Comparison of ND:YAG laser beam quality between free running and Q-switched modes

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In this paper, we present the comparison result of M^2 factor between free running and Q-switched mode of Nd:YAG laser. The system consists of sensitive infrared IR detector, lenses, distance scanner and a single array detector. Developed photographic paper was used to detect the invisible of IR beam which instantly and permanently records the beam spot. The beam spot was scanned and send to computer for analysis via Matrox Inspector version 5 software. A homemade scanner was utilized to ease the mobility of the detector. It moves in two directions; parallel and perpendicular to the optical axis. The beam width of near field and far field along the Rayleigh region were measured. The results showed that the M^2 factor for free running of Nd:YAG laser are 7.68 and 7.38 and for Q-switch mode are 25.62 and 19.48 corresponding to both lenses with focal distance of 15 and 20 cm respectively. The free running operation is found to have better beam quality in comparison to Q-switch mode. The reason for the poor quality of Q-switch mode is due to the large beam width of near field induced by giant pulse, losses of energy and shorter duration.

I. INTRODUCTION

Lasers are widely used in scientific research, medicine and industry. In many application lasers are desired to have high beam quality. Therefore it is quite a crucial that, scientist and engineer need to work together to ensure the laser output having reliable performance. The poor beam quality or unmonitored beam may cause unsatisfactory production as well as undesired treatment.

There are many ways and a variety of instruments have been developed to measure the propagation factor M^2. There are four main methods of beam–measurement; camera-based system, knife-edge method, slit scanning method, and variable pinhole method. Each has specific advantages and disadvantages. Camera based profiler for example, is instantly record and display the entire optical pattern that impinges on the camera surface. But it has limitation cannot measure width greater than ~ 60 μm and is limited spectral range [1]. Furthermore, it is very sensitive to brightness and high potential of damage if expose with high power laser. Base on these weaknesses, other alternative method need to be considered.

Over the past decade a number of papers have been devoted to analysis the quality of laser radiation. Since the advent of laser, the research on the laser beam quality and laser beam propagation rule have been an active field in laser subject. Zheng *et al*. [2] have measured the beam quality of laser diode end-pumped $Nd:YVO_4$ laser using slit-scanning method. Other researchers like Wang and Zhou [3] have measured the optical beam quality of CO_2 laser and demonstrate the equivalent beam propagation factor of quantum well laser. Analysis of beam quality for semiconductor laser is also study base on numerical simulation [4].

Knife-edge method is a favorable technique due to it large signal-noise ratio and convenient operation. Several researchers [5-9] have used this method to measure the beam quality. This method is considered the best methods to measure the beam width of irregular transverse profiles [7,8]. However the disadvantages of this method are, desire a clipping level and a scale factor. The beam profile normally is complex which difficult to select proper scale factor [7].

In many cases the beam quality for high power laser is measured based on the brightness [10-15]. Astadjov *et al*. [13,14] have measured the beam quality of a master oscillator power amplifier MOPA CuBr laser pulse system based on time dependence of brightness and laser power by a beam analyzing technique. The M^2 factor from this measurement is in the range from 13-14 (small delays) to 5-6 (large delays) and filled-center radiation M^2 is 6-7 (small delays). Furthermore the brightness of the laser system was found increases further as the light is polarized. The brightness of linearly-polarized is at least 40% higher than that of partial or non-polarized beams. Other Similar research on MOPA of HyBrid cooper laser was reported by Giao *et al.* [15]. In this particular study, the beam propagation factor of the laser is $M^2 = 4.9$.

Recently Cortes *et al.* [16] have introduced a novel method based on diffractive optic for measuring M^2 of continuous Nd:YAG laser. Basically, camera base system was employed in this measurement, but additional optical devices a diffraction grating was introduced. The laser beam is expanded and filtering the laser to avoid damage and saturation in the CCD camera. Using the same type of Nd:YAG laser but operating in pulse mode was reported in other text [17]. In the later investigation, phosphor detector was used to convert the invisible into visible red light. The beam spot on the card was captured by digital camera. The camera was interfaced to personal computer for analyzing. The brightness of the laser beam is found to be linearly increases against the input power.

However not many the beam propagation factors of Q-switch lasers have been reported. In reality, the Q-switch mode lasers are widely used in industrial especially in material processing for welding, cutting and drilling. Therefore it is very important to measure the beam quality of pulse and Q-switch mode in order to provide reliable information about the performances of the laser for end user. In this attempt, a fundamental study was carried out to measure the beam quality of both pulse and Q-switch mode of Nd:YAG. The laser beam is directly measure without been expanded and attenuated.

II. ISO M^2 MEASUREMENT

International Standardization Organization ISO11146 [18] introduces a quantity, M^2 ('m-squared') which is referred as "times-diffraction-limited factor" which means the times of diffraction limit number. M^2 is also called 'propagation factor' since it does not change with distance as light beam propagates. The measurement of M^2 factor is mainly obtained through measuring the widths of the beam at different positions along the propagation direction and evaluating the data according to the multi-mode propagation theory [7]. Accurately measuring the width of the beam is the critical step in the whole process.

A variety of instruments have been developed to measure the propagation factor and M^2. Most are based on the same fundamental operating principle by focusing the incoming beam via a lens. This forms a beam that has a beam waist at the focal point, a near field in front of the lens, a far field at the focal point (within the Raleigh region). The beam diameter at the waist and the diameters at near-field and far-field points on either side of the waist are measured. According to the ISO, M^2 factor must be greater than or equal to unity, and the transverse fundamental mode Gaussian beam is regarded as a diffraction limited beam and has the best optical beam quality [16]. It is defined as

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

$$\theta = \frac{d_0}{2f} \tag{2}$$

where d_f is the beam waist at the focal point, θ is the half of divergence angle, d_0 is the beam diameter of input beam or at near field, f is the focal distance. All these parameters are illustrated in Fig. 1. In this present paper, the measurement of beam quality for Nd:YAG laser at different modes, free running and Q-switched laser are performed.

III. EXPERIMENT

In this study, flashlamp pumped Nd:YAG laser model HY200 manufacture from LUMONIC was employed as a light source. The fundamental wavelength is 1064 nm. The laser is operated in two modes, free running with pulse duration of 120 microsecond and Q-switched mode with 10 nanosecond pulse duration. The capacitor voltage of the flashlamp is remained constant at 650 V to produce laser output energy of 60 mJ. The laser was operated at repetitive mode with frequency of 1 Hz. The laser beam was focused using two convex lenses, with focal distance of 15 cm and 20 cm respectively. Sensitive photographic paper was developed to provide black or burnt paper. It was used to detect the existence of invisible beam. The advantage of using burnt paper, is that the real spot instantly and permanently record on it. Furthermore, no limitation in beam size, in spectral range as does with camera CCD system. In additional, no extra optical device is needed in the optical alignment either to attenuate or to expand the beam as desired with light directly impinge on the camera surface in most camera-based profiler method. The most important no damage and nonlinear effect involve to the camera surface if the high power laser such as focusing Q-switch laser was utilized. In fact the damage mechanism was utilized to absorb on the burnt paper which appeared as a beam spot. The most important the total energy delivered at tested position without reflection or scattering since the paper is black (un-glossy photographic paper was employed). The beam width on each spot was measured at various position along the beam propagation direction. A homemade scanner was utilized to ease the mobility of the detector either parallel or crossing to the laser beam axis. For accurate measurement the beam width at each location will be repeated at least ten times and the average is calculated. This is performed at constant location (in parallel direction) but sliding the detector on the scanner across the beam. The exposed papers were scanned and exported to the personal computer for further analysis. Matrox Inspector version 5 software was conducted to process and analyze the image using line option. The whole experimental set-up is shown in Fig. 2.

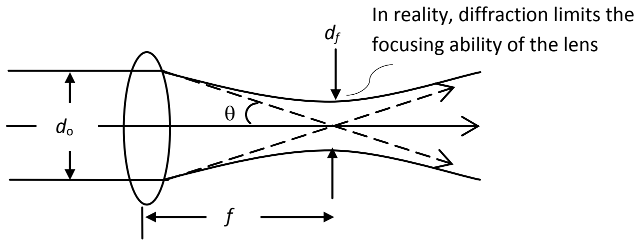

FIG. 1. Parameters of beam quality estimation.

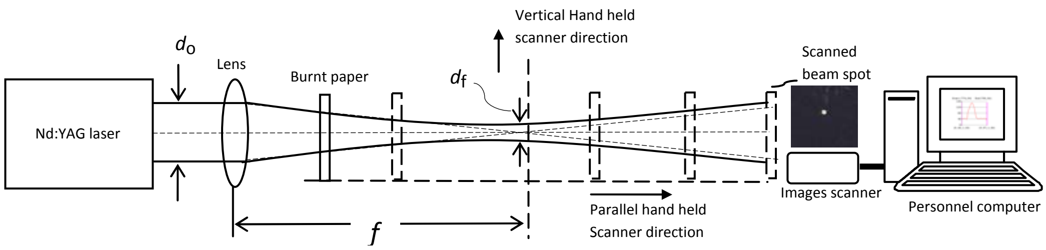

FIG. 2. Experimental set-up for beam quality parameters measurement.

IV. RESULT AND DISCUSSION

The typical beam spots at the near field and the far field (at focal point) associated with each individual beam profile obtained from this experiment are shown in Fig. 3. The first two pictures show the beam spot of near field. Fig. 3(a) show the beam spot of free running operation, and Fig. 3(b) for Q-switch operation. The first two beam spots are relatively larger compared to the spot at the focal point such as shown in Figs. 3(c) and (d) for free running and Figs. 3(e) and (f) for Q-switch. The laser beam was focused by lenses with respective focal distance of 15 and 20 cm. In all pictures only solid single beam spot are appear on each burnt paper which indicates that the beam having fundamental transverse electromagnetic mode TEMoo. Each individual absorption spectrum also indicates that, the beam spot is Gaussian beam with circular top-hat beam. This confirmed that the optical beam profiles is TEMoo Gaussian. The sensitivity of burnt paper allows the deformation following the configuration of the incident beam. The observation result show that the beam is in circular shape. The amplitude of the profile is represented the depth of the beam absorbed on the burnt paper. The higher the amplitude of the signal in the spectrum the deeper the absorption depth on the burnt paper. The inverse of such depth also can be interpreted as the power of the photon or the intense of the light. The size of the beam can be measured accurately based on the number of pixel at each signal in the absorption spectrum. The calibration for the beam spot measurement can be estimated according to the Eq. (3). The calibration had been included in the program of the software. The original size one of the beam spot in the real field was measured. The image size of the same beam spot on the screen was measured based on the deduction of the pixel numbers. The calibration was carried out by dividing these two sizes and multiplied with any interested size of the beam spot.

$$\text{Calibration} = \frac{\text{real size (in mm)}}{\text{image size (in pixel number)}} \times \text{any image size (in pixel number)} \qquad (3)$$

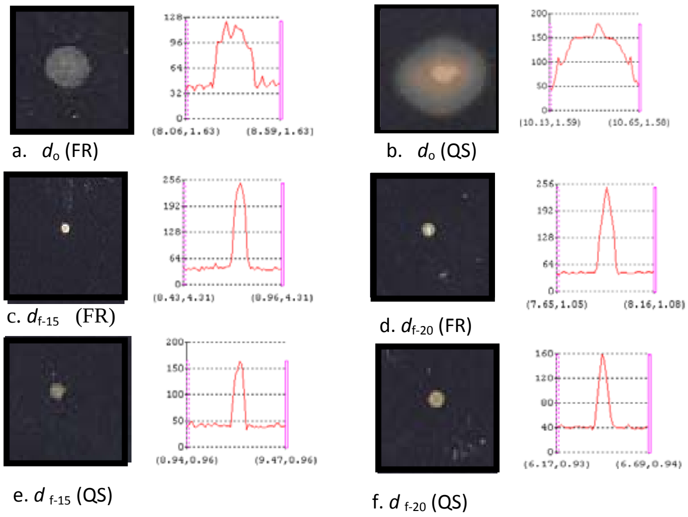

FIG 3. The beam spot of Free Running (FR) and Q-switched (QS) of Nd:YAG laser at (a) near field, d_0 (FR), (b) near field, d_0 (QS). Far field at focal point of the lenses with focal distance of (c) 15 cm (FR), (d) 20 cm (FR), (e) 15 cm (QS), (f) 20 cm (QS). Each spot is associated with corresponding absorption spectrum. (Magnification ~ 3X).

As a matter of statistics a dozen of samples (for each point) were averaged and their statistical parameters were derived. The collected data are presented in the graph of Figs. 4 and 5. Fig. 4 shows the Gaussian beam profile for both free running and Q-switched modes induced by lens with focal length of 15 cm, meanwhile Fig. 5 for 20 cm.

The minimum point from each curves of Figs. 4 and 5 are considered as the minimum beam size for each mode and lenses. The data obtained from the graphs are summarized in Table I. The M^2 factor is calculated by using the information provided in Table I and Eqs. (1) and (2). The calculation results are also included in the same Table I.

The M^2 factor induced by both lenses (15 and 20 cm focal distance) for free running mode is in the range of 7 to 8, whereas for Q-switch laser in the range 19 to 26. The lens with longer focal distance (20 cm) having relatively smaller M^2 factor in compared with lens of 15 cm focal distance. This result is in good agreement with the theory as shown in Eq. (1) which shown that M^2 is inversely proportional to the focal distance. The longer the focal distance the smaller the M^2 factor.

In general, M^2 factor for free running is found to be three times smaller than Q-switch mode. This indicates that the beam quality of free running operation is much better than Q-switched mode. In other word, Q-switched mode will diverge ~ 26 times as rapidly with distance as a true TEM_{oo} beam. Differently with free running laser the beam diverge only seven times. The possible reason for such result is due to the output energy carry by free running laser is much higher than the energy by Q-switched mode. Another factor is also contributed by the beam width at near field. The larger beam width own by Q-switch laser is due to the giant pulse formation. However its average energy is low due to many losses during Q-switch mechanism.

The free running means the beam are free to amplify in the cavity without any destruction or disturbance from the modulation process. For example the existence of pockel cell which used to switch the light through the influence of high electric field. The polarity of the light will rotate when the electric is applied on the pockel. In this way no light is amplified in the cavity. This is how the energy in the cavity will be lost. However during this time, the gain medium accumulated as many as possible the excited atoms in the upper level. When no electric is applied on the crystal, the stimulated emission generates a giant pulse which result the formation of large annular beam spot at the near field. Since theoretically the M^2 factor directly proportional to the beam size d_0 regarding to Eq. (1), the larger the beams the greater the beam propagation factor M^2. Consequently the beam size affects the beam quality of the Q-switch mode.

Furthermore the pulse duration of the laser beam also play an important role for determination of beam quality. The longer the time the more thermal induce and interact with the sensitive paper. The free running laser has 120 microsecond pulse duration. This is the reason for the burnt paper to absorb more energy rather than the Q-switch mode laser. Although the size of the beam is large but the duration to interact with the burn paper was too short that is only 10 nanosecond. The transient time produced by the Q-switched laser does not allow the burnt paper to absorb enough energy from the infrared beam. All these factors contribute to the beam quality of the Q-switch mode turn to be poor in compared with the free running beam.

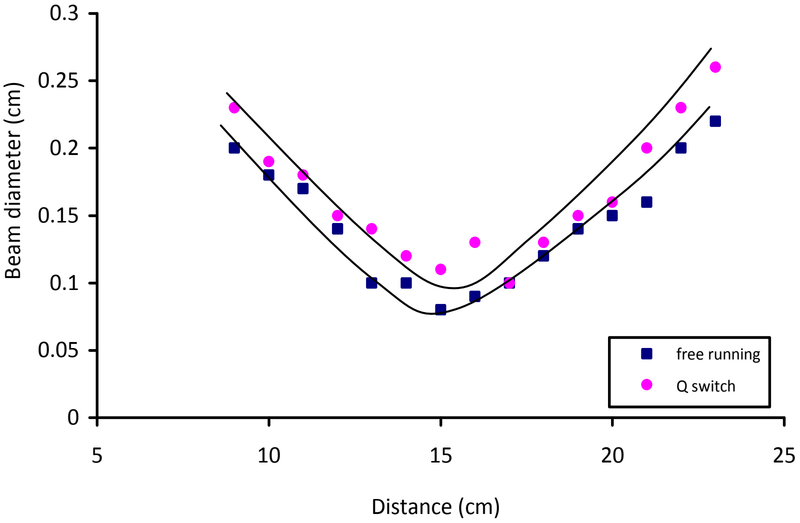

FIG. 4. Beam size profile of different laser modes free running and Q-switch induced by lens with focal length of 15 cm.

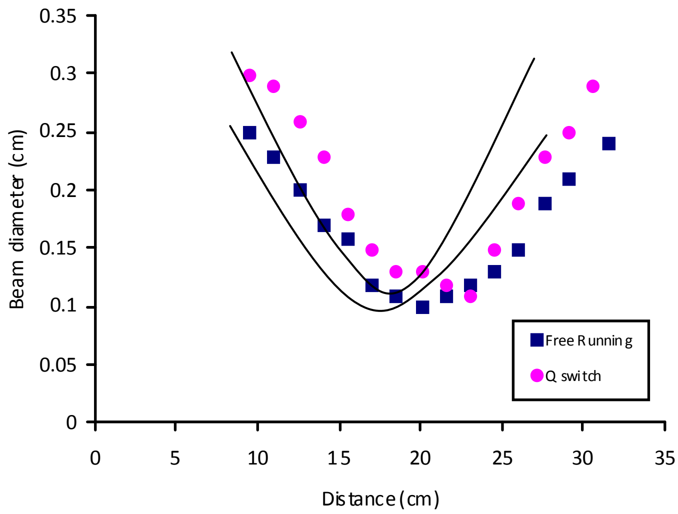

FIG. 5. Beam size profile of different laser modes free running and Q-switch induced by lens with focal length of 20 cm.

TABLE I. Estimation of beam quality for different laser modes.

Focal length, f (mm)	**M^2 parameters at different Laser modes,**							
	Free running				**Q-switch**			
	***D_0*, mm**	**θ, rad**	***d_f*, mm**	**M^2**	**d_0, mm**	**θ, rad**	***d_f*, mm**	**M^2**
150	2.0	0.013	0.8	7.68	4.0	0.032	1.1	25.97
200	2.0	0.010	1.0	7.38	4.0	0.024	1.1	19.48

V. CONCLUSION

The beam quality of free running mode of Nd:YAG laser is found to be almost 3 times better than the Q-switch mode. The loss energy during beam modulation, the formation of giant pulse in the Q-switch operation, and the shorter pulse duration, are the factors contribute to the poorness of optical beam propagation factor M^2. The focal distance of lens used to focus the beam also play an important role for determination of the M^2 factor. The longer the focal distance the smaller the size of the focal spot, the better the beam quality.

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