The selection of Q-Switch for a 350mJ air-borne 2-micron wind Lidar

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ABSTRACT

In the process of designing a coherent, high energy 2µm, Doppler wind Lidar, various types of Q-Switch materials and configurations have been investigated for the oscillator. Designing an oscillator with a relatively low gain laser material, presents challenges related to the management high internal circulating fluence due to high reflective output coupler. This problem is compounded by the loss of hold-off. In addition, the selection has to take into account the round trip optical loss in the resonator and the loss of hold-off. For this application, a Brewster cut 5mm aperture, fused silica AO Q-switch is selected. Once the Q-switch is selected various rf frequencies were evaluated. Since the Lidar has to perform in single longitudinal and transverse mode with transform limited line width, in this paper, various seeding configurations are presented in the context of Q-Switch diffraction efficiency. The master oscillator power amplifier has demonstrated over 350mJ output when the amplifier is operated in double pass mode and higher than 250mJ when operated in single pass configuration. The repetition rate of the system is 10Hz and the pulse length 200ns.

1. INTRODUCTION

High energy 2µm laser has been recognized to be the system of choice for global wind measurement. In addition to the eye-safety, the transmission wavelength of the transmitter suitably matches the aerosol size in the lower troposphere. With a minor adjustment, it has been shown that this wavelength regime can be used to measure CO_2 [1]. NASA has invested considerable amount of resources to get this technology matured and to reduce the risk associated with high energy space borne lasers. As a result, the physics behind 2 micron producing laser crystals is well understood and optimized [2], joule level energy output is achieved with reasonable efficiency [3] and in an effort to enhance the technology readiness level, advanced thermal management system has been demonstrated that removes the heat in a totally conductive manner [4][5]. More and more fielded 2µm lasers are deployed to measure wind and CO_2. This paper discusses a system that will be fielded both as ground and airborne instrument with emphasis on the Q-switch, one of the crucial components in the oscillator. This lidar transmitter is capable of producing 350mJ at 10Hz repetition rate. It is composed of a seed laser for injection seeding, an oscillator and an amplifier. The amplifier can be configured to operate in either single or double pass arrangement.

Laser components that are used for 2 micron system are constantly improving and are steadily moving from ‘custom’ to ‘off the shelf’ category. Semiconductor lasers used for pumping Thulium lasers have gone from 60 to 200 watts/bar and the efficiency of these diodes has enhanced from mid 30% to mid 50%. The number of high quality laser crystal suppliers has increased; optical coatings that withstand high energy at 2µm wavelength have become readily available. Diagnostics tools such as cameras, spectrometers, high speed detectors are obtainable with a reasonable effort.

The objective of this effort is to determine a suitable Q-switch for 2µm coherent lidar transmitter. Among the myriad switching systems that are on the market, this study looks at two distinct switching systems; electro optics and acousto-optics Q-switches. In the end, since the Acousto-optics (AO) is deemed suitable for the application, detailed device performance is presented.

1.1. Oscillator specification and design consideration

The selection of the Q-switch is driven by the specification of the oscillator. The oscillator specification is given in table 1. The laser wavelength for wind speed measurement does not have to be a locked to a specific wavelength as in DIAL instrument. However, it has to avoid atmospheric absorption lines such as CO_2/H_2O in the 2µm regime.

Laser wavelength :	2.053 µm
Laser material:	Ho:Tm:$LuLiF_4$
Oscillator Output energy:	100mJ
Pulse length:	>150 ns
Pulse repetition rate:	10 Hz
Laser operating mode:	Single transverse and single longitudinal mode
operating temperature:	5-15 degrees Celsius
Laser output polarization:	Linear polarized >100:1
Beam Quality:	<1.3X Diffraction limited
Pulse laser spectral width:	Transform limit<5 MHz

Table 1. Oscillator specification

Output energy of 100mJ is considered to satisfy certain design constraints like limiting the internal circulating energy in the resonator while approaching the saturation energy which is beneficial for higher amplifier gain extraction. The laser material used for producing 2µm wavelength is a LuLF host co-doped with Holmium and Thulium. Compared to Nd:YAG, this material has a smaller emission cross-section. As a result, the optimum output mirror reflectivity falls between 0.7 and 0.8 which leaves a high circulating fluence inside the resonator that exceeds $30J/cm^2$. This causes the internal circulating energy in the resonator to be prohibitively high for low damage threshold optical materials to be used as switching medium.

While a long pulse length has the advantage of providing narrow line width which enhances the frequency resolution of the lidar measurement, if the pulse is too long it can compromise the range resolution. To meet the long pulse requirement, the oscillator length is set to 3 meters and formed with six mirrors having 8 bounces. The pulse length has a direct correlation to the line width of the laser. The final temporal pulse width at HWFM is 200ns. For a Gaussian beam, this offers a transform limit line width of 2.25 MHz. The 10 Hz repetition rate is limited by the pump laser duty cycle which is in the order of 1.3%. To take advantage of the long upper laser level lifetime of the Tm:Ho system, the pump laser is operated at 1ms long pulse.

To operate in a single transverse mode, a traveling wave resonator design is chosen; this scheme avoids spatial hole-burning and facilitates seeding. Two curved mirrors are selected to match the pump mode volume in the rod. The pump volume in the rod is derived from a Monte Carlo ray optics analysis which calculates the absorption flux for the particular geometry used in the design. The TEM00 mode volume in the resonator is calculated using ABCD matrix. Injection seeding is implemented to narrow the line width of the oscillator wavelength.

The design of the oscillator is such that the rod is uniformly pumped and does not experience thermal gradient and careful attention has been paid to avoid any kind mechanically induced stress on the rod, as a result the beam quality or beam propagation factor of this system has been in the order of 1.1 times diffraction limited.

2. Q-SWITCH OPERATION AND SELECTION

In Ho:Tm co-doped crystals where the Ho $^5I_7$ is populated by energy transfer from the Tm $^3F_4$, there is a large difference between the normal mode and the Q-switch laser outputs. In a typical operation, the normal mode energy has a slope efficiency of 22% while the slope efficiency of the Q-switched output is only 8%. In normal mode operation, the Ho upper laser level population is clamped around 0.3 of the maximum inversion; therefore, at this inversion level, up conversion or any other high population inversion related losses to do not occur. In Q-switched operation, the loss in the resonator is kept high to allow build up in the Ho $^5I_7$. During this time, the population inversion is adversely affected by up conversion, energy back transfer to Tm and other radiative and non-radiative mechanisms.

The ratio of the converted energy from normal mode to Q-switch varies with the pump energy. At low pump energy, 80% of the normal mode energy can be converted to Q-switched energy, but as the pump energy grows, the percentage drops down to 46% at the 100mJ output level in LuLF.

Some of the earlier experiments were conducted using a Lithium Niobate electro optics device. This device operates by manipulating the polarization in the resonator. Some of the findings of the experiment are summarized below:

a) This application usually requires an additional optics like a polarizer to function. This creates a detrimental effect by raising the overall loss in the resonator. It is preferable to keep the resonator loss as low as possible.
b) The electro optics device usually exhibits ringing which produces post-lasing. This is a significant problem in this laser material since the Tm is pumping the Ho even after the Q-switch is initiated. Fig. 1 shows the Q-switch timing of this system.
c) The pulse evolution time interval is relatively long as a result the high voltage electronics pulse will have to be stretched to about 10 microseconds.
d) And finally the low damage threshold of the optical device limited the output energy.

The Acousto-optic Q-switch that has been used for 2μm lasers is primarily chosen for its low loss and high damage threshold and high transmission. It operates with 24Mhz rf frequency and requires 100 watts of power over 3ms the high power is associated to the fused silica substrate. Although materials like Tellurium dioxide (TeO2) can provide higher diffraction efficiency for a given rf power, the damage threshold makes them unsuitable for this application.
When such a device is used in a resonator, a portion of the beam intensity incident on this grating diffracts out of the main beam into one or more distinct orders having different direction than the beam path. This inhibits the oscillator from lasing by lowering the Q of the resonator and allows population buildup in the Ho:5I7 . Removing the rf eliminates the grating and the device acts as a regular transparent optical material. The beams collapse and join back the main path. If the laser gain has sufficiently built-up, resonator produces a single giant pulse.

When an acoustic wave is launched in the AO Q-switch, an optical phase grating is created in the fused silica due to the photo-elastic effect, which couples the index of refraction to the modulating strain field. The strain amplitude is given by [7].

$$S := \sqrt{\frac{2 \cdot Pac}{L \cdot w \cdot \rho \cdot \upsilon^3}} \qquad (1)$$

Where Pac is the acoustic power applied to the Q-switch, L and w are the length and width of the transducer and ρ is the density if fused silica.
The change in the index of refraction is related to the strain and the photo elastic coefficient, P.

$$\Delta n := \frac{1}{2} \cdot S \cdot P \cdot n^3 \quad (2)$$

The amplitude of the phase grating is

$$\Delta\phi := 2\pi \cdot \frac{L \cdot \Delta n}{\lambda_0} \quad (3)$$

The intensity of the diffracted beam for a Bragg operating device is

$$I_d := \sin\left(\frac{\Delta\phi}{2}\right)^2 \cdot I_{in} \quad (4)$$

Depending on the acoustic interaction length, (*l*) acoustic wavelength (Δ) and the operating laser wavelength (λ), two diffraction effects can be produced. In this case, a 2 micron wavelength and a 24 MHz rf frequency resulted in Bragg scattering regime. This occurs when the product of the interaction length and the laser wavelength is greater than the square of the acoustic wavelength. ($l\,\lambda > \Delta^2$) . In Bragg the regime, two beams are produced when the device is activated. While the 0^{th} order beam stays aligned and the 1^{st} order or the diffracted beam will be frequency shifted by the value of the rf frequency up or down depending on the angle of the input beam. This frequency shift does not interfere with the operation of the laser unless injection seeding is performed through the Q-switch even then the impact is minimal.

For the 2-micron oscillator the diffraction efficiency was 25%. If the oscillator is pumped with high gain, the induced loss will not be satisfactory to achieve hold-off.

To avert this problem Raman Nath diffraction is considered and the performance examined. For Raman Nath scattering, the following should be true $l\,\lambda < \Delta^2$. The acoustic wavelength Δ is defined as $\upsilon/\nu_{rf,}$ which is the acoustic velocity divided by the rf. The value of Δ is modified by lowering ν_{rf} from 24MHz to 13.5 MHz. The advantage of operating in this mode is that it provides substantial optical loss in the 0^{th} order by diffracting the beam in multiple orders. In our case we have observed up to 7 modes. It also provides an option to lower the rf power. The intensity of individual orders, in Raman Nath operation, ($I_{n)}$, is given by [8]

$$I_n := {J_n}^2(\Delta\phi) \cdot I_{incident} \quad (5)$$

where J_n is the Bessel function of the nth order.

2.1.1. Test setup

Two different types of setups were used to evaluate and compare the performance of the Q-switches. The first setup, examined the diffraction type, Q-switch turn-off time and the dispersion angle. The second was inside a laser resonator, which looked at laser hold-off, pulse build-up time and pulse evolution time interval as a function of beam position relative to the transducer.

The first setup is shown in fig. 1, where a 2µm continuous wave laser was used. The polarization of the beam was set perpendicular to the acoustic propagation vector. This polarization was chosen for two reasons. First, the photo elastic effect is 2.2 times larger and second the amount of power required to get the same level of diffraction is 5 times smaller. A thermo-electric cooled Indium Antimonide (InSb) detector mounted on a vertical translation stage is used to measure the intensity and the dispersion angle of the individual orders. A camera was used to align the Q-switch and record the picture.

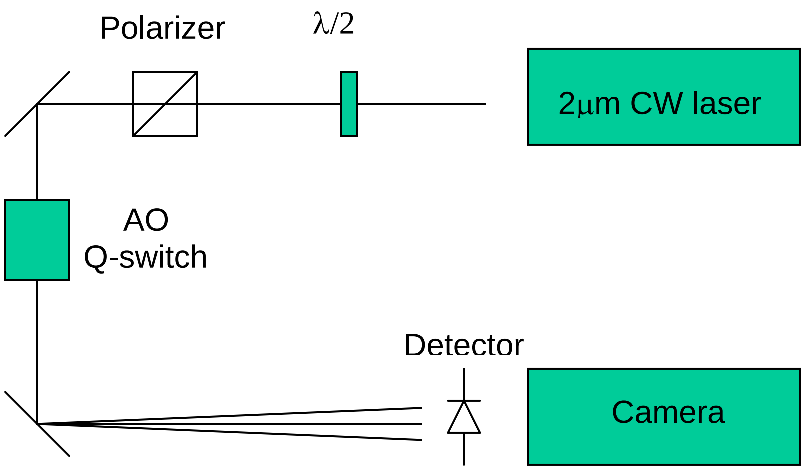

Figure 1. Experimental setup

2.1.2. Results

Five different Q-switches operating in a Raman Nath diffraction regime were used in this experiment. Using the above setup, the relative intensity of each order and position is measured. The measured and the calculated values are tabulated below. The calculated value is in reasonable agreement with the measurement. This experiment clearly shows that the device diffracts over 90% of the 0^{th} order in to other orders. This Q-switch is suitable in a resonator with very high gain where an unyielding hold-off is required.

	Intensity distribution in the different Orders when 13MHz rf is applied						
Diffraction order	-3	-2	-1	0	1	2	3
		10.5%	38.9%	9.5%	30.8%	7.75%	
		8.65%	35.3%	10.8%	35.3%	8.65%	
		10.8%	36.7%	9.7%	34.3%	7.6%	
	0.9%	18.4%	28%	5.8%	33%	6%	
		12.8%	29.3%	7%	31%	13%	0.8%
Calculated	2.440%	15.06%	31.44%	1.68%	31.44%	15.06%	2.440%

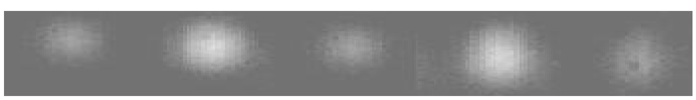

Table 2. Measured and calculated values of 5 Q-switches operating in the Raman Nath regime with corresponding picture

2.2. Measurements inside a resonator

The objective of this test was to compare if there is a performance difference between the 24 MHz and 13 MHz Q-switch. Some of the crucial measurements that were performed include the output energy in normal mode and Q-switch mode. In Q-switch mode, the pulse build up time and the pulse width are measured as a function of pump energy. In addition, the pulse build-up time was measured as a function of beam position in the Q-s material. Q-switch turn-on and turn off times were also measured.

A 3m long ring resonator was set up to evaluate the performance of the Q-switches. A large TEM_{00} mode volume that matched the pump volume was set in the rod while setting a beam waist in the Q-switch position to clear the beam aperture of the device.

pump(mJ)	NM output no QS In cavity (mJ)	NM with turned off Q-S in cavity (mJ)	Q-S (mJ)	PW (ns)	PBT (µs)	NM to Q-S conversion η
1810		5	3	2100	15.2	0.6
1979	16	16	10.5	890	6.2	0.65625
2147	35.5	35.5	21.5	437	3.5	0.60563
2316	56.5	57.5	33	37	2.8	0.57391
2485	81	82.5	44	218	2.39	0.53333
2653	108.5	107.5	54	214	2.15	0.50233
2822	137	137.5	62.5	194	1.99	0.45455
2991	166.5	168	72.5	180	1.83	0.43155
3159	200	202.5	81.5	178	1.76	0.40247

Table 3. Measurement of a 24MHz Q- switch was virtually the same as the 13 MHz device

The comparison between the two Brewster angle cut switches is strikingly the same. The only difference that is observed is the difference in the pulse build-up time and the pulse width. The difference in the pulse build up time could be related to the beam position with respect to the acoustic transducer.

The pulse build time is generally defined as the time interval between the Q-switch turn-off signal and the peak of the laser temporal pulse. In this case it is the combination of the electrical delay, the acoustic turnoff time and the laser pulse evolution period.

The electrical is the shortest of the three delays. This is the time interval between the removal of the rf and the actual turn-off. This occurs within one cycle of the rf.

The opening time of the AO Q-switch is determined by the time required for the acoustic wave to pass through the beam diameter. For fused silica the acoustic velocity (υ) is 5950cm/sec. Therefore it takes the traveling grating 168ns to travel a distance 1mm. It is advantageous to place the Q-switch in the vicinity of the waste of the TEM_{00} mode volume to achieve faster turn-off time. To shorten the opening delay the distance from the transducer to the beam should be as short as possible. A beam waist (ω_o) of 1mm requires an opening time of 336ns.

The third delay that is associated to the build-up time where the rapid growth of intensity inside the cavity results in a large stimulated emission and a rapid extraction of energy. The stimulated emission rate depends on the pump intensity. At lower pump, the rate slows which results in longer pulse evolution time interval.

The pulse evolution time interval has been evaluated as a function of beam proximity to the transducer. At first the beam was placed at the bottom of the Q-switch very close to   (2mm) the transducer; then pulse build-up time, the energy, and the pulse width of the laser was measured. The measurement was repeated for with the beam places 9mm away from the transducer. As expected, the setup with the beam closer to the transducer produced a shorter pulse build-up time. Figure 2 shows the delay of the temporal pulse as a function of beam is proximity the transducer.

On the average the time difference of the pulse build-up time is 1.87µs, which corresponds to the time required for the acoustic wave to travel 7mm, which is the difference of the two beam positions.
The pulse width looks very similar. However, a closer look reveals that the beam further from the transducer has shorter pulse width. This could be an indication that the Q-switched pulse starts evolving before it is fully opened. Given that the pulse width required for the final application calls for long temporal width, in the hundreds of nanoseconds, the oscillator design will always have a pulse stretching mechanism built into it. In this case a long resonator length is chosen to satisfy this requirement.

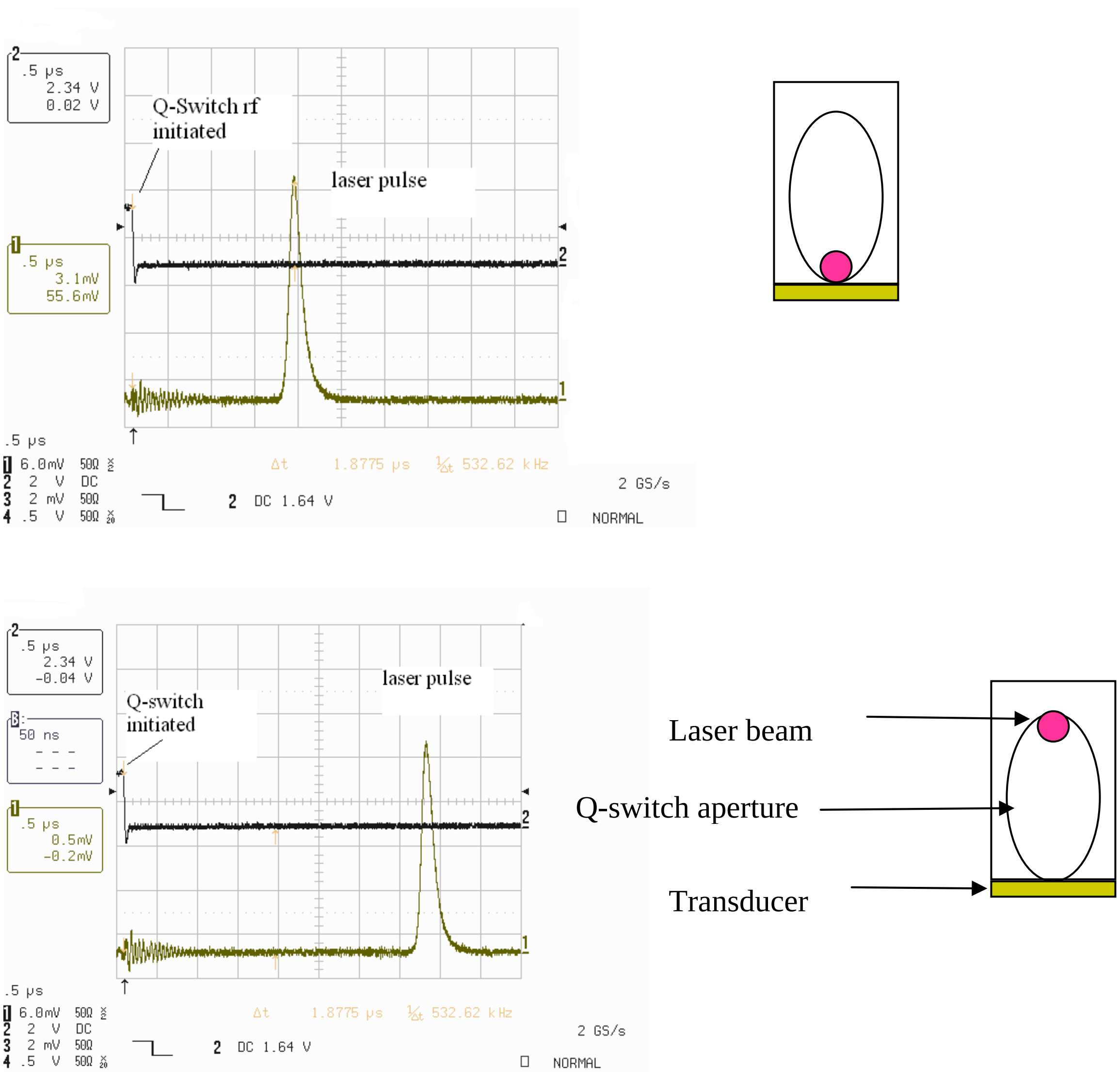

Figure 2. These plots show the effect of beam position on pulse build-up time . the beam is placed 2mm and 9mm from the transducer for the top and bottom graphs respectively.

2.3. Injection seeding considerations

This system should be injection seeded and to narrow the line width. The preferred method for injection seeding for such a system is the ramp and fire scheme. There are two primary reasons why such a system is suitable for airborne type applications where the transceiver is subjected to vibrations. The first is that the length adjustment for forcing resonance is initiated for each pulse as opposed to other schemes like shortening the pulse build-up time where the electronics has to depend on successive pulses to t adjust the length of the resonator. Second the entire ramping, sensing and firing the Q-switch occurs in less than 100µs. This is fast enough to overcome most kinds of mechanical induced vibrations.

Once the Q-switch performance is evaluated, a trade study was conducted to determine which Q-switch should be used for an air borne system with output energy of 350mJ. This decision is driven by the injection seeding robust performance. If a 13MHz device is used, the seed will have to be injected through the first order of the Q-switch, which couples 30% of the beam into the resonator. However, since the Q-switch is on during the crucial ramp and fire time segment, and the transmission of the 0^{th} order which is less than 10% reduces the intensity of the resonance signal. A 27MHz Q-switch on the other hand, diffracts only 25% of the seed beam during the critical time segment for injection seeding and has minimal detrimental effect. For this configuration, the seed laser could be injected either through the Q-switch or the output coupler. Finally the 24MHz switch was deemed suitable for the pump level that the oscillator is operating.

The architecture of the system consists of an oscillator and an amplifier. The 3m long oscillator has six mirrors and eight bounces including the output mirror. One of the mirrors is mounted on a PZT to adjust the length of the oscillator during injection seeding. The final output energy is 100mJ at 10Hz repetition rate. The laser energy stability measurement showed that 99.4% of the pulses within ±3mJ. This test was done over an hour. This result is satisfactory given that the injection seeding tends to vary the switching time by as much as 70µs in the injection seeding process.

The amplifier can perform in either single pass or double pass configuration. Although the energy in double pass configuration is much higher, the beam can experience distortion due to uneven energy extraction and thermally induced lensing in the rod.

In addition to the amplifier and the oscillator, the transceiver houses a seed laser an AO modulator to accommodate intermediate frequency and a fiber network to separate and route the local oscillator and the lidar signals.

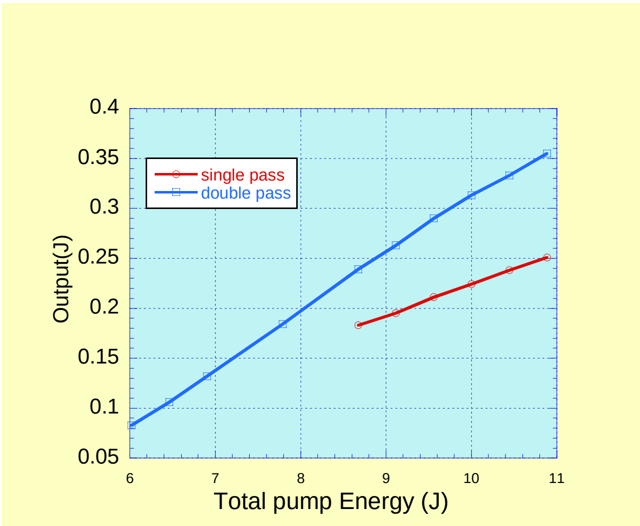

Figure 3. The final energy out of the amplifier with 93mJ input from oscillator of the system

3. ACKNOWLEGMENT

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4. CONCLUSIONS

A.O. Q-switches with 13.56 MHz rf frequency are evaluated for 2µm laser application. By reducing the rf from 24 MHz to 13.56MHz, it has been shown that the 2µm operation changes from Bragg setup to Raman Nath setup. This change has provided two benefits, the first is a much higher diffraction that was needed for hold-off is achieved and the second is reduction of acoustic power required to maintain hold-off. The shortcoming associated is that the seed laser beam is attenuated which causes a weak resonance signal for injection seeding. This can be corrected by reducing the acoustic power just to satisfy hold-off condition. If the seed beam is inserted through the first order, about 30% can be coupled into the resonator.

5. REFERENCES

1. G. J. Koch, B. W. Barnes, M. Petros, J. Y. Beyon, F. Amzajerdian, J. Yu, Davis, S. Ismail, S. Vay, M.J. Kavaya, and U.N. Singh, "Coherent Differential Absorption Lidar Measurements of CO_2," Applied Optics 43(26), 5092-5099 (2004)
2. B. M. Walsh, N.P. Barnes, M. Petros, J. Yu, and U.N. Singh, "Spectroscopy and modeling of solid state lanthanide lasers: Application to trivalent Tm3+ and Ho3+ in YliF4 and LuLiF4," Journal of Applied Physics, 95, 3255-3271 (2004).
3. J. Yu, B. C. Trieu, E. A. Modlin, U. N. Singh, M. J. Kavaya, S. Chen, Y. Bai, P. J. Petzar, and M. Petros, "1 J/pulse Q-switched 2-µm solid-state laser," Optics Letters 31(4), 462-464 (2006)
4. Mulugeta Petros, Jirong Yu, Tony Melak, Bo Trieu, Songsheng Chen ,Upendra N. Singh, Yingxin Bai ," Totally conductive cooled, diode pumped, 2µm laser transmitter" Proceedings of SPIE 5653 Jan.2005 Lidar Remote Sensing for Industry and Environmental Monitoring
5. B. Trieu, J. Yu, M. Petros, L. Ramos-Isquierdo, G. Byron, P. Sohn, S. Chen, Y. Bai, M. J. Kavaya, and U. N. Singh, "Design of a totally conductively cooled, diode pumped, 2µm laser amplifier," Proc. SPIE 5887, p. 126, Lidar Remote Sensing for Environmental Monitoring VI, San Diego, CA (31 July – 4 Aug. 2005)
6. Douglas A. Pinnow "Guide Lines for selection of Acoustooptic materials" J.QE-6,233,(1970)
7. W. Koechner *Solid state laser Engineering* Springer-Verlag, 5^{th} Ed. pp 502