Experimental Studies on High Power Diode Pumped Q-Switched Double Clad Flower Shape Codoped-Er^{3+}/Yb^{3+} Fiber Laser

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Abstract

A diode pumped acousto-optic Q-Switching Er^{3+}:Yb^{3+}co-doped single mode TEM $_{00}$ high power fiber laser has been reported, laser output average power in excess of 1.65 W was achieved for Q-switching at high repetition rates from 10 kHz to100 kHz. The shortest pulse duration obtained was 10 ns, giving a highest peak power of 9.8 kW and 98μJ energy per pulse, is the highest yet reported from any type of active Q-switched flower double clad fiber laser operating in low order mode. The pulse train with high pulse-to-pulse stability of 95% occurred at a range of high repetition rates up to100kHz with peak power of 0.4 kW, 40ns pulse width and 16μJ energy per pulse at 1550 nm for a launched pump power of 5W.Optical chopper Q-switching technique for Er^{3+}:Yb^{3+}co-doped fiber laser has been investigated, it was found that the narrowest pulse width of 35 ns with peak power of 15.5kW and energy per pulse 0.5mJ at pulse repetition frequency of 1 kHz. The pulse-to-pulse stability was moderate of 75% occurred at a range of high repetition rates. A comparison between optical chopper Q-switching technique and acousto-optic Q-switching has been done at repetition rate of 20 kHz, the reported high energy per pulse, pulse width and the average power of an optical chopper Q-switching technique are greater than that of acousto-optic Q-switching but the pulse width is narrower and so the high peak power of an acousto-optic Q-switching pulse is greater than that of optical chopper Q-switching technique at high repetition rates of up to 100 kHz.

Keyword: High power fibre lasers; Diode pumped fibre lasers; Flower shape fibre laser, Er^{3+}:Yb^{3+} co-doped fiber, Q-switched lasers; AOM.

1. Introduction

For designing and implementation of diode pumping Q-switching flower double cladding Er^{3+}:Yb^{3+} co-doped fiber laser has more stable output pulse with higher peak power, narrower pulse width and higher beam quality at high repetition rates useful for many eye safe military applications (LIDAR-range finder- designation systems) and others medical applications, two types of Q-switching have been used, acousto-optic modulator and mechanical chopper Q-switching techniques.

Rare-earth doped optical fibre lasers operating in the mid-infrared have now established themselves as leading contenders for a range of high power applications in range finding, remote sensing, pumpsfor optical parametric oscillators.Short pulse fiber lasers at 1550 nm make attractive sources for long range high spatial resolution distributed temperature sensors based on the technique of optical time domain reflectometry (OTDR), eye-safe light detection and ranging [1] ultralow-loss long span communications and photomedicine [2,3]. The three principal techniques used for the generation of short optical pulses are gain switching [4], Q-switching and mode-locking. Q-switched fibre lasers can generate high-peak-power and relatively long-duration pulses, ranging from several nanoseconds to several hundred nanoseconds. The cavity can be switched from a high-loss to a low-loss regime by using, for example, a mechanical Q-switch [5], an acousto-optic modulator (AOM) [6, 7] or an electro-optic modulator (EOM) [8].

Q-switching is a widely used laser technique in which we allow a laser pumping process to build up to a much larger than usual population inversion inside a laser cavity, while keeping the cavity itself from oscillating by removing the cavity feedback or greatly increasing the cavity losses, in effect by blocking or removing one of the end mirrors. Then, after a large inversion has been developed, we restore the cavity feedback, or “switch” the cavity Q back to its usual large value, using some suitably rapid modulation method. The result in general is a very short, intense burst of laser output which dumps all the accumulated population inversion in a single short laser pulse, typically only a few tens of nanoseconds long. Resonators are characterized by a quality factor Q, which is defined as the ratio of energy stored in the resonator to power dissipated from the resonator per unit angular frequency ω_0. The Q of a laser system is defined as [9]

$$Q = 2\pi \frac{\text{energy contained within cavity}}{\text{energy loss per cycle}} \tag{1}$$

$$Q = 2\pi \left[1 - \exp\left(\frac{-T_0}{\tau_c}\right)\right]^{-1} \approx \frac{2\pi\tau_c}{T_0} = 2\pi\nu_0\tau_c, \tag{2}$$

Where

$$\omega_0 = 2\pi\nu_0 = \frac{2\pi}{T_0}.$$

The loss mechanism, besides limiting the lifetime of the oscillation, causes a broadening of the resonance frequency. The width $\Delta\nu$ of the resonance curve at which the intensity has fallen off to half the maximum value is [9]:

$$\Delta\nu = (2\pi\tau_c)^{-1}. \tag{3}$$

If we introduce this expression into (4) we obtain for the Q value

$$Q = \frac{\nu_0}{\Delta \nu}. \tag{4}$$

The decay time constant of radiation τ_c can also be defined as the average lifetime of the photons in the resonator. A photon in the resonator will have some average lifetime before being scattered or emitted or lost in other ways to the optical system.

If the laser is pumped while the losses in the cavity are high, a large population inversion will build up – i.e. $N_2 >> N_1$. This will give a laser medium with very high gain, but the system will not lase, due to the high cavity losses. If the losses in the cavity are suddenly reduced, the high gain medium will give a short, high power laser pulse, with a much larger peak power than the laser could provide if run CW. A number of methods are available for switching the Q of the laser cavity. These will be considered.

There are many practical applications, including laser ranging, laser cutting and drilling, and non-linear optical studies, where such a short but intense laser pulse is much more useful and effective than the same amount of laser energy distributed over a longer time. The Q-switching approach is therefore a technique of great practical importance in many different laser systems[1, 9].

The addition of Ytterbium to an Erbium doped fiber increases the pump absorption by 2 orders of magnitude. This allows shorter fibre lasers to be constructed, which reduces the cavity round trip time and also the duration of the output of the Q-switched pulse. Er^{3+}:Yb^{3+} co-doped phosphate fibers also have the added advantage of a broad absorption band ranging from 800 nm to 1100 nm which offers greater flexibility in selection of the pump wavelength. Er^{3+}:Yb^{3+} doped fiber lasershave been previously pumped and Q-switched using the 980nmpump wavelengths.

We demonstrate advances in the CW and Q-switched operation of the Er^{3+}:Yb^{3+} fibre laser pumped by a laser diode at 980 nm, which leads to minimal excited state absorption (ESA) [1]. The laser reported in this paper generates 35 ns pulses with 15.5 kW peak powers at a highest repetition rate of 1kHz and high energy per pulse of 0.5 mJ using optical (mechanical) chopper.

To the best of our knowledge, this is the shortest pulses duration in combination with high peak powers, high energy per pulse at higher repetition rates ever obtained for a diode pumped flower double cladding Er^{3+}:Yb^{3+} co-doped fiber laser.This paper also reports recent improvements obtained with a Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using acousto-optic modulator(AOM). High peak power of 9.8 kW and pulse duration of 10ns at a higher repetition rate of 10 kHz were reported.

2. Experimental Studies:

2.1 Diode Pumped CW Er^{3+}:Yb^{3+} doped silica double clad flower shape fiber laser:

The experimental sets-up used for the CW Er^{3+}:Yb^{3+}doped silica double clad flower shape fiber laser (model CP1500Y)are shown in Figure 2 (a,b). The fibre hadEr ion density of 5.68 x 10^{43} m^{-3}, Yb ion density 4.27 x $10^{26}$$m^{-3}$, inner core diameter of 5μm with a numerical aperture (NA) of 0.22 and pump guidefibre core diameter of 85-105μm, with a NA of 0.22-0.26 and outer fibre diameter of 125 ± 1μm.

In the CW mode of operation, the performance parameters such as the input power of 6.5 W, launched power of around 5.3 W and the maximum output powers of 2.544 W have been measured, from which the laser threshold of around 200 mW, launch efficiency of 70 % and maximum slope efficiency of 50% were determined at the optimum Er^{3+}:Yb^{3+}doped silica double clad flower shape fiber laserlength of 1.5 m.

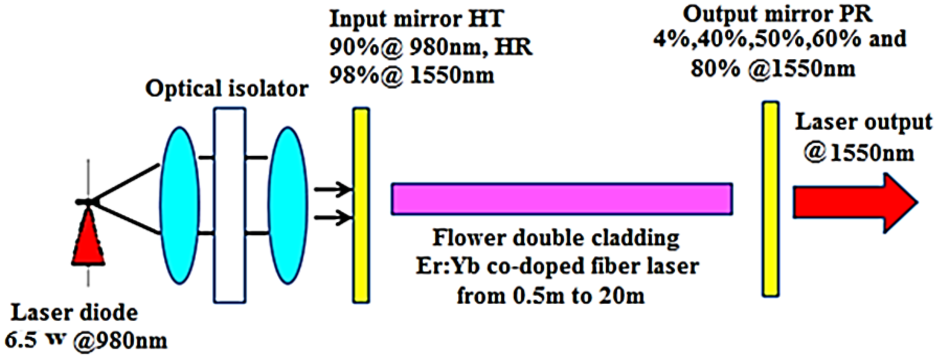

Fig. 2(a) Schematic drawing of the experimental setup of CW flower double cladding Er^{3+}:Yb^{3+}co-doped high power fiber laser operating at 1550nm wavelength.

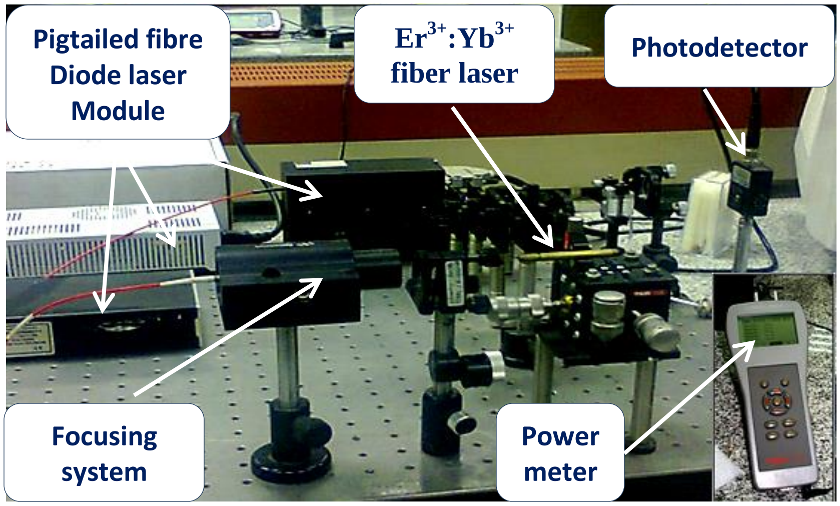

Fig. 2(b) Photograph of the experimental setup of flower double cladding Er^{3+}:Yb^{3+}co-doped high power fiber laser operating at 1550nm wavelength.

The pump laser was a high power diode laser module (JenOptik model - UM DiTec 60/8000 TEC OEM), operating at 975nm in the fundamental transverse TEM_{00} mode with the maximum available output power up to 6.5 W. The used high power diode laser module was a fiber coupled @ 975 nm ± 2 nm. The highest brightness was achieved by transforming the asymmetric radiation from the laser diode into a symmetrical beam, using micro optics and finally this beam could be coupled into 125µm pigtailed fiber with core diameter of 50 µm.This laser was focused and launched into the Er^{3+}:Yb^{3+}doped silica double clad flower shape fiber laser by using 1:1 high transmission imaging optics at 980 nm as a collimating and focusing optics.

A mirror with high reflectivity (> 98 %) at the fibre laser wavelength of 1550 nm and highly transmissive of (>90%) at the pump wavelength of 980 nm was placed before the input end of the fibre, and output coupler reflectivity of all available (4%, 40%, 50%, 60%and 80%) partially reflective mirrors was butted to the distal end of the fibre which formed part of the fibre cavity arrangement to guide the fibre laser output radiation into a fiber optic integrating spheres connected to a high resolution spectrometer to measure the fiber laser wavelengths. This high resolution spectrometer (HR4000CG model) with a 3648-element linear-array CCD detector that provided better optical resolution produced by (Ocean Optics Inc.) providing 200nm to 1100 nm wavelengths ranging with 0.75nm optical resolution at (FWHM) is used in the experimental setup,“Spectra Suite” spectrometer software was used in analyzing and viewing our measurements.

In order to observe laser pulses and Q-switched laser traces at this wavelength, the amplifiedInGaAs photodiode (DET 10C - Thorlabs Inc.) was linked to a digital sampling oscilloscope (Tektronix Model TDS 210, 60 MHz).

The fibre laser output power has been measured as a function of the input pump power using a calibrated optical power meter system (PM100GmbH) was provided by (Thorlabs Inc.) with two different detectors; (S120B) silicon sensor with spectral band ranging from 400nm to 1100nm measuring an optical power ranging from 50nW to 50mW and the other (S213A) thermal sensor has spectral band ranging from 250nm to 1064nm measuring up to 30W. The silicon sensor was used for low power measurement since its response is a wavelength dependent.

CP1500Y has a hard, doped-silica optical cladding 125 µm in diameter - enabling the use of standard fiber fixtures and providing similar reliabilitycharacteristics to conventional, telecoms-type fibers. The multi-lobed shape of the pure-silica first cladding effectively disrupts pump modes so that they decay into the Er^{3+}:Yb^{3+}doped single mode core whilst its 105µm diameter makes it compatible with typical pump diode pigtails.

Firstly, the longer fiber lengths of 3m,5m,8m,10m,15m and 20m were tested with all available output coupler reflectivities of 4%, 40%, 50%, 60% and 80%, then the fiber lengths were tested from

0.5 m to 2.5m with step of 0.5 m with all available output coupler reflectivities to get the optimum fiber length and optimum output coupler reflectivity which produce maximum output power and maximum slope efficiency.Figure 3 shows that no output power was obtained from flower double cladding Er^{3+}:Yb^{3+}co-doped high power fiber laser at lengths of 3m,5m,8m,10m,15m and 20m at 4% Fresnel reflection. The same experiment was repeated with the other output coupler reflectivities 40%, 50%, 60% and 80% and no output power was obtained as well from flower double cladding Er^{3+}:Yb^{3+}co-doped high power fiber laser.

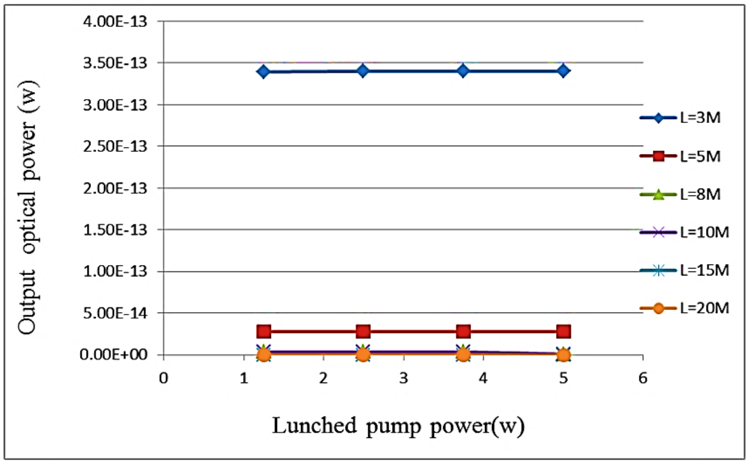

Fig. 3 Output power versus lunched power at lengths from 3m to 20mat 4% Fresnel reflection.

The maximum output power of the flower double cladding (CP1500Y)Er^{3+}:Yb^{3+}co-doped high power fiber laser versus input pump power at lengthes from 0.5m to 2.5m with all available output coupler reflectivities 4%, 40%, 50%, 60% and 80% was 2.544 W at 1.5m with 4% Fresnel reflection for lunched pump power of 5.3 Was shown in Figures (4, 5) and the summary is shown in table 1. The slope efficiency of 50% and lunching efficiency of 77% were measured as shown in Fig. 6.

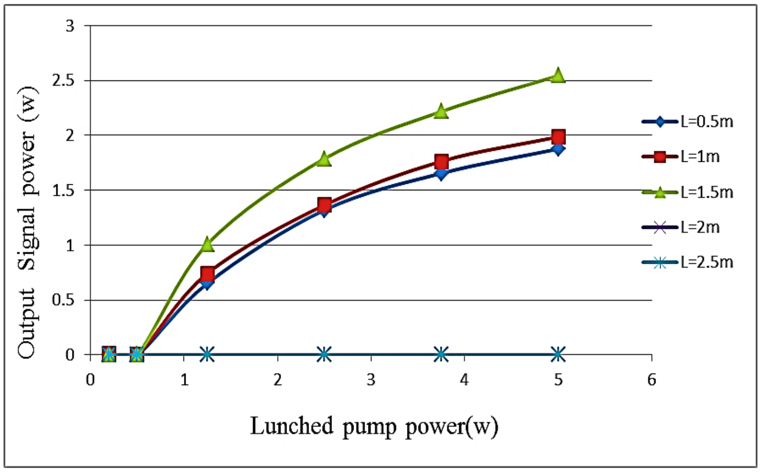

Fig. 4. Output power versus launched power at lengths from 0.5m to 2.5m at 4% Fresnel reflection

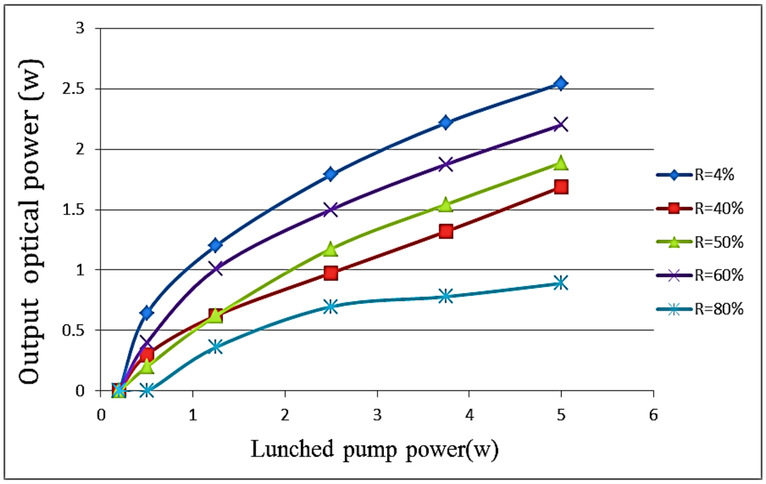

Fig. 5. Output power versus launched power at 1.5m length for 4%, 40%, 50%, 60% and 80% output coupler reflectivities.

Table 1 shows that the max output power for flower double cladding CP1500Y Er^{3+}:Yb^{3+}co-doped high power fiber laser is 2.544W was achieved at 1.5m fiber length and 4% Fresnel reflection output mirror reflectivity with lunched pump power of 5.3W from 6.5W input pump power with 77% lunching efficiency.

Table 1. Output characteristics of CW Er^{3+}:Yb^{3+}fiber laser at optimum fiber length 1.5m:

Fiber length (m)	Output mirror reflectivity (%)	Slope efficiency (%)	Maximum O/P (W)
1.5	**4**	**50**	**2.5445**
	60	47	2.2087
	50	44	1.8867
	40	40	1.6862
	80	27	0.8903

The wavelength of the output radiation from the fiber laser was measured by using the high resolution spectrometer (Ocean Optics HR4000CG-UV-NIR). Figure 7 shows the spectrum of the laser output for optimum fiber lengths of 1.5m at output mirror reflectivity of 4%Fresnel reflection and lunched input power of 5.3 W. The output laser wavelength of 1550 nm was measured at 1.5m fiber length with some of the remaining pumped wavelength of 980 nm before rejecting it using narrowband filter at FWHM between (970-1000 nm).

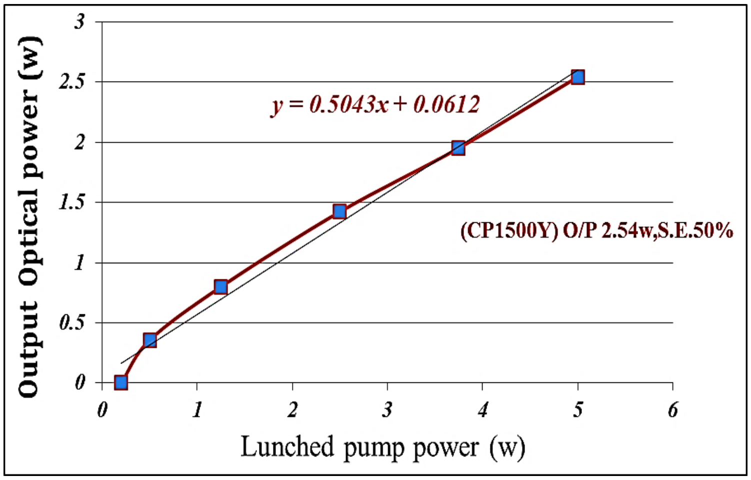

Fig. 6.Maximum output power and slope efficiency obtained from flower double cladding (CP1500Y) Er^{3+}:Yb^{3+} co-doped high power fiber laser operating at 1550nm wavelength.

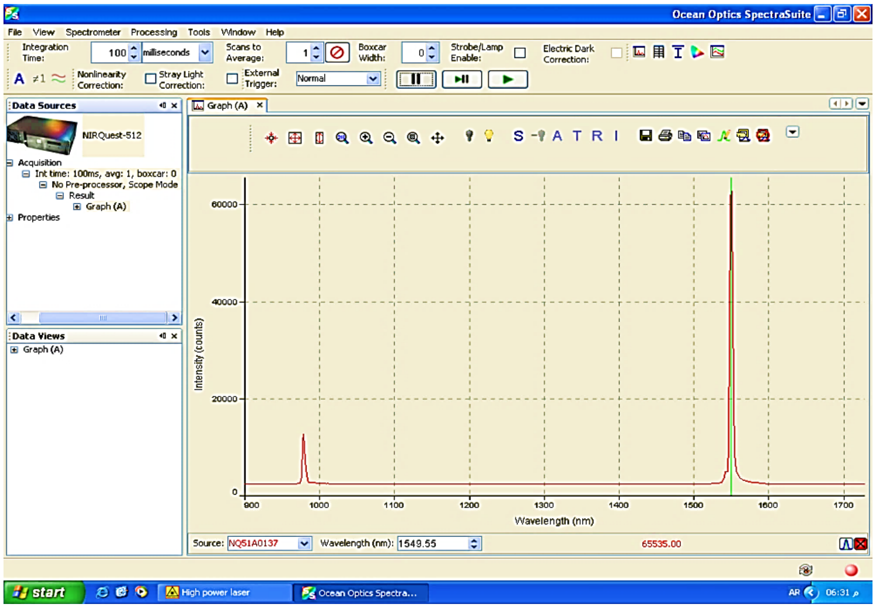
Integration Time: 100 milliseconds
Scans to Average: 1
Boxcar Width: 0
Strobe/Lamp Enable: ☐
Electric Dark Correction: ☐
Nonlinearity Correction:
Stray Light Correction: ☐
External Trigger: ☐ Normal
Acquisition
Int time: 100ms, avg: 1, boxcar: 0
No Pre-processor, Scope Mode
Source: NQ51A0137
Wavelength (nm): 1549.55
65535.00

Fig. 7. The measured output laser wavelength of 1550 nm atfiber length of 1.5m.

Spatial beam profile of CW flower double cladding (CP1500Y)Er^{3+}:Yb^{3+}co-doped high power TEM_{00}fiber laser operating at 1550nm eye safe wavelength has been measured using thethermal imager as a beam profiler model Fluke Ti20 as shown in Fig. 8.

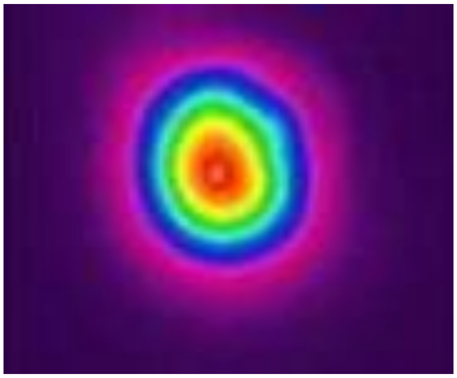

Fig. 8.Spatial beam profile of flower double cladding (CP1500Y)Er^{3+}:Yb^{3+}co-doped high power fiber laser at 1.5 m fibre length.

2.2Diode Pumped Q-switched flower double claddingEr^{3+}:Yb^{3+} fiber laser:

a) Mechanical Q-Switching:

The first mechanical Q-switch consisted of nothing more than a rotating disc containing an aperture [10], 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 [5].To demonstrate the pulsed operation, the cavity was extended by the use of a 1.5 - 2μm AR coated microscope objective to collimate the fibre output and a highly reflecting mirror at the same wavelength range to close the cavity. Laser action was achieved using the 4% Fresnel reflection from the pumped end of the fibre. Pulsed operation was achieved using a mechanical chopper (Edmund Optics Model G55-783) placed close to the distal end of the fibre as shown in Fig. 9 (a), the specifications are mentioned in [5].

Figures 9 (a, b) shows the experimental setup and photograph for an actively Q-switched flower double cladding (CP1500Y)Er^{3+}:Yb^{3+}Co- doped fiber laser using an optical (mechanical) chopper.

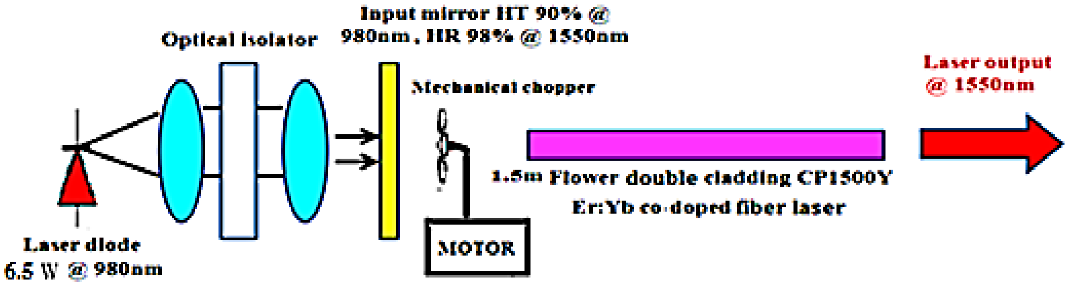

Fig. 9(a) Schematic drawing of the experimental setup of Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using mechanical chopper.

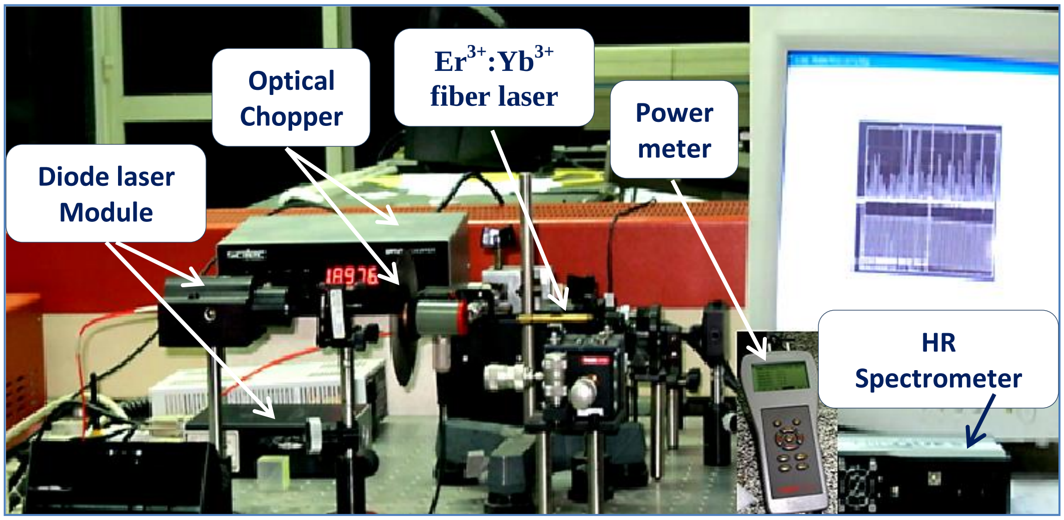

Fig. 9(b) Photograph of the experimental setup of Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using mechanical chopper.

The pump light was launched into the input facet end of the Er^{3+}:Yb^{3+}doped fiber via collimated optics and optical isolator and then focused into the fiber through the diachroic back mirror HR at 1550nm and HT at 980nm. The Er^{3+}:Yb^{3+}doped fiber used in this Q-switched study was of length of 1.5 m as described before. Due to the high gain in the Er^{3+}:Yb^{3+}fiber at 1550nm, an output coupler was not required, and the fiber laser was lased with only the 4% Fresnel reflectionat the distal end of the fiber.

The Q-value of fiber laser cavity was modulated using an optical (mechanical) chopper placed close to the input mirror. The rotating chopper was used as rotating shutter and the chopper radicals between 2 and 200 segment shop apertures were employed as shown in Fig. 10, allowing a maximum modulation frequency of 20 kHz [5]. The laser output power at 1550nm and the time resolved measurements were measured using an amplified InGaAs fast photodetector (ThorlabsPDA 10CS-ES 700-1800 nm) with a response time of 1ns, connected to a 100MHz digital storage oscilloscope – DSO (Tektronix TDS220).

Fig. 10. All types of mechanically reticules optical choppers.

Table 2 shows measurement for output average power, pulse width, energy per pulse, peak power, frequency for each reticule of mechanical chopper. All data were measured at lunched input optical power of 5w at wavelength of 980nm from the high power diode laser module. It was found that the reticule #5 had the widest pulse width 50nsec with peak power 1.3 kW and energy per pulse 65 µJ at pulse repetition frequency of 20 kHz, but reticule #3 had the narrowest pulse width of 35 ns with peak power of 15.5kW and energy per pulse of 0.5mJ at pulse repetition rate of 1 kHz [11-13].

Table 2. Measurements for output average power, pulse width, energy per pulse, pulse peak power and repeat ion rate for each of the mechanical choppers:

Reticules	Average power (W)	Pulse width (ns)	Repetition rate (kHz)	Peak power (kW)	Energy per pulse (mJ)
Reticule#5	1.357	50	20.07	1.3	0.065
Reticule#4	1.309	40	3.111	6.5	0.2
Reticule#3	**1.142**	**35**	**1.085**	**15.5**	**0.5**

The train of Q-Switched pulses trace and Q-switched pulse shape respectively from reticule #5 with pulse width of 50 ns at repetition rate of 20 kHz are shown in Fig. 11(a, b). Figures 12(a, b) show the train of Q-switched pulses trace and Q-switched pulse shape respectively with pulse width of 40 n at repetition rate of 3 kHz obtained using reticule #4. The train of Q-Switched pulses trace and Q-switched pulse shape respectively from reticule #3 with pulse width of 35ns at repetition rate of 1 kHz are shown in Fig 13 (a, b) [12-14].

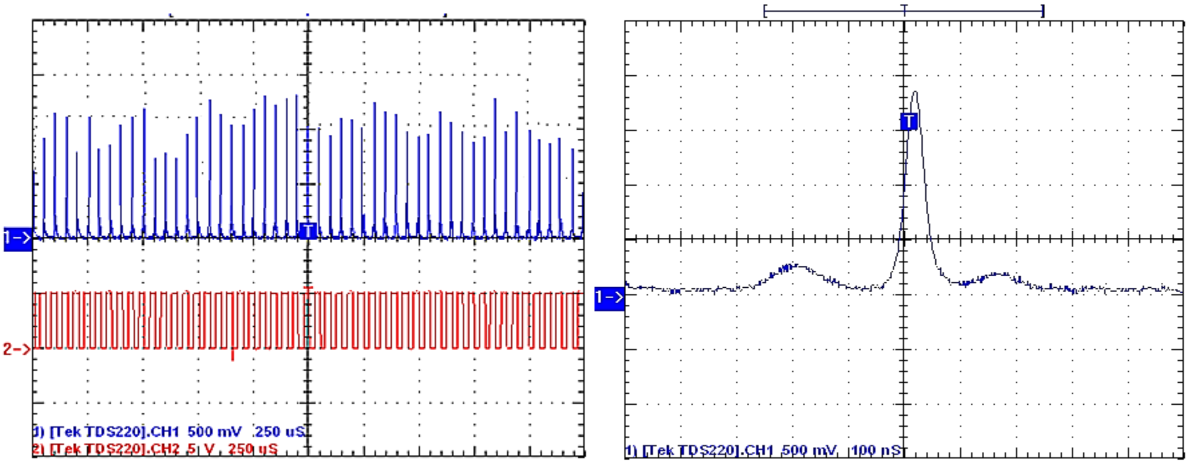

Fig 11 (a) Train of Q-switched pulses using optical chopper, **(b)**Pulse shape from reticule#5 with pulse width of 50 ns at repetition rate of 20 kHz and 1.5m fiber length.

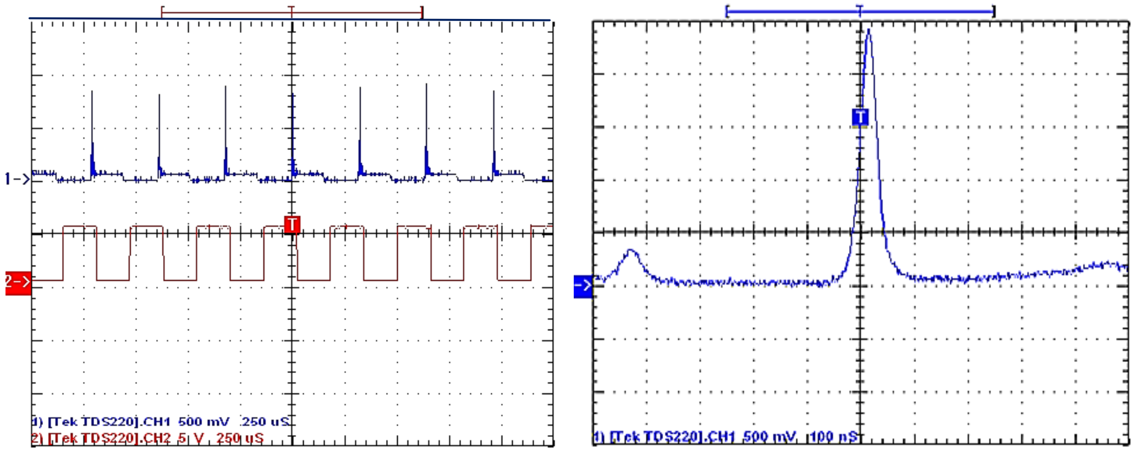

Fig 12 (a) Train of Q-switched pulsesusing optical chopper, **(b)**Pulse shape from reticule#4 with pulse width of 40 ns at repetition rate of 3 kHz and 1.5m fiber length.

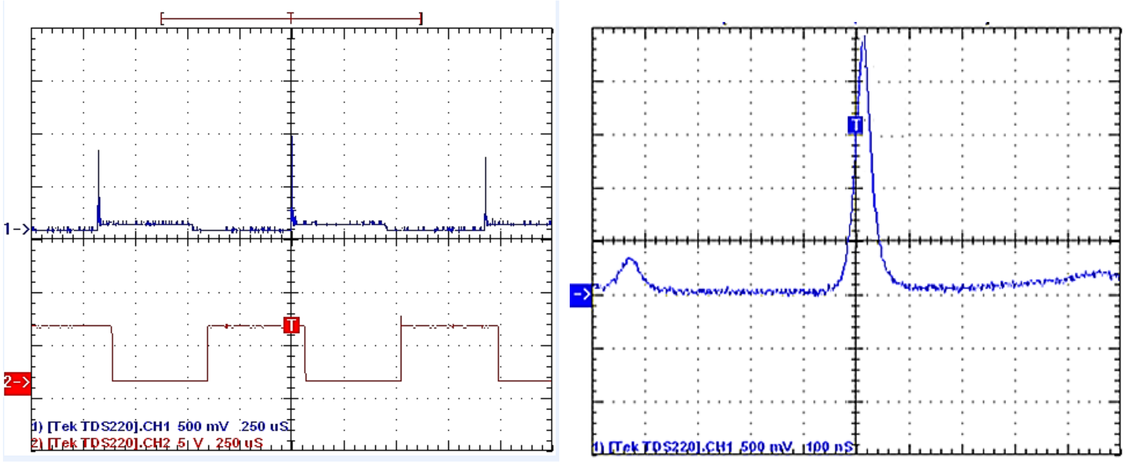

Fig 13 (a) Train of Q-switched pulsesusing optical chopper, **(b)**Pulse shape from reticule#4 with pulse width of 35 ns at repetition rate of 1 kHz and 1.5m fiber length.

While reticule #1 and reticule #2 show a very low Q-switching pulses because of the output laser pulse are the superimposed of narrow Q-switching pulse and a square pulse, its width matched with the width of electrical chopping signal. So, a great portion for the energy inside this square optical pulse represent a losses in the energy confined in our Q-switched pulse. Figure 14 shows the Q-switched peak power and pulse width as a function of repetition rate, it is clear that as the repetition rate increases the peak power decreases but the pulse width increases[14,15]. The pulse width of Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser pulse at 20 kHz repetition rate was broadened as shown in Fig. 14.Figure 15 shows the Q-switched energy per pulse and average power as a function of repetition rate, it is clear that as the repetition rate increases the energy per pulse decreases but the average power increases.

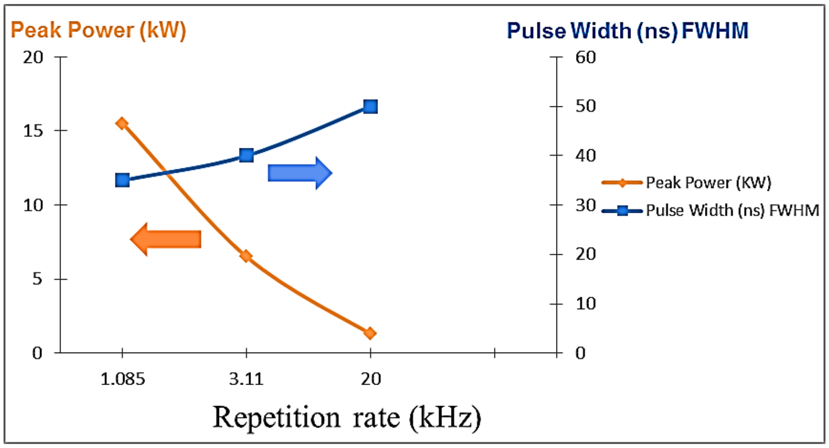

Fig. 14 Q-switched pulse peak power and pulse width as a function of repetition rate.

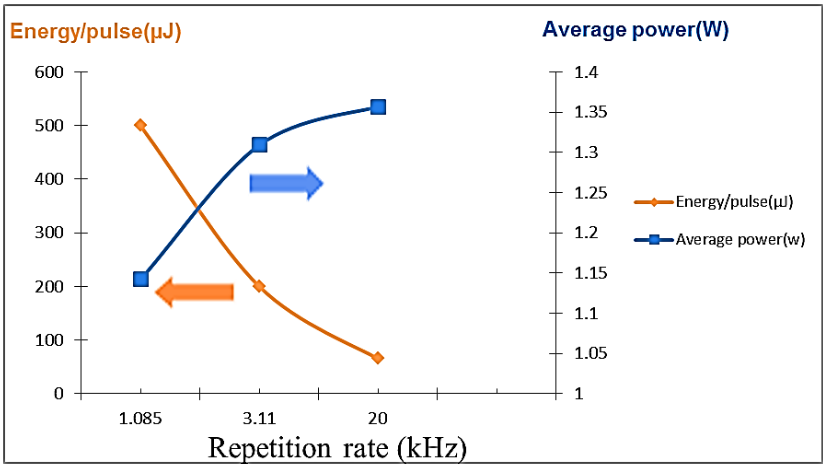

Fig. 15 Q-switched energy per pulse and average power as a function of repetition rate.

The beam profile was good and the pulse to pulse stability was moderate about 75%.Spatial beam profile of Q-switched single mode TEM_{00}laser pulses at repetition rateof 20 kHz using an optical chopper has been measured using a beam profiler model Fluke Ti20 as shown in Fig. 16.

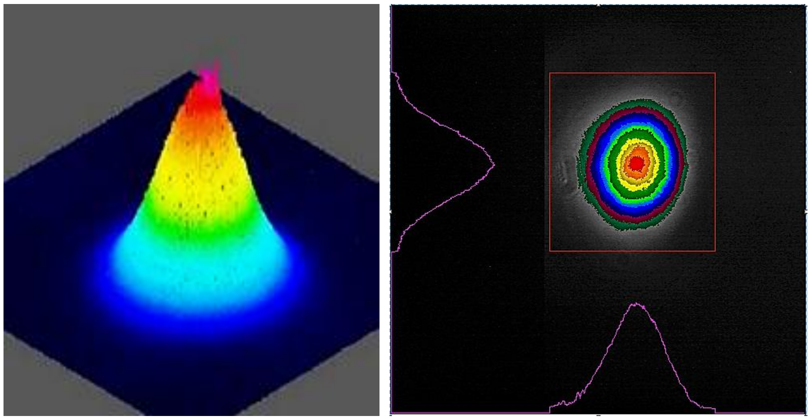

Fig. 16 Spatial beam profile of mechanical chopper Q-switched pulses at 20 kHz repetition rate.

b) Acousto-optic Q-switching (AOM):

In order to provide modulation of the cavity finesse with this technique, a specially designed polarization-insensitive bulk TeO2 Bragg cell (NEOS Model N36027) was introduced intra-cavity just in front of the high reflection mirror to provide Q-switching as shown in Figure 1 (b), the Q-switch crystal specifications are mentioned in [6]. The AOM was used in the transmission mode or "zero order mode". In this arrangement the high-Q state is achieved with the AOM off. Opening times on the order between 50 ns to few μs were obtained, short enough not to interfere with the pulse build-up.

AOMs exhibit diffraction efficiency significantly lower than 100 % (typically 40 % in the longer wavelength region near 1.5μm). This is due to the intensity of light diffracted (deflected) being proportional to the acoustic power (Pac), the material figure of merit (M2), geometric factors "length/height" (L/H) and inversely proportional to the square of the wavelength [16,17]:

Diffraction efficiency =

$$\eta = sin^2\left(\frac{\pi}{\lambda}\left(\frac{L}{2H}M_2P_{ac}\right)^{1/2}\right) \tag{5}$$

The quantity M_2 is a material parameter that indicates the suitability of a particular material for this application. It is defined by [18]:

$$M_2 = \frac{n^6 p^2}{r\upsilon^3} \tag{6}$$

Where p is the photoelastic constant of the material, r is its density, and υ is the velocity of sound in the material. This figure of merit relates the diffraction efficiency to the acoustic power for a given device. It is useful when specifying materials to yield high efficiency, but in practical devices bandwidth is also important, so that specifying a high value of M_2 alone is not sufficient [18].In the acousto-optic interaction, the laser beam frequency is shifted by an amount equal to the acoustic frequency. This frequency can be used for heterodyne detection applications, where precise phase information is to be measured [19-21].

The schematic diagram and photographof the experimental setup of high power Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using AOM are shown in Figure 17 (a, b). The available maximum pump power was 6 W, but the lunched input power at the fiber input facet end was 5 W with coupling more than 80% from high power diode laser module operating at 980 nm. The beam was collimated and then passed through an optical isolator to prevent back reflections from the input fiber end damaging the high power diode laser module. The pump radiation was focused into the Er^{3+}:Yb^{3+}fiber through a dichroic input high reflection mirror, which was 98% reflecting at 1550 nm and 90% transmitting at 980 nm[22-27]. The fiber distal end face was butted against the output coupler mirror as part of the feedback of fibre laser cavity. A length of 1.5 cm of flower double cladding Er^{3+}:Yb^{3+}fiber was used with an N.A. of 0.2, cut-off wavelength 1300 nm and Er^{+3} concentration of 870 ppm. The length of the fiber was optimized to minimize signal re-absorption due to insufficient pumping;and the lasing threshold was about 200mW.

To Q-switch the fibre laser, an acousto-optic modulator (AOM) provide by NEOS Tech. Inc. (Model 34027-1.5-SF10) Q-switch uses a flint glass optical material with a Lithium Niobate transducerwas introduced into the cavity after the input high reflection mirror as shown in Fig. 17 (b). The AOM modulator has a rise time of 165 ns/mm beam diameter, loss modulation ranges from 30% to 60% and maximum operating frequency of 27.12 MHz [28].

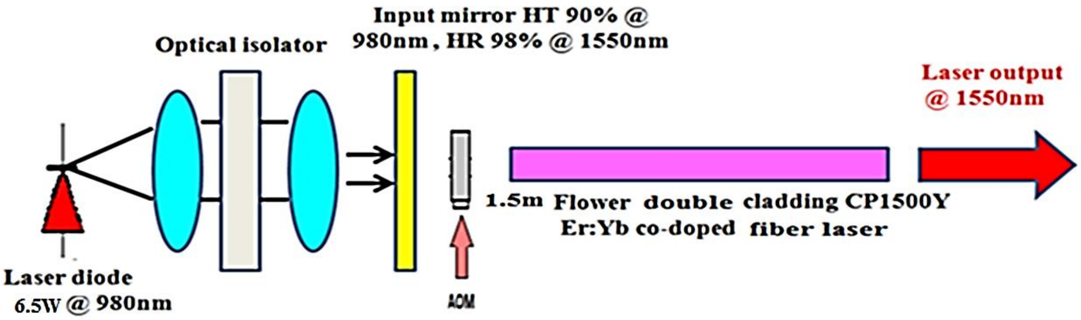

Fig. 17(a) Schematic drawing of the experimental setup of Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using AOM.

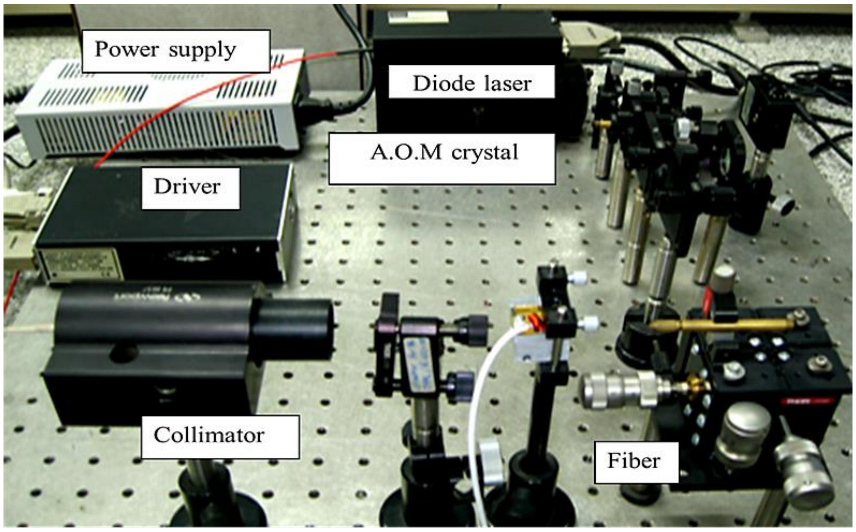

Fig. 17 (b) Photograph of the experimental setup of Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser operating at 1550nm using AOM.

The use of (AOM) for Q-switching of Er^{3+}:Yb^{3+}glass laser are for several reasons: the modulators are commercially available, they can be made very compact and with very low insertion losses and as such are compatible with the low-gain Er^{3+}:Yb^{3+}glass microchip lasers [27, 29].The acousto-optic modulator was operated in zero order mode. In this arrangement the undefeated beam is fed back into the fibre by the butted output coupler mirror. As a result of the short length of Er^{3+}:Yb^{3+}fibre, and therefore low round trip gain of the laser, hold-off was sufficient to prevent CW lasing, despite the low diffraction efficiency of the modulator.The laser output power at 1550nm and the time resolved measurements were measured using an amplified InGaAs fast photodetector (ThorlabsPDA 10CS-ES 700-1800 nm) with a response time of 1ns, connected to a 100MHz digital storage oscilloscope – DSO (Tektronix TDS220).Q-switched operation generated high peak powers of 9 kWand narrowest pulse width of 10ns at a high repetition rate of 10 kHz for a launched pump power of 5 W using AOM.

Table 3 shows the dependence of average power, peak power, pulse energy and pulse width on repetition rate in a diode pumped Q-switched flower double cladding Er^{3+}:Yb^{3+}fiber laser using acousto-optic modulator (AOM).It was found that the widest pulse width of 40ns with peak power of only 0.4 kW, energy per pulse 16 µJ, highest average power of 1.64 W at the highest repetition frequency of 100 kHz, while the narrowest pulse width of 10 ns with highest peak power of 9.8kW, energy per pulse of 98 µJ at pulse repetition rate of 10 kHz was achieved.

Table 3. Measurements for output average power, pulse width, energy per pulse, pulse peak power and repeat ion rate using AOM:

Freq. (kHz)	Peak power (KW)	Pulse width (ns)	Energy/ pulse (µJ)	Average power (W)
10	9.8	10	98	0.9886
20	3.9	15	58	1.1984
60	1.6	25	40	1.4024
100	0.4	40	16	1.6470

The train of Q-switched pulses trace and Q-switched pulse shape respectively with narrowest pulse width of10 ns, and highest pulse peak power of 9.8 kW at repetition rate of 10 kHz are shown in Fig. 18(a, b). Figures 19(a, b) show the train of Q-switched pulses trace and Q-switched pulse shape respectively with pulse width of 15 ns, peak power of 3.9 kW at repetition rate of 20 kHz The train of Q-Switched pulses trace and Q-switched pulse shape respectively with pulse width of 25ns, peak power of 1.6 kW at higher repetition rate of 60 kHz are shown in Fig 20(a, b). Finally, widest pulse width of 40 ns, and pulse peak power of 0.4 kW at highest repetition rate of 100 kHz are investigated and shown in Fig. 21(a, b).Figure 22 shows that as the repetition rate increases the pulse width increases but the peak power decreases [5-9]. While the repetition rate increases the average power and pulse width increase, and the pulse energy and peak power decreases as shown in Fig. 23.

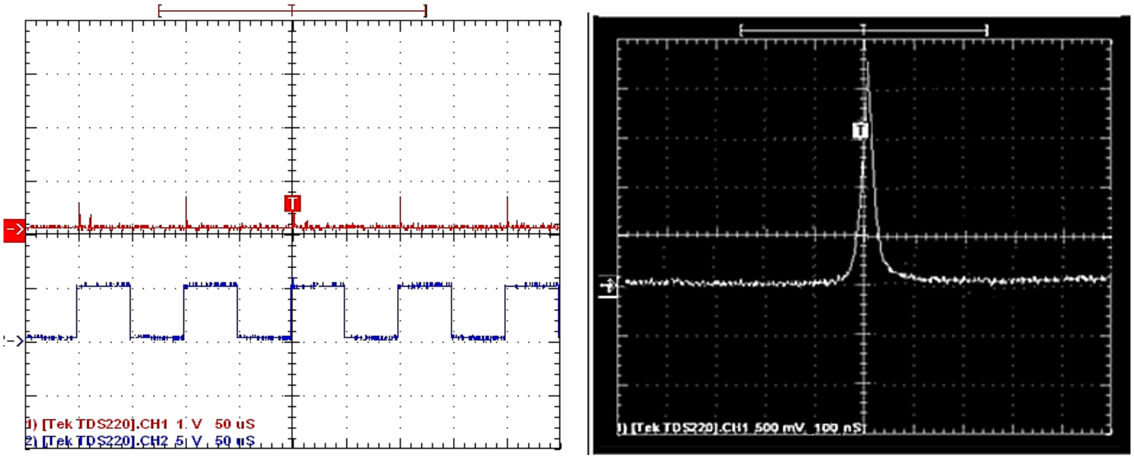

Fig 18 (a) Train of Q-switched pulses using AOM, **(b)**Pulse shape with pulse width of 10 ns and highest peak power of 9.8 kW at repetition rate of 10 kHz and 1.5m fiber length.

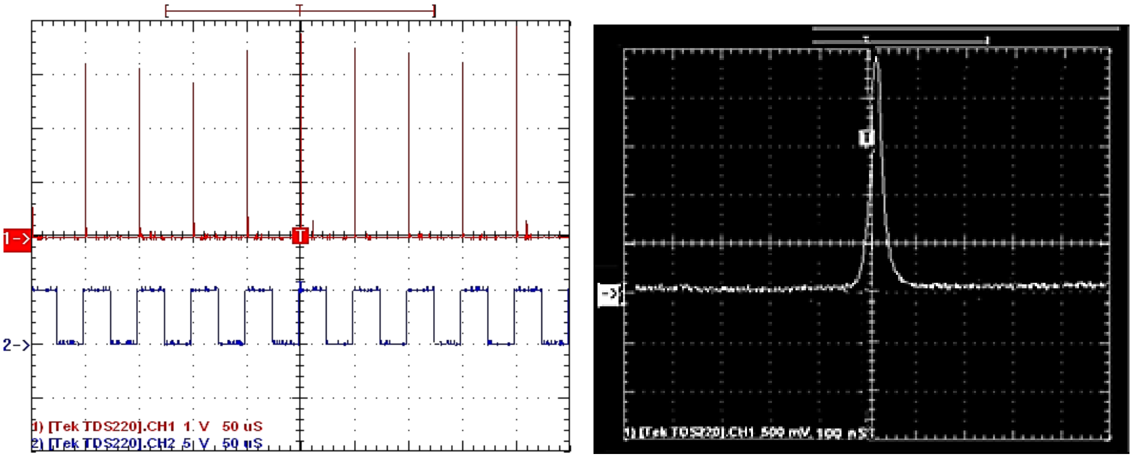

Fig 19 (a) Train of Q-switched pulses using AOM, **(b)**Pulse shape with pulse width of 15 ns and high peak power of 3.9 kW at repetition rate of 20 kHz and 1.5m fiber length.

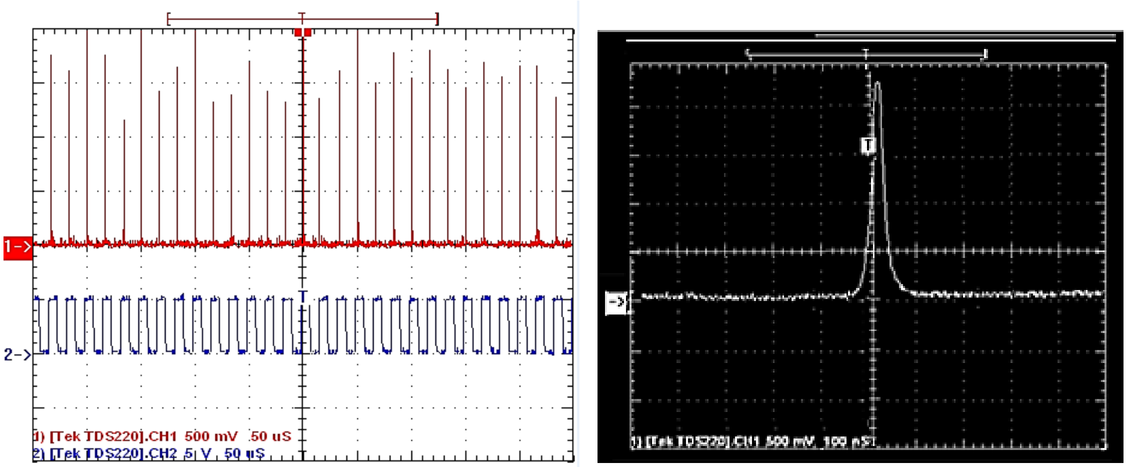

Fig 20 (a) Train of Q-switched pulses using AOM, **(b)**Pulse shape with pulse width of 20 ns and peak power of 1.6 kW at repetition rate of 60 kHz and 1.5m fiber length.

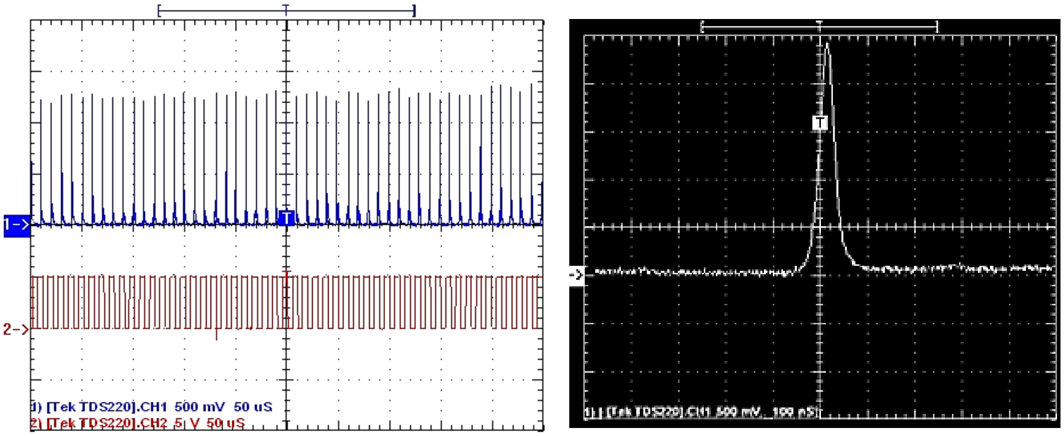

Fig 21 (a) Train of Q-switched pulses using AOM, **(b)**Pulse shape with widest pulse width of 40 ns and peak power of 0.4 kW athighest repetition rate of 100 kHz and 1.5m fiber length.

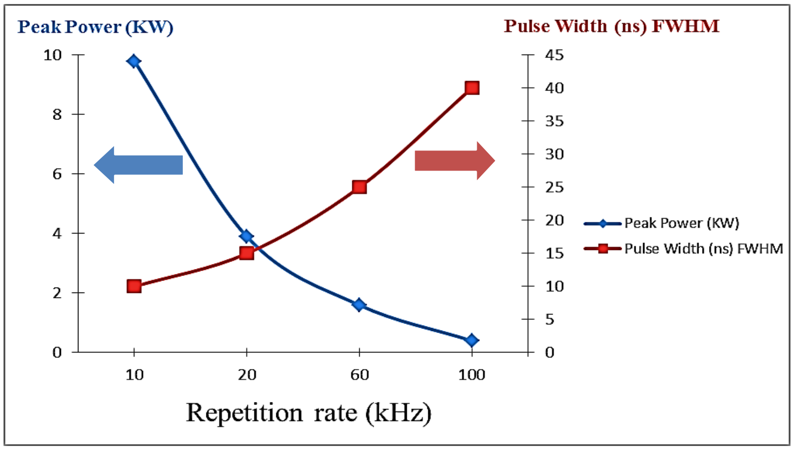

Fig. 22 Q-switched pulse peak power and pulse width as a function of repetition rate using AOM.

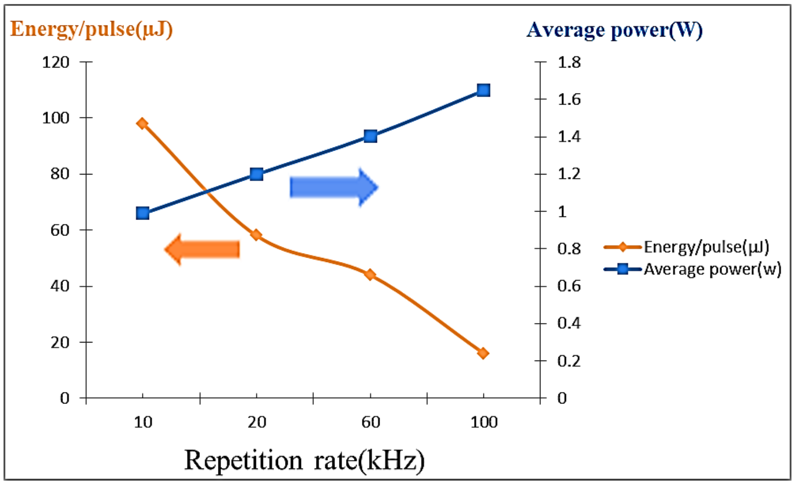

Fig. 23 Q-switched energy per pulse and average power as a function of repetition rate using AOM.

Spatial beam profile of an acousto-optics modulator (AOM) Q-switched flower double cladding Er^{3+}:Yb^{3+}single mode fiber TEM_{00}laser pulses at repetition rate of 20 kHz has been measured using thermal imager as a beam profiler model Fluke Ti20 and shown in Fig. 24.

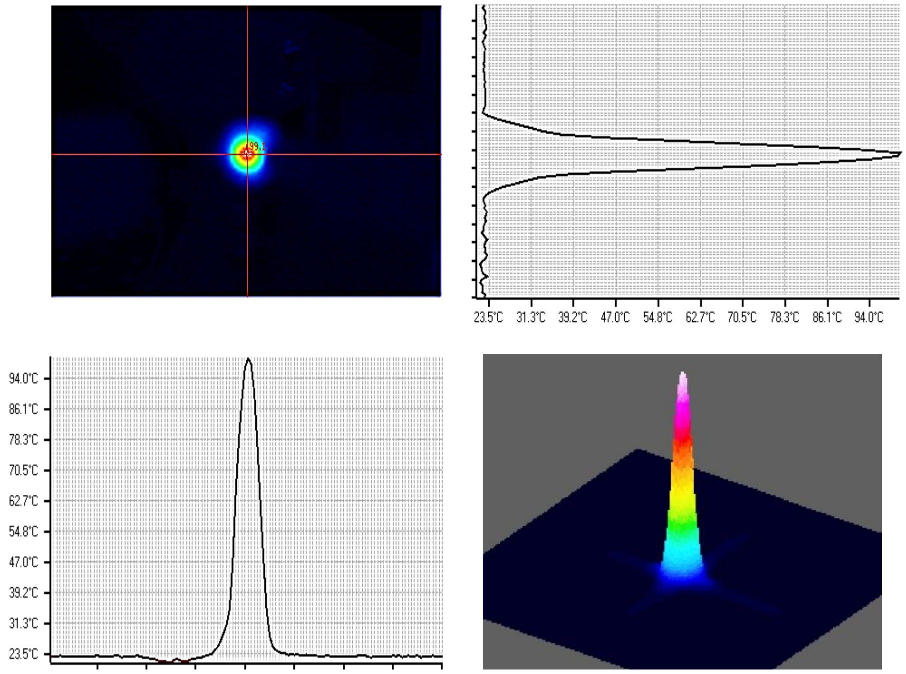

Fig. 24 Spatial beam profile of AOM Q-switched TEM_{00}pulses at repetition rate of 20 kHz.

3. Comparison between mechanical chopper and AOM Q-switched techniques at repetition rate of 20kHz:

Table 3shows the comparison between optical (mechanical)chopper and AOM Q-switched techniquesfor Q-switching of theflower double cladding Er^{3+}:Yb^{3+}single mode fiber TEM_{00} laser pulses at repetition rate of 20 kHz is shown:

Type of Q-switching	**Average power (W)**	**Pulse width (ns)**	**Peak power (kW)**	**Energy per pulse (μJ)**	**Beam profile Quality TEM_{00}**	**Pulse to pulse stability**
Mechanical chopper	1.357	50	1.3	65	Good	Moderate
AOM	1.1984	15	3.9	58	High	High

The output pulse of acousto-optic (AOM) Q-switching technique was more stable, higher peak power, narrower pulse width and higher beam quality than that by using mechanical chopper Q-switching technique, while the energy per pulse is higher by using mechanical chopper Q-switching technique rather than that obtained by using AOM.

4. Discussions and Conclusions:

Optical (mechanical) chopper Q-switching technique for diode pumped flower shape double cladding Er^{3+}:Yb^{3+}co-doped high power single mode TEM_{00}fiber laser has been developed. It was found that by using the reticule #5, pulse width of 50 ns peak power of 1.3 kW, energy per pulse 65 µJ and average output power of 1.357W at pulse repetition rate of 20 kHz was achieved. While by using reticule #3, narrower pulse width of 35ns, higher peak power of 15.5 kW, higher energy per pulse of 0.5mJ and higher average output power of 1.142W at pulse repetition rate 1 kHz was investigated. With reticule # 5 the pulse to pulse variation of nearly ±75% and minimum variation of 18.75% was measured. Average power and pulse width have been increased as the repetition rate increased but the peak power and pulse energy decreased.

A diode pumped acousto- optic modulator (AOM) Q-switched Er^{3+}:Yb^{3+}co-doped high power fiber laser has been developed. The shortest pulse duration obtained was 10 ns, giving a highest peak power of 9.8 kW, 98µJ energy per pulse and average power0.988Wat 10 kHz pulse repetition rate. The pulse train with high pulse-to-pulse stability of nearly 95 % measured at a range of high repetition rates up to100 kHz with peak power of 0.4kW, 40ns pulse width, 16µJ energy per pulse andaverage power 1.647Wat 100 kHz pulse repetition rate at 1550nm for a launched power of 5W.As the repetition rate increased the average power and pulse width increased but the pulse energy and peak power decreased.

A comparison between mechanical chopper Q-switching technique and acousto-optic (AOM) Q-switching has been done at repetition rate of 20 kHz, the reported energy per pulse, pulse width and the average power of mechanical chopper Q-switching technique is greater than that of acousto-optic Q-switching but the narrower pulse width and a consequence of higher peak power using acousto-optic Q-switching as compared to that obtained by using optical (mechanical) chopper Q-switching technique. For mechanical chopper Q-switching technique the spatial beam profile quality was good and the pulse to pulse stability was moderate but for acousto-optic Q-switching technique the spatial beam profile quality and the pulse to pulse stability were high.

So, the output single mode TEM_{00}pulses of acousto-optic modulator (AOM) Q-switching technique were more stable, higher peak power, narrower pulse width and higher beam quality than the that of mechanical chopper Q-switching technique. while the energy per pulse is higher by using mechanical chopper Q-switching technique rather than that obtained by using AOM..

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