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Design and Development of Intracavity Optical Parametric Oscillator-based Eye Safe Laser Operating at 20 Hz without Forced Air Cooling

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ABSTARCT

In this paper we report the design and development of an electro-optically Q-switched diode pumped Nd:YAG laser with intracavity optical parametric oscillator, generating ~ 5 ns laser pulses of ~8 mJ energy at eye safe wavelength of 1534 nm. A Z-shaped laser resonator has been designed with porro prism end reflector in Q-switch arm containing RTP Q-Switch and a suitably oriented waveplate. The gain arm consists of a Ø3 x 72 mm Nd: YAG laser rod, pumped from one side by 3 x 5 bar laser diode array stack emitting total optical peak power of 740 W at 804 nm at 38 °C. Thermoelectric coolers (TECs) have been employed to maintain the optimum temperature of laser diode arrays and the combined heat load from the pump chamber and TECs is distributed over the system base plate with embedded heat pipes. Such cooling mechanism has eliminated the requirement of fins and fans in the laser system. Eye safe radiation is out-coupled through intra cavity KTA OPO (5 x 5 x 20 mm^3) placed in the gain arm. Laser was operated at 20 Hz for several duty cycles of 10 min on and 10 min off and output energy remained stable within ±0.5 mJ without any forced air/liquid cooling.

Keywords: Eye safe wavelength, intracavity optical parametric oscillator, diode pumped solid state laser, electro-optic Q-switching

NOMENCLATURE

c	Speed of light
ϕ	Photon density
n_l	Population inversion density
σ	Stimulated emission cross-section of Nd: YAG
γ	Inversion reduction factor
λ_p, λ_s, λ_i	Fundamental pump laser, signal, idler wavelength
l	Length of the pumped region
t_r	Round-trip time
t_c	Cavity decay time
R_p, R_s	Output reflectivity at fundamental pump, signal wavelength
ω_s, ω_i	Angular frequency of signal, idler
n_p, n_s, n_i	Refractive indices of pump, signal and idler
τ	1064 nm Q-switched laser pulse width
γ_s	Ratio of backward to forward pump pulse
g_s	Mode coupling coefficient of the cavity
d_{eff}	Effective non-linear coefficient
L_o	Optical length of OPO cavity
l_o	OPO crystal length
$2a_o l_o$	Round trip loss OPO crystal
ε_o	Permittivity of free space

1. INTRODUCTION

Lasers operating around 1540 nm are not only eye safe but have higher transparency in the atmosphere, silica based optical waveguides and fibers thus are in great demand for applications in laser range finding, remote sensing, lidar systems and optical communications etc. One of the most promising approaches for high-peak-power eye-safe laser sources is based on intracavity optical parametric oscillators (OPO)[1-5]. With the advent of high damage threshold nonlinear crystals and efficient diode-pumped Nd-doped lasers a resurgence of interest in intracavity OPO's has been observed. Intracavity OPO has advantages of stability, compactness, low threshold and high efficiency.

Electro-optically Q-switched Nd: YAG - intracavity OPO eye safe lasers are generally based on mirror end reflectors, which are highly sensitive to misalignment. In this paper we report design and development of a Z-shaped laser resonator with porro prism end reflector in Q-switch arm. Besides providing mechanical stability the porro prism also results in better spatial profile of the output beam. Other special features of laser include solid state cooling mechanism employing thermoelectric coolers and heat pipes and use of motorized variable magnification (2-8X) beam expander at the output to control the laser spot size at different ranges. Present paper however focuses on the laser resonator design details and experimental results. Details pertaining to thermal management and beam divergence control shall be reported separately.

2. RESONATOR DESIGN

A Z-shaped laser resonator (Fig. 1) has been designed with porro prism end reflector in Q-switch arm containing RTP Q-Switch and a suitably oriented waveplate. Two high extinction ratio polarizers with high damage threshold coatings have been employed such that s-component of polarization oscillates in the resonator. The gain arm consists of a φ3 x

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72 mm Nd: YAG laser rod, pumped from one side by 3 x 5 bar laser diode array (LDA) matrix stack emitting total optical peak power of 740 W at 804 nm at 38 °C. On opposite side of LDA, a gold coated V-shaped reflector has been used to reflect any unabsorbed pump radiation. Thermoelectric coolers (TECs) have been employed to maintain the optimum temperature of LDA and the combined heat load from the pump chamber and TECs is distributed over the system base plate with four embedded heat pipes. Such cooling mechanism has eliminated the requirement of fins and fans in the laser system. Eye safe radiation is out-coupled through intra cavity KTA-OPO (5 x 5 x 20 mm^3) placed in the gain arm, which includes Nd: YAG laser rod pump chamber. Input face of the x-cut KTA crystal is coated with HT @ 1064 nm and HR @ 1534 nm while output face is coated with HR @ 1064 nm and 70 % R @ 1534 nm. A motorized variable magnification (2-8X) beam expander has also been employed at the output to control the laser spot size at different ranges.

3. DESIGN ANALYSIS

For eye safe wavelength generation from Nd: YAG laser, intracavity OPO design philosophy has been chosen as it gives advantages of stability, compactness, low threshold and high efficiency. KTA crystal[6-7] is preferred over KTP due to large nonlinear coefficient, high figure of merit, higher optical damage threshold and high transparency range (350-5300 nm).

3.1 Resonator without OPO

Laser resonator as shown in Figure 1 with a high reflecting mirror replacing OPO crystal has been analyzed theoretically for calculating the laser (1064 nm) parameters by solving the rate equations. The Q-switched laser (1064 nm) output parameters were analyzed numerically by solving the coupled rate equations of photon (φ) and population inversion density (n_l)[8-9].

$$\begin{cases} \dfrac{d\phi}{dt} = \phi\left[\dfrac{2\sigma n_l l}{t_r} - \dfrac{1}{t_c}\right] \\ \dfrac{dn_l}{dt} = -\gamma\sigma c\phi n_l \end{cases} \tag{1}$$

Theoretical estimations were carried out for the available input powers from LDA to validate the design capability for generating required energies and pulse widths at 1064 nm. Estimated temporal variation of inversion density and photon density is shown in Fig. 2 for the parameters listed in Table 1.

Figure 3 (a) and 3 (b) shows the effect of variation of input

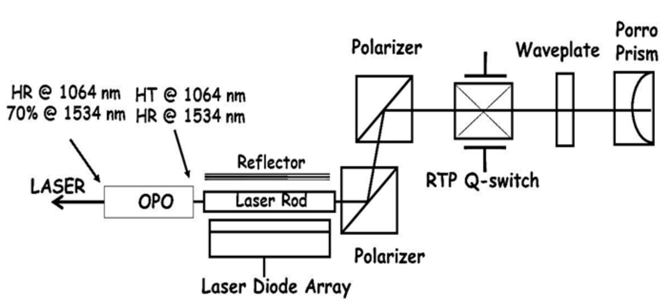

Figure 1. Optical layout of laser resonator.

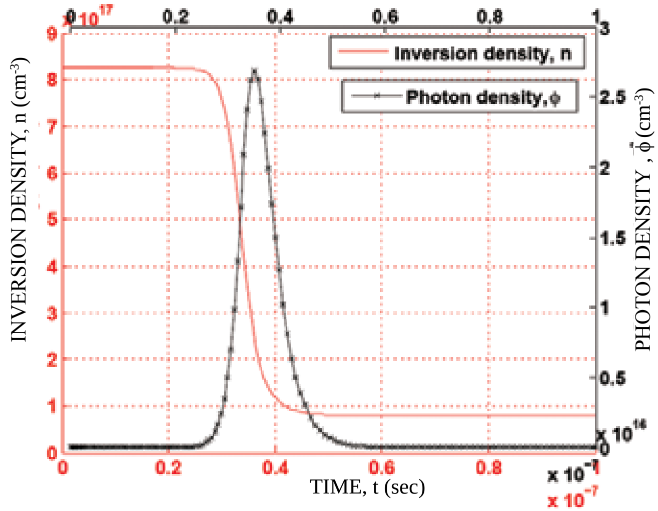

Figure 2. Temporal variation of inversion density and photon density

Table 1. List of parameters

Parameter	Value
Stimulated emission cross section, σ (cm^2)	2.8 x 10^{-19}
Spontaneous emission life time, t_{spon} (μs)	230
Inversion reduction factor, γ	1.2
Quantum efficiency, ξ	0.965
Square pulse pump duration, t_p (μs)	245
Double pass absorbed fraction, α	0.8
Pump coupling efficiency, χ	0.9
Reduction factor, η	0.615

diode pump power (175 mJ, 260 mJ and 350 mJ) and output reflectivity on output energy and pulse widths respectively. Figure 4 shows the intracavity circulating energy in the resonator for carrying out intracavity operation. These results helped in selection of the diode peak power output for the generation of sufficient power at 1064 nm exceeding threshold intensity. Analyses of these results together with threshold calculations for OPO cavity as carried out in Section 3.2 are discussed together in Section 3.3.

3.2 Theoretical Estimation of Pump Laser Threshold Intensity for KTA OPO

KTA belongs to the orthorhombic crystal system, and therefore is optically biaxial. The indices of refraction for any propagation direction are given by the index ellipsoid defined by[6]

$$\frac{\sin^2\theta\cos^2\varphi}{n^{-2}-n_x^{-2}} + \frac{\sin^2\theta\,\sin^2\varphi}{n^{-2}-n_y^{-2}} + \frac{\cos^2\theta}{n^{-2}-n_z^{-2}} = 0 \tag{2}$$

where θ is the angle to the z axis, and φ is the angle to the x axis in the x–y plane. The indices of refraction versus wavelength are given by Sellmeier equations[6]:

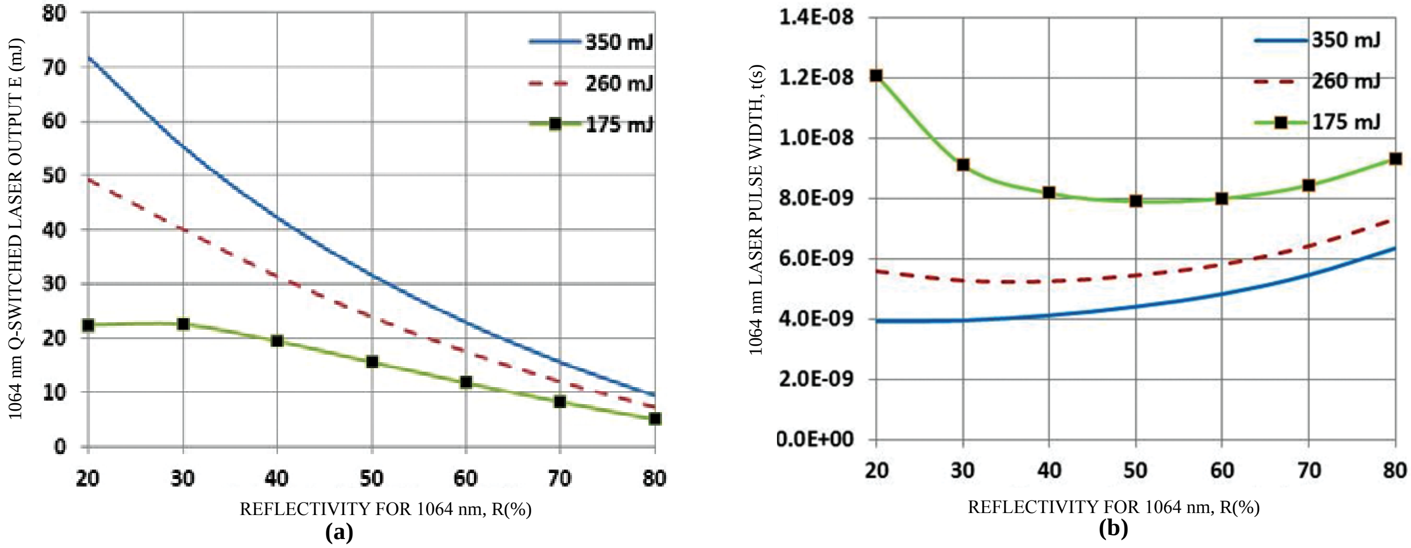

Figure 3. Variation of (a) output energy and (b) pulse width.

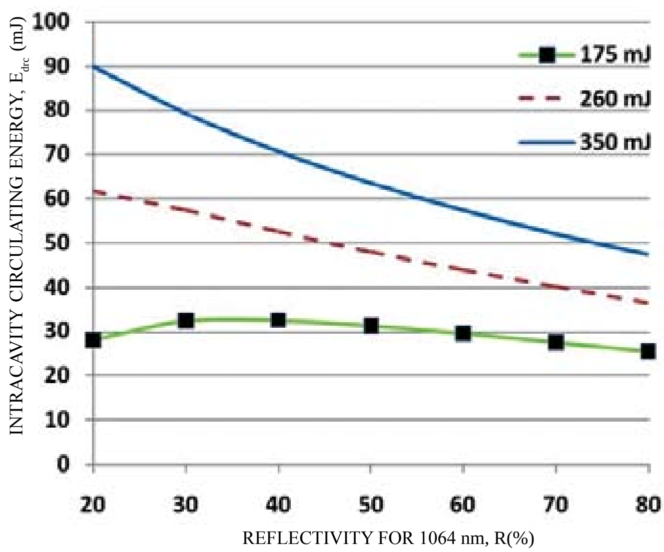

Figure 4. Intracavity circulating energy.

$$\begin{cases} n_x^{\,2} = 5.55552 + \dfrac{0.04703}{\lambda^2 - 0.04030} + \dfrac{602.9734}{\lambda^2 - 249.6806} \\ n_y^{\,2} = 5.70174 + \dfrac{0.04837}{\lambda^2 - 0.04706} + \dfrac{647.9035}{\lambda^2 - 254.7727} \\ n_z^{\,2} = 6.98362 + \dfrac{0.06644}{\lambda^2 - 0.05279} + \dfrac{920.3789}{\lambda^2 - 259.8645} \end{cases} \quad (3)$$

Due to very small value of nonlinear coefficients in type I interactions, type II interactions are widely used in the KTA. For propagation in the x-z plane ($\varphi = 0°$), type II interactions correspond to type II phase matching in a positive uniaxial crystal (Non-critical phase matching, NCPM). For propagation in x-z plane, the polarization of the pump wave is along the y-axis (ordinary wave, 'o-wave') of the crystal as is that of the signal wave. The idler wave is polarized in the x–z plane (extraordinary wave, 'e-wave'). For this type II phase matching, the wavelengths for three waves should satisfy energy conservation and the momentum-matching condition,

$$\begin{cases} \dfrac{1}{\lambda_p} = \dfrac{1}{\lambda_s} + \dfrac{1}{\lambda_i} \\ \dfrac{n_y(\lambda_p)}{\lambda_p} = \dfrac{n_y(\lambda_s)}{\lambda_s} + \dfrac{n(\theta, \lambda_i)}{\lambda_i} \end{cases} \quad (4)$$

Figure 5 shows the tuning curve calculated signal, idler wavelengths and effective non-linear coefficient for KTA optical parametric converter pumped at 1064 nm propagating in x-z plane. It shows that for NCPM condition, $\theta = 90°$, $\varphi = 0°$, a signal wavelength of 1532.4 nm shall be generated with maximum nonlinear coefficient of 3.64 pm/V.

The threshold pump intensity, I_{th} for a singly resonant NCPM OPO with reflection of the pump from the OPO output coupler is given by[6]:

$$I_{th} = \frac{1.8}{\kappa g_s l_o^{\,2} (1+\gamma_s)^2} \left[\frac{25 L_o}{c\tau} + 2\alpha_o l_o + \ln\frac{1}{\sqrt{R_s}} + \ln 2 \right]^2 \quad (5)$$

where

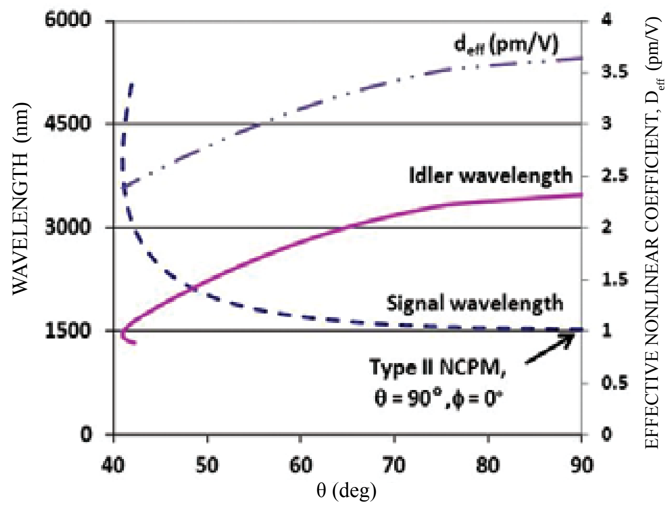

Figure 5. Calculated tuning curves in x-z plane for KTA-OPO pumped at 1064 nm.

$$\kappa = \frac{2\omega_s \omega_i d_{eff}^{\ 2}}{n_s n_p n_i \varepsilon_o c^3} \qquad (6)$$

Figure 6 shows the threshold intensities required for the generation of KTA-OPO eye safe laser (signal) wavelength for different output reflectivities at 1534 nm.

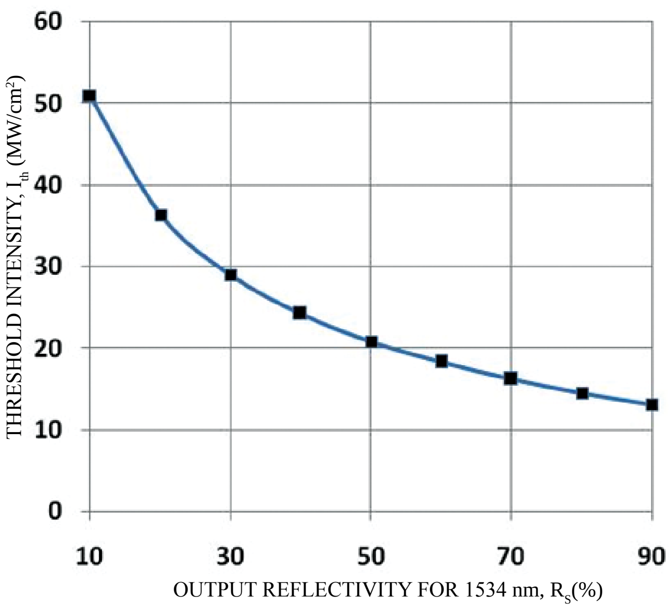

Figure 6. Calculated threshold intensity required for KTA-OPO eye-safe laser.

3.3 Results Analysis

Threshold intensity in Fig. 6 has been plotted using the pulse width of ~ 8 ns for the pump laser from Fig. 3 (b) (175 mJ diode output energy). As per thumb rule[10] for designing an efficient OPO, pumping intensity should be at least 4 times above the threshold pump intensity for maximum efficiency. Therefore, for output reflector, R_s value of 70 %, the intensity required is ~ 75 MW/cm^2 (4 times the value from Fig. 6, 16.2 MW/cm^2). For the pump mode size of ~ 1.4 mm, the resultant intracavity power and circulating energy are 4 MW and 32 mJ respectively. From Fig. 4, intracavity circulating energy (for 175 mJ diode output energy) is ~ 31 mJ, while for the same threshold power requirements, if extra cavity operation were to be carried out, the diode output pump power would have to be increased by ~ 50% (Fig. 3 (a) for 40% R). Thus intracavity approach was finalized for efficient operation.

4. EXPERIMENTAL DETAILS AND RESULTS

4.1 Temperature Stability

Before full assembly and alignment, temperature stability of LDA was observed by mounting only the pump chamber on the base plate with embedded heat pipes. Figure 7 shows the LDA case temperature variation with time, base plate just below the pump chamber and room temperature recorded using Yokogawa XL100 data logger. As can be seen in the graphs, before starting the operation, initial temperature of all points was at room temperature (~ 30 °C) the trend was recorded for ~ 7 min, then TEC controller was switched on with set temperature at 38 °C. Till the LDA power is switched on its temperature fluctuates within 2 °C but later a good temperature stability of ± 0.5 °C was achieved.

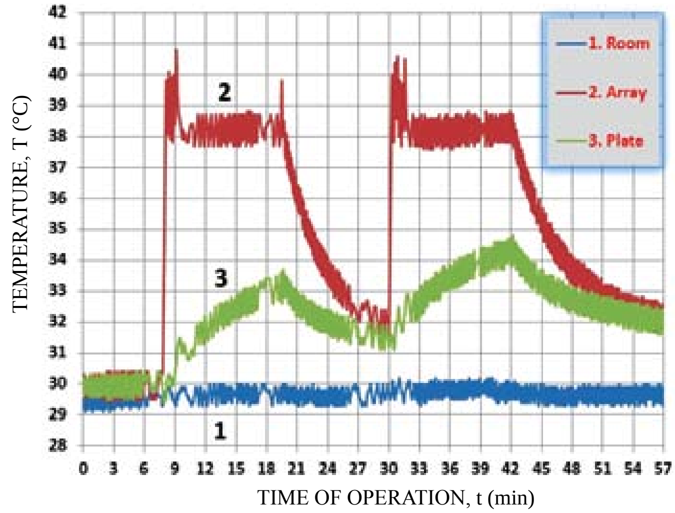

Figure 7. Temperature stability.

It was observed that the plate temperature remains ~ 1 °C higher to room temperature after 10 minutes operation. Thus, numbers of cycles were repeated to see the long term stability. Figure 8 shows that there is no further rise in temperatures for 5 hrs continuous operation for 10 min ON / 10 min OFF duty cycle.

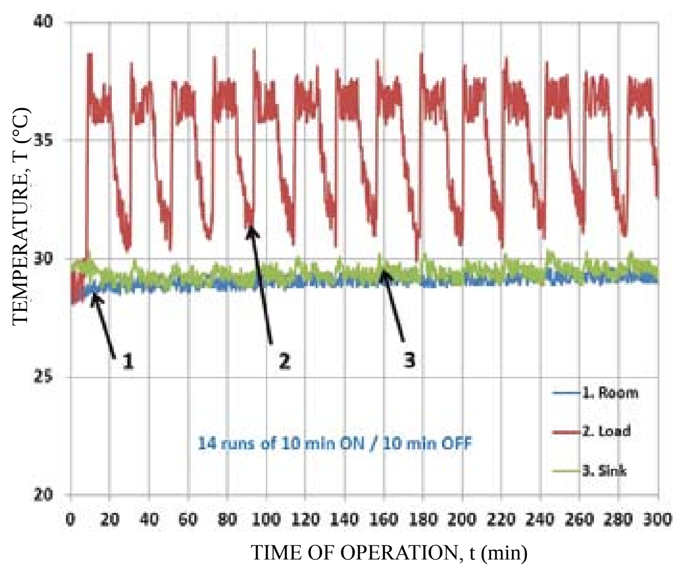

Figure 8. Temperature stability.

4.2 Free Running Performance

After resonator assembly and alignment, laser was first operated in free running mode (no voltage to Q-switch) by adjusting the waveplate to achieve maximum output through the polarizer in Q-switch arm (Fig. 9). In this case as the intracavity intensity does not overcome the threshold for nonlinear conversion, the OPO crystal acts like an HR mirror for fundamental wavelength. Figure 10 shows the free running performance at different input energies recorded using Ophir's

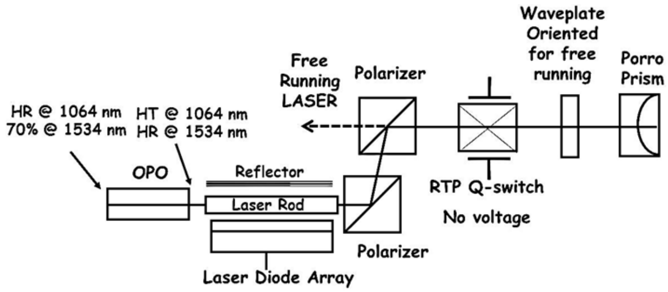

Figure 9. Free running resonator setup.

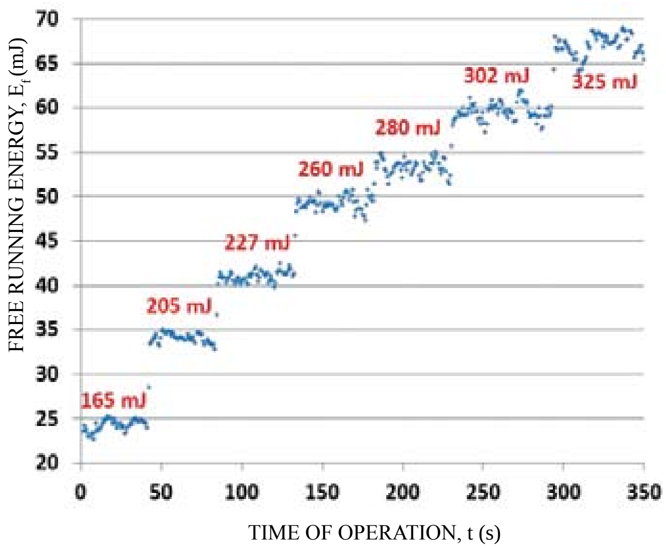

Figure 10. Free running fundamental laser.

PE50BBDIFF detector with USBI-4 interface. As can be seen output energy remains stable and ~ 20 % optical to optical efficiency was achieved. The arrays were intentionally operated at ~804 nm to reduce thermal problems otherwise higher efficiencies are possible. In the present design, since the high reflectivity mirrors were coated directly on the OPO crystal, therefore Q-switched performance for 1064 nm was not carried out. However, free running energy results corroborate very well with the simulated Q-switched results (175 mJ input energy), where for 30 % output reflectivity, ~ 20 mJ Q-switched energy should be obtained (~ 80 % Q-switching efficiency). Figure 11 shows the uniform output spatial profile obtained for the free running operation.

4.3 Eye Safe Operation

For eye safe operation, waveplate was adjusted to create high loss condition so that no oscillations occur in the resonator. Towards end of the pump pulse (245 µs duration) quarter wave voltage was applied to the Pockels cell and Q-switched output is achieved directly at eye safe wavelength. Figure 12 shows laser pulses for eye safe wavelength detected from gain arm and residual pump laser detected through Q-switch arm and recorded using New Focus 1623 and Alphalas UPD-200-UD detectors respectively. As can be seen clearly after OPO conversion pulse width reduces from ~ 7 ns to 5 ns. Laser was operated for several duty cycles of 10 min on and 10 min off at 175 mJ input energy, Figs. 13(a) and 13(b) depict output

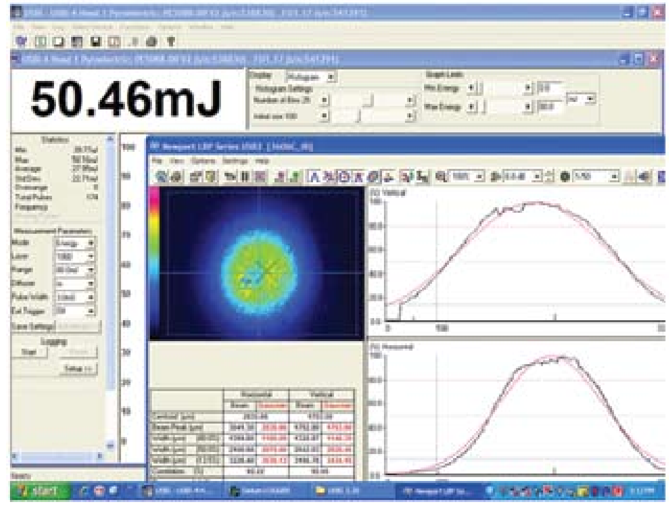

Figure 11. Free running spatial profile of 1064 nm output.

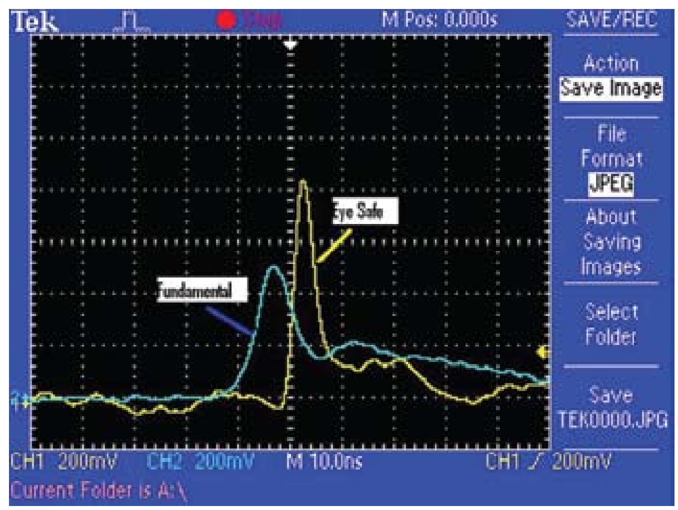

Figure 12. Pump and signal Q-switched laser pulses.

performance at 20 Hz. Energy output was stable within ± 0.5 mJ.

The far field divergence of the eye safe laser pulse was monitored using the Newport LBP beam profiler as shown in Fig. 14. The measured divergence using lens of focal length 100 mm was 1.9 mrad and 2.6 mrad in *x* and *y* directions respectively at 2X magnification of beam expander.

5. CONCLUSIONS

In this paper, theoretical design and experimental results of an electro-optically Q-switched diode-pumped Nd: YAG laser with intracavity KTA OPO, generating ~ 5 ns laser pulses of ~ 8mJ energy at eye safe wavelength of 1534 nm are reported. Advantage of intracavity operation has been highlighted using the theoretically generated curves for 1064 nm pump laser and threshold condition for OPO operation. The results match very well with the experimental results. Special features of laser include Z-shaped laser resonator with porro prism end reflector in Q-switch arm and solid state cooling mechanism employing thermoelectric coolers and heat pipes.

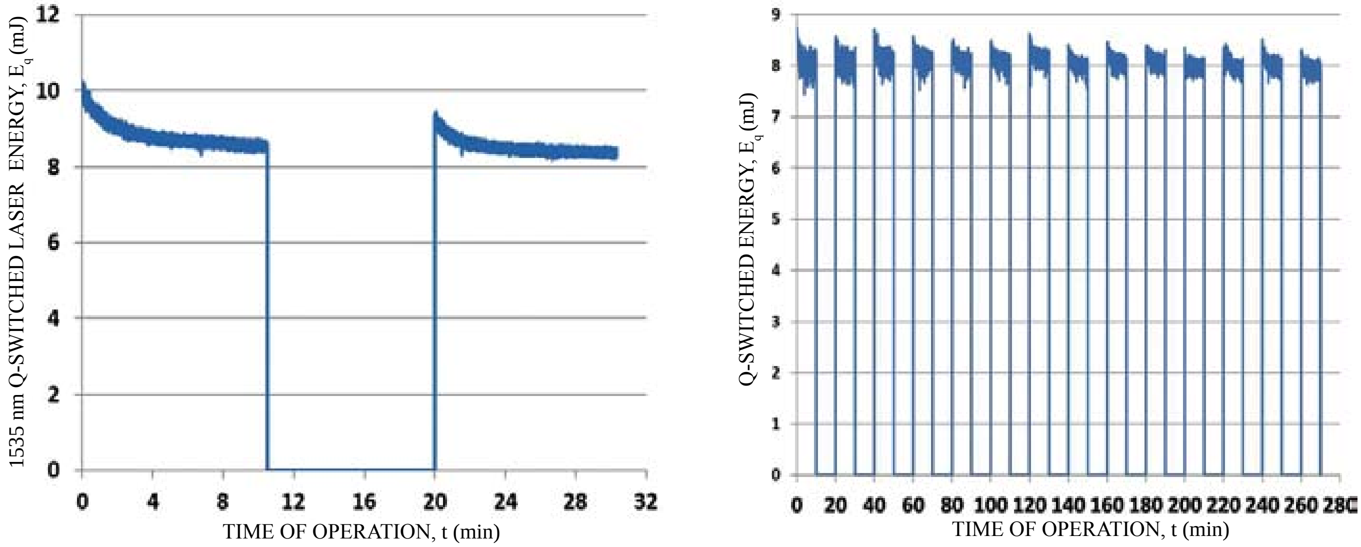

Figure 13. Signal laser at 20 Hz operation (a) 02 cycles, (b) 14 cycles.

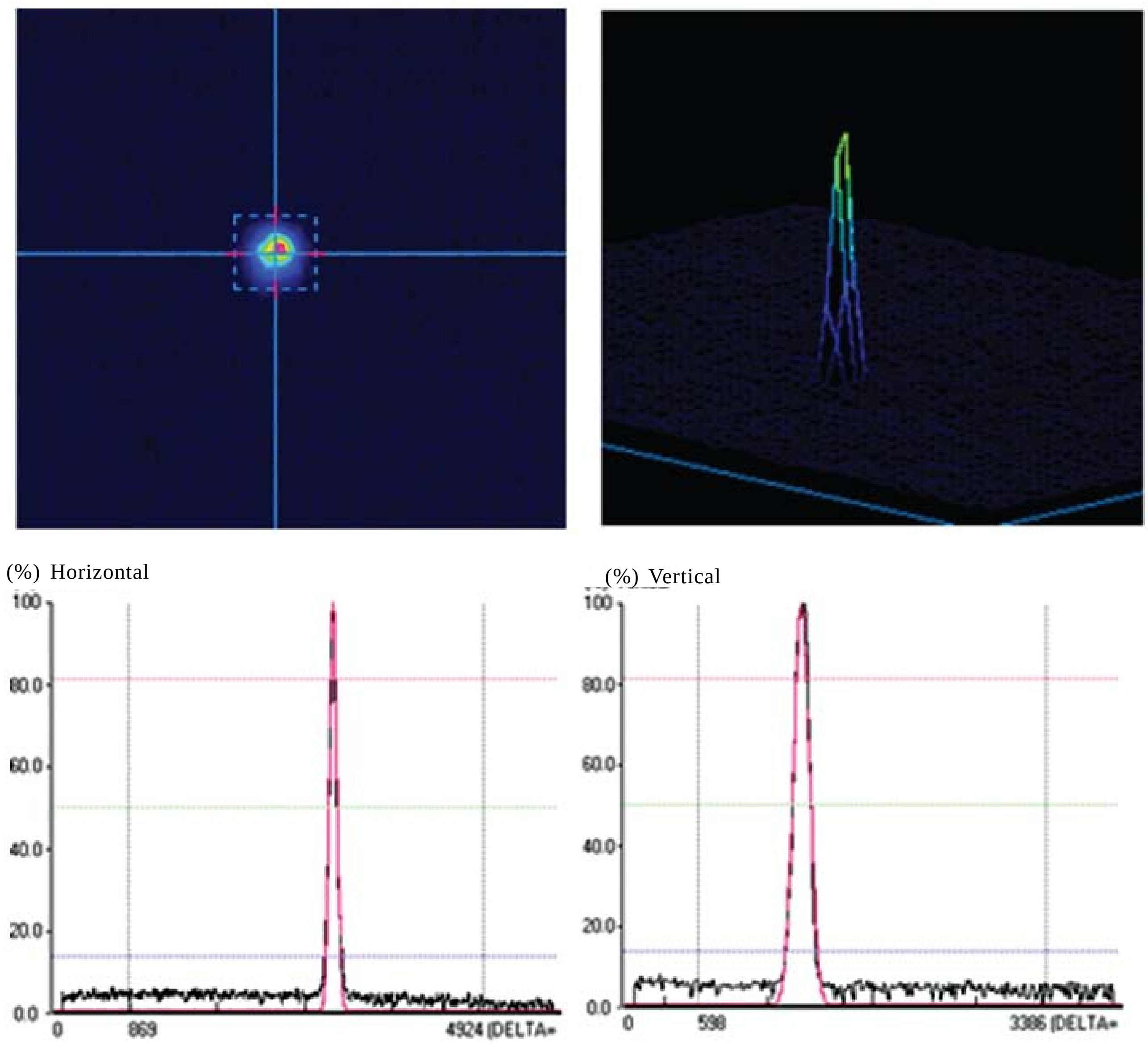

Figure 14. Far field spatial profile of eye safe laser.

Far field beam divergence at 2 X magnification is measured to be 1.9 mrad and 2.6 mrad in x and y directions respectively. Laser was operated at 20 Hz for several duty cycles of 10 min on and 10 min off and output energy remained stable within ± 0.5 mJ without any forced air / liquid cooling.

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