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ScienceDirect

Optics Communications 272 (2007) 178–181

OPTICS COMMUNICATIONS

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Diode-pumped passively Q-switched mode-locked Nd:YLF laser with uncoated GaAs saturable absorber

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Received 2 July 2006; received in revised form 17 October 2006; accepted 25 October 2006

Abstract

We have demonstrated passively Q-switched mode-locked all-solid-state Nd:YLF laser with an uncoated GaAs wafer as saturable absorber and output mirror simultaneously. Q-switched mode-locking pulses laser with about 100% modulation depth were obtained. The average output power is 890 mW at the incident pump power of 5.76 W, corresponding to an optical slop efficiency of 20%. The temporal duration of mode-locked pulses was about 21 ps. At the Q-switched repetition rate of 30 kHz, the energy and peak power of a single pulse near the maximum of the Q-switched envelope was estimated to be about 1.6 μJ and 76 kW.

PACS: 42.55.Xi; 42.60.Gd

Keywords: Diode-pumped; Nd:YLF solid-state laser; Mode-locking; Passively Q-switched; GaAs wafer

1. Introduction

Passively Q-switched mode-locking (QML) all-solid-state lasers by using saturable absorber are attractive for their inherent simplicity, low cost, high pulse energy and reliable operation. In the regime of QML, laser pulses are modulated in the Q-switched envelope. Compared with continuous wave (cw) mode-locking lasers, QML lasers are of significantly higher per pulse energy due to the pulses concentrated in Q-switched envelope. QML all-solid-state lasers employing simple solid-state saturable absorber are desirable in nonlinear frequency conversion, precise fabrication of microstructure, surgery and spectroscopy. Especially, in the nonlinear frequency conversion, the transmit efficiency of second harmonic generation is higher in QML operation than in cw mode-locking operation [1].

The Nd:YLF laser crystal has been widely used in commercial laser products and research field. Compared with other neodymium doped laser crystals, Nd:YLF exhibits good thermal–optical property owning to its natural birefringence and weak thermal lensing, especially to c-cut crystal corresponding to the σ polarization operated at 1053 nm. The weak thermal lensing is the combination of negative temperature dependence of the refractive index ($\approx -2\times10^{-6}\,\mathrm{K}^{-1}$) and positive bulging of the end-faces. According to Ref. [2], the thermal lens of Nd:YLF is about a factor of 17 smaller than Nd:YAG under the comparable pumping conditions. Nd:YLF laser transitions at 1053 nm have upper-state lifetime and cross section around 500 μs and $1.2\times10^{-19}\,\mathrm{cm}^2$, respectively, versus 230 μs/$2.8\times10^{-19}\,\mathrm{cm}^2$ for Nd:YAG and around 90 μs/$25\times10^{-19}\,\mathrm{cm}^2$ for Nd:YVO$_4$. The gain bandwidth is about 1.35 nm at 1053 nm [3]. The small gain cross section and long upper-state lifetime of Nd:YLF are favorable for obtaining passively QML operation, in which the mode-locked pulses are modulated under Q-switch envelope of typical repetition rate in kilohertz range [4]. The wider gain

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doi:10.1016/j.optcom.2006.10.082

bandwidth is favorable for obtaining shorter mode-locked pulses for more longitudinal modes are available for locking. Nd:YLF laser operated at 1053 nm is an indispensable device of pulse amplification in Nd:glass master-oscillator power amplifier (MOPA) system.

A variety of materials have been used to generate mode-locking operations: LiF:F_2, dry, Cr^{4+}:YAG, and other semiconductor saturable absorber, such as GaAs. The GaAs has photochemical and thermal stability, large optical nonlinearity and high damage threshold. Although the semiconductor saturable absorber of quantum-well structure applied in mode-locked lasers has advantageous of compactness, flexibility, and wide band gap. GaAs is still attractive for easily fabrication and inexpensive. It was first used as saturable absorber for passively mode-locking by Zhang et al. and Kubecek et al. [5,6]. Diode-pumped, Q-switched Nd:YAG [7,8] laser, cw mode-locked Nd:$GdVO_4$ [9] laser, Nd:$GdYVO_4$ [10] laser and Nd:YAP [6] laser with GaAs as saturable absorber have been reported. QML Nd:YVO_4 laser with uncoated GaAs has been reported too [11]. But a passively QML Nd:YLF laser by using an uncoated GaAs single crystal has not been reported to our knowledge.

In this paper, we present an end-pumped passively QML Nd:YLF laser at 1053 nm using GaAs as saturable absorber and output mirror simultaneously. At the incident pump power of 5.76 W, the average output power is 890 mW corresponding to an optical slope-efficiency of 20%. Within the whole rang of incident pump power from 1.20 W to 5.76 W, the frequency repetition rate increased from 5 kHz to 30 kHz. The mode-locked pulses inside the Q-switched envelope have a repetition rate of 163 MHz, and the pulse width of 21 ps. The energy and peak power of a single pulse near the maximum of the Q-switched envelope were estimated to be about 1.6 μJ and 76 kW, respectively. The Fabry–Perot effect of the uncoated GaAs wafer on mode-locked pulse width is also indicated.

2. Experiment and discussion

Although the theory of QML using GaAs as absorber is not very clear, it is believed that the combination of all these effects including free electrons transitions from EL2 to the conduction band produce free electrons while valence transitions to $EL2^+$ produce free holes and neutral EL2 donors, two-photon absorption generates free electrons and holes, free-carrier absorption promotes electrons higher into the conduction band and holes deeper into the valence band could contribute to the process [12]. Valley and Smirl developed an energy-level model for energy transfer process [13]. Kajava introduced two-photon absorption and free-carrier absorption to explain the saturable absorption process [8]. For good passive Q-switching, the saturation of the absorber must occur before the gain saturation in the laser crystal (the second threshold condition). According to the analysis of the coupled rate equations, the criterion for good passively Q-switching is [14]

$$\frac{2\alpha_a L_a}{2\alpha_g L_g}\frac{\sigma_a}{\sigma_g}\frac{A_g}{A_a} > \frac{\gamma}{1-\beta}, \tag{1}$$

where α_a, L_a, and σ_a are the small-signal absorption coefficient , the thickness, and the absorption cross section of the saturable absorber; A_a is the laser beam area in the saturable absorber; α_g, L_g, and σ_g are the small-signal gain coefficient, the thickness, and the emission cross section of the laser medium. According to the laser oscillation theory, α_g equals to $\Delta N\sigma_g$ for typical four-level systems; ΔN is the inversion population density, which depends on the dopant concentration, the emission cross section and the lifetime of the laser medium; β is the ratio of the excited-state absorption cross section to that of the ground-state absorption cross section in the saturable absorber; γ is the population reduction factor, which equals to 1 for the ideal four-level system and 2 for the three-level system. Considering the output coupling and other dissipative losses of the laser cavity, the quantity $\alpha_a L_a/\alpha_g L_g$ in (1) is usually less than 1. Since σ_a ($\approx 1.0\times 10^{-16}\ \mathrm{cm}^2$), σ_g and β (≈ 0.23) are constant for given laser material and saturable absorber, the ratio of A_g/A_a is crucial to determine the laser's operation. Experimental and theoretical results have shown that a ratio greater than 3.0 is sufficient for Q-switching [15]. In our experiment, the mode radius on GaAs is around 20 μm and the ratio A_g/A_s is about 100. The tight focusing of laser beam on absorber is benefit to reduce the pulse built-up time, which should be sufficiently short for the mode-locked pulses generation.

A schematic of the laser is shown in Fig. 1. A cavity was designed to provide mode matching with the pump beam and tight focusing on the absorber. The pump source was a fiber-coupled diode laser rated at 6 W with a fiber core diameter of 0.4 mm and N.A of 0.22, emitting at the wavelength around 796 nm. By using a collimator with ratio of 3:5, the pump beam was imaged on the host crystal with a radius of 0.3 mm. The host crystal was c-cut Nd:YLF with a concentration of 1.0% and dimensions of 4 mm × 4 mm × 8 mm. Both of its light-passing faces were coated for antireflection at lasing wavelength of 1053 nm and pump wavelength of 796 nm. The laser crystal was wrapped in indium foil and was mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. The folded cavity composed of two mirrors M_1, M_2 and a 580 μm-thick uncoated GaAs wafer. M_1 was high

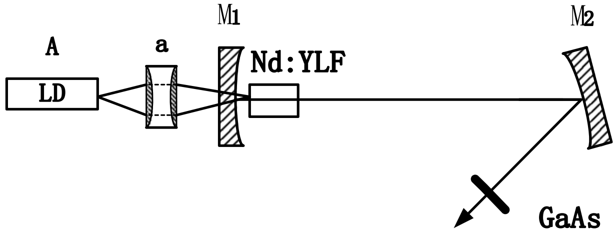

Fig. 1. Configuration of a passively Q-switched mode-locking Nd:YLF laser with an uncoated GaAs absorber. A: diode laser; a: coupling system and M_1, M_2: cavity mirrors.

reflection coated at 1053 nm and high transmission coated at 796 nm, while M_2 was high reflection coated at 1053 nm. The radii of M_1 and M_2 are 80 mm and 200 mm, respectively. Because the Fabry–Perot effect with the uncoated faces of the wafer, GaAs can be used as output mirror and saturable absorber simultaneously. The maximum reflectivity of uncoated output mirror is given by $R = \frac{4r}{(1+r)^2}$, $r = \left(\frac{n-1}{n+1}\right)^2$, where n is the refractive index of GaAs. The calculated maximum reflectivity of the GaAs wafer is approximately 70%. The distance between M_1 and M_2 was 800 mm. The whole length of the cavity was about 915 mm corresponding to a round-trip time of around 6.1 ns. The output behavior of the laser was investigated. The laser output was detected with a 1 ns-risetime InGaAs photo detector (New Focus 1623-AC) and a 1 GHz digital oscilloscope (Tektronix TDS 5104). Fig. 2 shows the average output power and repetition rate in relation to the incident pump power. The incident pump power was measured after the input mirror M_1. The laser threshold is 1.20 W and the maximum output power is about 890 mW at the incident pump power of 5.76 W corresponding to an optical slope-efficiency of 20%. The low laser threshold implies that the unsaturable loss of the GaAs wafer is insignificant. The picosecond pulses were superimposed upon the Q-switching pulse envelope even at the laser threshold and the modulation depth enhanced as we slightly increased the pump power. The performance implied that the larger ratio of A_g/A_a induces a higher energy density on the saturable absorber and in further matches easily to the mode-locking threshold. The repetition rate increased from 5 kHz to 30 kHz as the pump power was increased. A train of Q-switched pulses at the incident pump power of 2 W was shown in Fig. 3. The width of the Q-switched envelope was around 120 ns, varied a little as the pump power was increased, which was in agreement with Ref. [11]. The mode-locked pulses inside the Q-switched envelope have a repetition rate of ~163 MHz, which consistent with the length of the cavity.

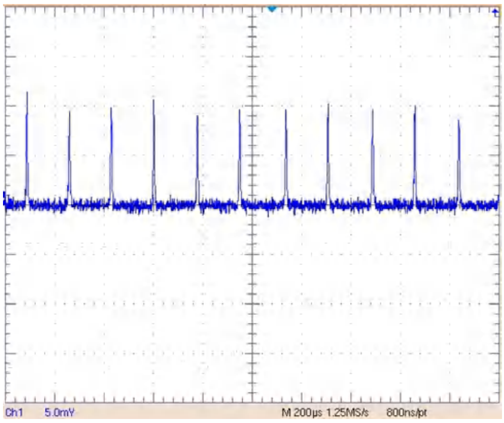

Fig. 3. Oscilloscope traces of a train of Q-switched pulses.

Over the incident pump power of 5.50 W, the QML pulses with about 100% modulation depth were obtained. The QML envelope and the mode-locking pulses inside the envelope at the incident pump power of 5.76 W are shown in Fig. 4 and the inset. The temporal duration of the mode-locked pulse was measure by an autocorrelator (FR-103XL, Femtochrome Research, Inc.). Fig. 5 shows the autocorrelation trace fitted with ideal sech^2 pulse profile. The full width at half maximum (FWHM) of the trace is about 1.05 ms and the pulse width is estimated about 21 ps. At the repetition rate of 30 kHz, the pulse energy near the maximum of the Q-switched envelope was estimated to be about 1.6 μJ. The maximum peak power of the mode-locked pulse was about 76 kW. But for cw mode-locking operation under the similar pump power, the single pulse energy is only in the order of nanojoule [6,9,10]. During the experiment, the output power increased monotonously as the pump power was increased, which can be explained by the cavity stability mainly due to the weak thermal lensing effect of Nd:YLF. Fig. 5 inset shows the laser spectrum measured by a spectrum analyzer (ANDO AQ-6315A). The laser spectra bandwidth was

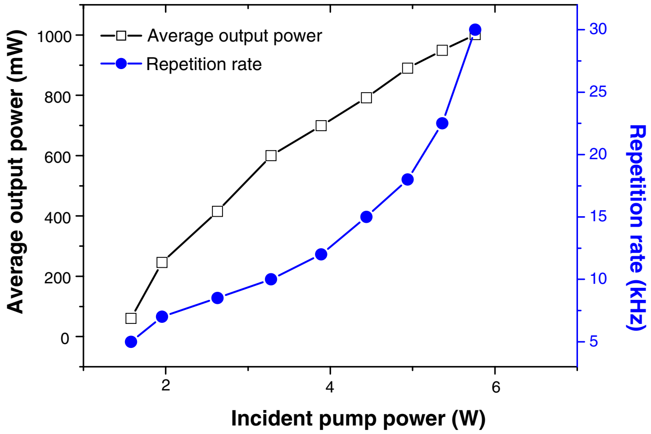

Fig. 2. Average output power and repetition rates with respect to incident pump power.

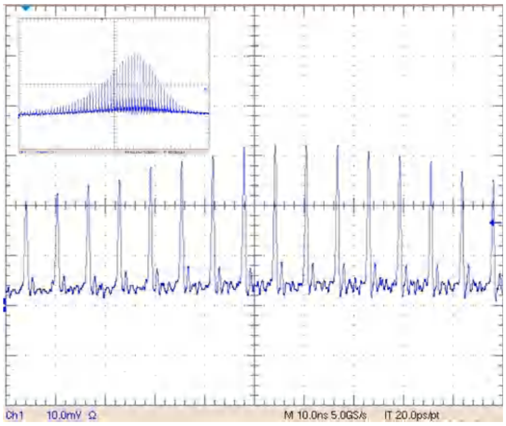

Fig. 4. Expanded temporal shape of a single Q-switched pulse and oscilloscope traces of a train of mode-locked pulses (inset).

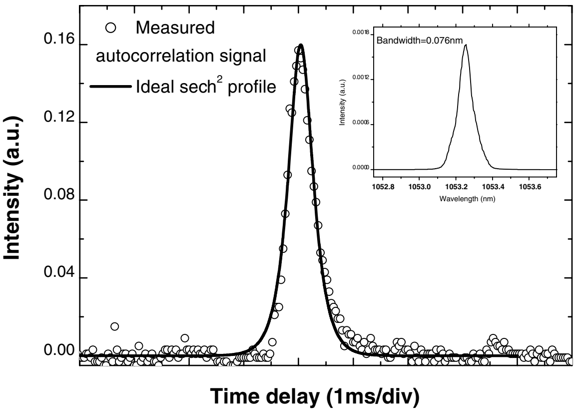

Fig. 5. Autocorrelation trace of the mode-locked pulses (doted line) and sech^2 fitted profile (solid line) and laser output spectrum (inset).

about 0.076 nm. The pulses were 1.3 times transmit limited according to the time-bandwidth product of a sech^2 function.

It is worthwhile to mention that etalon effect of the GaAs wafer has a direct affect on the pulse formation. The free spectral range and effective pass-band width of the GaAs wafer is: $\Delta\lambda = \lambda^2/2nd$, $\delta\lambda = \Delta\lambda/F$, where λ is the laser wavelength, n is the refractive index of GaAs, d is the thickness of the wafer and $F \approx 2$ for $r < 0.5$. We can obtain the free spectral range $\Delta\lambda$ is about 0.27 nm, and the effective pass-band width $\delta\lambda$ is around 0.14 nm. The gain bandwidth of the Nd:YLF is about 1.35 nm, nearly half number of the longitudinal cavity modes were sifted out by the Fabry–Perot effect of GaAs wafer. In our previous work, an output coupling semiconductor saturable absorber mirror (SESAM) with antireflection coated to eliminate the F–P effects was used for cw mode-locking operation [16]. Two picaseconds mode-locked pulses were obtained with about 30% of the longitudinal modes locked. But in this work, F–P effect induced fewer longitudinal modes oscillation and only about 6% of the longitudinal modes were locked, as a result, the temporal duration of the mode-locked pulse increased.

3. Conclusion

In conclusion, we have demonstrated QML Nd:YLF laser by using an uncoated GaAs wafer as saturable absorber and output mirror simultaneously. The laser operated in QML even at the threshold pump power and the Q-switched envelope with about 100% mode-locked modulation was obtained. The maximum average output power is 890 mW and the overall optical slope-efficiency is about 20%. At the repetition rate of 30 kHz, the pulse energy and peak power of the mode-locked pulse near the maximum of the Q-switched envelope was estimated to be about 1.6 μJ and 76 kW, respectively. We believe that this compact system generating picosecond pulses with several microjoules of energy and repetition rates in the multi-megahertz range directly obtainable from the QML laser are interesting to numerous scientific and industrial applications. We also analyzed that the uncoated GaAs wafer has influence on the pulse formation of the laser.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 60478009) and Ph.D. Degrees Foundation of Ministry of Education of China (Grant No. 20050445001). Jingliang He is the corresponding author and his e-mail address is <jlhe@icm.sdu.edu.cn>.

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