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Generation of 170-fs Laser Pulses at 1053 nm by a Passively Mode-Locked Yb:YAG Laser *

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A novel method is developed to obtain 1.05 μm laser operation by the Yb:YAG laser. By adopting Yb:YAG crystal with proper length and doping concentration, femtosecond Yb:YAG laser is realized at the central wavelength of 1053 nm. The measured pulse duration and spectral bandwidth (FWHM) are 170 fs and 7 nm; the repetition rate is 80 MHz. Under the power pump of 2 W, average mode-locking power of 180 mW is achieved.

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In recent years, there has been great interest in the lasers based on the Yb doped crystals. Among a variety of Yb doped crystals, the Yb:YAG crystal is one of the most important laser media. It has several important advantages: excellent thermal-mechanical properties, ease of growth in high-quality crystal, and high doping concentration without quenching, etc. Due to these favorable properties, remarkable progresses have been reported in continuous-wave,[1] Q-switched,[2] and passively mode-locked Yb:YAG lasers. Femtosecond Yb:YAG oscillators with an average power as high as 80 W[3] and a pulse energy of 11 μJ [4] at the wavelength of 1030 nm have been reported. However, limited by the width of the narrow gain peak at 1030 nm, the shortest pulse-width ever reported at this wavelength is 340 fs,[5] and most achieved pulses are longer than 500 fs.[3,4,6−9] On the other hand, the Yb:YAG crystal has another main emission wavelength at 1.05 μm. The emission spectrum at this wavelength is much flatter and can support much shorter pulses generation.[10] Although the emission cross section at this wavelength is lower, considering the excellent quality of this host material, 1.05 μm ultrafast source based on Yb:YAG with high power, high energy, and sub-100 fs pulses is highly promising.

Since the peak emission cross section of the Yb:YAG crystal lies at 1030 nm, to obtain oscillation at 1.05 μm by Yb:YAG laser, one must suppress the oscillation at 1030 nm. Several techniques were used to accomplish it. The first demonstration was realized by adopting a saturable absorber mirror (SAM) which introduced higher loss at 1.03 than at 1.05 μm.[6] In 2005, Uemura *et al.*[10] obtained 1050 nm Yb:YAG laser pulses by using chirped mirrors which have lower reflectivity at 1.03 μm than at 1.05 μm. Both the methods resort to the external optics to distinguish the two neighboring wavelengths, which inevitably bring additional loss and usually lead to low efficiency.

In this Letter, we first investigate the preferred emission wavelength versus the length and doping concentration of the crystal theoretically, and then develop a new method to obtain 1.05 μm operation based on the Yb:YAG laser. We realize 170-fs self-starting femtosecond Yb:YAG laser at the central wavelength of 1053 nm. To our best knowledge, this is the first demonstration of femtosecond Yb:YAG laser centering at the wavelength of 1053 nm.

The Yb:YAG laser is a typical quasi-three-level laser. For the quasi-three-level longitudinally pumped laser, the thickness of the gain medium is more crucial for the laser oscillation than in a four-level laser. In a quasi-three-level laser, the terminal level of the laser transition is thermally populated. Then, a minimum pump intensity is required for reaching population inversion. As the pump is absorbed when traveling in the gain medium, for a given pump intensity the required minimum pump intensity is reached after a length which is the so-called optimum crystal length. The emission transitions of Yb:YAG are from the upper level u_1 to lower level l_3(1030 nm) and l_4(1050 nm). The corresponding optimum crystal lengths of the two transitions are different. For single pass pumping and cw laser, using the model presented in Refs. [11,12], we can obtain the expression of the optimum crystal length:

$$L_{\rm opt} = \frac{-1}{f_p - f_l} \ln\left\{ \sqrt{R_m R_s}^{\frac{1}{g_0}} \beta^{\frac{1}{\alpha_0}} \right\}, \tag{1}$$

with

$$f_p = \frac{f_{l1}}{f_{l1} + f_{uj}}, \quad f_l = \frac{f_{lk}}{f_{lk} + f_{u1}},$$

where f_{ab} are the Boltzmann partition factors of the sublevel b of the manifold a. The pump transition starts from the lowest sublevel of the fundamental

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level (l_1) and the laser transition starts from the lowest sublevel of the upper level (u_1). The terminal level for the pump and the laser are u_a and l_b. R_s and R_m are the reflectivity of the output and rear mirror respectively (in our case, we assume that all the losses of the cavity are taken into account in the loss of the rear mirror),$\beta = \dfrac{f_l}{f_p - f_l}\dfrac{1}{I_p(0)}$, where $I_p(0)$ is the launched pump intensity normalized to the saturation intensity and $(f_p - f_l)$ is positive. The linear coefficients of gain g_0 and absorption α_0 are given by

$$\alpha_0 = \sigma_p N_{Yb}(f_{l1} + f_{uj}), \quad g_0 = \sigma_l N_{Yb}(f_{lk} + f_{u1}),$$

where σ_l and σ_p are the emission and absorption cross sections respectively, N_{Yb} is the Yb^{3+} ion concentration.

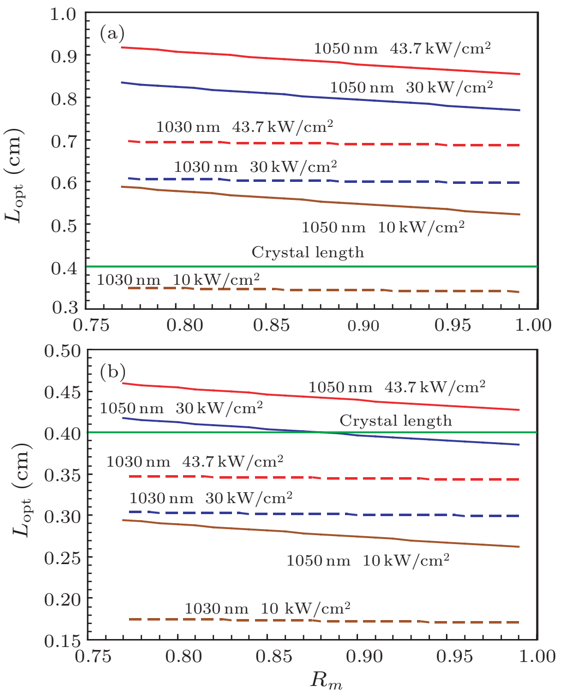

Fig. 1. Optimum length versus reflectivity of the rear mirror for various pump intensities: (a) 5% doping, (b) 10% doping.

Using Eq. (1), we compute the optimum crystal length versus the rear mirror reflectivity for various pump laser intensities. Figure 1 shows the computed optimum lengths for the two wavelengths of 1030 and 1050 nm. We notice that for a crystal length of 4 mm with 5 at% doping, the crystal length is much lower than the optimum lengths for 1050 nm oscillation at different pump intensities, but close to the 1030 nm optimum length. As a result, oscillation at 1030 nm is favored. It shows good agreement with the results reported in Ref. [5], in which a 5%-doped, 3.5-mm-long Yb:YAG crystal was used, and under the pump intensity of about 36 KW/cm^2, laser oscillation was achieved at the wavelength of 1.03 µm. However, for the 10 at% doped crystal, one can notice that the situation is different from Ref. [5]. The preferred crystal length is much shorter than that of 5 at% doping crystal. Only when the crystal is very short, oscillation at 1030 nm will be preferred. However, if the crystal length reaches a proper value, such as 4 mm, the 1030 nm laser is more likely to be re-absorbed and suppressed. This indicates a new way to suppress 1030 nm and the oscillation at 1050 nm is obtained only by choosing Yb:YAG crystal with proper ion doping concentration and length.

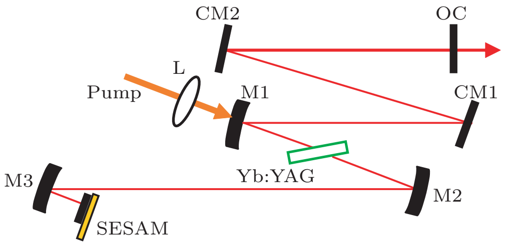

Fig. 2. Schematic of arrangement of the femtosecond Yb:YAG laser. M1-M3: concave mirrors with the radius of curvature of 100 mm; CM1 and CM2: GTI mirrors; OC: output coupler; SESAM: semiconductor saturable absorber mirrors; L: lens.

We performed the experiment using a 10 at% doped Yb:YAG crystal with the length of 4 mm. The experimental setup is depicted in Fig. 2. A typical Z-shape cavity was used with two concave mirrors (M1, M2) around the crystal. The output coupler has 0.5% transmittivity. To compensate for the intra-cavity dispersion, we applied a pair of Gires-Tournois interferometer (GTI) mirrors (CM1, CM2), which introduce a group delay dispersion (GDD) of -1200 fs^2 in the wavelength range 1020–1080 nm. All the coatings for the intra-cavity mirrors are identical for 1030 and 1050 nm. For self-starting mode-locking, a concave mirror with the radius of curvature of 100 mm (M3) was used to reduce the incident beam size on an SESAM, which was designed for 0.4% modulation depth and saturation fluence of 120 µJ/cm^2 at the central wavelength of 1040 nm (by Batop GmbH). We employed a 940-nm cw Ti:sapphire laser as the pump. The maximum available power is 2 W. The pump beam was focused onto the crystal by a 100 mm focal lens L. Firstly, we replaced the SESAM with a high reflective mirror and investigated the cw operation. The wavelength of the free-running laser was measured with a scanning spectrometer. The threshold pump power of the lasing was measured to be 510 mW. When the pump power was added to 2 W, the output power increased to 260 mW. In this process, the emitting wavelength was keeping at 1050 nm. This result can be well explained by the theoretical mode shown in Fig. 1(b). When the pump power was added from 510 mW to 2 W, the pump intensity at the front face of the Yb:YAG crystal is calculated to be from 11.1 kW/cm^2 to 43.7 kW/cm^2. One can notice from Fig. 1(b) that under these pump intensity levels, the length of crystal is near the optimum length of 1050 nm oscillation and much longer than that of 1030 nm oscillation. 1030 nm lasing is more likely to be re-absorbed and oscillation at the wavelength of 1050 nm can be preferred.

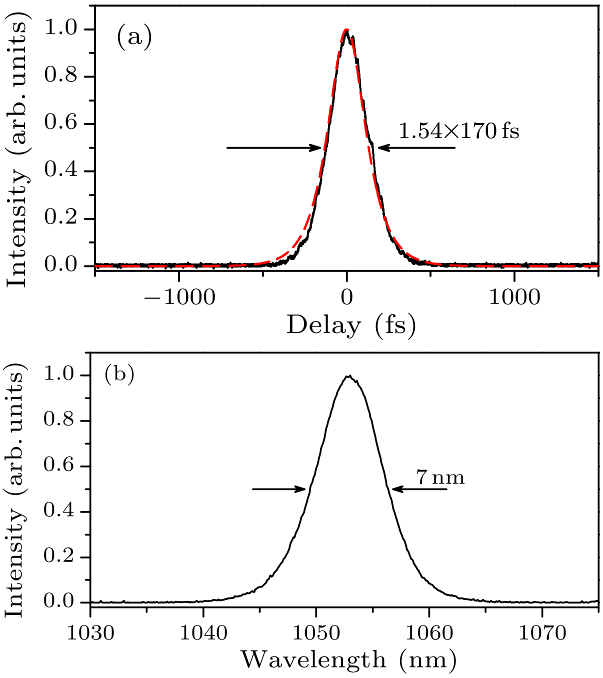

Fig. 3. (a) Typical intensity autocorrelation trace of the pulses; (b) the laser spectrum of mode-locking operation.

With the SESAM in the cavity and careful alignment, stable self-starting mode-locked pulses were obtained. Figure 3 shows the measured autocorrelation trace and the spectrum of the pulses. The pulse width is 170 fs assuming a sech^2-shape pulse. The FWHM spectral bandwidth of the femtosecond pulses reaches 7 nm and the central wavelength is 1053 nm. In contrast, the best corresponding values ever achieved by a 1.03 µm Yb:YAG laser are 3.4 nm and 340 fs,[5] respectively. Under the maximum pump power of 2 W, the output mode-locking power is 180 mW. It is worth mentioning that the central wavelength of this femtosecond Yb:YAG laser is exactly the working wavelength of high energy Nd:glass based ultrafast amplifier system. This experiment indicates that the femtosecond Yb:YAG laser has the potential to be an excellent seed source for the above system.

In conclusion, we have carried out a numerical simulation of the preferred emission wavelength of a Yb:YAG laser and developed a novel way to obtain 1.05 µm oscillation with this laser. By just adopting the Yb:YAG crystal with proper length and ion concentration, we have suppressed the 1030 nm oscillation and demonstrated femtosecond Yb:YAG laser at the central wavelength of 1053 nm, with the pulse width of 170 fs and spectral bandwidth of 7 nm. The pulsed power of 180 mW is achieved under the pump power of 2 W. It is believed that the results of the present study can indicate a new way to obtain 1053 nm femtosecond pulses by Yb:YAG laser. Due to the potential broad emission bandwidth and the excellent properties of this crystal, 1053 nm femtosecond Yb:YAG laser with high power, high efficient and sub-100 fs operation is hopeful, which will be excellent seed source for glass based high energy ultrafast laser systems.

References

[1] Yang P, Deng P, Zhang Y, Liu Y, Huang G, Chen W and Xu J 2000 *Chin. Phys. Lett.* **17** 104

[2] Zhang Q, Feng B, Zhang D, Fu P, Zhang Z, Zhao Z, Deng P, Xu J, Xu X, Wang Y and Ma X 2003 *Chin. Phys. Lett.* **20** 1741

[3] Innerhofer E, Südmeyer T, Brunner F, Paschotta R and Keller U 2004 *Laser Phys. Lett.* **1** 82

[4] Marchese S V, Baer C R E, Engqvist A G, Hashimoto S, Maas D J H C, Golling M, Südmeyer T and Keller U 2008 *Opt. Exp.* **16** 6397

[5] Hönninger C, Paschotta R, Graf M, Morier-Genoud F, Zhang G, Moser M, Biswal S, Nees J, Braun A, Mourou G A, Johannsen I, Giesen A, Seeber W and Keller U 1999 *Appl. Phys.* B **69** 3

[6] Hönninger C, Zhang G, Keller U and Giesen A 1995 *Opt. Lett.* **20** 2402

[7] Weitz M, Reuter S, Knappe R, Wallenstein R and Henrich B 2004 *Technical Digest of Conference on Lasers and Electro-Optics* (Washington, DC: Optical Society of America) paper CtuCC

[8] Aus der Au J, Spühler G. J, Südmeyer T, Paschotta R, Hövel R, Moser M, Erhard S, Karszewski M, Giesen A and Keller U 2000 *Opt. Lett.* **25** 859

[9] Innerhofer E, Südmeyer T, Brunner F, Häring R, Aschwanden A, Paschotta R, Hönninger C, Kumkar M and Keller U 2003 *Opt. Lett.* **28** 367

[10] Uemura S and Torizuka K 2005 *Jpn. J. Appl. Phys.* **44** L361

[11] Bourdet G L 2000 *Appl. Opt.* **39** 966

[12] Bourdet G L and Bartnicki E 2006 *Appl. Opt.* **45** 9203