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Efficient delivery of 60 J pulse energy of long pulse Nd:YAG laser through 200 μm core diameter optical fibre

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Abstract. Most of today's industrial Nd:YAG lasers use fibre-optic beam delivery. In such lasers, fibre core diameter is an important consideration in deploying a beam delivery system. Using a smaller core diameter fibre allows higher irradiances at focus position, less degradation of beam quality, and a larger stand-off distance. In this work, we have put efforts to efficiently deliver the laser output of 'ceramic reflector'-based long pulse Nd:YAG laser through a 200 μm core diameter optical fibre and successfully delivered up to 60 J of pulse energy with 90% transmission efficiency, using a GRADIUM (axial gradient) plano-convex lens to sharply focus down the beam on the end face of the optical fibre and fibre end faces have been cleaved to achieve higher surface damage thresholds.

Keywords. Nd:YAG laser; long pulse laser; fibre-optic beam delivery; axial gradient index lens; beam quality.

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1. Introduction

Even today, Nd:YAG lasers have continued to find new applications and to grow in its importance. Lasers in combination with the optical fibre increase the safety, automation and the flexibility of whole industry [1]. In order to enhance the quality and range of material processing applications, it is desirable that the core diameter and numerical aperture (NA) of the optical fibre should be kept as low as possible. The fibre selection for beam delivery depends on laser beam quality. Thus, to satisfy the needs of material processing applications, Nd:YAG lasers with high powers and improved beam quality are being developed [2]. One of the important components of such lasers is the pump chamber and its reflector. There are two common types of reflectors which are used in such cavities: gold-coated elliptical reflector, and ceramic diffuse reflector. Gold-coated elliptical reflectors provide highly directional reflectance and therefore tend to create 'hotspots' in the laser output [3]. Therefore, these systems suffer from poor beam quality, whereas a diffuse reflector is based on diffuse reflection of the flash-lamp light, which averages out pump light and provides uniform pumping, providing better beam quality. In addition to that, care should be taken in choosing a coupling lens. Standard spherical conventional lenses (homogeneous) produce substantial aberrations (primarily spherical) and larger focussed spot sizes. As a result, the geometrical and angular coupling efficiencies are reduced and it becomes difficult to launch high power laser beams through smaller core diameter optical fibres due to coupling of light in the cladding region and hence damage of outer coating and jacket [2]. To overcome this issue, we have used axial gradient index (GRADIUM) lenses. These lenses are well-corrected optical elements, without requiring aspheric surfaces [4]. If z is the distance along the optical axis and n is the refractive index, then axial gradient index can be expressed as

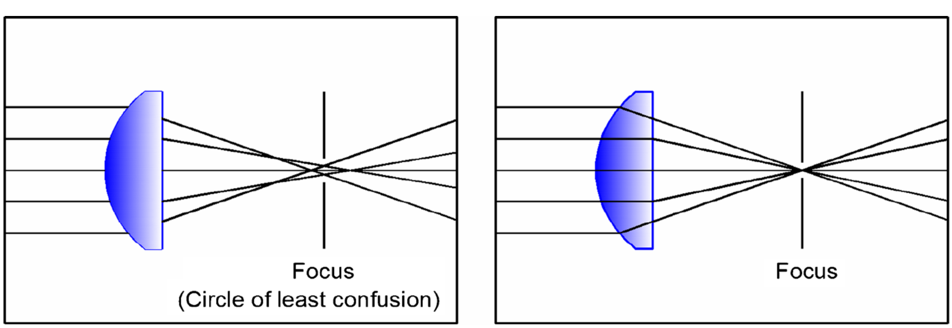
$$n(z) = n_{00} + n_{01}z + n_{02}z^2 + \cdots . \tag{1}$$

Refractive index profile of GRADIUM lens is such that it bends rays while travelling through the lens, resulting in a better focus and smaller spot diameter (figure 1). In this paper, we present utilization of ceramic reflector-based pump chamber and GRADIUM glass optics for efficient beam delivery of high power industrial Nd:YAG laser. Figure 2 shows schematic of focussing and launching of laser beam at the fibre end.

2. Launching conditions

For an optical fibre, step-index profile refers to a refractive index profile characterized by a uniform refractive index within the core, made of glass (silica) and a sharp decrease in refractive index at the core–cladding interface so that the cladding is of a lower refractive index (figure 3a).

Light is guided through the core by the phenomenon of total internal reflection (figure 3b). In order to launch light into the fibre core, the angle between the light ray and the fibre axis can be determined according to the law of refraction and provides the



(a) (b)

Figure 1. Focussing by (**a**) standard spherical lens and (**b**) GRADIUM glass lens.

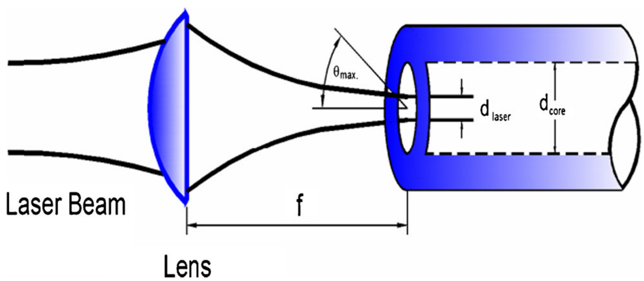


Figure 2. A schematic of focussing and launching of laser light into optical fibre.

largest possible acceptance angle θ_{max}. The sine of the acceptance angle is called the numerical aperture of the fibre [1],

$$\theta_{max} = \sin^{-1}\left(\sqrt{n^2_{core} - n^2_{cladding}}\right), \ \text{NA} = \left(\sqrt{n^2_{core} - n^2_{cladding}}\right).$$

Low coupling losses require that the beam diameter is equal to or smaller than the core diameter (figure 2) and the full angle beam divergence is smaller than $2\theta_{max}$ for the fibre,

$$d_{laser} \leq d_{core} \quad \text{and} \quad \theta_{laser} < 2\theta_{max}.$$

It should be considered that the beam parameter product (BPP), of a laser beam is defined by

$$\text{BPP} = \frac{d_{laser}\theta_{laser}}{4}.$$

This remains the same as beam propagates and cannot be reduced by optical systems without introducing losses. Thus for efficient beam delivery,

$$\text{BPP} < \frac{d_{core}\theta_{max}}{2}.$$

This is a crucial condition for coupling of laser beam through optical fibre. Thus, the fibre selection for beam delivery depends on laser beam quality. In general, the efficiency (η) of the coupling is affected by three different factors: geometrical efficiency (η_{geo}), angular efficiency (η_{ang}) and Fresnel efficiency ($\eta_{Fresnal}$).

$$\eta = \left(\frac{P_{input}}{P_{source}}\right) = \eta_{geo} \times \eta_{ang} \times \eta_{Fresnal}, \tag{2}$$

where P_{input} is the power coupled into the fibre and P_{source} is the power emitted by the source.

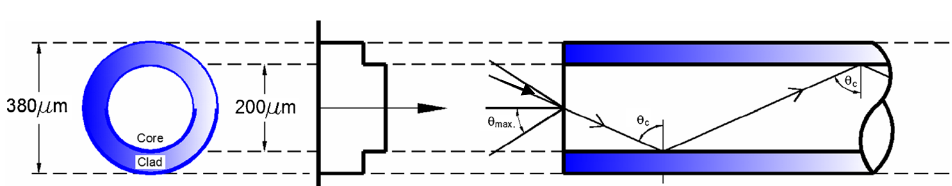


Figure 3. A step-index optical fibre. (**a**) Refractive index profile and (**b**) total internal refraction at the core–clad interface and numerical aperture.

3. Experimental details

An in-house built lamp-pumped Nd:YAG laser has been used for coupling laser beam through optical fibre. It consists of a pump chamber containing 7 mm bore diameter krypton-filled flash lamp, an 8 mm × 150 mm, 1.1 at % Nd-doped YAG rod and ceramic reflector having rectangular shape of cross section ∼ 30 mm × 150 mm. A 10% samarium oxide-doped glass plate has been inserted between the lamp and the rod to absorb the unwanted UV radiation from the lamp (which may create colour centres in Nd:YAG rod). In addition, the samarium oxide-doped glass plate enhances pumping efficiency by the absorption of UV radiation and emission in the pump bands of Nd:YAG rod. The laser resonator is of plano-concave type, in which a 7 m ROC concave mirror with 99.8% reflectivity has been used as rear mirror and a 60% reflectivity plane mirror has been used as output coupler. A 6 mm diameter circular aperture has been inserted in the resonator to select lower number of modes and thereby improve its beam quality.

The ceramic reflector used in our pump chamber is made up of 'Sintox AL Alumina' [5], which is a high-purity commercially available alumina (Al_2O_3) material (99.7% Al_2O_3), that works particularly well for Nd:YAG crystals and shows 97.8% reflectance efficiency at 1000 nm. The optical damage threshold of pure silica is about 10 GW/cm^2, but the experimentally observed damage threshold very much depends on fibre-end surface preparation. The fibre has been cleaved with a large diameter fibre cleaver to achieve mirror-like surface with high damage threshold. The cleaved fibre ends were examined through a 100X microscope and the surface was found to be extremely smooth and plane without any scratches or chippings. In addition to that, overall mechanical stability of the laser system is equally important because high power applications impose stringent requirements on fibre connector designs. For that, we have designed a robust connector to perform well for repeatable precision reconnections and ruggedness. The focussed laser

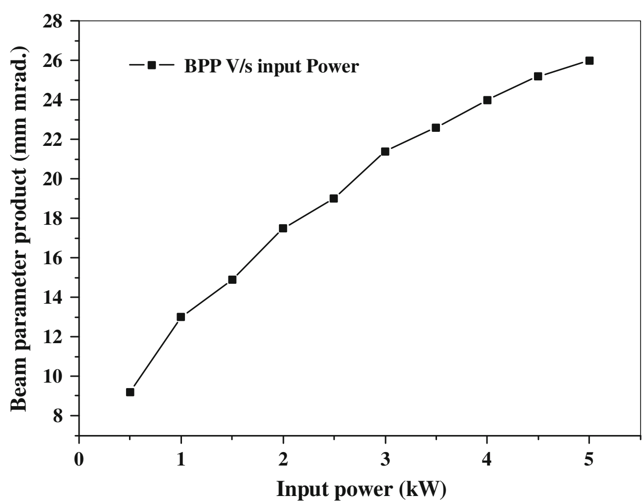


Figure 4. Beam parameter product as a function of power (without aperture).

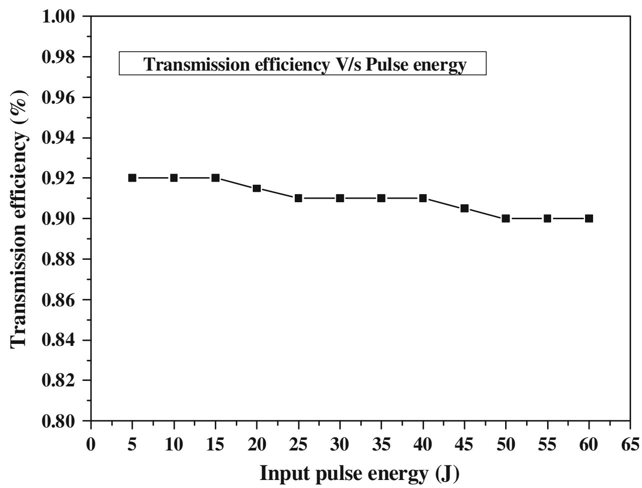


Figure 5. Transmission efficiency as a function of input pulse energy.

beam was launched properly with minimum possible undue heating effects. Water cooling arrangement of the fibre was also done to remove any unwanted heat generated in the connector. Pump pulse energy is given by

$$E = K_0 I^{3/2} t_\mathrm{p}, \tag{3}$$

where K_0 (=18) is a constant for the given flash lamp, I is the lamp current and t_p is the pulse duration. For our home-built laser system, laser pulses are having rectangular shape and electrical pump input to laser output conversion efficiency is about 5%. We have kept the current at a fixed value of $I = 300$ A and varied the pulse duration between 2 and 20 ms to have a maximum value of pulse energy of 100 J. We have measured BPP and M^2 using knife-edge method. Variation of BPP with input pump power is shown in figure 4.

The output beam was then focussed onto the end face of the optical fibre. We have used a GRADIUM lens of 22 mm focal length and 12.5 mm diameter. The optical fibre was a step index type with 200 μm core diameter and 0.22 NA. We were able to couple up to 60 J per pulse energy through a 150 m long fibre, with 90% transmission efficiency. The transmission efficiency as a function of input pulse energy is shown in figure 5. The 10% loss in transmission may be accounted for 4% Fresnel reflection losses from each fibre end and the rest is geometric and angular losses with small transmission losses. This laser was utilized for microwelding dissimilar components such as iridium and copper and its further utilization is under progress.

4. Conclusion

In conclusion, we have efficiently delivered Nd:YAG laser beam of up to 60 J of pulse energy in long pulse operation in the range of 2–20 ms through a 200 μm core diameter optical fibre. Delivery of high pulse energy through small core diameter optical fibre was made possible by using GRADIUM glass lens to have aberration-free focus spot and cleaved fibre facets to achieve higher surface damage thresholds. This laser is being used for cutting and microwelding applications.

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