Frequency Doubling with Nd:YAG laser

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We have repaired the Quantronix 116 Nd:YAG laser in the Modern Optics Lab. In particular, the water filter, the deionizer, and the Krypton pump lamp were replaced. With these changes, we have observed up to 14W of CW IR output at 1064nm. We then used the newly-repaired laser to perform frequency doubling with a KDP crystal, producing green light at 532nm. Finally, frequency doubling efficiency was measured as a function of input IR power, yielding a constant conversion efficiency of approximately 5.2% over the input IR range of 0.5 to 4W.

1. Introduction

In this paper, we first describe our repair of the Quantronix 116 Nd:YAG laser in the Modern Optics Lab (6.161). According to the manual that accompanied the laser system, the model is dated June 16, 1978; and was last serviced by Quantronix personnel on March 30, 1981. During the project, we have been informed by Prof. Warde that the laser had not been operational for at least ten years. Following our work, we have observed up to 14W of CW IR power, and were able to conduct an optical experiment with the output.

Our repair efforts were guided by insights from previous attempts. In particular, we had been informed that the plumbing associated with the cooling system required renovation. It was also suspected that the flash lamp in the laser head was malfunctioning. After we addressed these issues, the laser produced IR output following a relatively painless alignment of the cavity mirrors.

We have spent the majority of our time working on the plumbing system. We have therefore established standard procedures for various plumbing-related maintenance, such as:

- Refilling the reservoir,
- "Wetting" the pump for initial run,
- Location of electrical reset for the pump.

Our methods will be useful for future maintenance of the Quantronix 116. Hence, a detailed description of these standard procedures can be found in this paper.

Following the repair, we have performed a nonlinear optics experiment with the laser output. We have achieved frequency doubling with a KDP crystal. Frequency doubling is particularly interesting at our wavelength of 1064nm, since the initial light is invisible, but the doubled 532nm is a visible, green beam.

In the second half of this paper, we describe our experiment to characterize the efficiency of frequency doubling as a function of input IR power. The Quantronix 116 provides an analog control of the current delivered to the flash lamp. Using this feature, we were able to vary the input IR power from roughly 500mW to 14W. (Due to fears of destroying the crystal, we went up to only 4W in the frequency doubling experiment.) At the same time, we have constructed an optical setup that allowed us to measure only the green beam power at the output.

Our measurements unambiguously show that the efficiency of conversion is constant at 5.2% over the input IR range of 0.5 to 4W. This is inconsistent with the theoretical analysis, which predicts that the converted beam intensity has a quadratic dependence on the fundamental power. In the worst case, this result indicates a flaw with our optical setup; it may also indicate that the input range was not wide enough to probe the nonlinear behavior.

1.A. Bill of materials

For later reference, we give a list of parts that we have used to carry out the repair. Laser replacement parts were obtained from the Quantronix Laser Company (Web: `www.quantronixlasers.com`; Phone: 1-800-289-7707). The invoice can be found in the Appendix to our report. The total cost was $379.00 plus shipping.

Item	Part number	Cost
Krypton lamp	2601-00168	$285.00
Water filter	2802-00254	$9.00
Deionization cartridge	3002-01062	$85.00

Table 1. Replacement parts for the Quantronix 116.

Interestingly, the items we received from Quantronix did not have the part numbers that we found in the manual (and then ordered). Despite this confusion, we found that all replacement parts could be used in our system. Table 1 lists part numbers of the items that we *actually* received from Quantronix.

Miscellaneous items (i.e. hoses, clamps and epoxy for plumbing) were purchased from a local hardware shop. We have spent less than twenty dollars for such materials.

1.B. Laser startup procedure

Here is the initial procedure to turn on the Quantronix 116.

1. Turn the key ignition to "ON". See Figure 1.
2. The pump should be running on the *system-side*. If not, press the "COOLER" button.
3. Turn on the laser by flipping the rocker switch for the flash lamp. The current delivered to the lamp can be controlled by the knob next to the ammeter.

If the laser fails to turn on due to a (plumbing-related) interlock, please consult our troubleshooting section 2.B.4 on page 6. If the laser malfunctions for some other reason, then we wish you the best of luck with your repair!

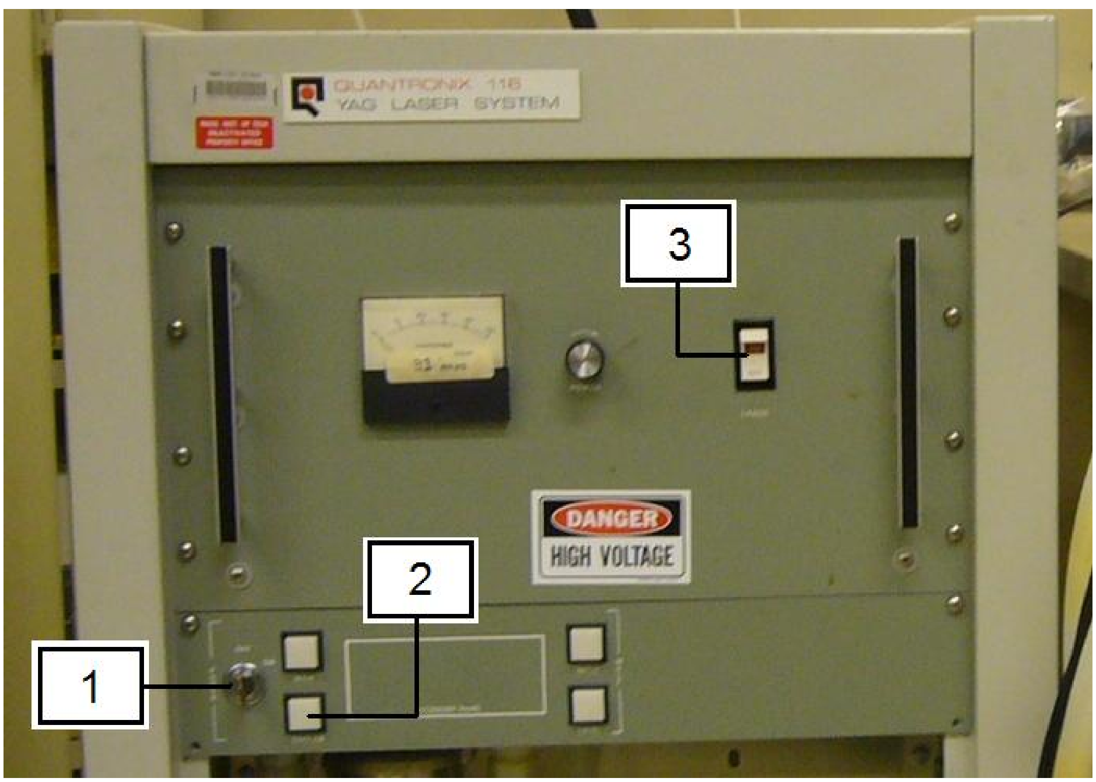


Fig. 1. Front panel of the Quantronix 116 power supply. The numbered boxes refer to the corresponding step in the startup procedure.

2. Laser repair

2.A. Principles of operation

We will be brief in the description of laser physics. A good general discussion can be found in [1]. The basic layout of the Quantronix 116 is shown in Figure 2.

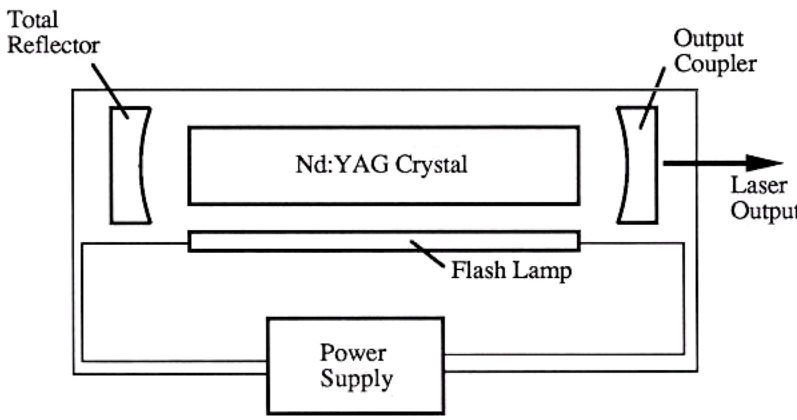


Fig. 2. Schematic of the Quantronix 116. The lasing medium is a Nd:YAG crystal, which is placed inside an optical resonator. Population inversion in the crystal is achieved by a flash lamp, which must be water-cooled. Diagram from [2]

The lasing medium is a neodinium (Nd^{3+}) doped YAG crystal, optimized for the production of 1.06 micron radiation. The population inversion is achieved by a krypton flash lamp. With a typical efficiency of about 3%, most Nd:YAG systems produce thirty times as much waste heat as laser output [2]. The excess heat must be removed in order to ensure proper laser operation. In the Quantronix 116, the flash lamp and the crystal are both submerged in an actively-cooled water bath. Hence, it is important to use deionized water in order to minimize electrical conduction through the water.

2.B. Restoration of the cooling system

The Quantronix laser system utilizes a water-cooling system for the laser head (and the AOM module). As we began the project, the cooling system was in a state of disrepair. In particular, we sought to replace the water filter and the deionization cartridge. We have also fixed miscellaneous leakage problems. In this section, we describe our repair efforts, and give tips for future maintenance.

2.B.1. General discussion

The manual (on page 4-22) provides a detailed flow diagram for the cooling system. However, given our limited background in interpreting such charts, we have produced a simplified block-diagram in Figure 3 that reflects our observations of the plumbing system.

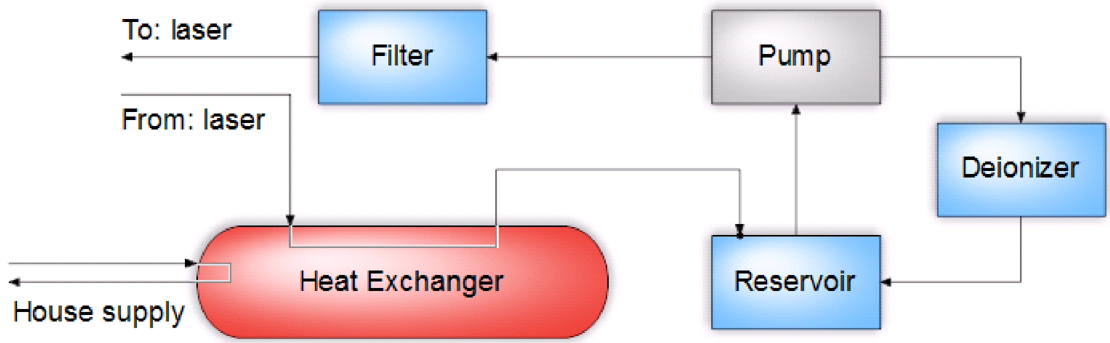


Fig. 3. A simplified flow diagram for the Quantronix 116 cooling system.

In order to operate the house supply, three valves must be opened in the MOL. Two are located behind the black curtains near the output end of the laser rail. These can be easily traced down by following the two "house supply" water hoses from the back of the heat exchanger. The third is located above the water sink, at the other end of the lab. The valves should be opened before the laser is turned on, although there will only be flow *after* the system is powered. Of course, the purpose of the house circuit is to dissipate the heat from the laser-side circuit.

On the laser side, Fig. 3 shows that there are two basic flow "loops" to consider. In the primary (left) loop, the return water from the laser is first cooled in the heat exchanger, then dumped in the reservoir. The pump then draws current from the reservoir and sends it through the filter towards the laser head.

At the same time, in the secondary loop (right), the pump sends a smaller portion of the incoming flow towards the deionization cartridge. The processed water is then returned to the reservoir. Through this mechanism, the system continuously cleans its own supply.

2.B.2. Replacement of the in-line water filter

The replacement of the water filter was very straightforward. The filter is contained inside a metallic canister, which can be opened by loosening the nut at the top. This is illustrated in Figure 4.

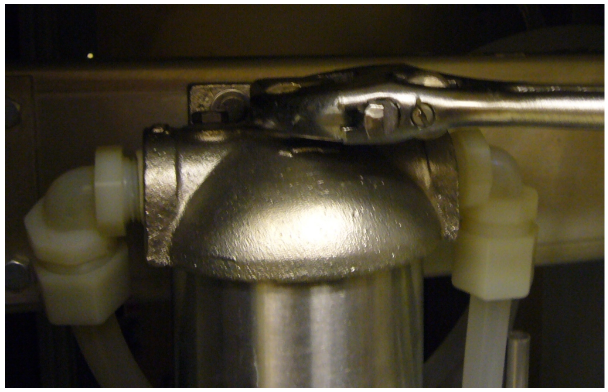


Fig. 4. The water filter is contained inside the canister, and can be extracted by loosening the nut on the top. To gain access to this part of the machine, a front panel must be removed.

2.B.3. Deionization cartridge

In contrast, the replacement of the deionization cartridge was much more involved. This was due to the complicated mounting mechanism that was previously used, which required the cartridge to be a very specific shape. Unfortunately, the replacement part that we received from Quantronix was considerably shorter than the older part. Hence, the old mounting system could not be utilized.

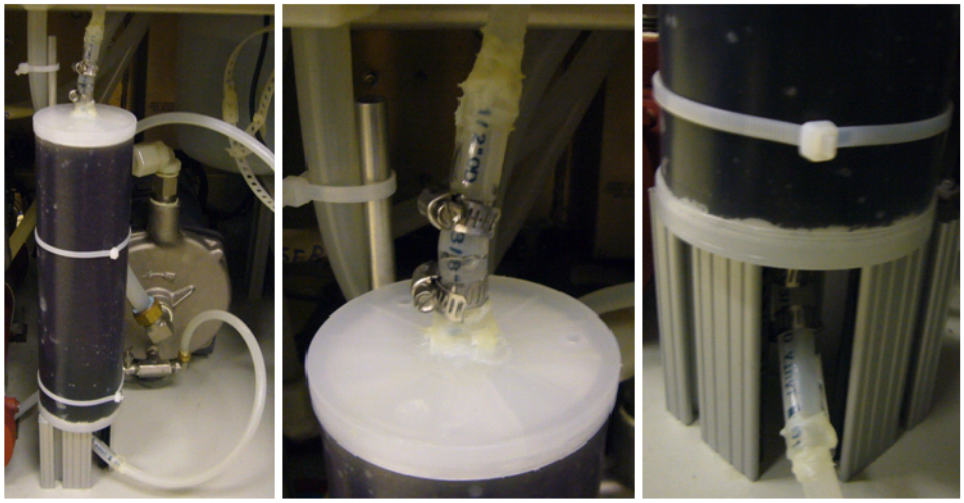
Therefore we have machined a small base and holder for the new cartridge, as shown in Figure 5. We have attached tubes directly to the nipples of the cartridge using 3/8" (inner diameter) tubes, clamps and epoxy. While we have successfully operated the cooling system without leaks prior to the epoxy (i.e. with just clamped tubes), we have chosen to apply the epoxy for maximum protection against leaks. The downside of this approach is that the tubes will be have to recut for the next replacement of the deionization cartridge.

2.B.4. Plumbing system troubleshooting

Depletion of the water reservoir. When the water level in the reservoir is too low, an interlock in the power supply will be triggered, and the laser will not function. The fastest way to fill the water reservoir is the following:

1. Identify the tube that carries water from the deionization cartridge to the water reservoir. This is located at the top of the deionizer. See Figure 5(b).

2. Pull the tube from the water reservoir. There is a cutout in the lid of the reservoir where the tube used to be inserted.



(a) (b) (c)

Fig. 5. (a) The new deionizer cartridge and its mount. (b) The connection at the top feeds the reservoir from the deionizer. (c) The connection from the pump to the deionizer. The connections were made by fastening a 3/8” ID tube over the nozzle, and then epoxying the ends.

3. Connect the external water supply to the system reservoir using a tube through the vacancy. Fill the reservoir.

Initial “wetting” of the pump. Following a draining of the system, the tubes will be empty. The main “reservoir-to-pump line” must be initially filled in order to initiate flow.

1. Locate the “fill line”, which is one of the thinner tubes connected to the pump. The line can be identified by a large metallic cap at the end. See Figure 6.

2. Remove the tube from the metallic cap. The filling water must be forced down the tube directly. (The cap does not conduct water.)

3. Inject enough water as to fill the main reservoir-to-pump line by about 10”.

4. Close the tube with the metallic cap. CAUTION: If this is not done securely, then the pump will spray water through the fill line when the system is powered on!

We have been unable to fill the reservoir-to-pump line *completely* by this method. However, we have successfully obtained sustained flow by one or two attempts of the above procedure.

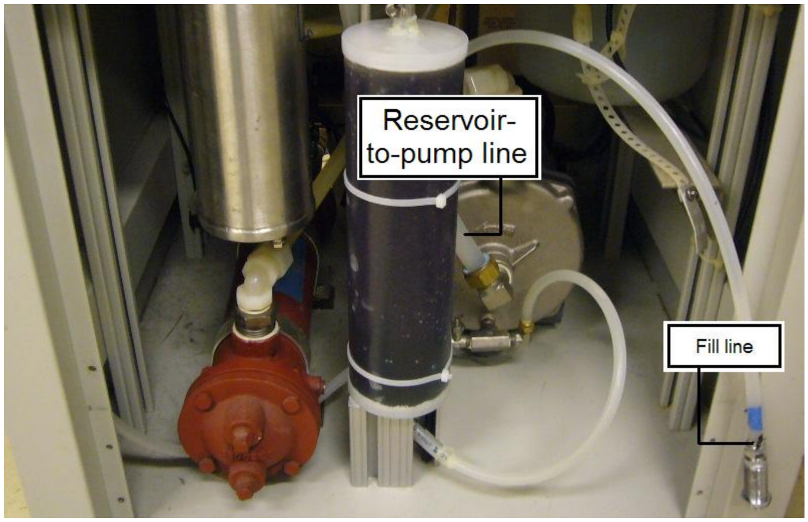


Fig. 6. A “fill-line” which can be used to initially wet the pump. The “reservoir-to-pump” line must be initially filled in order for the pump to operate.

Water pump electrical reset. We have encountered this problem just once during our project. However, it was sufficiently alarming, and hence we include it in the report. Near the end of our project, we found that the water pump would suddenly refuse to turn on, even though the system was properly powered. This problem was resolved by manually resetting the pump electronics.

1. Turn off and unplug the power supply.
2. Unscrew the back panel to expose the manual reset buttons. The view should look as in Figure 7. Note, however, that the model in the MOL does not have the optional components (i.e. the 301 L.V.P.S. and 301 RF driver).
3. Press both the “Thermal overload reset plunger” and the “Contactor K3” switch.

The pump should then be operational.

Additional troubleshooting procedures are listed in the Quantronix manual on pages 4-24 through 4-27, which discusses non-plumbing failure modes as well.

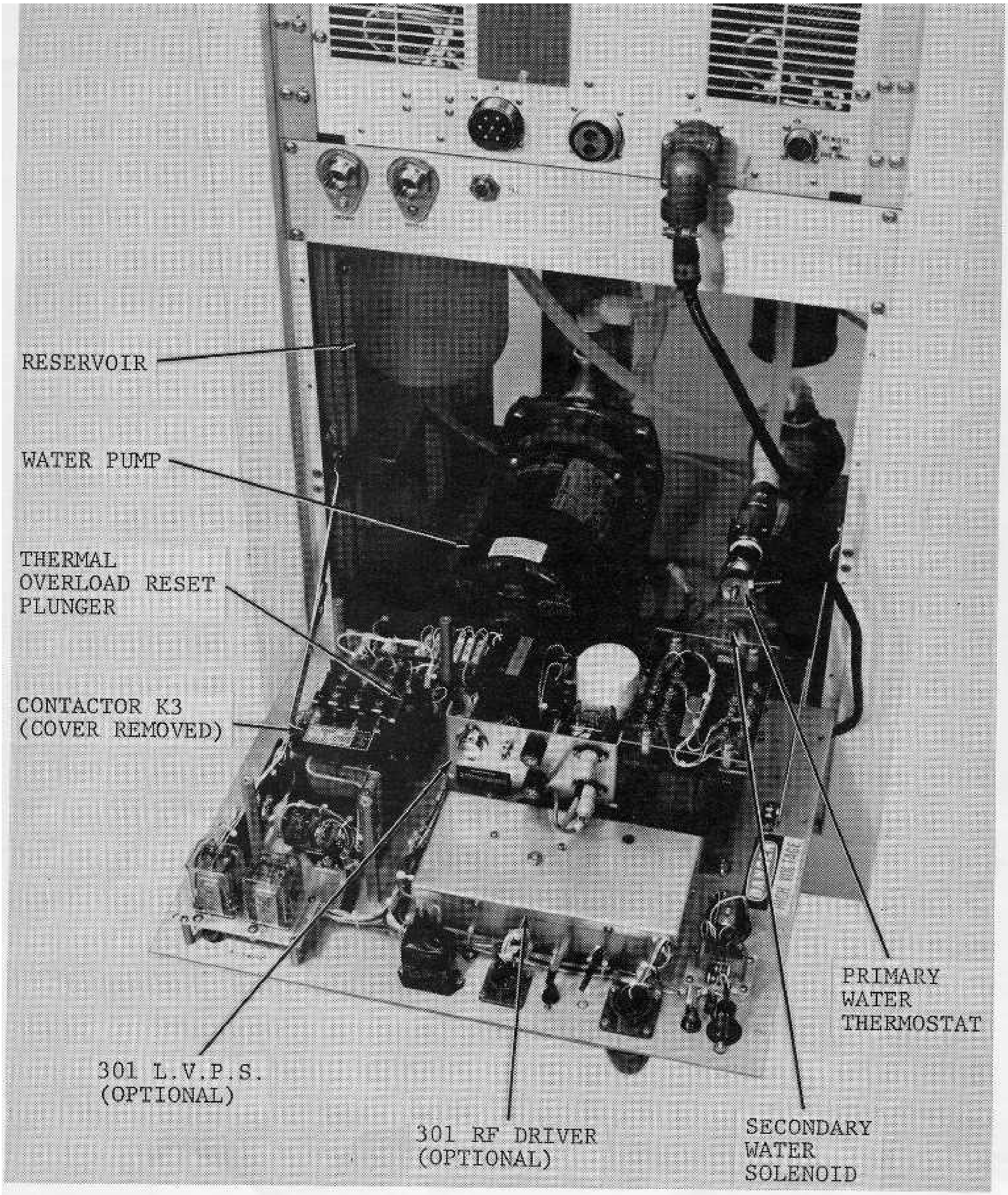


Fig. 7. The electrical reset for the pump is located at the back of the power supply. In the case of water pump failure, follow the procedure for "Water pump electrical reset". Press both the "Thermal overload reset plunger" and the "Contactor K3" switch. Figure is from the manual (Page 4-3).

2.C. *Flash lamp replacement*

At the beginning of our project, it was suggested that the flash lamp in the laser head was malfunctioning. This suspicion was confirmed, as we discovered that the old flash lamp had in fact shattered, and its electrodes were completely rusted away. In Figure 8, the old lamp is compared to the replacement part that we inserted.

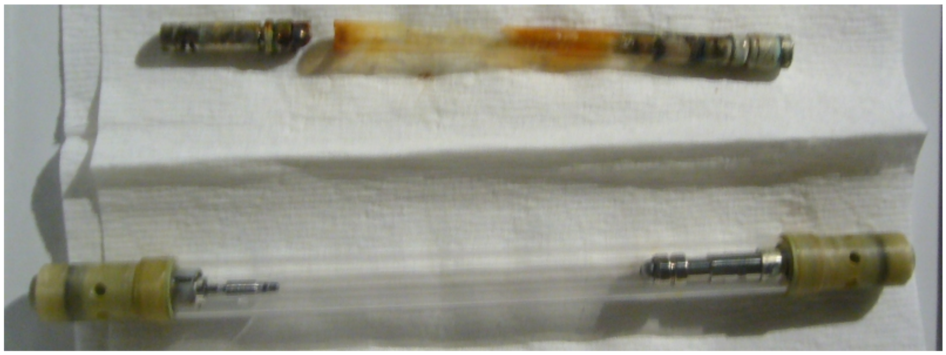


Fig. 8. The old flash lamp is shown on top. Below, we show the new lamp inside the water jacket assembly.

For future maintenance of the flash lamp, a spare water jacket assembly should be considered. During our work, we noted that the threading on the jacket assembly was severely damaged, which led to leaks. We have overcome this problem temporarily by wrapping the washers with layers of Teflon tape. For the long-run, however, a spare assembly is recommended.

For removing the flash lamp, the mechanical diagrams on pages 4-10 and 4-15 of the manual were helpful. After draining the laser head, we began by removing the screw-on "Int. power cables" connected to the flash lamp. (This step should be done carefully, since the threads on these plastic screws were also damaged.) We then completely removed the pressure plates on *both sides* of the laser head. With slight nudging, the entire water jacket assembly could then be pulled out of the laser head.

To remove the lamp from the jacket assembly, we unscrewed the threaded retainer on both sides. Then, both cathode and anode assemblies can be pulled from the jacket, leaving only the glass tube and the plastic ends. We thoroughly washed the glass tube before installing the new flash lamp.

2.D. *Laser cavity alignment*

Following the cooling-system repair and the flash lamp replacement, we found that we could activate the flash lamp. The remaining task was to align the cavity mirrors to achieve lasing.

The initial cavity distance was approximately 150cm. Despite numerous attempts, we could not attain lasing at this cavity distance. Whenever the lamp was turned on, we noted a pulse of laser output, which however failed to sustain itself. Therefore, we decreased the cavity length to roughly 40cm in order to relax the geometric lasing condition at the cost of multimode operation. Following this change, the cavity was painlessly aligned to achieve CW IR output.

2.E. Laser output power characteristic

The Quantronix 116 power supply offers an analog knob to control the amount of current delivered to the flash lamp. After achieving lasing, we characterized the input current vs. output IR power curve. Figure 9 shows the relationship for our alignment.

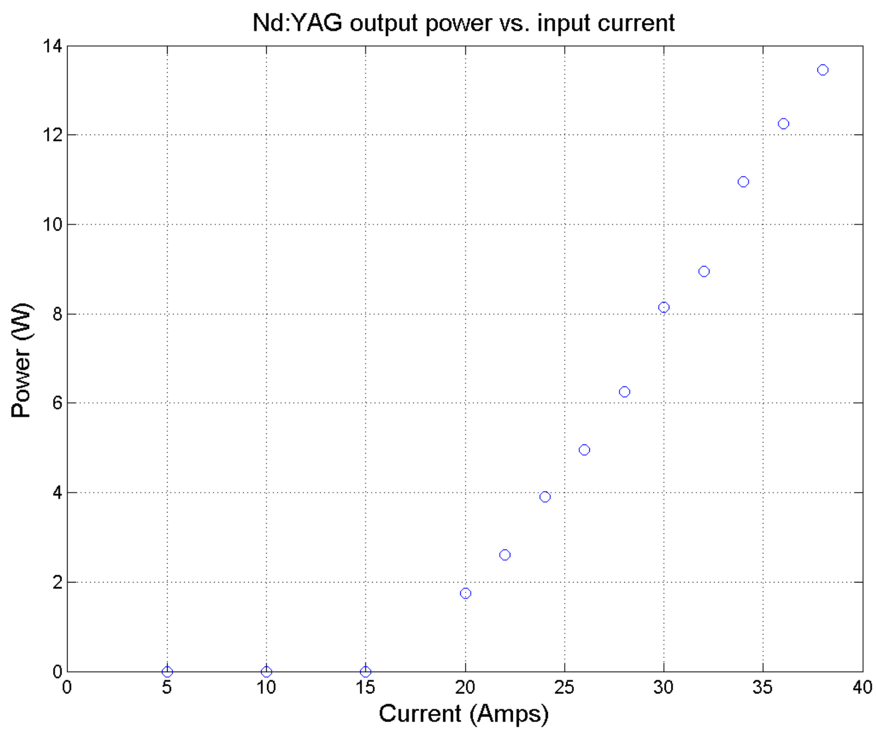


Fig. 9. Output IR power as a function of input lamp current.

We note that it was difficult to achieve low output power (e.g. less than 500mW) because at such current values, the flash lamp was prone to shutting off completely. To conclude, Figure 9 confirms that approximately 14W of IR power had been attained following our repair and alignment.

3. Frequency doubling experiment

3.A. Brief theory and experimental goals

Frequency doubling, also called "second harmonic generation", is a nonlinear phenomenon observed in some birefringent crystals, in which some of the incident beam is converted by the crystal into light with twice the frequency. In our case, the experiment consisted of a KDP (potassium dihydrogen phosphate) that converted the invisible 1064nm light from the Nd:YAG laser into visible, green light at 532nm.

We offer a simple classical explanation. The nonlinear effect is due to a term in the material polarization P that responds to the square of the external applied field E, as in:

$$P = \epsilon_0 \chi_2 E^2 \tag{1}$$

where χ_2 is a constant that represents the strength of the quadratic polarizability.

Now, it follows that if $E \propto e^{-j\omega t}$, then $P \propto E^2 \propto e^{-j(2\omega)t}$. In other words, the material dipoles oscillate at twice the frequency of the incident radiation, and therefore re-radiate at 2ω.

Frequency doubling is a phase-sensitive process which requires "phase matching" to be efficient. That is, we require the field contribution from the different locations of the material to add constructively at the crystal's exit face [3]. Hence, careful alignment is needed to achieve frequency doubling, which was particularly difficult with our damaged crystal.

Assuming the phase-matched condition, rate equations for the intensities in the two frequency modes ($I(\omega)$ and $I(2\omega)$) can be solved for the steady state. Refer to [4] for the details. The intensity of the frequency doubled beam is shown to be:

$$I(2\omega) = \frac{\omega^2 \chi_2^2 l^2}{2 n_{2\omega} n_\omega^2 c^3 \epsilon_0} I^2(\omega) \tag{2}$$

where l is the length of the crystal; and n is the refractive index at the denoted frequency. Notably, there is a quadratic dependence of the $I(2\omega)$ on $I(\omega)$. This is consistent with the classical Larmor radiation picture, in which dipole radiation is shown to be proportional to the square of the dipole. Since in our discussion $P \propto E^2 \propto I(\omega)$, we are again led to $I(2\omega) \propto I^2(\omega)$.

The objective of our experiment is then to measure the output green power as a function of input IR power.

3.B. Experimental setup

Our experimental setup to measure the conversion efficiency is shown in Figure 10. The IR light is represented by a red beam. The dashed, blue element represents a pickoff mirror which was periodically inserted to measure the input IR power by redirecting the beam towards the bolometer.

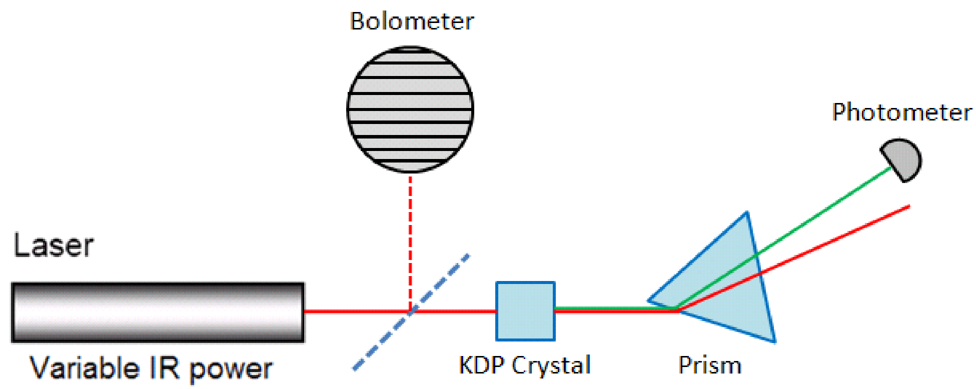


Fig. 10. Frequency doubling experimental apparatus. Green light was generated from the input IR beam by sending the latter through a KDP crystal. We used a prism to disperse the output beam. By moving sufficiently far away from the prism, we achieved about 1cm separation between the IR and green beams. We then measured the intensity of the green beam only.

Following the KDP crystal, the converted green and residual IR beams are spatially overlapping. Therefore, we used a prism to disperse the two colors. By appropriately rotating the prism, and moving sufficiently far away, we were able to achieve an approximately 1cm separation between the two beams. We positioned the photometer as to measure the green power only. We provide an actual photograph of the optical setup in the appendix.

3.C. Results

We have measured the output green power as a function of input IR power over the range: 500mW to 4W. It was difficult to go below 500mW, since the flash lamp would shut off at such low currents. We did not go beyond 4W due to fears of damaging the crystal. Our results are plotted in Figure 11.

The data unambiguously suggests a linear relationship between the input power and the amount of green light produced by frequency conversion. The proportionality factor was attained by a least-squares regression, and is shown to be 5.2%.

The linear relationship is not the theoretically expected result. One possible explanation for the deviation is that the input range was not sufficiently large enough to capture the nonlinear dependence. Another possibility is that the IR beam managed to (partially) reach the detector, which then swamped the green signal. This latter scenario would obviously lead to a linear relationship between the input IR power and the measured output. In a future iteration of the experiment, this latter possibility may be examined by using a more powerful dispersive element, such as a diffraction grating.

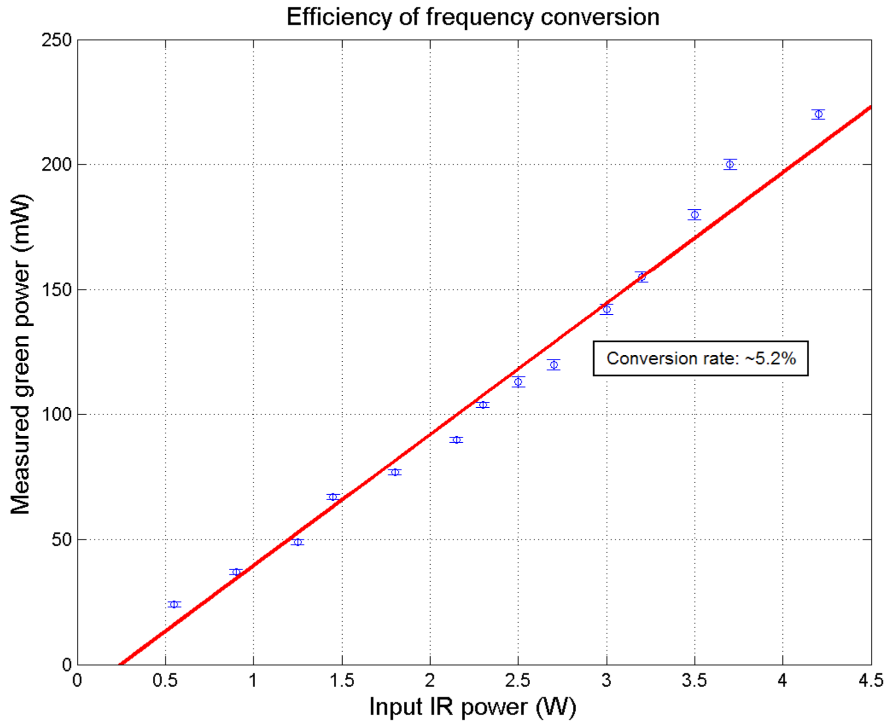


Fig. 11. Output green power as a function of input IR power.

4. Conclusions

We have successfully repaired the Quantronix 116 Nd:YAG laser system in the Modern Optics Laboratory. (MOL) At the time of the project conclusion, there were no known leaks, and up to 14W of IR output had been observed.

We then performed a frequency doubling experiment using the newly-repaired laser and a KDP crystal. We have investigated the conversion efficiency as a function of input power, and found a constant conversion efficiency of 5.2% over the input range of 0.5 to 4W.

Our project demonstrates that both the Nd:YAG system and the KDP crystal in the MOL are functional. Prior to our work, both were in questionable shape. Therefore, we have shown the feasibility of more advanced experiments using these components. For instance, one obvious follow-up experiment would be to lengthen the laser cavity of the Quantronix 116 to achieve single-mode operation, and to install the Quantronix mode-locking equipment which are already available in the MOL.

Acknowledgements. In closing, we would like to thank the other students in 6.161 who shared the lab with us throughout the term. They are Americo Caves, Amrita Masurkar, Matt Bieniosek and Raymond Cheng. They made the time in the lab much more enjoyable. In addition, we would also like to thank Mike "the Plumber" Szulczewksi, who shared his experience with us during the plumbing repair. Dave Dunmeyer, the former 6.161 TA, provided invaluable assistance in aligning the Nd:YAG cavity mirrors and the KDP crystal.

Bill Herrington, the current TA, was heroic in his devotion to the class. We benefited tremendously from his guidance throughout the entire semester.

Prof. Warde also gets our thanks for offering this very enjoyable class!

References

1. Cardinal Warde. *Chapter 9: Lasers*, 6.161/6.637 Class notes.
2. Y. Lawrence Yao. "Combined Research and Curriculum Development: Nontraditional Manufacturing" (Section 5.7: YAG laser machining of materials). `http://www.mrl.columbia.edu/ntm/level1/ch05/html/l1c05s07.html`
3. Rüdiger Paschotta. "Encyclopedia of laser physics and technology: Frequency doubling". `http://www.rp-photonics.com/frequency_doubling.html` Retrieved on 2008-12-13.
4. Robert Boyd. *Nonlinear Optics (Third Edition)*. Section 2.7: "Second-Harmonic Generation", pp. 96-101. New York: Academic Press, 2008.

A. Invoice for the Quantronix replacement parts

This is the invoice that arrived with the replacement parts. Hence, the information listed below correspond to the parts that are currently being used in the MOL.

QUANTRONIX CORP, 41 RESEARCH WAY, E. SETAUKET NY 11733

PICKING LIST DATE 11/12/08 12:24:33 PAGE

SHIP-TO ADDRESS ORIGINAL

JOHN SWEENEY
MIT RM 38-501
32 VASSAR STREET
CAMBRIDGE MA 02139
USA

CUSTOMER 497000 SCHEDULE DATE 11/12/08
COMPANY 1 REQUEST DATE 11/12/08

*** ACCEPTS BACKORDER
*** ACCEPTS PARTIAL SHIP

ORDER NO.	REFERENCE	DATE	TY
C124543	M/C CREDIT CARD-JOHN	11/12/08	I

SHIP INSTRUCTIONS - UPS GRD PPA 818

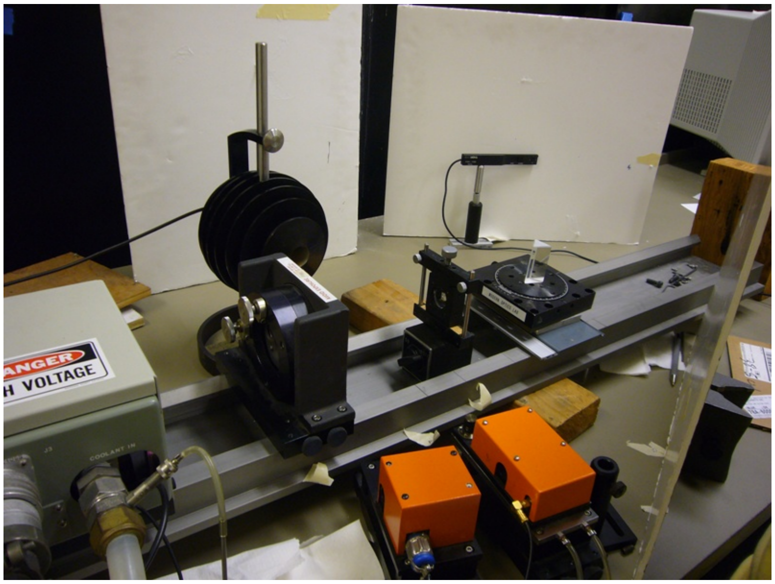
PACK CODE	WHS	LOCATION	ITEM NUMBER		QUANTITY ORDERED / QUANTITY SHIPPED	U/M	
09	04	BACK RM	2802-00254 CARTRIDGE,FILTER-10GPM/MICR		1.000 / 1	EA	$9.00
09	04	BACK RM	3002-01062 CRTG,DI 3/8 HOSE NIP 13.3IN	C	1.000 / 1	EA	$85.00
	04	BR-014	2601-00167 LAMP KR L6474 116	B	1.000 / 1	EA	$285.00
							$379.00 plus Shipping

Credit Card Charge
Acct # 146810[0] Obj. Code 420226
201184102
MN Date 11/24/08

Rec'd JS
For C. Warde
6161

B. Pictures from the Modern Optics Lab

A photograph of the optical setup for the frequency doubling experiment.



The following picture was taken by Bill following the completion of our project. Tony is on the left, and Ilan is on the right. Also note the distilled water jug, half of whose contents ended up on the floor during our project...