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Picosecond laser oscillator with a cavity design for stable CW mode-locking operation

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ABSTRACT

A detailed design of a picosecond laser oscillator is made by using optical resonance theory and semiconductor saturable absorber mirror continuous wave mode-locked technology. Mode parameters in the optical resonance including beam sizes on the laser crystal and mode locker are calculated. By theoretical calculations, 3.7 W output power is obtained at a pump power of 11 W and the optical to optical efficiency is 34% in the designed model of picosecond laser. Based on the detailed design, an experiment is proceeded and a picosecond laser oscillator of about 3.5 W output power with 10.6 W pump power is fabricated. The optical to optical efficiency of the laser is 33%, the pulse duration is about 20 ps, and the repetition rate is about 80.3 MHz. The oscillator presents long-term stability in the experiment.

1. Introduction

All-solid-state picosecond laser has been widely applied in many fields, such as high-precision micro-machining, laser display, and laser direct imaging in the printed circuit industry, due to its advantages of high peak power, high beam quality, and short pulse duration. By triple-frequency conversion of 1064 nm picosecond laser, 355 nm picosecond laser can be generated, and then picosecond laser with 177.3 nm wavelength can be obtained by pumping picosecond laser with 355 nm wavelength into $KBe_2BO_3F_2$ (KBBF) crystal [1]. The new laser source with 177.3 nm wavelength has been applied to generation of vacuum ultraviolet laser-based angle-resolved photoemission spectrometer, which has helped us to directly observe the superconducting state [2]. All-solid-state picosecond laser oscillator and amplifier have been extensively investigated in lots of papers [3–9]. Similar to other types of lasers, the tendency of development of picosecond laser is also high average power, high energy, high beam quality, and high stability. Amplifying the picosecond laser seed source is an important way to obtain high average power and high energy picosecond laser. For example, repetition rate of several kilohertz picosecond laser with high energy pulses of 2.3 and 16 mJ has been obtained by amplifying picosecond pulse selected from high repetition rate picosecond laser seed source by pulse selector [3,4], and high average power picosecond laser of 287 W has been obtained by amplifying high repetition rate picosecond laser seed [8]. Therefore, not only the amplification technology, but also the laser seed source is very important in the high average power and high energy laser system.

To ensure high beam quality and high stability for a picosecond laser seed, the important thing is to realize stable operation of the optical resonance and continuous wave mode lacking (CML). A nonlinear optical device, semiconductor saturable absorber mirror (SESAM), was utilized to realize CML. It is adopted in mode-locked laser extensively due to its excellent properties of simpleness and stability [10,11]. The aim of this paper is to use the results of a detailed design to guide the experimental study of creating a high beam quality and high stability picosecond laser seed source. Beam sizes on the laser crystal and mode locker in the optical resonance are calculated by optical resonance theory. Appropriate parameters on the SESAM are adopted to ensure the realization of CML and to avoid damage on the SESAM.

2. Theoretical calculations and design

The thermal lens effect of the laser crystal is an important factor that should be considered in the design of laser optical resonance. Laser crystal absorbing pump energy is often regarded as a lens and then, using *ABCD* matrix and self-consistent condition, the mode parameters in the resonance can be obtained. When a laser beam propagates in an optical resonance, the

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transform matrix of a round trip is $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$, in which thermal focal length is included. According to the *ABCD* law, the self-consistent condition is

$$q_1 = \frac{Aq_1 + B}{Cq_1 + D} \tag{1}$$

where q_1 is q parameter of Gaussian beam. When other mode parameters in the resonance are known numbers, the curvature radius of wave front R_1 and beam radius w_1 at any place in the resonance can be deduced by

$$R_1 = \frac{2B}{D-A} \tag{2a}$$

$$w_1^2 = \frac{\lambda_0 B}{\pi\sqrt{1-(A+D)^2/4}} \tag{2b}$$

where λ_0 is the laser wavelength.

Beam sizes on the laser crystal and mode locker should be considered firstly when optical resonance is designed. They are important parameters because the former relate to mode matching between resonance mode and pump laser mode, affecting the output power, conversion efficiency, and beam quality. The later determines if CML can be realized whereas the mode locker avoids damage. Q-switched mode locking (QML) appears as single pulse energy E_p is smaller than critical single pulse energy $E_{p,c}$ in the oscillator and only when $E_p > E_{p,c}$ CML can be achieved. The critical pulse energy is [11]

$$E_{p,c} = \sqrt{E_{sat,L} E_{sat,A} \Delta R} = \sqrt{F_{sat,L} F_{sat,A} A_{eff,L} A_{eff,A} \Delta R} \tag{3}$$

where $F_{sat,L}$ and $F_{sat,A}$ are saturation fluences of laser crystal and absorber, $A_{eff,L}$ and $A_{eff,A}$ are their effective areas, respectively, and ΔR is the modulation depth.

Configuration of designed laser oscillator is shown in Fig. 1, where M1 is 90% reflection output coupler, M2 and M3 are plane reflection mirrors, and M4 is a concave mirror with a radius of curvature of 300 mm. M4 can cause astigmatism, causing decrease of beam quality and instability of CML. Thus, to decrease the effect of astigmatism on beam quality and CML, the angle θ was designed to be $\theta < 8°$. Laser beam is focused on the SESAM by M4 to ensure enough fluence. Distance between M2 and crystal is 22 mm, L1 is 310 mm, and L4 is 170 mm. Geometrical length of the optical resonance is about 1.86 m, the length of crystal Nd:YVO_4 is 15 mm, and thus the repetition rate is about 80 MHz.

Output power of the oscillator can be calculated by [12]:

$$P_{out} = A_{eff,L}\left(\frac{1-R}{1+R}\right)F_{sat,L}\left[\frac{2g_0 l}{L-\ln\ R} - 1\right] \tag{4}$$

where R is reflectivity of the output coupler, g_0 is small-signal gain coefficient, l is length of the crystal, and L is all of the losses in the oscillator. The output power is denoted as solid line shown in Fig. 2, where the solid line denotes the calculation results and the square line the experimental results discussed later. The figure indicates the laser starts to be generated with pump power of 1.5 W, and 3.7 W output power is obtained with a pump power of 11 W. Effects of thermal focal length on beam radii of resonance mode on laser crystal and SESAM were investigated as shown in Fig. 3. It is known from the figure that beam radii on laser crystal and SESAM are about 0.44 and 0.056 mm, respectively, when thermal focal length f=300 mm. We made an experiment to measure the thermal focal length. In this experiment, we used a symmetric cavity with two plane mirrors and a 0.3 at.% doped $3\times3\times15\ mm^3$ Nd:YVO_4 crystal located in the middle of the cavity. The crystal was put in Cu heat sink with water cooling. Fiber coupled diode laser with core diameter of 400 μm, NA=0.22, and wavelength of 808 nm was used as the pump source. Pump laser from the fiber was coupled into Nd:YVO_4 crystal with end pumping and cross section area ratio of 2:1. When distance between the mirror and the crystal is 600 mm, the

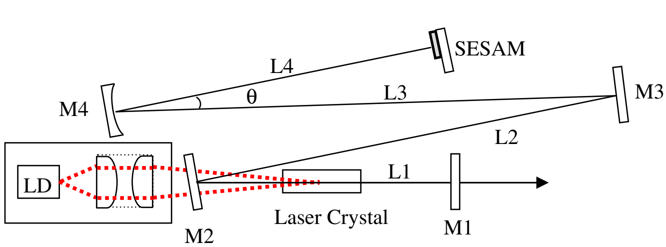

Fig. 1. Configuration of the laser oscillator. M1 is 90% reflection output coupler, M2 and M3 are plane reflection mirrors, and M4 is a concave mirror with radius of curvature of 300 mm. $\theta < 8°$. Distance between M2 and crystal is 22 mm, L1 is 310 mm, and L4 is 170 mm. Nd:YVO_4 is a laser crystal.

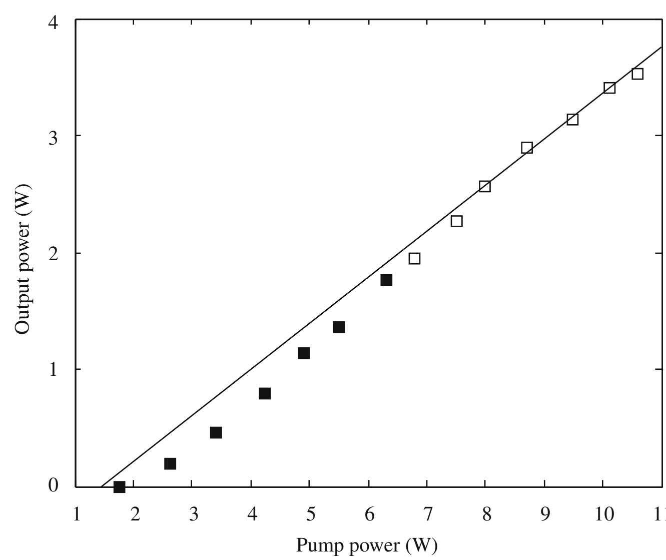

Fig. 2. Output power of picosecond laser oscillator. Solid line denotes theoretical results and square line experimental results.

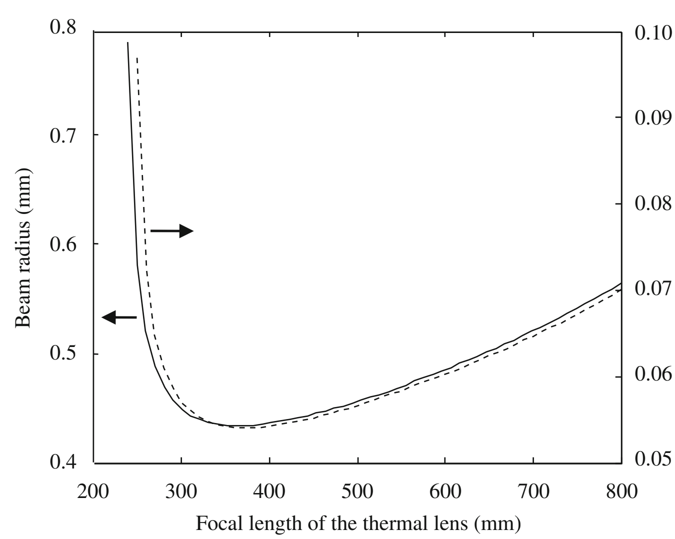

Fig. 3. Beam radii on the laser crystal (solid line) and SESAM (dashed line) versus thermal focal length.