1. INTRODUCTION

Nd:YAG crystal is one of the most prevalent materials for diode-pumped high power lasers because of its excellent optical and mechanical properties. Generally, Nd:YAG lasers operate at the most commonly used wavelengths of 1064, 1319, and 946 nm [1–7]. In recent years there has been a great interest in 1123-nm Nd:YAG laser due to its wide applications.

1123-nm Nd:YAG laser can be used as the pump source for thulium upconversion fiber lasers to generate blue lasers [8]. It can be used for frequency doubling to generate 561 nm yellow-green light [9], which has potential applications in the regions of display, illumination, molecular biology and chemistry. Moore et al. demonstrated a continuous wave (CW) Nd:YAG laser at 1123 nm with 1.7 W output power [10]. Chen et al. and Guo et al. reported the realizations of passively and actively \(Q\)-switched 1123 nm Nd:YAG lasers, respectively [11–13]. And Zhang et al. obtained CW 1123 nm lasers from ceramic [14] and composite [15] Nd:YAG rods. Recently, Li et al. demonstrated a high power and high beam quality diode-side-pumped 1123 nm laser [16]. In order to make further investigation of 1123 nm laser properties, one must consider thermal effects that will impact optical performance. Besides thermal lensing effect, thermally induced birefringence is one of the most serious thermal problems for isotropic crystals such as Nd:YAG. Bifocusing, induced by birefringence [17], makes the pumped laser rod behave as a thermally induced lens with two focal lengths relating to radial and tangential directions, respectively. This leads to a deterioration of the beam quality and severe problems with regard to resonator stability. The ratio of tangential focal length to radial focal length is defined to indicate bifocusing strength of Nd:YAG [18]. And bifocusing strength under 1123 nm lasing condition has never been reported. Several methods for determining the focal length of thermal lens in diode pumped laser crystal have been presented [19–26], but most of them did not determine both radial and tangential focal lengths. According to [24], by finding both the radial and tangential critical pump powers at which thermally induced focal length will cause the laser cavity to be unstable, respectively, the corresponding radial and tangential focal lengths can be determined.

In this paper, the thermal focal lengths of the diode side-pumped Nd:YAG rod operating at 1123 nm both in radial and tangential directions are measured for the first time. The results reveal that the thermal focal lengths of two directions ratio which represents the bifocusing strength is 1.17 under 1123 nm lasing condition, and is 1.10 under 1064 nm condition. And 1123-nm thermal focal lengths are shorter than those of 1064-nm laser due to higher quantum defect. Laser output performances of 1123 nm in terms of stability, output power and beam quality influenced by pump power at different cavity lengths are also discussed with a convex-piano cavity.
Output power, W

\[ \lambda = 1123 \text{ nm} \]

![Graph showing the dependence of output power on incident power with different cavity lengths at 1123 nm. The arrows indicate an example of the location of critical input power.](image)

**Fig. 1.** The dependence of output power on incident power with different cavity lengths at 1123 nm. The arrows indicate an example of the location of critical input power.

### 2. THERMAL FOCAL LENGTHS

The simple setup (plano-plano cavity) of CW laser was utilized to measure the focal lengths of thermal lens. The coatings of the cavity mirrors were designed for the oscillation of 1123 nm and the suppression of other lines. The rear mirror (RM) was coated for high-reflection (HR) at 1060–1180 nm \((R > 99.8\%)\). The output coupler (OC) was a flat mirror that was coated for partial-reflection at 1123 nm \((R = 98\%)\) and high-transmission at 1064 and 1319 nm \((T > 95\%)\). The laser head (Northrop Grumman, USA) consisted of an Nd:YAG rod \((1.0 \text{ at } %, 3 \times 63 \text{ mm}^2)\), a cooling sleeve, a diffusive optical pump cavity and three diode array modules operating at 808 nm. The Nd:YAG laser head was water cooled with the water temperature of 20°C.

To begin with, we measured the output optical spectra from this laser configuration with a wide-range optical spectrum analyze (Yokogawa AQ 6315A, 350–2000 nm). And only 1123 nm line was observed because the output coupler had HT coatings at 1064 and 1319 nm, laser oscillations at these two wavelengths were not able to occur. The output coupler could have higher transmissions at 1112 nm \((T = 5\%)\) and 1116 nm \((T = 4\%)\) than at 1123 nm \((T = 2\%)\), so the 1112-nm and 1116-nm components were not able to oscillate.

In order to make sure that the laser was running in the TEM\(_{00}\) mode without high-order modes, the optimization of the cavity was done near the pump threshold. And while the pump power was increased, optimizing average power was not allowed. The laser powers were measured with an EPM 2000 power meter (Coherent Inc.). Output average power of 1123-nm laser at different cavity lengths were shown in Fig. 1. As a comparison, thermal focal lengths of 1064-nm laser were also studied with the same cavity except that another OC (plane-plane and \(T = 13\%\) at 1064 nm) was employed. Because of the limited pump power in our experiment, unstable operation only occurred in long cavities. In our experiment, they were at least about 350 mm for 1123 nm and 500 mm for 1064 nm, respectively. Figure 1 showed that in long cavities, output power fluctuated with pump power and there were two troughs in every curve except that a few cavity lengths had three troughs. For the curves with three troughs case, we attributed the slight increase of output power after the third trough to multimode generations induced by more serious thermal lensing effect at higher input power. And they made no effect to thermal focal lengths measurement. Critical pump powers are determined based on unified criterion: the first trough stands for the critical radial pump power and the second trough stands for critical tangential pump power [24]. From the standard ABCD matrix approach, the focal length of critical thermal lens that corresponds to the critical pump power is given by [28]:

\[
\begin{align*}
 \frac{1}{f_{th}} &= \frac{1}{d_2^*} - \frac{1}{r_1 - d_1^*} \\
 d_2^* &= d_2 + \frac{l}{2n_0} \\
 d_1^* &= d_1 + \frac{l}{2n_0},
\end{align*}
\]

where \(d_1\) and \(d_2\) are the distances from the two ends of the laser rod to the RM and the OC, respectively, \(l\) is the length of the laser crystal, \(r_1\) is the radius of curvature of the rear mirror, \(n_0\) is the refractive index of the laser crystal. By finding the critical pump powers of different cavity lengths, we obtained the effective thermal focal lengths using Eq. (1). The theory predicts that the thermal focal lengths vary inversely with pump power and for side-pumped configuration can be expressed by [18]:

\[
\begin{align*}
 f_{th, \phi} &= \frac{K_{r, \phi}}{P_{in}} \\
 K_{r, \phi} &= \frac{\pi K_r r_0^2 (1 + \frac{3}{2} \frac{dn}{dT} + n_0^3 \alpha C_r, \phi + \frac{a r_0 (n_0 - 1)}{l})}{\eta_h},
\end{align*}
\]

where the subscripts \((r\text{ and } \phi)\) represent radial and tangential direction, respectively, \(K_r\) is the thermal conductivity, \(r_0\) is the radius of the active medium in the unit of mm, \(\eta_h\) is the fractional thermal loading, \(P_{in}\) is the pump power in the unit of watt (W), \(n_0\) is the...