) with 3 GHz bandwidth and 10 kHz resolution bandwidth. The signal-to-noise ratio was more than 40 dBm, proving the relative clean CW mode locking (Fig. 5(a)). The M^2 factors in horizontal and vertical directions were 1.9 and 1.5, respectively, recorded by a M2-2000S-USB beam propagation analysis. To better understand the output beam mode, the transverse beam

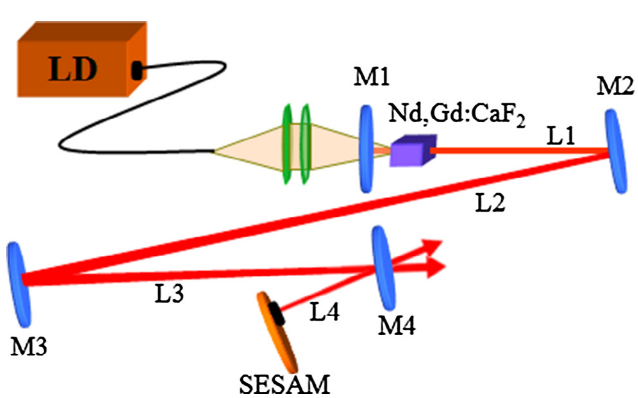

Fig. 1. Schematic diagram of the Nd^{3+},Gd^{3+}:CaF_2 mode locked laser. Radius of curvature of the M1, M2, M3 and M4 are ∞, 200 mm, 800 mm, 80 mm. The cavity length of L1, L2, L3 and L4 are 96 mm, 1100 mm, 600 mm and 42 mm, respectively.

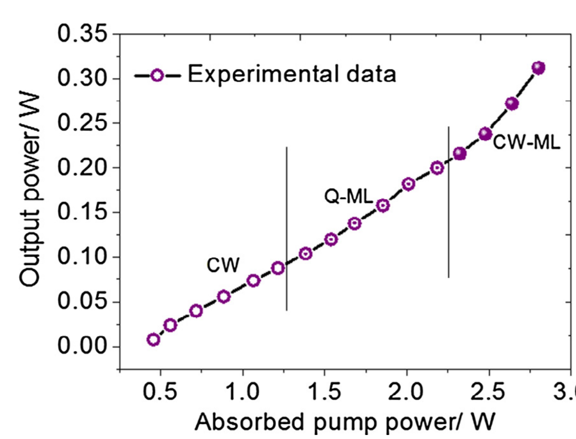

Fig. 3. Output power versus the absorbed pump power in CW, Q-ML and CW-ML regime.