Study of a Second Harmonic Nd:YAG Laser

ABSTRACT

A second harmonic generator was designed and set-up. The factors affecting conversion efficiency and beam quality were discussed. The performance of the second harmonic generator was investigated. The beam quality was measured by a laser beam profiler. The conversion efficiency and beam propagation factor M^2 reached 48.72% and 1.07 respectively.

Keywords: Nd:YAG laser, second harmonic, laser beam quality, conversion efficiency

1 Introduction

For material processing applications, CO_2 or Nd:YAG lasers have traditionally been used. In general, Nd:YAG laser performs better because of its shorter wavelength, which is more easily absorbed by metals.

In addition to CO_2 and Nd:YAG lasers, argon and excimer lasers are also being applied for material processing applications. An argon laser operates in continuous wave, while an Nd:YAG laser operates either in CW Q-switched mode to provide short, high-peak-power pulses, or in pulsed mode to provide high pulse energy. The optical properties of the Nd:YAG laser allow it to be focused to a small spot, while the excimer laser beam generally needs to be imaged through a mask for high-resolution processing. For many applications, therefore, the ideal laser would have the short visible or ultraviolet wavelength of the argon or excimer laser, together with the operating characteristics of the Nd:YAG laser. Nonlinear crystals have been used to frequency-double, -triple, and even -quadruple Nd:YAG laser beams, which have wavelengths of 0.532-, 0.355-, and 0.266-µm respectively. These new wavelengths extend the applications of the Nd:YAG lasers.

The second harmonic Nd:YAG laser has many advantages over the fundamental Nd:YAG laser:

(1) Smaller focused spot size

For a TEM_{00} laser diffraction limited optics, the focused spot size, s, can be given by[1]

$$s = 1.27\, l\, \frac{f}{d} \qquad (1)$$

where l is the laser wavelength, f is the lens focal length, and d is the diameter of the beam (entering the lens). It is obvious that the focused spot is proportional to the laser wavelength. The spot size reduces by a factor of two and the focused spot area does by a factor of four when the laser wavelength is converted from 1.06 µm to 0.532 µm.

(2) Better absorption coefficient

In general, the reflectance of metals drops as the wavelength drops[2]. For example, gold reflects about 99% of the energy at 1.06 µm, thereby absorbing only 1%. At 0.532 µm, the reflectance drops to about 60%, corresponding to an absorption of 40%.

For semitransparent materials, not all the non-reflected energy is absorbed at the surface. Instead, a portion of the beam is transmitted, following the Beer-Lambert law[3]. However, the absorbed-power density is highest at the top surface but drops exponentially as the beam penetrates the material.

(3) Higher power density

Laser cutting, scribing, drilling, marking, and micro-machining all involve material vaporisation, which requires high absorbed-power density. The absorbed power depends mainly on three factors: laser input power, focused spot size, and absorption properties of the material at the given laser wavelength. Although the laser in the TEM_{00} mode limits the maximum output power from the laser generator, the beam can be focused to a much smaller spot, thus resulting in a higher power density. If a beam waist for a TEM_{00} mode is ω_0, the beam waist for the first some modes are shown in Table 1[4].

Table 1 Spot sizes for high-order modes

Mode	TEM_{00}	TEM_{10}	TEM_{20}	TEM_{01}	TEM_{11}	TEM_{21}
Spot size	ω_0	$1.50\omega_0$	$1.77\omega_0$	$1.92\omega_0$	$2.21\omega_0$	$2.38\omega_0$

In Q-switched applications, power density is generally more important than spot size. Frequency doubling reduces the area by a factor of four. The resulting increase in power density, however, is mediated by losses in converting the 1.06 µm radiation to the 0.532 µm beam. Conversion efficiency depends on many factors, including the type of nonlinear crystals, the 1.064 µm power, and the Q-switch frequency. Under optimum conditions, the conversion efficiency is 50% or more. Combining the 50% reduction in power with the four-times reduction in spot size yields a doubling of power density with frequency doubling.

(4) Smaller heat-affected zone and higher processing quality

Thermal induced damage in laser processing is significantly reduced at short laser pulses and high peak power, which cause a fast material vaporisation[5,6]. Experiments on laser cutting of wafer demonstrated that the efficiency of the cutting process and the work quality were improved due to the absorption characteristics of the mono-crystalline silicon using a frequency-doubled Nd:YAG laser[7].

2 Basic Theory of Second Harmonic Generation

2.1 Basic Equation of Second Harmonic Generation

Frequency conversion utilises the non-linear optical response of an optical medium in intense radiation fields to generate new frequencies. If Maxwell's equations are solved for a coupled fundamental and the second harmonic (SH) wave propagating in a non-linear medium, then the ratio of the power generated at the second harmonic frequency to that incident at the fundamental (namely, conversion efficiency *h*) is given by[8]

$$h = \frac{P_{2w}}{P_w} = l^2 K \frac{P_w}{A} \frac{\sin^2(\Delta kl/2)}{(\Delta kl/2)^2} \qquad (2)$$

where l is the length of the non-linear crystal, K is a constant relative to the fundamental beam and crystal materials, A is the area of the fundamental beam, and Dk is the wave number difference. For a given wavelength and a given non-linear material, K is a constant.

The conversion efficiency depends on the length of the crystal, the power density, and the phase mismatch.

2.2 Critical Parameters Affecting the Doubling Efficiency

(1) Power density

From Equation (2) it is seen that the conversion efficiency is proportional to the power density of the fundamental beam, whereas the harmonic power itself is quadratically proportional to the fundamental power. For the YAG laser used in the study is a CW pumped laser, both the peak power and power density are very low. Therefore, frequency doubling a CW pumped laser system would result in an unacceptably low harmonic power. Thus, intra-cavity frequency doubling is adopted, namely, the crystal is placed inside the laser resonator, where the circulating power is approximately a factor ($1/T$) larger than the output power. The power is coupled out of the resonator at the second harmonic wavelength by replacing the output mirror with one which is 100% reflective at the fundamental and totally transmitting at the second harmonic.

(2) Phase-matching angle

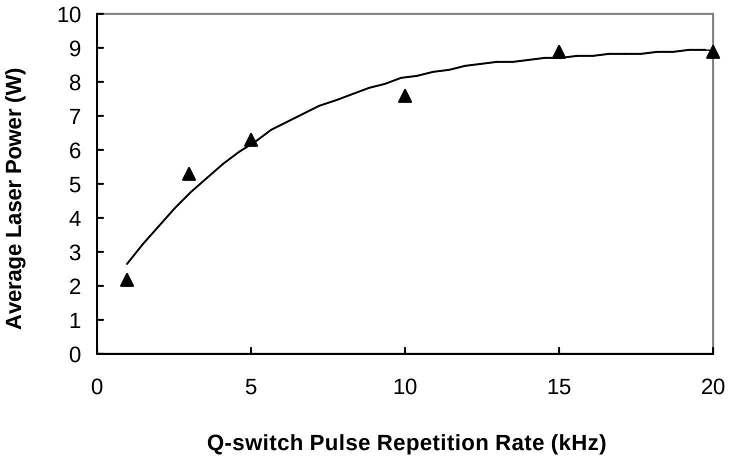
The harmonic power is at maximum when Dk = 0. That is termed phase matching. By an appropriate choice of polarisation and direction of propagation it is often possible to obtain Dk = 0.

Generally speaking, the non-linear crystal is machined to make the beam incident plane perpendicular to the optical axis. Careful adjustments are needed to achieve phase-match, which in turns maximise the second harmonic power.

(3) Q-frequency

The quality factor Q in a laser cavity is defined as the ratio of the energy stored in the cavity to the energy loss per cycle. Energy is stored in the laser rod by optical pumping while the cavity Q is lowered to prevent the onset of laser emission. The high peak power can be obtain while the cavity Q is increased to the highest very fast. By this technique, laser peak power, pulse repetition rate, and pulse width can be changed.

Q-frequency affects not only the average laser power, but also pulse width and peak power. Figure 2 shows the relationships. In general, the higher the *Q*-frequency, the higher the average laser power, the higher the peak power, and the longer the pulse width.



(a) Average power vs. Q-switch pulse repetition rate

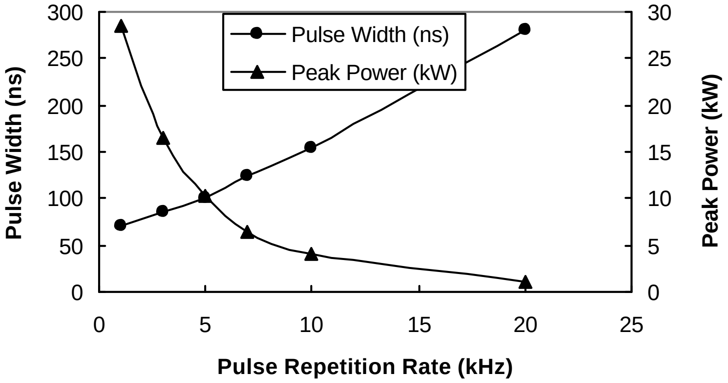


Fig. 2 Relationships among average power, peak power, pulse width, and pulse repetition rate[9]

(4) Others

Optical homogeneity, non-linear coefficient, spectral brightness are also important parameters in second harmonic generation, but they are mainly determined by materials and the laser itself, and therefore, not discussed here.

2.3 Properties of Non-linear Crystals

The most important nonlinear materials in second harmonic generators are KD*P, KTP, LBO, BBO, $LiNbO_3$ and $LiIO_3$. At the present time, the leading candidate material is KTP, since the crystal has a large nonlinear coefficient, high damage threshold and large angular and temperature acceptance range.

KTP (Potassium Titanyl Phosphate, $KTiOPO_4$) is the most commonly used material for frequency doubling of Nd:YAG lasers and other Nd-doped lasers, particularly at the low or medium power density. To date, extra- and intra-cavity frequency doubled Nd:lasers using KTP have become a preferred source of pumping visible dye lasers and tuneable Ti: sapphire lasers as well as their amplifiers. When applied to diode pumped Nd:laser, KTP has provided the basis for the construction of compact visible solid state laser system.

The basic properties and non-linear optical properties of KTP crystal employed in the study are given in Tables 1 and 2[10].

Table 2 Basic properties of KTP crystal

Crystal structure	Orthorhombic, space group Pna2, point group mm2
Cell parameters	a = 0.6404 nm, b = 1.06 nm, c = 1.28 nm, Z = 8
Melting point	1172 °C incongruent
Curie point	936 °C

Mohs hardness	≈ 5
Density	3.01 g/cm^3
Colour	colourless
Hydroscopic susceptibility	no
Specific heat	0.1643 cal/g.°C
Thermal conductivity	0.13 W/cm/ °K
Electrical conductivity	3.5×10^{-8} s/cm (22°C, 1 kHz)

Table 3 Non-linear optical properties of KTP crystal

Phase matchable SHG range	0.497 - 1.8 μm	
Non-linear optical coefficients	d_{31} = 1.9 pm/v, d_{32} = 3.5 pm/v, d_{33} = 13.7 pm/v d_{24} = 3.3 pm/v, d_{15} = 2.6 pm/v $d_{eff}(II) = (d_{24}-d_{15})\sin^2\phi\sin^2\theta-(d_{15}\sin^2\phi+d_{24}\cos^2\phi)\sin\theta$	
For type II SHG of a Nd:YAG laser at 1.064 μm		
PM angle	θ = 90°, ϕ = 23.3°(θ and ϕ are polar angles referring to Z (=c) and X (=a)	
Effective SHG coif.	$d_{eff} \approx 8.3\times10d_{36}$(KDP)	
Angular acceptance	25 °C-cm	
Spectral acceptance	5.6 Angstrom - cm	
Walk-off angle	4.5 mrad	
Optical damage threshold	> 450 MW/cm^2 (@1.06 μm, 10 ns, 10 Hz)	
Electro-optic coefficients	Low frequency(pm/V)	High frequency (pm/V)
r_{13}	9.5	8.8
r_{23}	15.7	13.8
r_{33}	36.3	35.0
r_{51}	7.3	6.9
r_{42}	9.3	8.8
Dielectric constant	ε_{eff} = 13	

3 Design of Second Harmonic Generator

3.1 Set-up of Second Harmonic Generator (SHG)

The second harmonic laser is developed based on a CW lamp -pumped Nd:YAG laser[11]. It consis ts of the resonator (rear mirror and output coupler), intra-cavity aperture, YAG rod, Q-switch, and KTP crystal, as shown in Figure 3. The size of the YAG rod size is ϕ4×100 mm. The KTP crystal is in a type II phase-matched condition, i.e. the polarization vectors of the two incident beams are orthogonal. The KTP size is 4×4×8 mm. The phase-matching angle is 23.3°. The crystal is AR coated for 1.06 μm and 0.532 μm. The angular acceptance and temperature are sufficiently large that no adjustments of the doubling crystal are necessary once the angle is set.

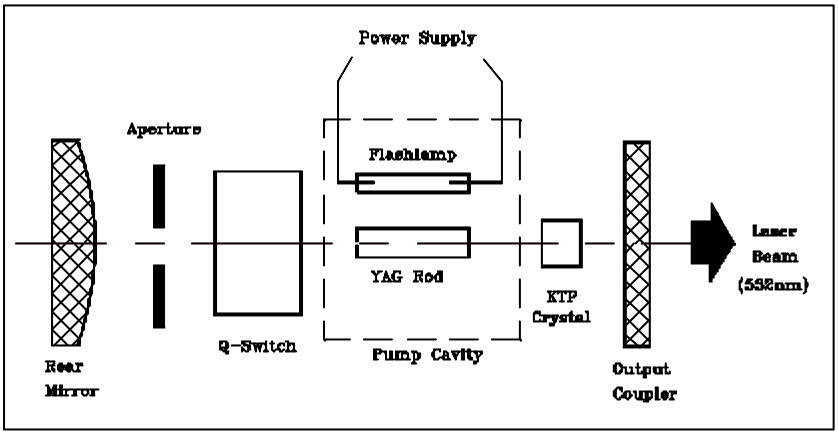


Fig. 3 Diagram of the second harmonic laser

The cooling of the KTP crystal is necessary in intra-cavity frequency doubling. A cooling mount for the KTP crystal is designed and manufactured. The mount can be used to orient the crystal to achieve phase matching and to precisely align the KTP crystal with the optical axis.

3.2 Resonator Mirrors

The resonator consists of the rear mirror and the output coupler, as shown in Figure 3. The specifications of the resonator are as follows:

Rear mirror	:	Plano-convex Radius of curvature: 0.5 m or 1 m Reflectivity: 99.5% @ 1.064 & 0.532 μm
Output coupler	:	Flat Reflectivity: 99.5% @ 1.064 μm Transmission: 99.5% @ 0.532 μm
Resonator length	:	670 mm

The apertures used are 1.2 mm or 1.6 mm in diameter. They are cooled by water to maintain the laser power stability.

4 Performance of Second-Harmonic Output Beam

4.1 Laser Power

Figure 4 shows the second harmonic average laser power as a function of pumping power. The rear mirror has a radius of curvature of 1 m. The aperture is removed, that is, the laser beam has multimode profiles. The experiment shows that the maximum power of 3 W is obtained at the pumping power of 3.56 kW and the Q-switch frequency of 5 kHz.

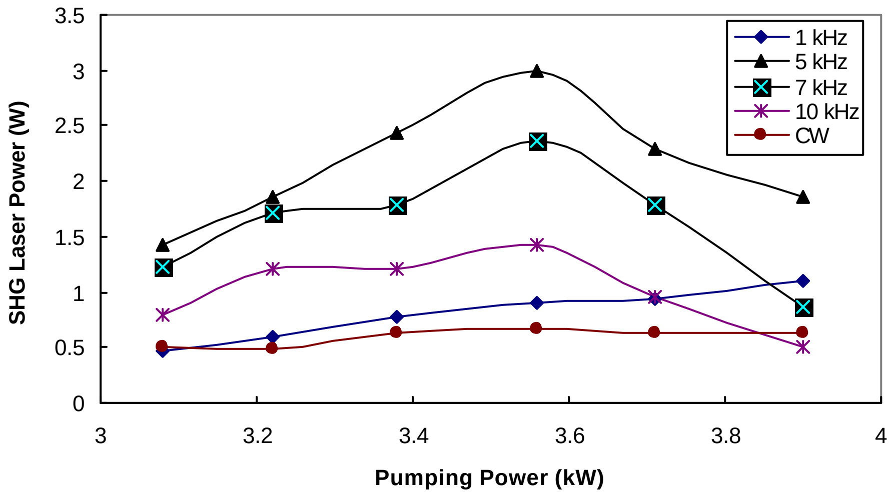


Fig. 4 Second harmonic laser power vs. pumping power

The change of the average laser power at the Q-switch frequency of 5 kHz in Fig. 4 is typical. At first, the second harmonic laser power increases with an increase in pumping power, until it reaches the maximum laser power and optimal frequency-doubling conditions. Then, the second harmonic laser power decreases with further increase in pumping power, but the 1.064 μm laser power remains increasing with an increase in pumping power (as shown in Fig. 5). However, the pulse width becomes wider when the pumping power is increased. For example, the pulse widths of the 1.064 μm beam are 100 ns, 125 ns, and 160 ns respectively corresponding to the pumping powers of 3.25 kW, 3.43 kW, and 3.58 kW at the same Q-switch frequency of 5 kHz. Wider pulse width leads to a lower peak power. Another factor is that at higher intensities, the crystal is slightly overdriven and re-conversion of 532 nm radiation to 1064 nm photons starts to become noticeable[12]. The other possible reasons for a reduction in laser power of the second harmonic output are lower power density and higher beam divergence when the pumping power is increased.

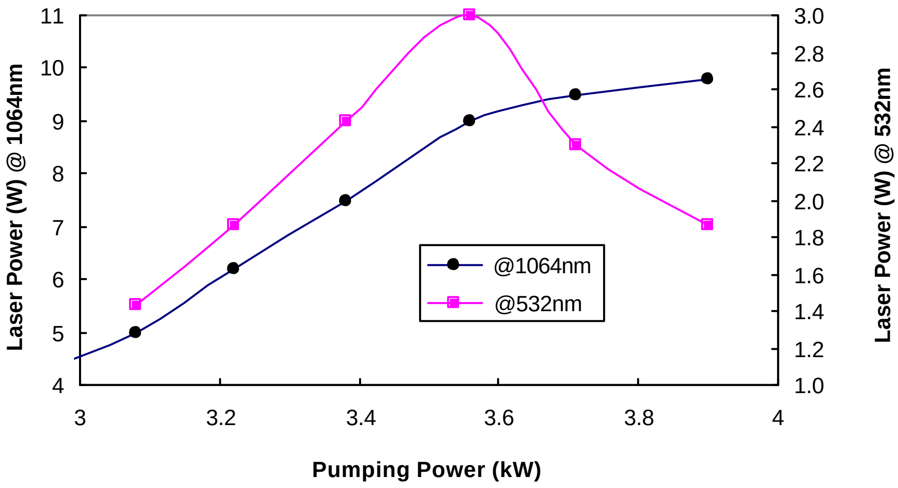


Fig. 5 Laser powers at 532 nm and 1064 nm as a function of pumping power at a Q-switch frequency of 5 kHz

Fig. 6 shows the average laser power at the fundamental and frequency-doubled wavelengths as a function of Q-switch frequency. Here the aperture with ϕ1.6 mm is used. The pumping power is 3.56 kW. It is obvious that the laser power at the fundamental wavelength increases with an increase in Q-switch frequency, while the laser power at the frequency-doubled wavelength reaches a peak and then drops. The factor resulting in this is the conversion efficiency (to be discussed below).

Figure 7 shows the second-harmonic average laser power as a function of pumping power at the aperture of 1.6 mm in diameter. The experiments show that the maximum power of 2.64 W is obtained at the pumping power of 3.71 kW and the Q-switched frequency of 5 kHz (the second harmonic laser power is 2.29 W at the pumping power of 3.56 kW and the Q-switched frequency of 5 kHz). Comparing Fig. 7 with Fig. 4, it is seen that the optimal pumping power at the aperture of ϕ1.6 mm is higher than that with no aperture. This is because the loss inside the resonator at the aperture of ϕ1.6 mm is larger. The difference in mode shapes will be discussed later.

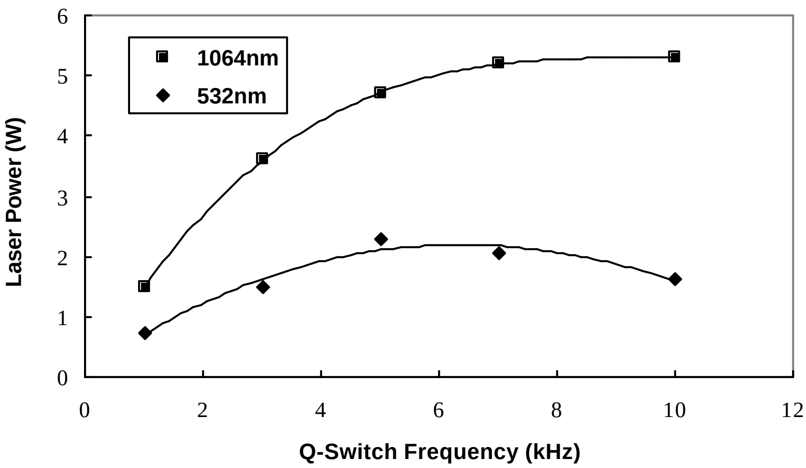


Fig. 6 Laser powers at 532 nm and 1064 nm as a function of Q-switch frequency at the aperture of ϕ1.6 mm

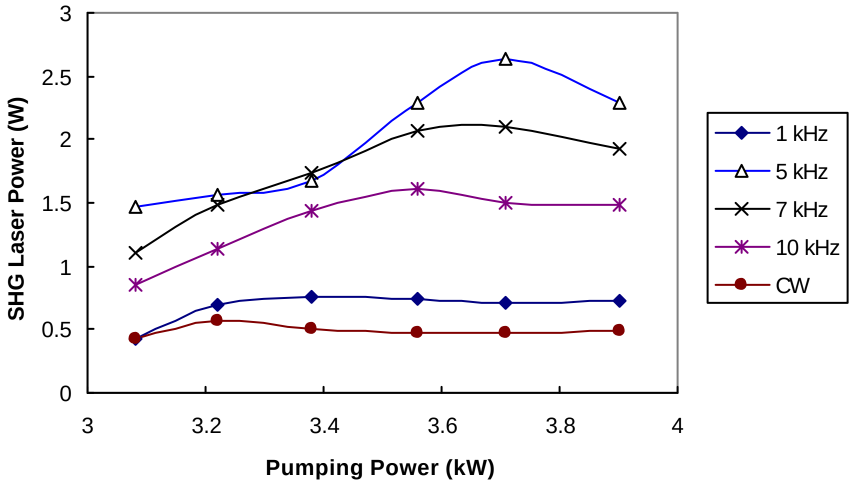


Fig. 7 Second harmonic laser power
vs. pumping power at the aperture of ϕ1.6 mm

When an aperture of 1.2 mm in diameter is used in the laser, the maximum second harmonic laser power is 1.06 W at the pumping power of 3.56 kW and the Q-switch frequency of 5 kHz.

4.2 Conversion Efficiency

Figure 8 shows the conversion efficiency as a function of *Q*-switched frequency at the aperture diameter of 1.6 mm based on the powers shown in Fig. 6. From Fig. 8, it is observed that, although the fundamental wavelength laser power at the *Q*-switched frequency of 1 kHz is only at 1.5 W, the peak power is highest at 28.5 kW. Thus, the conversion efficiency at the *Q*-switch frequency of 1 kHz is high, reaching 48%. After that, the second harmonic laser power and the conversion efficiency increase with increasing *Q*-switch frequency, till the optimal conversion efficiency. After the optimal conversion efficiency, both the second harmonic power and the conversion efficiency decrease with increasing *Q*-switch frequency. The highest second harmonic laser power of 2.29 W and the best efficiency of 48.72% are reached at the *Q*-switch frequency of 5 kHz. It is observed that the conversion efficiency drops at high frequencies. This is because of the low peak power of the Q-switched pulses. At the operation of CW mode, the second harmonic laser power is 0.065 W only, and the conversion efficiency is about 1.1%. Therefore, the peak power is a key factor in achieving high conversion efficiency.

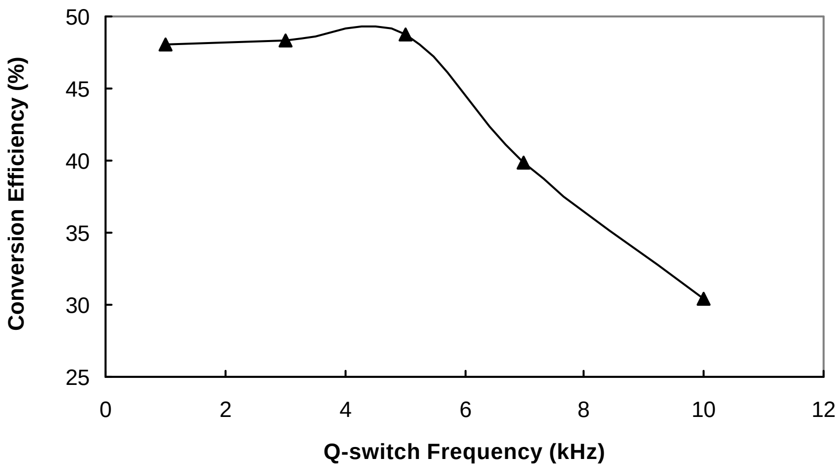


Fig. 8 Conversion efficiency vs. Q-switch frequency

4.3 Beam Propagation Factor M^2

A laser beam profiler is used to measure the beam quality. It is shown in Figure 9[13]. Within 100% to 10% of the incident beam is reflected from the wedged beamsplitter (depending on the incident polarization). 5% of the beam incident upon the retro reflector is reflected through the beamsplitter towards the imaging lens to create a near field image or far field profile of the beam on the CCD camera detector array. The filter reduces the overall beam power to an acceptable level. The video signal containing the information about the spatial intensity distribution is digitized and stored in the computer's memory. The false color coded digital image is displayed on a PC monitor. The processing software can allow 3D and cross-section plotting, histograms, curve fitting, and propagation analysis.

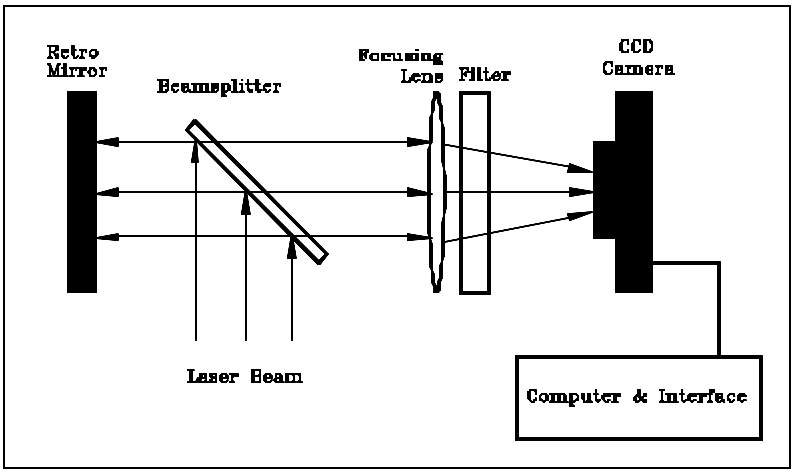


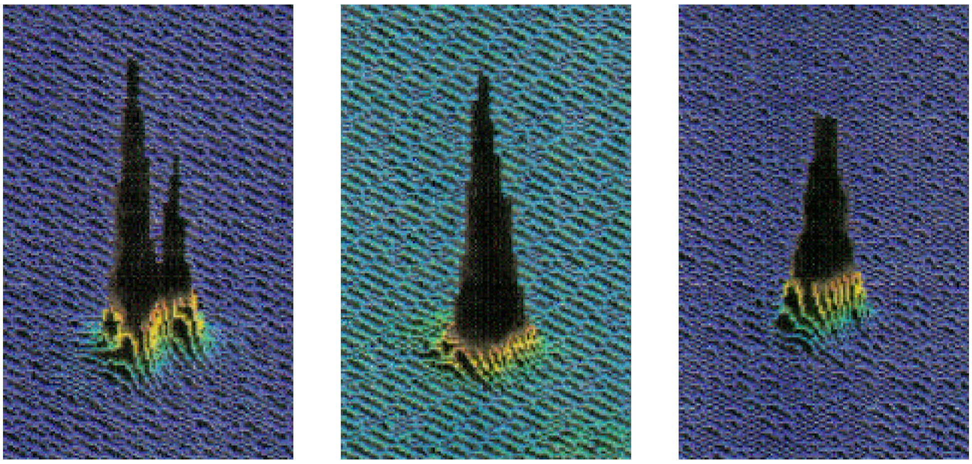
Fig. 9 Schematic of laser beam profiler

The beam propagation factors (M^2) and other relevant parameters are measured and shown in Table 4. The resonator for the second-harmonic laser consists of a plane output coupler and a convex rear mirror with a radius of 1 m. The pumping power and the *Q*-switch frequency are 3.56 kW and 5 kHz respectively.

Table 4 Second harmonic beam propagation factors and relevant beam parameters

	No aperture	ϕ1.6 mm	ϕ1.2 mm
M^2	3.16	2.6	1.17
Measured spot size focused by lens with f = 133mm (μm)	124	113	90.4
Calculated laser beam waist (mm)	0.55	0.47	0.36
Calculated divergence (full, mrad)	3.88	3.73	2.22
Laser power (W)	3.00	2.29	1.07

The beam energy distributions are shown in Fig. 10. The distribution looks like a TEM_{00} mode at the aperture of ϕ 1.6 mm, and the distribution without any aperture is multi-mode.



(a) No aperture (b) Aperture ϕ1.6 mm (c) Aperture ϕ1.2 mm

Fig. 10 Laser beam energy distributions at 532 nm

5 Conclusions

A second harmonic laser is set-up. Its performance is investigated. A maximum second harmonic laser power of 3 W is obtained. The conversion efficiency can reach as high as 48.72% and the beam propagation factor M^2 can reach as low as 1.07.

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