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1.31 and 1.32 μm dual-wavelength $Nd:LuLiF_4$ laser

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ABSTRACT

We demonstrate the operation of $Nd:LuLiF_4$ laser with efficient 1.31 and 1.32 μm dual-wavelength. Maximum continuous-wave output power of 1.63 W is obtained at an incident pump power of 9.97 W and 8% transmission of output coupler (OC), giving a slope efficiency of 17.9%. When monolayer graphene is employed as saturable absorber, stable passively Q-switched 1.31 and 1.32 μm dual-wavelength laser operation still remains. The maximum average output power of 1.33 W, the largest pulse energy of 17.3 μJ and the highest peak power of 111.6 W are achieved with the 8% OC. Meanwhile, the shortest pulse duration of 133 ns and the highest repetition rate of 91 kHz are rendered by the 3.8% OC cavity.

1. Introduction

Recently, simultaneous multiple wavelengths lasing attract great attentions due to the applications in the fields of medical instrumentation, optical frequency up-conversion, spectral analysis, and THz frequency generation, etc. As an important transition band besides 0.94 μm and 1.06 μm of Nd^{3+}, laser emission at 1.3 μm could be utilized to produce red radiation by frequency doubling. The 1.31 and 1.32 μm dual-wavelength lasers have been attracted increasing attentions for their applications in the silver atom optical clock [1].

Dual-wavelength of the Nd-doping crystals has been investigated by several research groups. In 2009, Wang et al. reported the passively Q-switched (PQS) dual-wavelength ceramic Nd:YAG laser at 1052 and 1064 nm [2]. Using the identical host medium, 1319 and 1338 nm dual-wavelength operation was obtained by Guo et al. [3]. In 2013, Zhao et al. reported the dual-wavelength synchronously Q-switched solid-state Nd:LYSO laser at 1076 and 1079.7 nm with multi-layered graphene as saturable absorber for the first time [4]. Dual-wavelength Nd:YLF lasers at 1312 and 1322.6 nm have been demonstrated by Louyer et al. [1]. In 2013, Li et al. reported continuous-wave (CW) dual-wavelength $Nd:LuLiF_4$ (Nd:LLF) laser operation at 1314 and 1321 nm [5]. However, the PQS dual-wavelength Nd:LLF laser at 1.3 μm with V:YAG was only obtained with the 3% output coupling beyond a certain absorbed pump power. In this report, to realize superior performance, graphene monolayer is used as saturable absorber, the PQS dual-wavelength Nd:LLF lasers at 1.31 and 1.32 μm with different output couplers (OCs) are systematically investigated.

As known, passive Q-switching is another effective technology besides passive mode-locking to obtain short pulse duration and high peak power. Passive Q-switching possesses the merits of compact structure and simplicity of operation. Saturable absorber is an important component in the PQS laser, and the saturation intensity of saturable absorber is a crucial parameter determining the performance of Q-switching laser. The traditional saturable absorbers, such as GaAs, Cr:YAG, and semiconductor saturable absorber mirrors (SESAMs), are restricted by the wavelength sensitivity. Contrarily, graphene is a zero-bandgap material and wavelength insensitive. Meanwhile, graphene possesses honeycomb crystal lattices and a two-dimensional structure, which determines unique characteristics such as topological, electronic, and optical properties, etc. [6–10]. Recently, graphene has been demonstrated to present a saturation intensity of 0.7 MW/cm^2 which one order lower than SESAM [10]. The low saturation intensity is conducive to passive Q-switcher according to the analysis of Keller [11,12]. Therefore, graphene is a promising saturable absorber for Q-switched laser operation.

In this paper, we demonstrate, for the first time to our knowledge, the efficient 1.31 and 1.32 μm dual-wavelength PQS Nd:LLF laser with monolayer graphene as saturable absorber. The threshold pump powers for stable PQS dual-wavelength lasers are 2.32 W and 2.65 W with 3.8% and 8% OCs, respectively. At 9.97 W pump power, the shortest pulse duration of 133 ns and the highest repetition rate of 91 kHz are obtained with 3.8% OC. The maximum average output power of 1.33 W, largest pulse energy of 17.3 μJ and

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highest peak power of 111.6 W are achieved by the 8% output coupling.

2. Experimental setup

Fig. 1 schematically illustrates the setup of dual-wavelength operation of Nd:LLF laser. The pump source came from a 30 W fiber-coupled laser diode (LD) with the central wavelength of around 792 nm at room temperature. The fiber core was 200 μm in diameter with a numerical aperture (NA) of 0.22. Through the 1:1 focusing optics, the pump beam was focused into the laser crystal with a beam radius of ~100 μm. The compact plane-concave cavity was employed. The total length of the cavity was 35 mm. The concave mirror M1 with the curvature radius of 150 mm was antireflection (AR) coated at 792 nm on the pump face, high-transmission (HT) coated at 792 nm and high reflection (HR) coated at 1.3 μm on the other side. The plane mirror M2 with a transmission of 3.8% or 8% at 1.3 μm was employed as output coupler. The high-quality Nd:LLF crystal used in the experiment was grown by the Czochralski method with Nd-doping concentration of 1 at%. The crystal was [100] cut with a dimension of $3 \times 3 \times 6$ mm^3. The two faces of the crystal were polished and AR coated at 792 nm and 1.3 μm. To efficiently remove the heat generated by the Nd:LLF under high pump power, the Nd:LLF was wrapped with indium foil and mounted on water-cooled copper block whose temperature was maintained at 13 °C during the whole experiment process. A laser power meter (MAX 500AD, Coherent, USA) was used to measure CW output power and average output power. The pulse temporal behavior was recorded by a digital oscilloscope (1 GHz bandwidth and 20 G samples/s sampling rate, DPO7104C Tektronix Inc., USA) and a fast InGaAs photodiode detector with a rise time of 400 ps (New Focus model 1611, Newport Inc. USA).

The monolayer graphene employed in this experiment was purchased from JCNano Co. Ltd., China and fabricated by CVD method which was analogous to the technique mentioned in Ref. [13]. The monolayer graphene was transferred onto a quartz substrate with a size of 2×2 cm^2. The Raman spectroscopy of the monolayer graphene was detected by a Horiba Jobin Yvon Raman system with a 514.5 nm pump laser. Fig. 2 depicts the Raman spectra of the monolayer graphene. As shown in Fig. 2, the *G* peak and 2-*D* peak are at 1589.3 cm^{-1} and 2647.6 cm^{-1}, as indicated by the Lorentzian curve fitting, corresponding to FWHM of 16.9 cm^{-1} and 35.5 cm^{-1}, respectively. While the nonsaturable loss, modulation depth, and saturation fluence of the monolayer graphene are 1.2%, 0.6%, and 12 μJ/cm^2, respectively.

3. Experimental results and discussions

Firstly, the LD pumped dual-wavelength Nd:LLF laser was operated in CW regime. The threshold pump powers of dual-wavelength laser operation were 2.18 and 2.26 W with 3.8% and 8% OCs, respectively. Here, in order to compare the experiment results with those in Ref. [5], these two output coupling transmissions

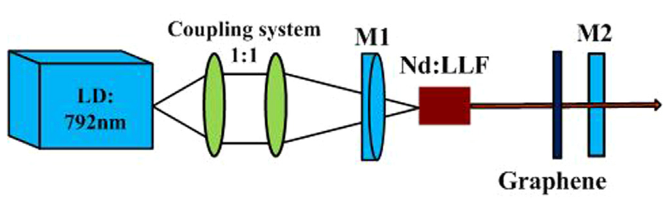

Fig. 1. Schematic setup of diode-pumped dual-wavelength Nd:LLF laser.

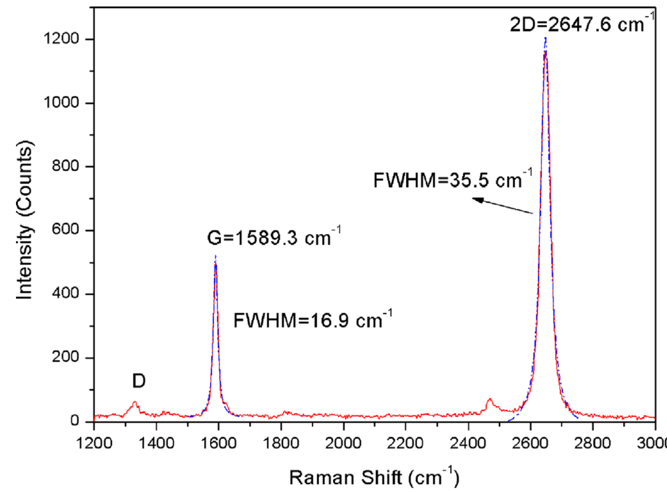

Fig. 2. Raman spectra of monolayer graphene.

were chosen. Further increasing the pump power, the FWHM of the laser spectrum in each wavelength became broader. However when the pump power was beyond 7.56 W, the FWHM kept constant. The reason leading to the variation tendency in the spectrum was because the population inversion on the upper laser level increased with the augment of the pump power. As a result, more electrons with slightly different energies involved in the stimulated emission. So the FWHM became broader until the advent of the gain saturation of the laser crystal. Under the incident pump power of 9.97 W and T_{OC}=3.8%, the emission wavelengths were centered at 1313.2 and 1320.8 nm with FWHM of 1.4 and 1.5 nm, respectively. While changing the OC to 8%, the emission wavelengths were centered at 1313.6 and 1321.4 nm with FWHM of 2.0 and 1.5 nm, respectively.

In Nd:LLF crystal, wavelengths for the two polarization of the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition were reported to be 1.313 and 1.321 μm [14]. While the emission cross sections for π polarization and σ polarization are 5.1×10^{-20} and 2.2×10^{-20} cm^2, separately. Compared with σ polarization for 1.31 μm laser, π polarization for 1.32 μm laser possesses larger branching ratio and emission cross section, so 1.32 μm laser has lower lasing threshold than 1.31 μm laser. Therefore, 1.32 μm laser oscillates at beginning. Further increasing the pump power, a larger intra-cavity population inversion increases the gain at 1.31 μm to overcome cavity loss. Thus, 1.31 μm laser oscillates, then dual-wavelength 1.31 and 1.32 μm laser can be observed.

The output power of dual-wavelength Nd:LLF laser with different OCs at 1.3 μm is described in Fig. 3. By using T_{OC}=3.8%, the maximal output power of 1.52 W was achieved at an incident pump power of 9.97 W, giving a slope efficiency of 16.7% and optical efficiency of 15.2%. Under the same pump power, 1.63 W output power was obtained with T_{OC}=8%, resulting a slope efficiency of 17.9%. To protect the host medium, we did not further increase the incident pump power. With the maximum output power and T_{OC}=3.8%, the M^2 factor of the CW dual-wavelength laser beam was 1.17 in tangential plane and 1.23 in sagittal plane, respectively. The results indicate that a nearly diffraction limited dual-wavelength laser beam is obtained, which is better than that in Ref. [5].

By inserting the graphene into the cavity, passively Q-switched dual-wavelength Nd:LLF laser was obtained. Fig. 4 depicts the average output power with different OCs. At 9.97 W pump power, the maximal average output power was 1.03 W, giving a slope efficiency of 12.1% with the 3.8% OC. Increasing the output coupling transmission to 8%, the maximum average output power and slope efficiency increased to 1.33 W and 13.7%, respectively.