Detection and analysis on versatile coding strategies of high frequency active Q-switched Nd:YVO_4 laser for designation of different targets

Ashraf F. El-Sherif*[1] and Mahmoud Talaat[2]

[1]Laser Photonics Research Group, Engineering Physics Dept., MTC, Cairo, Egypt.

[2]Military Technical Institute, Cairo, Egypt.

*ashraf.alsharif@staff.aast.edu

Abstract

We report an active Q-switching with different coded schemes generated in the high power diode end pumped Nd:YVO_4laser (DEPSS)using two different techniques of special combination of optical choppers and acousto-optic modulator (AOM) at higher repetition rates of 100 kHz for the first time to the best of our knowledge in any practical laser target designation (LTD) systems.This paper presents experimental studies on a high-efficiency, high power diode laser module of 6W at 808nm end-pumped 3×3×10mm Nd: YVO_4 laser with high efficient water cooling system. An optical slope efficiency to be around 76%, the final conversion efficiency to be 63% and an output laser power of over 3.8W at 1064nm laser was obtained with a high beam quality factor of M^2 <1. A single Q-switched pulse with high peak power of 1.1 kW and pulse width of 40-ns at FWHM is produced at input pumping power of 3W using optical chopper. The pulse-to-pulse stability was measured and improved to be ~ 96.7 % with frequency near 20 kHz.The highest peak power of 95.4 kW with lowest pulse repetition frequency of 221.6 Hz and pulse width of 46 ns at FWHM with the pulse-to-pulse stability of ~ 95 % was measured at certain regime of operation. Special modulation and coding of high stable, high peak power Nd: YVO_4 laser pulses at 1064nm using the combination of different optical chopper blades were achieved. A high peak power is increased to be more than 4.84 kW with shortest pulse width of 25 ns at FWHM have been obtained using an acousto-optic modulator (AOM) as an active Q-switched. The pulse-to-pulse stability was measured and improved to be ~ 97 % at high repetition rate ranges from 10 kHz to 100 kHz. The performance and availability for the DEPSS laser cavity with two different techniques for producing high frequencies and an output controlled laser coding schemes which can be used in military equipment as laser target designation systems and laser range finders were investigated.

Keywords: Q-switched lasers, High power solid state laser, DPSS, Nd:YVO4, Designation system.

1. Introduction

Nowadays, Q-switched (QL) nanosecond and mode-locked (ML) picosecond lasers, producing large peak power are key instruments for a lot of biological applications such as in fluorescence measurements, ultrafast spectroscopy and microscopy [1]. Furthermore these lasers have been demonstrated to bealso suitable for micromachining, in particular for the treatment of temperature-sensitive materials with an ablation process based on multi-photon-ionisation [2]. For this last application it seems very interesting to develop a very robust, highly-efficient system based on diode-pumped solid-state lasers (DPSSL). And, for nanosecond and picosecond DPSSLs, Neodymiumdoped crystals (in particular Nd-doped vanadates) are particularly suitable because of their high gain [3]. In this point of view, Neodymiumdoped Yttrium Orthovanadate crystal (Nd:YVO_4) and the Neodymium-doped Gadolinium Orthovanadate crystal (Nd:$GdVO_4$) seems to appear an interesting and alternative to the well-established [3,4,5].

Neodymium-doped single vanadate crystals including Nd:YVO_4 and Nd:$GdVO_4$ have been identified as excellent laser materials for diode-pumped solid-state lasers because of their large absorption and large emission cross sections [6-13]. In the Q-switching operation, however, the large emission cross sections usually limit their energy storage capacities. Such solid-state laser media, of neodymium-doped crystal, was used also in applications like laser fusion, material processing, optical communications, product marking, remote sensing and surgery [14, 15].

Today; reliable one and two-dimensional laser diode arrays are commercially available with continuous-wave and quasi-CW peak powers up to 100 W and 10 kW respectively [16]. Great attention has been paid to high peak power, high repetition rate all-solid-state second and triple harmonic green–blue laser for some applications, such as medical applications, spectroscopy, display, optical data storage, undersea detection and communications and day/night military designation systems. Furthermore, laser-diode-pumped all solid-state laser device has high efficiency, small volume and compact structure, very convenient for different applications.

In fact, active Q-switched operation of Nd:$YVO_4$with different wavelengths in the range of only fewtens of kHz has already been achieved [17 - 19]. We are demonstrating in this paper higher peak power actively Q-switched DPSSL Nd:YVO_4 laser at higher repetition rate of hundreds of kHz using both intracavity acousto-optic modulator (AOM) and optical chopper, different laser coding and modulation schemes using multi-combinations of optical chopper blades as a new technique of higher peak power, higher repetition rates ofspecial coded for advanced laser designation systems were investigated for the first time (to our best knowledge).We will see that this techniques allows us to demonstrate a very stable and robust higher repetition rate systems.

In this paper, we present the first demonstration of a diode-pumped actively coded Q-switched high power diode pumped Nd:YVO_4laser with an intracavityAOM crystal to produce 300 W peak power with 50 ns pulse width (FWHM) at highest repetition rates of 100 kHz, and nearly 1.7 kW with pulse width of 30 ns (FWHM) at repetition rate of 25 kHz, this peak power increased up to maximum peak power of 5 kW with shortest pulse width of 25 ns operating at high repetition rate of 10 kHz. While by using intracacity optical chopper, higher peak power of nearly 95.5 kW with pulse width of 45 ns at lower repetition rate of 222 Hz, the peak power decreased to be 1.15 kW with pulse width of 40 ns at higher repetition rate of 20 kHz. It gives better result in comparison with the current laser designator sources in service from the point of pulse to pulse stability which reached more than 95%,Gaussian pulse shape and higher frequencies of the code schemes.

2. Active Q-switching using optical chopper

One of the earliest Q-switched lasers used a mechanical rotating aperture [20]. While this method of Q switching was abandoned for faster switching techniques, the current generation of high-quality mechanical choppers presents the opportunity to reinvestigate the use of such a device as an intracavity Q switch.

Using CW mode of operation for the laser diode of 6 W at 808 nm as a pumping source for 1% Nd:YVO_4 rod, and optical chopper was placed intracavity as anactive Q-switching element. High power diode laser module was a continuous GaAlAs quantum-well laser diode module with a maximum power of 6 W. The length of the cavity was 4.3cm, output coupler reflectivity of 85 %. Fig. 1 shows experimental set-up and photograph for the active Q-switched Nd:YVO_4 laser system using optical chopper.Q-switched pulsed laser at 1064 nm with narrow pulse width and high peak power were achieved using fiveoptical chopper plats with different number of reticles openings.

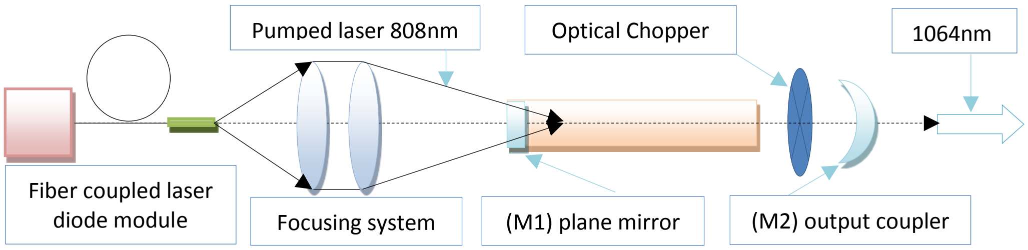


Fig. 1.Experimental setup for a Q-switched DEPSS laser cavity using optical chopper,

Figure 2 illustrates that the optical-to-optical slope efficiency to be around 76 % and the final conversion efficiency to be 63 % at free running CW mode of operation.The maximum cw output power was 3.9 W at 6 W of absorbed pump power.The output measurements were being averaged to 5 readings and measured at a constant diode temperature of 25°C. Fig. 2 shows the DEPSS (Nd:YVO_4) optical output power versus optical pumped one with an optimized output coupler of 85% reflectivity at 1064 nm with threshold pumping power of 860 mw.

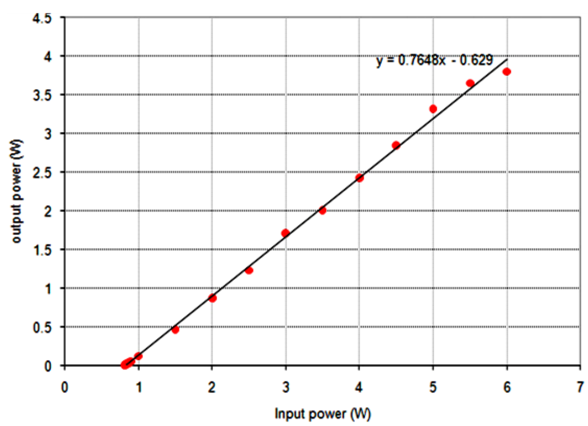


Fig.2. (Color online) (DEPSS) CW Nd:YVO_4 optical output power versus optical pumped power.

Table (1) shows the best optical data achieved experimentally for each optical chopper at pumping power of only 3 W at wavelength of 808. It was found that the highest average power of 0.972W had been occurred by reticle#5 with the highest peak power of 95.4 kW at lower repetition rate of 221.6Hz and pulse width of 46 ns. While by using reticle#1 a narrower pulse width of 40ns at higher repetition rate of 20 kHz and a peak power of 1.115 kW was investigated. Fig. 3 shows the output average power, pulse width, and peak power versus frequency for pumping power ranges from 3W to 5W using reticle #1.
The active Q-switched laser power at 1064 nm had an average range from 0.4 W to 1.05 W using an optical chopper for different pumping power.

Table (1) shows the optical data achieved experimentally for each optical chopper:

Type	Average power (W)	Pulse width (ns)	Pulse repetition frequency (kHz)	Peak power (kW)	Input power (W)
Reticle#1 	0.895	40	20.076	1.115	
Reticle#2 	0.9231	50	3.1112	5.9	
Reticle#3 	0.890	45	1.08	17.98	3W
Reticle#4 	0.88	55	0.5473	29.23	
Reticle#5 	0.972	46	0.2216	95.4	

Figure 3(a) shows the pulse repetition rate ranged from 5 kHz to 20 kHz. Pulse width ranged from the shortest one of 18 ns at higher pump power of 5 W and repetition rate of 20 kHz to the largest pulse width of 75 ns at the lower pump power of 4 W and repetition rate of 5 kHz, as seen in Fig. 3(b). The highest peak power of 35 kW at a limited repetition rate of 1 kHz and a shortest pulse width of 25 ns were achieved as in Fig. 3(c).

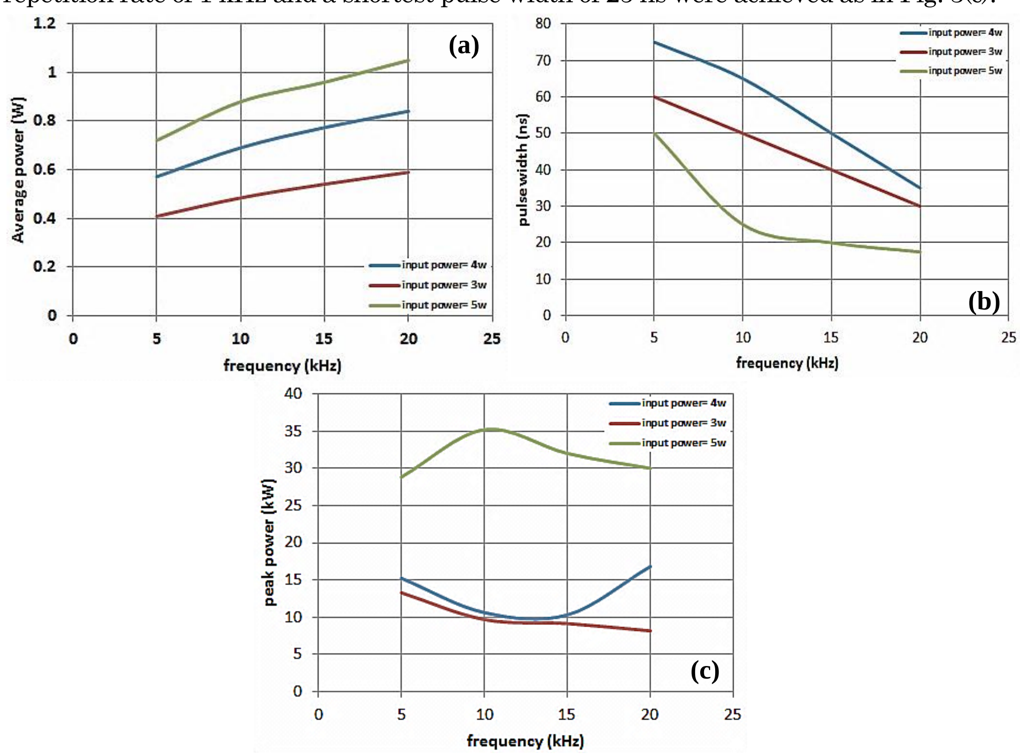


Fig. 3. (a) Average output power, (b) Output pulse width and (c) Peak power vs. frequency for different pumping powers ranges from 3W to 5W using only reticle#1.

It is found that the optical chopper active Q-switch had the highest average power of 1.05 W, highest repetition rate of 20 kHz and most uniform beam profile shape using reticle #1.

The laser was Q-switched with different plats of optical chopper. Fig. 3 summarizes the best performance of each scheme. The main Q-switched pulse peak power of 35 kW with pulse duration of nearly 25 ns at the moderate frequency of 10 kHzwas obtained, whereas the average power not approached to the CW value of 3.9 W even when the frequency was set to the highest one with optical chopper of 20 kHz.

Figure 4(a) shows the oscilloscope trace of the output pulse train emitted from diode pumped Q-switched diode pumped Nd:YVO_4 laser at 20 kHz using reticle #1, pulse width of nearly 35 ns at FWHM with pumping power of 4 W and output peak pulse power of 17 kW. Fig. 4(b) shows the trace of the pulse train emitted at nearly 5 kHz, pulse width of nearly 50 ns with pumping power of 5 W and higher output power of 28 kW for the main Q-switch pulse, there is an evidence of preleasing at all frequencies using this techniques due to out of optimization on and off time of the resonator [21].

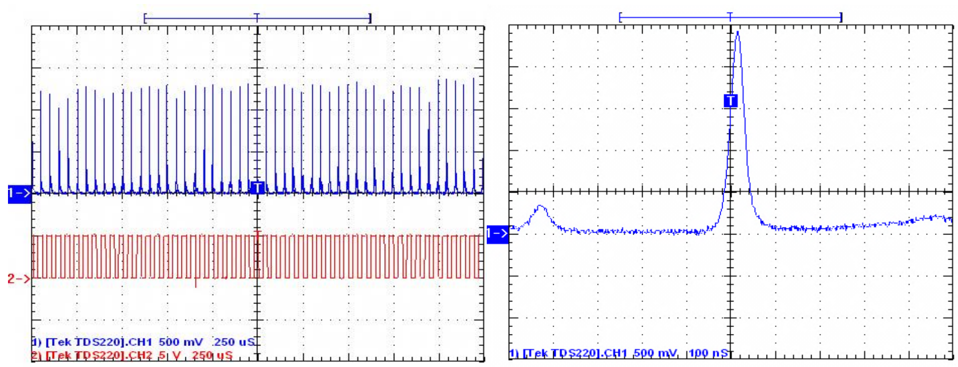


Fig. 4(a) Pulse trace (left) and pulse width (right) of 35 ns at frequency of 20 kHz using reticle #1.

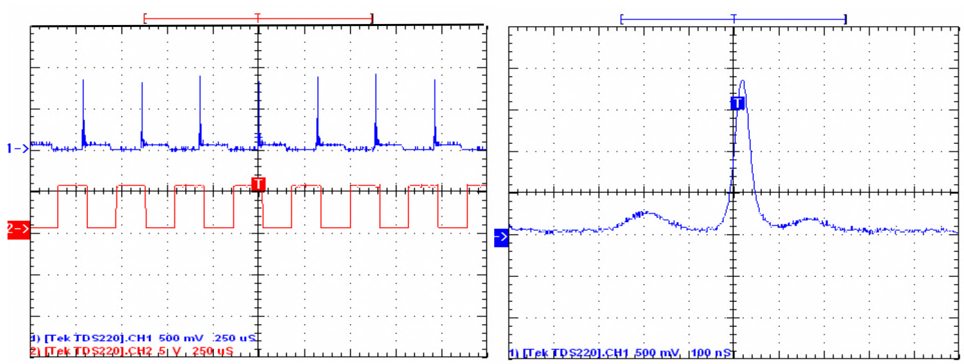


Fig. 4(b) Pulse trace (left) and pulse width (right) of 50 ns at frequency of ≈5 kHz using reticle #1.

The time characteristics of the highest and fast active Q-switched laser pulses were measured with the help of a fast vacuum photodiode (Thorlab Inc. model PDA10C) and Tektronix oscilloscope TDS 3052B (200 MHz, 2 GS/s). Using a CCD beam profiler camera (Coherent model) and spectrometer (HC4000 – Ocean Optics model) from ocean optics and a power and energy meter (Gentech- solo 2 model). The highest performance output waveforms and pulses trace of the produced peak power laser signal of 30 k W with pulse width less than 18 ns at moderate repetition rate of 20 kHz using reticle #1.

2.1. Versatile coding technique of laser signals using combinations of optical chopper

At this section a trial for generating a certain laser scheme or codes using a simple coupling or combinations of two different optical chopper plates was investigated. The best combination for generating a determined scheme from active Q-switched Nd:YVO_4laser pulses to be known as a pulse repetition frequency (PRF) code was found by using the optical chopper with reticle #1 as a main chopper in all possible combinations to generate a Q-switched laser pulses and the second chopper determined the output scheme orcodesof the output generated laser pulses. Fig. 5shows a plan of optical chopper combinations that had been used.

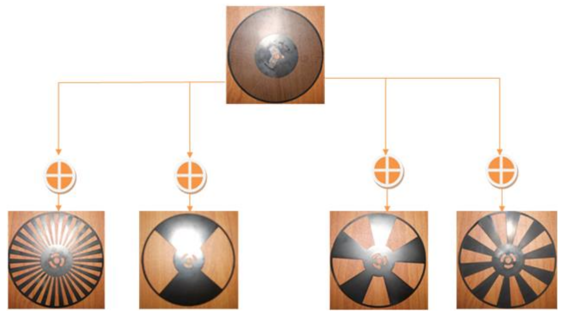
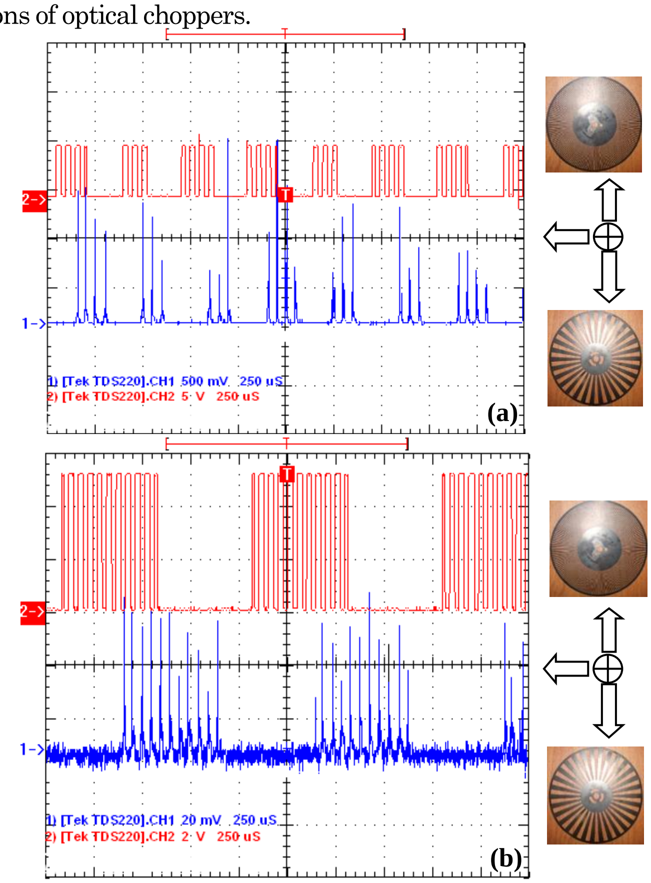


Fig. 5. Combinations of the different optical chopper with reticle #1 as a main chopper and different of choppers as a coding unit.

Figure 6(a-c) shows the output laser pulseswaveforms or pattern and code schemes from a certain combinations of two different optical chopper plats operating at wavelength of 1064 nm. The highest performance output waveforms and pulses trace of the produced peak power laser signal of 30 k W with pulse width less than 18 ns at repetition rate of 20 kHz using reticle #1 combined with one of the either reticles of #2, #3 or #4. There is no evidence of prelasing or postlasing using these versatile laser coding techniques using these combinations of optical choppers.



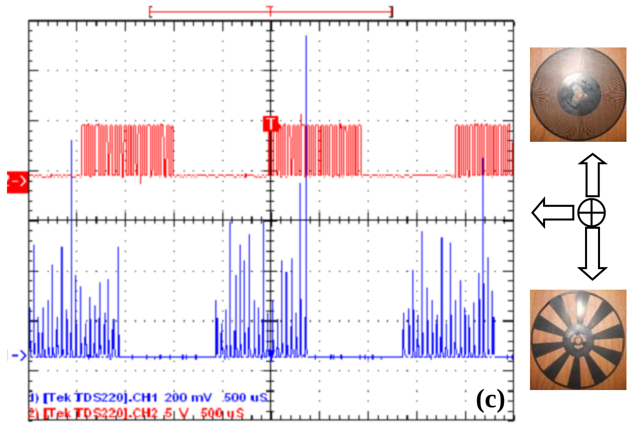


Fig. 6 Pulse trace and code schemes for pulse width of 18 ns and high peak power of 30 kW using reticle #1 combined with other reticles (a) #2, (b) #3 and (c) #4.

3. Experimental set-up and measurements of high frequency active Q-switching using AOM crystal

Using CW mode of operation for the laser diode of 6 W at 808 nm as a pumping source for 1% Nd:YVO_4 rod, and acousto-optic modulator (AOM) of the type NEOS 34027-1.5-SF10 Q-switch crystal uses a flint glass optical material with a Lithium Niobate transducer crystal was placed intracavity as anactive Q-switching element [22-27]. The Q-switch assembly was mounted on a fixture to provide sufficient adjustment to peak the Q-switch's efficiency (horizontal, vertical, and Bragg angle) and to provide a sufficient heat sink to ensure the housing temperature does not exceed 50°C. The Q-switch can be driven by any good driver with a nominal 50 ohm output of 27.12 MHz and no more than 4 watts RF power, however, we recommended that a NEOS driver be used to drive this Q-switch to achieve optimum performance. The Q-switch has been designed and verified to satisfy the specifications [28].Fig. 7 shows experimental set-up for the DEPSS active Q-switched Nd:YVO_4 laser system using intracavity AOM crystal.

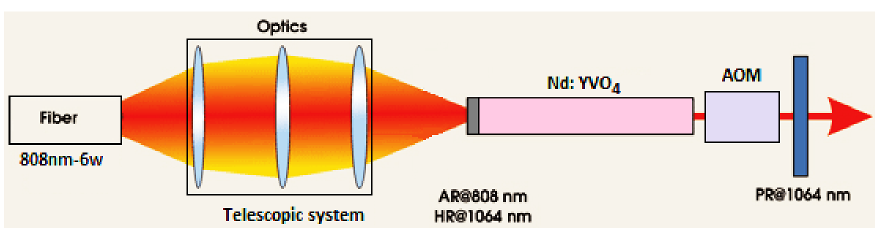


Fig. 7.(a) Experimental setup for a Q-switched DEPSS laser cavity using intracavity AOM crystal, (b) Photograph of the experimental set-up.

An acousto-optical Q-switch with high diffraction loss at 1064 nm was placedbetween rod and outputcoupler mirror.RF driver may be modulated in "Fixed" duration mode at any frequency from 1 Hz to 500 kHz by an external frequency source. In "Variable" duration mode, the RF driver can be modulated from DC to 500 kHz. The RF energy can be modulated off in a short period of time (50 ns typical) [28].

3.2. The output data results from the active AOM Q-switching experiment

Table (2) shows a summery for the data results at frequencies of 10, 25, 50 and 100 kHz. From the table, it found that the maximum operating frequency for a DPSS laser system at cavity length of 55mm with best Gaussian shape of TEM_{00} at higher repetition rate of 100 kHz with peak power of 4.840 kW, pulse width of 50 nsat FWHM and average power of 1.51W were achieved,while the shortest pulse width of 25 ns at lower repetition rate of only 10 kHz and average power of only 1.21 W was measured. This result indicates that it is possible to generate a new generation from versatile coding schemes for the novel high frequencylaser target designation system with law IR print.

Table (2) the best output data at different driving frequencies of the intracavity AOM:

Frequency (kHz)	Average power(W)	Laser output width (ns)	Peak power (W)
10	1.21	25	4840
25	1.26	30	1680
50	1.38	45	613
100	1.51	50	302

Figure 9 (a-c) shows the modulation frequency with the average, pulse width and peak power measured during the intracavity active AOM Q-switching experiment.

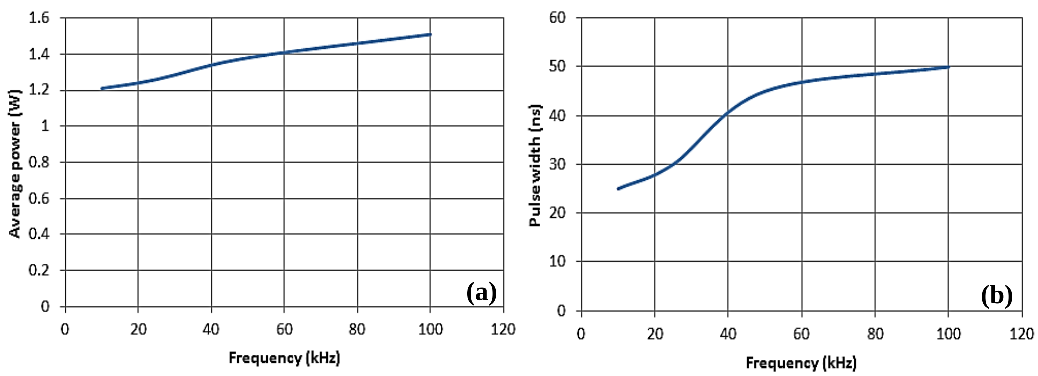


Fig. 9 (a, b) Show the average output power of active Q-switched DEPSS Nd:YVO_4 laser, (b) pulse width at FWHMagainst driving frequencies of the AOM Q-switching element.

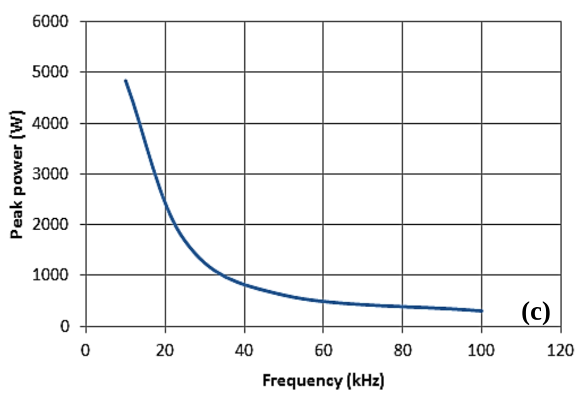


Fig. 9 (c) Show output pulses peak power against driving frequencies of the intracavity AOM Q-switching element.

Figure (10) shows the output Q-switched pulse shape which represents logic one in coding point of view and it was 25nsec.

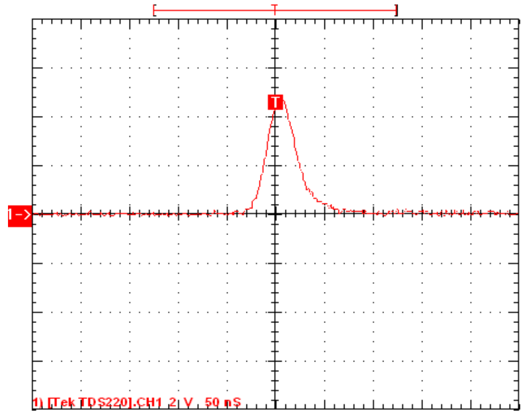


Fig. 10.The output pulse width 25nsec at FWHM.

Figure 11 (a,b) shows the 2D and 3D beam profile of astable and high frequency active Q-switched DEPSS Nd:YVO4 using intracavity AOM crystal.

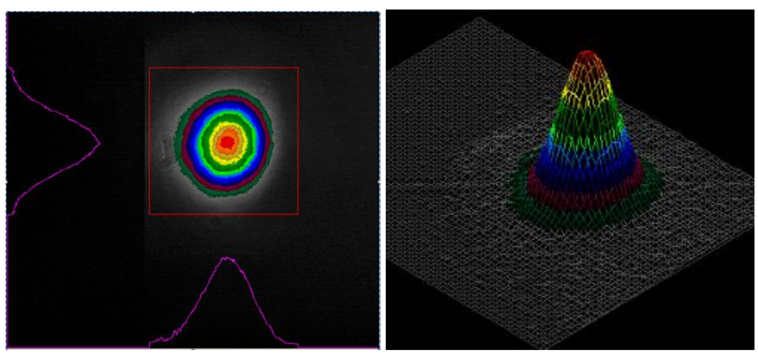


Fig.11. (DEPSS) AOM active Q-switched Nd:YVO_4 laser (a) Two dimension of beam profile, and (b) Three dimension laser beam profile.

3.3. Coding schemes of laser signals using AOM Q-switching element

It was noticed that a two modulation can be done by changing the setting of the Q –switch driver which are variable or fixed modulation and a two modes for analogue modulations like RF off Analogue Control or Analogue Modulation (A05 / A13) but our study focused on the fixed digital modulation schemes like FPS (First Pulse Suppression) or PPK (Pre-Pulse Kill). The controlling here considered external modulation because the Q-switch element was modulating the laser beam after emerging from the Nd: YVO_4 rod. Fig. 12(a-e) shows the output scheme for 10, 20, 40, 60 and 100 kHz. The output was achieved at higher repetition rates in the range of hundreds of kilo Hertz. It gives better result in comparison with the current laser designator sources in service from point of pulse to pulse stability which reached more than 95%, Gaussian pulse shape and ery high frequencies of the codes.

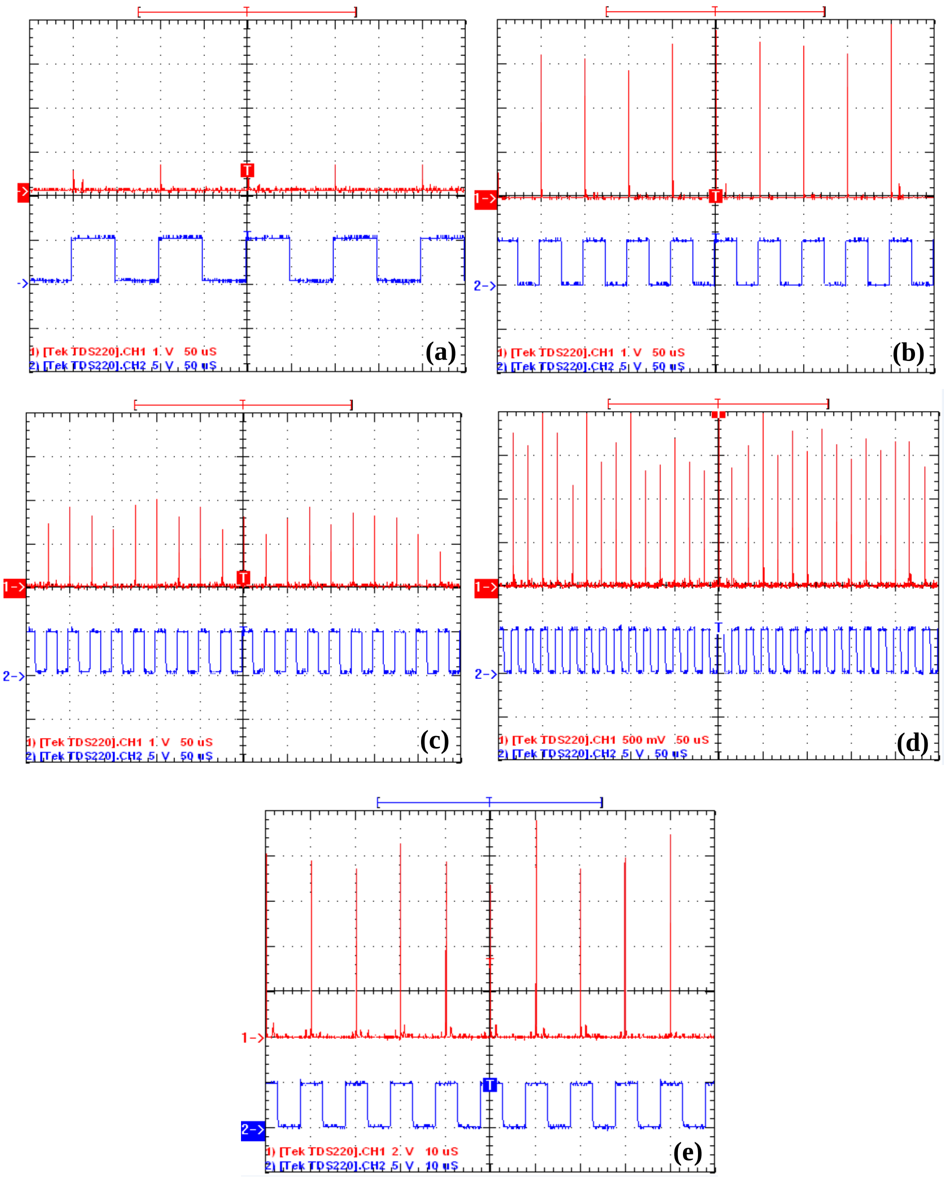


Fig.12. Shows the output pulse trace schemes for controlling the external driver at fixed mode at (a) 10 kHz, (b) 20 kHz, (c) 40 kHz, (d) 60 kHz and (e) 100 kHz.

4. Experimental setup for detection and analysis of the irradiance from similar target with two different materials

Figure (13) shows a schematic block diagram for the used experimental setup. In this experiment a high repetition rates active Q-switchedDEPSS Nd:YVO_4 laser using intracavityAOM techniquewas used as a transmitter of laser signal and designates a fixed three different targets at fixed distance and dimensions from the same DPSS laser transmitter and the receiver is (InGaAs Avalanche photodiode – Thorlab model PDA10C), the material of one target is from sands and the second is from wood and the third material is from metal similar to the real ones used in the military targets for battle fields.The results of these scattered laser signals from this laser designation experiment will be collected by the amplified InGaAs Avalanche photo diode and signal conditioning data acquisition feature in the used oscilloscope (Tektronix oscilloscope TDS 3052B, 200 MHz, 2 GS/s), these acquired scattered laser signals are analyzed using our own matlab software program and by using cross correlation functionswe able to produce the correlation factor (R) which give a strong overview informationabout the correlation between the laser designation irradiation (transmitted) and the reflected or scattered (received) laser signals for this three different targets materials.

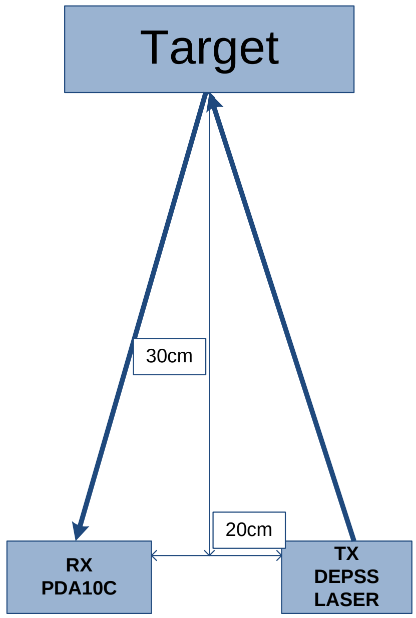


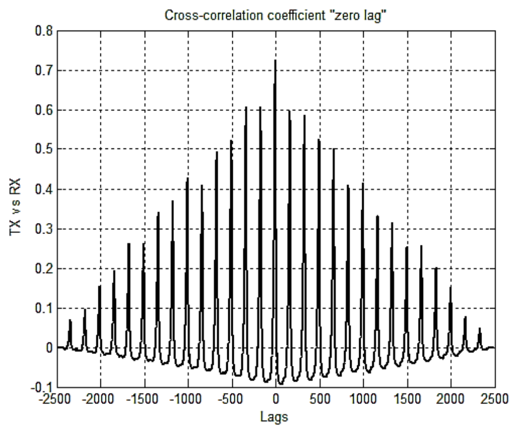
Fig. 13.Shows a block diagram for the experimental setup

Table (3) shows the output of the collected data from three different target materials at different high frequencies of nearly 10, 15 and 20 kHz.

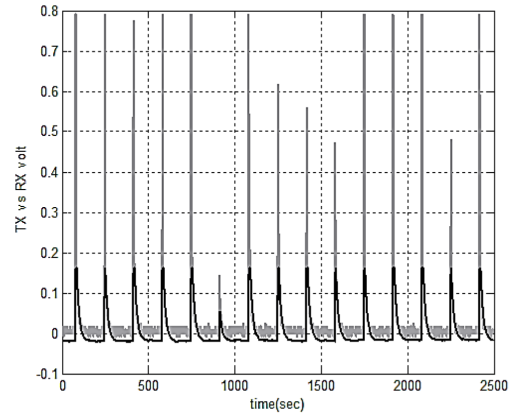
Frequency of AOM modulation (Hz)	Cross correlation R factor for different target material	
	Metal	Sand
9240	0.797559560071369	0.690455060453050
15000	0.664704279013353	0.525054830911959
20121	0.614032824498570	0.590626496959562

From Table (3) it found that the cross correlation factor R in case of metal material is the largest one and the difference value between the sand and wood materials was very small or almost similar.

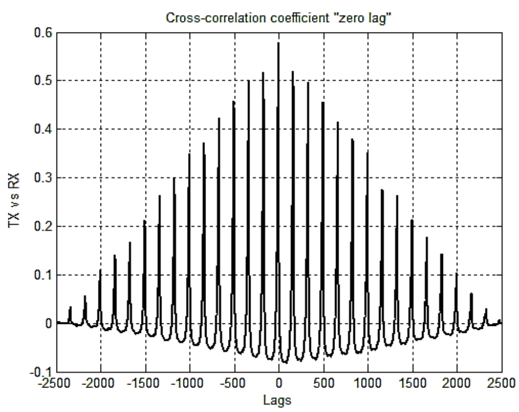
Figure (13) shows the output signals in time domain which collected from the digital signal oscilloscope (DSO) software and shows the cross correlation for AOM modulation frequency of 15000Hz in case of each target material.By taking the reflected or scattered results from irradiation of the fixed targetaround different angles of (0°, 5°, 10°, 15°, 20°, and 25°) as shown in Figure (14).



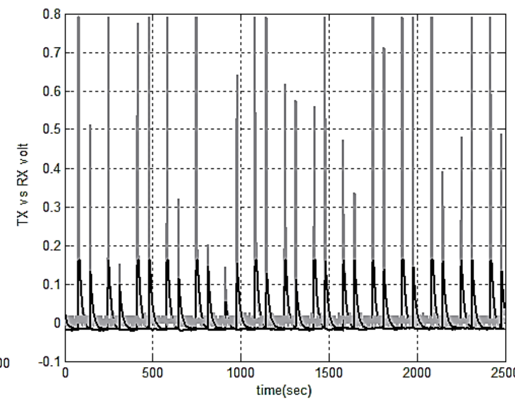
(a) Cross correlation for metal



(b) Time domain representation for transmitted and scattered laser signals from metal



(c) Cross correlation for sands



(d)Time domain representation for transmitted and scattered laser signals from sands

Fig.13. Cross correlation and scattered signals in time domain representations

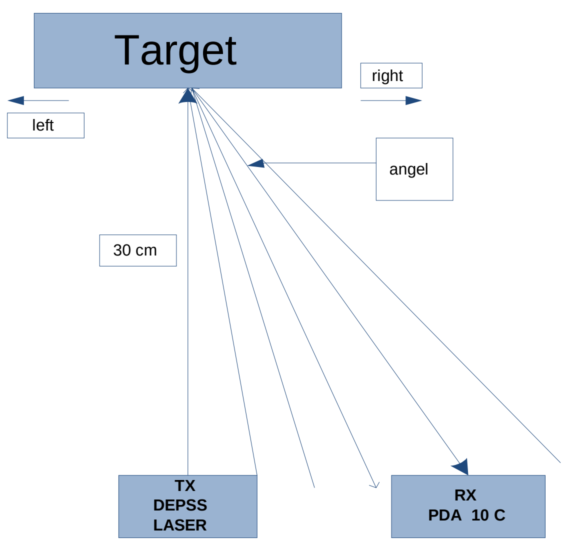


Fig.14. Shows a block diagram for changing receiver reception angles by 5° around the fixed target

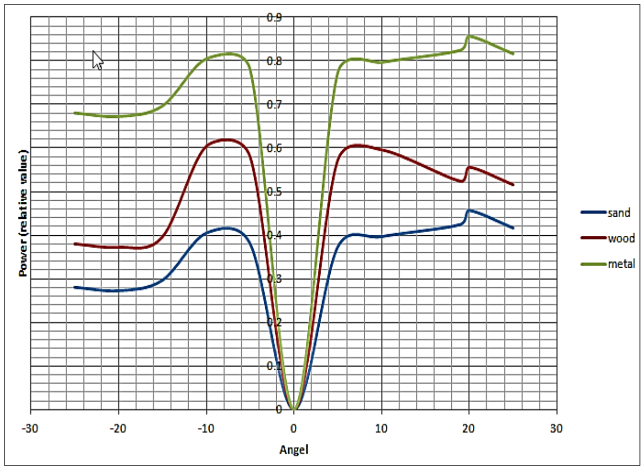


Fig.15.Output power versus different angles around fixed target with variousmaterials (sands, wood and metal)

5. Conclusions and discussions

This designation investigations were a result of optimizing optical parameter of the high power diode end pumped DEPSS Nd:YVO_4 rod through coated the input mirror on the undoped end of the rod to reduce thermal lensing. Also using multi axis alignment system in addition to a good cooling system facilitated the experimental work and contributed in achieving better parameters and enhanced the performance of the AOM active Q-switched DEPSS laser operation.
By using a mechanical optical chopper as a first method for active Q-switching techniques, it was found that the highest average power of 0.972 W had been occurred by reticle # 5 and highest peak power of 95.4 kW with the highest pulse repetition frequency of 221.6Hz and pulse width of 46ns.Reticle # 1 had the narrowest pulse width of 40ns with lowest pulse repetition frequency of 20 kHz and lowest peak power of 1.115 kW.
By using this data a different coding schemes could be generated by using a certain combinations from two or more optical choppers for a multi and wide range of any desired code.This method is an efficient and reliable technique for generating coding schemes with output laser pulses with high peak power and high repetition frequencies at the range of kilo hertz, which are higher rates than any other current designation systems used in the real battle field
While, the optimum technique in generating coding schemes was the using of AOM, which generate a faster and stable output laser pulses ranges from 10 kHz to 100 kHz. The highest peak power output laser pulses of 4.8 kW are generated from this system with pulse to pulse stability of nearly 97%, pulse width of 50 ns and average power of 1.51 Wwith a good beam profile, which is similar to the highest average power comparable with the other techniques.The main advantage in the use of AOM was the capability, reliability and automatic dynamic styles for generating any coding using electronictechniques such as analogue or digital modulation for the output laser pulses beam.
Experimental studieson a new high frequency and wide range of coded laser designation system using two different active Q-switched Nd: YVO_4 crystals at various pumping

power regimes and at different higher repetition rate were investigated. The highest performance of coded laser operation and highest peak power of nearly 30 kW, shortest pulse width of less than 18 ns at higher repetition rate of 20 kHz with the use of combinations of two optical choppers are obtained. While the other AOM technique produces high performance at higher repetition rates of 100 kHz, but with lower peak power of nearly 300 W, to the best of our knowledge this is the highest repetition rate of a versatile coded schemes of a DEPSS used in military laser target designation (LTD) systems.

The correlation between the coded laser irradiation (transmitted) and the scattered (received) laser signals for three different targets materials of sand, wood and metal using this laser designation system are examined and discussed. The output powers (relative value) with different angles for these three different material targets at different angles are measured. At angle 0° the output power will be zero if both transmitter and receiver in same level but reach to its maximum value at angle 0° but not in same level are investigated.

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