High beam quality 400W practical all-solid-state laser for laser beam texture

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ABSTRACT

A high-average-power and high-beam-quality diode-side-pumped solid-state laser was designed carefully for laser beam texture. By using of low concentration Nd:YAG crystals with thermally near-unstable resonator design and two-rod birefringence compensation technology, the 1064 nm cw output power of 400 W at pump power of 1170 W was achieved with the beam quality factor $M^2 \sim 15$, corresponding to an optical-to-optical conversion efficiency of 34.2%.

Keywords: all-solid-state laser, Nd:YAG laser, laser beam texture

1. INTRODUCTION

The strict demands of consumers on the cold rolled steel products dictate controlled topographical surface characteristics regarding formability and appearance. The key point to satisfy these characteristics is the production of sheet metal with a predefined texture, which is imparted to the surface by the use of textured rolls in both tandem and skin pass mills. For example, The automotive industry world-wide use textured cold rolled steel and aluminium sheet/strip in order to aid formability, through the retention of a lubricant film and to improve the appearance of the painted product [1-2]. Similarly, stainless steel strip used for architectural roofing/cladding applications may employ a defined surface texture as a means to minimize glare from reflected light and mask minor imperfections resulting from the rolling process.

Traditionally, specific roll textures were produced using cross-grinding and shot blasting, however, these have largely been supplanted over the last 20 years by electrical discharge texturing (EDT) and laser beam texturing (LBT) [3-4]. Such processes allow rolls to be produced with greater consistency/repeatability with specified roughness/texture parameters. Average arithmetic roughness (Ra) and peak count in peaks per cm (Pc) are two well-known parameters to define such a surface. High peak counts with constrained average surface roughness are the essentials for outer auto body panels [5]. However, EDT can't control accurately the shape and the depth of the

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craters, which determine the surface roughness of the rolls. By laser roughing, not only topography and roughness of the roll surface can be controlled accurately, but also the roll surface can be strengthened and toughened. Therefore, in production, the performance of laser roughed rolls is superior to EDT rolls and the rolled textured sheet or strip has better quality.

At the start, CO_2 laser was used as the laser source of roll textures. However, CO_2 laser ceaselessly lets off waste gas, and its volume is huge. In 1989, flash lamp pumped Nd: YAG laser was successfully used for roll textures, which provide possibility for miniaturization and minimizing cost of the laser rough equipment. Therefore, flash lamp pumped Nd: YAG laser speed up the practicality of the new means for specific roll textures. Entering into 21 century, the cost of laser diode (LD) becomes cheaper, and it's inevitable that the LD pumped Nd:YAG laser replaces the flash lamp pumped Nd:YAG laser, with the advantage such as high efficiency, long life, good beam quality and low running cost.

In this paper, a high-average-power and high-beam-quality diode-side-pumped solid-state laser was designed carefully for laser beam texture. In order to achieve high power and high beam quality simultaneously, the following techniques have been employed: firstly, using a thermal near-unstable resonator design and two-rod birefringence compensation technique to acquire large fundamental mode size in Nd:YAG rod so that the laser line has a higher intracavity power and good beam quality as well; secondly, the Nd:YAG crystals is designed to operate in a low doping concentration to ensure a uniform gain distribution; and finally, by using of birefringence compensation technology, the two fundamentals, the beam quality is improved more excellently. The 1064 nm cw output power of 400 W at pump power of 1170 W was achieved with the beam quality factor $M^2 \sim 15$, corresponding to an optical-to-optical conversion efficiency of 34.2%.

2. THEORY AND EXPERIMENT SETUP

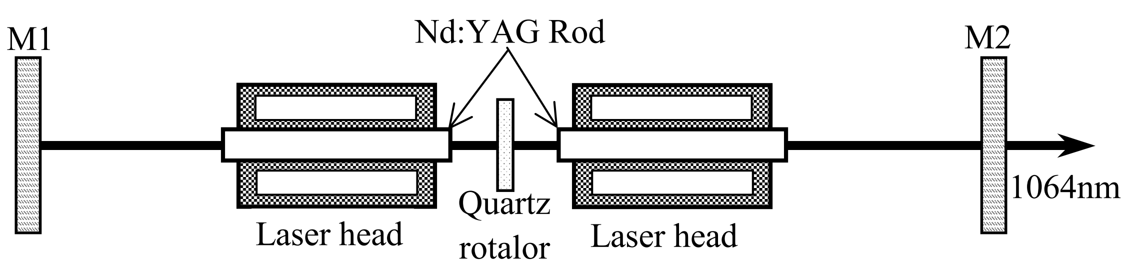

Fig.1. Schematic of the 1064 nm cw laser: M1, flat high reflector at 1064 nm; M2, flat partial output coupler at 1064 nm.

Figure 1 shows a schematic of the experimental setup. Two identical Nd: YAG rods with a quartz 90° rotator between them are placed in the symmetrical flat-flat resonator. The quartz rotator produces a 90° rotation of every component of the electric field of the laser beam. The fundamental mode sizes in two Nd:YAG rods are the same, which enhances the efficient birefringence compensation. The total length of the flat-flat cavity is about 1200 mm, and the transmittance of the partial output coupler is 35 %.

The optical pumping process in a solid-state laser material is associated with the generation of heat, so a uniform pumping is important for a laser head. Otherwise, nonuniform pumping will produce temperature gradients in the rods, and lead to thermal lensing and thermal stress-induced birefringence, which may induce stress fracture [6]. Moreover, the transmitted and aberrant wave front from the rod causes diffraction loss in the resonator. Therefore, the power output with nonuniform pumping is limited. In addition, to achieve effective bifocusing compensation, thermal-lensing uniformity within the cross section of the rod is also required.

The laser head consists of five dual-line diode continuous wave (cw) arrays and an Nd: YAG rod with a diameter of 5 mm and a length of 140 mm, and is surrounded by a flow tube and reflectors. The low Nd doping of 0.6 % in Nd: YAG is used to decrease thermal absorption. Five diode arrays are located evenly around the rod to produce a uniform pump-light distribution within the rod's cross-section. The combination of the uniform pump and the low thermal absorption is favorable for the production of a uniform gain distribution. Each array contains 60 diode bars with a wavelength of 808nm, power output of 40 W. To match Nd: YAG absorption band at 808 nm, a given cooling temperature of the diode bars are selected carefully to obtain a low spectral dispersion. The reflectors can reflect the pump radiations back to the Nd: YAG rod, which increases the absorption of pump light and the optical-to-optical conversion efficiency. In addition, by selecting an Nd: YAG rod with a diameter of 5 mm, the high mode laser is restrained while maintaining a high beam quality.

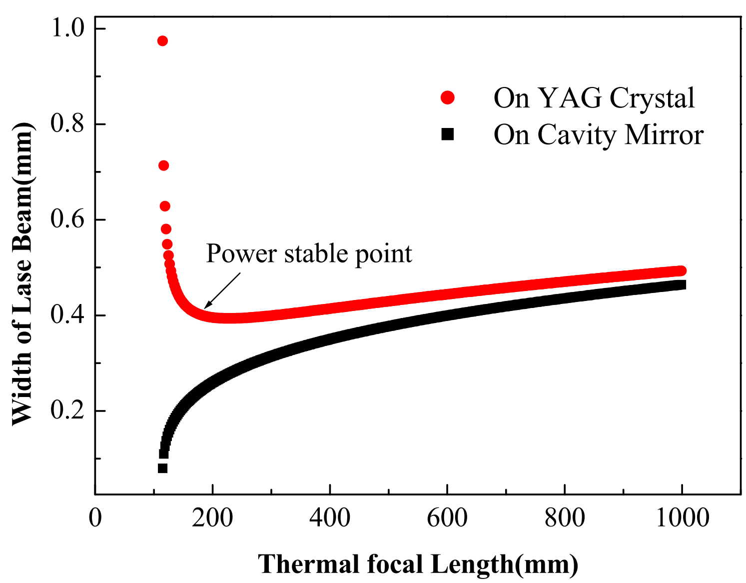

Fig.2. The beam radius of fundamental mode on the Nd:YAG rod and the cavity mirror at different thermal focal length

Thermally induced spatial variation of the refractive index in the high-power-pumped Nd: YAG causes the rod to act as a lens with a variable focal length, which influences the zones of stable laser operation. Thermally induced stresses in the isotropic laser rod create birefringence, and the cavity mode is split into two components that are projected along the radial (r) and the tangential (φ) axes. The stable laser can be achieved only in the zones for the r- and the φ-polarization modes overlapped. As shown in Figure 1, two identical Nd: YAG rods with a quartz 90° rotator between them are placed in the symmetrical flat-flat resonator. The quartz rotator produces a 90° rotation of every component of the electric field of the laser beam. Part of the mode that is radially polarized in the first rod is tangentially polarized in the second rod, and vice versa. Since each part of the beam passes through nearly identical regions of the two rods, the phase difference between the two parts will be removed. Therefore, the stable zones of different polarization modes overlap each other, which consequently can improve the power output. Taking the thermal lensing into account, the symmetrical flat-flat cavity acts as a thermally-near-unstable resonator, which can output beams with higher power and better beam quality [7-8].

On the basis of accurate measurement of the thermal focal length, by using the standard ABCD ray propagation matrix as an auxiliary tool [9-10], the beam radius of fundamental mode on the Nd:YAG rod and the cavity mirror was computer simulated as a function of the thermal lensing focal length of the diode-side-pumped Nd:YAG rod. The conversion from the pump power to the thermal lensing focal length of the rod is experimentally confirmed with the unstable-resonator method [11], and then a thermally-near-unstable resonator was proposed.

As shown in fig.2, the dependence of the fundamental mode radius ω_0 at the center of the rods and the cavity mirror on the maximal pump power is illustrated, when the cavity optical path is 1200 mm. When the pump power is low, the thermal effects are slight so as to the 1064 nm beam quality are good. With the pump power increasing, the thermal effects become evident, the laser operates close to the middle of the stable region and the fundamental mode radius becomes smaller at the gain media, so the beam quality becomes worse and the M^2 reaches the highest value at the central pump power. Further increasing the pump power, the fundamental mode radius becomes larger and the laser operates close to the unstable region, and the cavity operates as a thermally near-unstable resonator. When the laser works at maximal pump power, which is power stable point, though the thermal effects become serious, the beam quality factors M^2 gradually drop to the lowest value.

Fig.2 can help us to understand why the beam quality factors show these behaviors as above, when such a flat-flat cavity operates near the unstable region, the laser beam size on the Nd:YAG rod is larger than that on the cavity mirror. where the fundamental mode size at the gain media is large so as to the diffraction loss of high order transverse modes are higher than that in a stable resonator such as a concave-concave cavity or a flat-concave cavity. Therefore, gain medium acts as a mode limiter at maximal pump power, which restrains resonance of high-order modes and guarantees not only high output power but also high beam quality, and so the high beam quality can be expected. In summary, the beam quality factors M^2 values are sensitive to the fundamental mode size in the gain media and the stable region position of the laser operation as well as the gain guiding. Finally, we experimentally gained 400W output power at 1064nm with high beam quality by an LD side-pumped Nd:YAG laser with this configuration. As we have expected, the laser beam quality becomes better at the right border of the stable region near the unstable region.

3 EXPERIMENTAL RESULTS

Figure 3 shows a plot of power output versus the pump power. When the diode pump power is 1170 W at a driving current of 24.5 A, the 1064nm cw power output is up to 400 W, corresponding to an optical-to-optical conversion efficiency of 34.1 % and an electrical-to-optical conversion efficiency of 27.2 %. The degree of linearity of the power output as a function of pump power is up to 99.6 %. At the power output of 400 W, the instability of the laser operation remains less than 1.5 % in two hours.

By using a scanning-slit method, the waist width of the output beam is measured to be 2 mm and the divergence is 10 mrad. The beam quality factors M^2 values are equal to

$$M^2 = \pi \frac{\omega\theta}{2\lambda} \tag{1}$$

For the above equations, ω is the waist radius of the output beam, θ is the divergence of the output beam, and λ is the wavelength of the output beam which is 1064nm. Then the corresponding to the beam quality factor M^2 being estimated at about 15.

According to the demand of the laser roughing, an acousto-optic modulator was placed in the resonator，and then the wave figure was modulated to satisfy practical application. Now this laser has been assembled as the light source of laser beam texture equipment, and textured cold rolls in production. Client feeds back good information that the stability and the maneuverability of the texture equipment are perfect, and the performance of laser roughed rolls is superior.

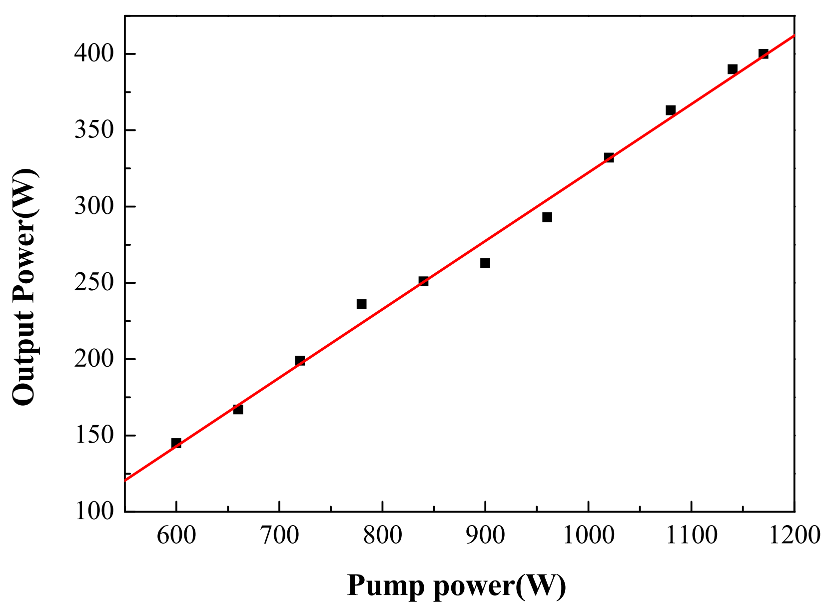

Fig.3. The plot of power output versus the pump power.

4. CONCLUSION

In conclusion, by using of low concentration Nd:YAG crystals and the thermally near-unstable resonator design with two-rod birefringence compensation in a flat-flat cavity, a high-average-power and high-beam-quality diode-side-pumped solid-state laser was designed carefully for laser beam texture. We have demonstrated that the beam quality is significantly improved for a high average power diode-side-pumped Nd:YAG rod laser. The 1064 nm cw output power of 400 W at pump power of 1170 W was achieved, corresponding to an optical-to-optical conversion efficiency of 34.2%, and the beam quality factor M^2 is 15 at the average output power of 400 W.

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