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575-fs passively mode-locked Yb:CaF_2 ceramic laser*

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A Yb-doped CaF_2 transparent ceramics was successfully fabricated by the hot-pressed method and its laser characteristics were studied. A broad tuning performance and mode-locked laser operation were demonstrated in this ceramics for the first time, to our best knowledge. A 60-nm continuous-wavelength tunable laser from 1019 nm to 1079 nm was obtained with a birefringent filter. By employing a semiconductor saturable absorber mirror without additional dispersion compensation elements, a continuous-wave mode-locked laser with pulse duration as short as 575 fs was delivered, at a central wavelength of 1048.5 nm. The oscillator is operated under a repetition rate of 55 MHz. These results indicate that the Yb:CaF_2 transparent ceramics is an ideal candidate for the development of ultrafast lasers in the near-infrared regime.

Keywords: mode-locking, tunable, transparent ceramics, solid-state lasers

PACS: 42.55.–f, 42.55.Xi, 42.60.Fc **DOI:** 10.1088/1674-1056/ab8ac5

1. Introduction

Great and growing interests in ultrashort pulse lasers have been attracted recently as their important applications in many fields such as physics, biology, and chemistry.[1–5] Yb^{3+} has a simple electronic structure, the ground state of $^2F_{7/2}$ and an excited state of $^2F_{5/2}$. There is no intrinsic process for concentration quenching. Yb^{3+} also owns high quantum efficiency, long lifetime, and broad emission spectra.[6,7] These features make Yb^{3+}-doped materials suitable for use as gain media for ultrashort and high-power lasers.[8–11] Prior studies have indicated that rare-earth ion-doped calcium fluoride (such as CaF_2, SrF_2) materials are promising for the development of ultrashort pulsed solid-state lasers.[12–18] Among these materials, Yb^{3+}-doped fluoride-based materials have attracted great attention because of the excellent properties such as broad range of transmittance, low phonon energy, high thermal conductivity, and low refractive index.[19–24]

In recent years, transparent ceramic materials have attracted great attention as laser gain media.[25–28] Yb^{3+}-doped CaF_2 transparent ceramics have been investigated because of their low cost, ease of manufacturing, and high doping concentration compared with single crystals. In fact, Dy^{2+}:CaF_2 is the first laser ceramics to achieve laser output in 1964 by Hatch.[29] After that, few works on fluoride-based transparent ceramics laser ceramics has been done for nearly half a century. In 2009, nanosized Yb:CaF_2 powders were synthesized by co-precipitation method and Yb:CaF_2 transparent ceramics were obtained by a hot-pressed (HP) method.[30] In 2013, the first laser generation was demonstrated in 3-at.% Yb:CaF_2 ceramics fabricated by HP method.[31] Then, Yb:CaF_2 transparent ceramics were fabricated using hot isostatic pressing (HIP) method.[32,33] And output power of 1.6 W was reported by Aballea *et al.*[34] Recently, Shotaro Kitajima *et al.*[35] have investigated Yb:CaF_2-LaF_3 transparent ceramics by sintering fluoride nanocrystals in the air followed by the HIP method and reported maximum output power of 4.36 W in 2-at.% Yb, 3-at.% La:CaF_2 samples.

Except the HIP method, HP method is another efficient method to prepare transparent ceramics. There is no need for calcination, cold pressing, cold isostatic pressure, presintering, and other steps compared with HIP method. Although laser generation on 3-at.% Yb:CaF_2 ceramics fabricated by HP method was demonstrated in 2013,[31] few works have been done on tuning performance and mode-locked laser operation of the Yb:CaF_2 transparent ceramics by HP method.

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Based on the high optical quality of 5-at.% Yb:CaF_2 transparent ceramics obtained by hot-pressing method, the features of the continuous-wave-tunable operation on a diode pumped Yb:CaF_2 transparent ceramics laser were investigated. Besides, the minimum pulse duration as short as 575 fs was obtained by using a semiconductor saturable absorber mirror (SESAM). The oscillator operated under a repetition rate of 55 MHz at the central wavelength of 1048.5 nm with an average output power of 152 mW.

2. Experimental procedure

The 5-at.% Yb:CaF_2 powders were synthesized by co-precipitation method. Firstly, calcium nitrate (99.9%, Sinopharm) and ytterbium nitrate (99.99%, Aladdin) were dissolved in 64-ml distilled water together and potassium fluoride (99.9%, Sinopharm) were also dissolved in 128-ml distilled water. Then, solution of potassium fluoride was dropped wise to solution of calcium nitrate and ytterbium nitrate under magnetic stirring. The mixture was centrifuged at 1.1×10^4 rpm for 20 min after aging for 30 min. The obtained gel was washed with distilled water at least four times to remove the residual ions of of NO_3^- and K^+ in the solution. After dried at 80 °C for 12 h, the powders were grinded in an agate mortar and then spooned into the graphite mold. The 5-at.% Yb:CaF_2 transparent ceramics were sintered under 800 °C with the pressure of 40 MPa for 120 min. Final, both surfaces of the as-prepared ceramic sample were mirror-polished by different grades of diamond slurries. The details of the powders synthesized are reported in to our previous paper.[36]

The in-line transmittance and absorption spectra of the sintered 5-at.% Yb:CaF_2 transparent ceramics were performed using a PerkinElmer Lambda 750 UV–Vis–NIR spectrophotometer. The luminescence spectra measurements were recorded on an Edinburgh FLS1000 spectrofluorometer equipped with a 450-W xenon lamp as the exciting source. The emission signals were recorded with an NIR PMT (R5509-73, Hamamatsu). All the measurement was carried out at room temperature.

3. Results and discussion

Figure 1 shows the photograph and in-line transmittance curves of the 5-at.% Yb:CaF_2 transparent ceramics with the thickness of 3.5 mm. Transmittance of pure single crystal (1 mm in thickness) was also presented for comparison. It can be clearly seen that the obtained sample is colorless and transparent, indicated that the sintered ceramics by HP method have good optical quality. The transmittance curves of the 5-at.% Yb:CaF_2 transparent ceramics ranging from 200 nm to 1500 nm at room temperature for the width 3.5 mm in thickness is shown in Fig. 1(b). After laser-grade polishing, the in-line transmittance has reached 76.5% and 91.8% at the wavelength of 400 nm and 1200 nm, respectively, which is very close to the theoretical transmittance of CaF_2 at the wavelength of 1200 nm (about 94%). Transmittance of 2-at.% Yb:CaF_2 ceramics (3.82 mm in thickness) fabricated by HIP method in the wavelength of 400 nm and 1200 nm was estimated to be 82% and 93.3% in Ref. [31]. Although the transmittance of our ceramics is lower than the samples fabricated by HIP method, hot-pressing method is still an efficient and simple way to obtain high optical quality of Yb^{3+} ions-doped CaF_2 laser ceramics. It can be also seen from Fig. 1(b) that the transmittance of the pure CaF_2 single crystal in the wavelength of 400 nm and 1200 nm was 92.8% and 93.7%, respectively. The transmittances of ceramics obtained by HP and HIP methods were both lower than those of single crystal due to the residual pores and grain boundary in the ceramics. The optical quality of CaF_2 transparent ceramics still to be improved by adjusting powders properties and sintering process.

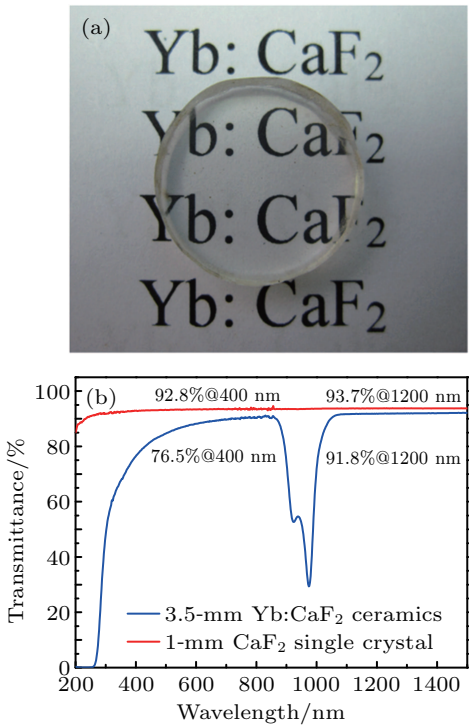


Fig. 1. The (a) photograph and (b) in-line transmittance of 5-at.% Yb:CaF_2 transparent cermics (16 mm in diameter, 3.5 mm in thickness).

The absorption coefficient of the Yb:CaF_2 transparent ceramics at room temperature is shown in Fig. 2(a). We can see that there are two absorption peaks located at 976 nm and 924 nm, corresponding to the transitions between $^2F_{7/2}$ and $^2F_{5/2}$. The absorption coefficients of the 5-at.% Yb:CaF_2 transparent ceramics 924 nm and 976 nm are about 2.43 cm^{-1} and 4.6 cm^{-1}. The ceramic exhibited a broad absorption line around 976 nm with full width at half maximum (FWHM) of about 31 nm, making it appropriate for direct pumping through a high-power InGaAs laser diode (LD). This will facilitate the miniaturization and high efficiency of solid state lasers.[37,38]

Figure 2(b) shows the fluorescence spectrum of the Yb:CaF_2 transparent ceramics with xenon lamp as the excitation source. According to the absorption spectra, the re-absorption effect is very serious at the wavelength between 900 nm to 1100 nm, so the excited wavelength was settled at 896 nm. The strongest emission peak (979 nm) corresponds to the zero-phonon line of Yb^{3+} ion. The main emission peaks located at 1011 nm and 1027 nm possess a wide bandwidth, which is beneficial for the generation of ultrashort laser pulses.

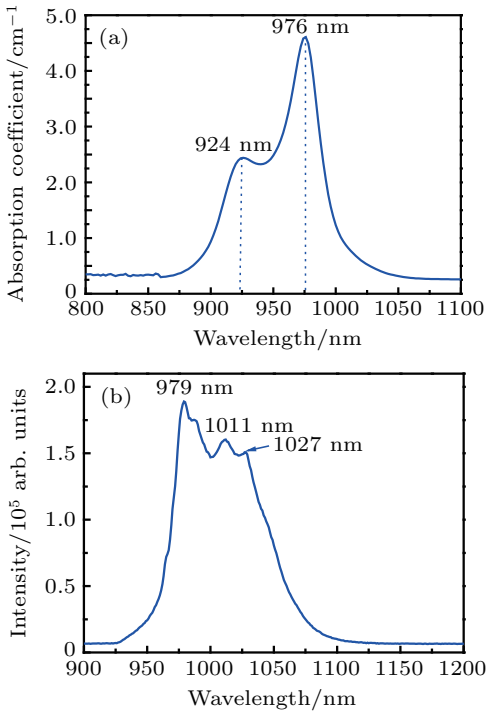


Fig. 2. Absorption spectrum (a) and emission spectrum (b) of the Yb:CaF_2 ceramics.

The experimental arrangement of tunable Yb:CaF_2 ceramic laser is shown schematically in Fig. 3. The pump source was a fiber-coupled 976-nm LD with core diameter of 105 μm and numerical aperture of 0.22. The 976-nm pump laser was coupled into the Yb:CaF_2 ceramic through a 1 : 2 focusing system. The Yb:CaF_2 ceramic was cut to a size of 3 mm×3 mm×3 mm, and two parallel end surfaces were uncoated and polished. The ceramic was wrapped in indium foil and embedded in a water-cooled copper block at 13 °C to ensure efficient heat dissipation. A three-mirrors V-type cavity was designed to achieve the tuning operation. The plane input mirror, M1, was high transmission coated around 980 nm and high reflection coated at 1030 nm–1080 nm. The concave mirror, M2, with a radius of curvature of 200 mm, was also high reflection coated at 1030 nm–1080 nm. The output coupler, M3, had a transmittance of 2% at 1030 nm–1090 nm. A birefringent filter (BF) was inserted at Brewster's angle between M2 and M3.

By rotating the angle of the BF in its plane, a broad tuning range of 59.9 nm, which covers wavelengths from 1019.6 nm to 1079.5 nm, at an absorbed pump power of 4.5 W was obtained. The average output powers *versus* wavelengths is presented in Fig. 4. Tuning to wavelengths below 1020 nm may be limited by the coating on the output mirror. In addition, the tuning curve is very broad and smooth, indicating that the ceramic was a suitable material to generate ultrashort laser pulses.

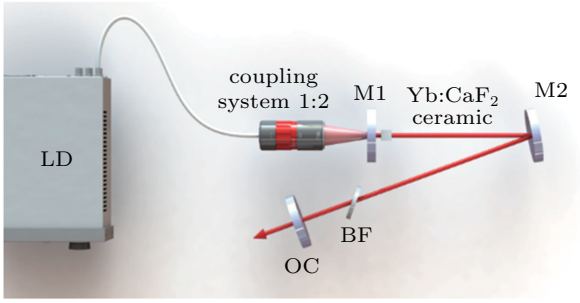


Fig. 3. Experimental setup of the Yb:CaF_2 ceramic tunable laser.

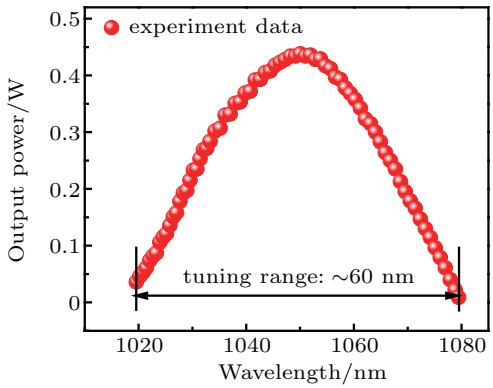


Fig. 4. Wavelength tuning curve of the Yb:CaF_2 ceramic.

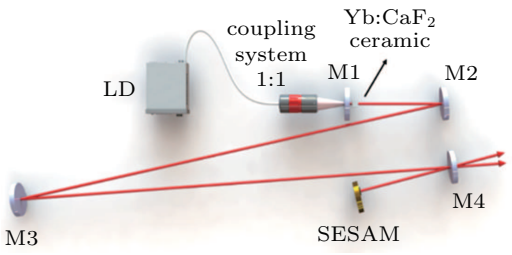


Fig. 5. Experimental setup of the CWML Yb:CaF_2 ceramic laser.

The setup of passively mode locked Yb:CaF_2 ceramic laser is presented in Fig. 5. The pump source, Yb:CaF_2 ceramic, and water-cooling setup were the same as those in the above experiment. The focusing system was changed to 1 : 1 to compress the pump laser. By using the ABCD-matrix method, the calculated oscillating spot radiuses in the crystal and SESAM were 55 μm and 50 μm, respectively. The curved mirrors, M3 and M4, had a radius of curvature of 800 and 200 mm, respectively. M3 was high reflection coated at 1030 nm–1080 nm, and the output coupler, M4, had a transmittance of 1% at 1030 nm–1090 nm. We used an SESAM at

the end of the cavity to generate and sustain mode-locked operation. The parameters of the SESAM were as follows: laser wavelength of 1064 nm, modulation depth of 1.2%, and relaxation time constant of 1 ps. The total length of the laser cavity was approximately 2.73 m.

The continuous-wave mode-locked (CWML) operation was successfully obtained after carefully adjusting the position of the SESAM and laser cavity. A plot of passively mode-locked average output power versus the absorbed pump power is shown in Fig. 6. The threshold absorbed pump power was measured to be 486 mW and the output power was found to be monotonically increased with the absorbed pump power. Under the absorbed pump power of 4.25 W, the maximum mode-locked average output power of 152 mW was obtained at the central wavelength of 1048.5 nm. The low output power is mainly caused by the nonlinear loss in the SESAM.

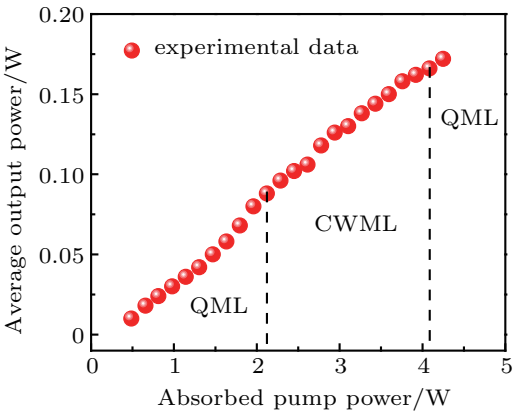


Fig. 6. Average output power *versus* absorbed pump power.

The mode-locked laser pulse signal was recorded by a fast InGaAs photodetector with a rise time of less than 175 ps and was displayed on a digital oscilloscope (Tektronix, DPO 4104, bandwidth 1 GHz). Figure 7 shows the recorded mode-locked pulse trains measured over two different time ranges. By using a spectrum analyzer (Rohde & Schwarz FSC 3), the radio-frequency (RF) spectrum was measured.

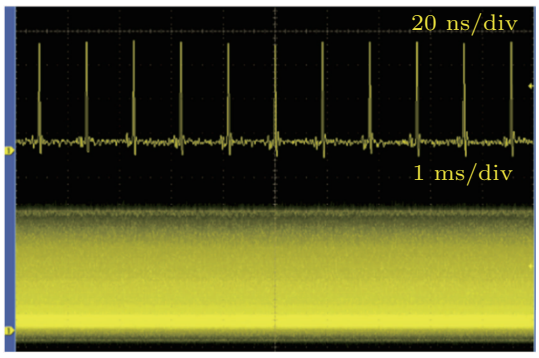


Fig. 7. Pulse trains on time scales of 20 ns/div and 1 ms/div.

As shown in Fig. 8, the pulse repetition rate was 54.94 MHz, which corresponds to a cavity length of 2.73 m, the signal-to-noise ratio of 30 dB, indicating that the mode-locked laser was stable and could be maintained for several hours.

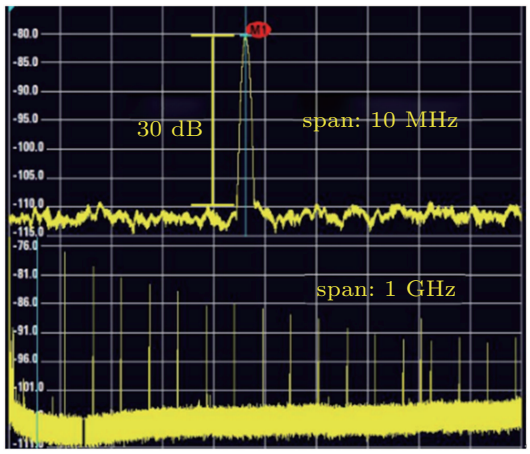


Fig. 8. RF spectrum recorded on the time spans of 10 MHz and 1 GHz.

The autocorrelation trace of the pulses shown in Fig. 9(a) was recorded by a commercial autocorrelator (APE, Pulse Check 150). Assuming a sech^2 shape, the minimum pulse duration of the mode-locked pulses was 575 fs. Figure 9(b) shows the mode-locked spectrum centered at 1048.5 nm with a full width at half maximum (FWHM) of 3.9 nm measured by an optical spectrum analyzer (Avaspec-3648-USB2). The corresponding time-bandwidth product is about 0.612, which is larger than the Fourier transform limit value of 0.315 for the sech^2-shaped pulses. Thus, we believe that a shorter pulse duration can be expected with dispersion compensation and an optimized laser cavity.

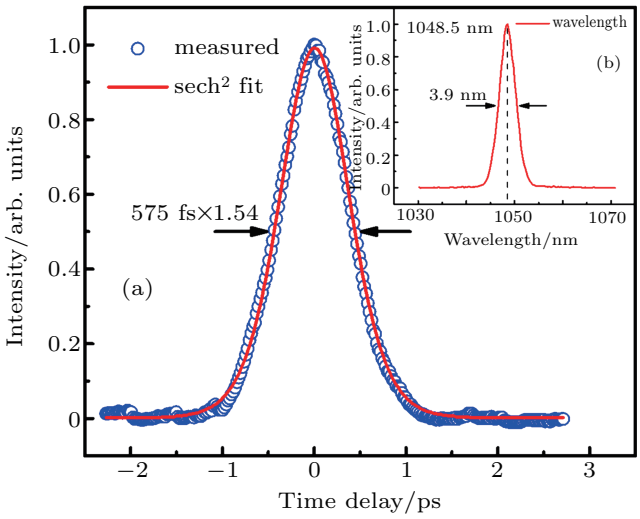


Fig. 9. Autocorrelation trace (a) and mode-locked spectrum (b) of the mode-locked laser.

Figures 10(a) and 10(b) present the beam quality and spatial beam profile of the passively mode-locked laser. The beam qualities of $M_x^2 = 1.134$ and $M_y^2 = 1.078$ show that the laser was operating under a nearly TEM_{00} Gaussian mode.

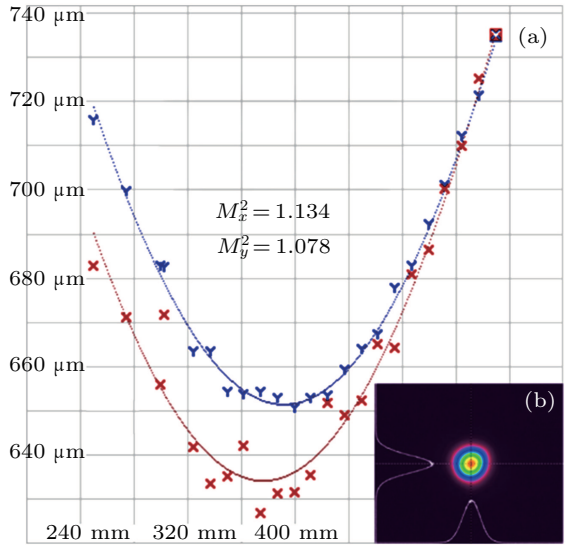


Fig. 10. Beam quality (a) and spatial beam profile (b) of the mode-locked laser.

4. Conclusion

In conclusion, a tunable laser and a passively mode-locked oscillator on a Yb:CaF_2 ceramic were demonstrated for the first time. A broad tuning range of 60 nm over the wavelength range of 1019 nm–1079 nm was observed. In addition, the passively mode-locked laser emitted stable 575-fs mode-locked pulses at a repetition rate of 55 MHz at 1048.5 nm. The experiment demonstrates that the Yb:CaF_2 ceramic is a promising gain medium for ultrashort pulse laser operation. By introducing dispersion compensation, it is anticipated that shorter pulse durations could be obtained.

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