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Injection Seeded, Diode Pumped Regenerative Ring Nd:YAG Amplifier for Spaceborne Laser Ranging Technology Development

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Abstract

We report on a small, all solid state, regenerative ring amplifier designed as a prototype for space application. Novel features include dual side pumping of the Nd:YAG crystal and a triangular ring cavity design which minimizes the number of optical components and losses. The amplifier is relatively small (3 ns round trip time) even though standard optical elements are employed. The ring regeneratively amplifies a 100 ps single pulse by $\sim 10^5$ at a repetition rate of 10 to 100 Hz. The amplifier is designed to be injection seeded with a pulsed, 100 ps laser diode at 1.06 μm, but another Nd:YAG laser system supplying higher pulse energies was employed for laboratory experiment. This system is a prototype laser oscillator for the Geoscience Laser Ranging System (GLRS)[1] platform. Results on measurements of beam quality, astigmatism and gain are given.

1. Introduction

The concept of regenerative amplificaiton of fast laser pulses has been around for some time.[2],[3] The work of Lowdermilk and Murray examined coupling problems and charaterized the performance of a linear Nd:YAG regenerative amplifier.[4] Most regenerative amplifier work has been directed at amplification of mode-locked pulses from pulsed or cw oscillators. The more recent research has concentrated on increased repetition rates, higher energies, faster pulses and the use of different gain media.[5],[6],[7],[8] We are ultimately interested in amplifying a single ~100 ps, 1.06 μm diode laser generated pulse in the ring amplifier to effect an all solid state laser "oscillator". This letter reports on the development of the regenerative ring amplifier portion of this "oscillator", seeded by a 170 ps pulse from a mode locked linear laser.

2. Regnerative Amplifier Design

The ring configuration shown in figure 1 was chosen over conventional two mirror cavities because fewer optical components and only one electro-optical polarization switch are required. Other advantages of a ring configuration are reduced sensitivity to feedback, reduced damage sensitivity due to no overlapping in the elements, and since there are no standing waves, there is no spatial gain hole burning. The base side of the isosceles ring triangle is 45 cm long and the round trip time is 3 ns. The angles were chosen so that the s polarization would be incident on the thin film polarizer (TFP) at an angle ~57° for a reflective loss of about 1% per pass at this element.

The optically isolated, p polarized, seed pulse enters the ring through the TFP, passes through the gain medium around to the pockels cell switch, SW1, which has a $\lambda/2$

voltage holding off any lasing action. On the first pass SW1 remains on and the p polarized beam is rotated 90°. Now an s polarized wave, the pulse is reflected by the TFP and again passes through the gain medium and on to SW1 which now has zero potential. The wave now remains in the s polarization state until it has made the required number of passes. When SW1 is turned on, the amplified pulse is rotated back to the p state and escapes the cavity via the TFP. The cavity losses are calculated to be 5-6% based on the measured individual losses of the components.

3. Diode Pumped Amplifier Head

A view of the pump head is shown in figure 2 A pair of 1 cm wide diode arrays pump a maximum of 40W each of 809 nm light in 230 μs pulses into the sides of the laser crystal. The highly divergent pump radiation is collimated towards the sides of the Nd:YAG crystal by 2 mm diameter cylindrical rod lenses. The input sides of the crystal are antireflection (AR) coated at the pump wavelength and the opposite sides of the crystal are coated for maximum reflectivity. The ends of the crystal are AR coated at 1.06 μm.

The transfer efficiency (η_T) from the pump diodes into the active medium is calculated at 75% for this configuration, including the overlap of the 809 nm pump bandwidth with the Nd:YAG absorption band. The stored energy in the upper level can be shown to be:

$$(1) \qquad E_{st} = \left(\frac{\nu_L}{\nu_D}\right) \cdot \eta_T \cdot \left(\frac{\tau_{sp}}{\tau_D}\right) \cdot \left[1 - e^{\tau_D/\tau_{sp}}\right] \cdot \eta_B \cdot E_D$$

where the first term is the color efficiency and the second is the transfer efficiency[9]. The time factors give the fraction of the pump power at the end of the diode pump pulse (τ_D) when this pulse is finite relative to the spontaneous lifetime (τ_{sp}) of the lasing level. A fill factor (η_B) has been added for the fraction of excited medium which can couple to the TEM_{00} mode. [In general, we follow the terminology of reference 9. The *D* subscript will refer to the diode and *L* to the laser transition of upper lasing level.] Our pump pulsewidth is equal to the spontaneous lifetime for the upper lasing level (230 μs) and assuming a fill factor of 0.7, a stored energy efficiency of 25% is obtained through equation 1. Due to the fact that the upper "level" in Nd:YAG is a doublet at room temperature, the effective stored energy E'_{st} is but 40% of the stored energy, as calculated using equation 1, or 2.84 mJ per pump cycle. The above value of stored energy yields a small signal gain coefficient g_0 of 0.35 cm^{-1}. Assuming a total round trip loss ~ 6% and active gain medium of 1 cm, a round trip gain of $\Gamma = 1.33$ is projected.

The ring cavity was Q-switched to characterize its performance prior to injection seeding. This was done by using the TFP in conjunction with a $\lambda/4$ pockels cell which required a hold-off voltage of approximately 900 V. In order for the sliced pulse from the FLP laser to be trapped in the ring, the electrical and optical timing associated with Q-switching the ring laser must first be known. The unseeded Q-switched ring laser revealed the energy build-up time to be a relatively long 1.5 μs as expected, due to the low single-pass gain of the cavity. The pulsewidth varied between 400 ns and 500 ns depending on the pockels cell alignment.

A flashlamp pumped, Nd:YAG laser with an active-passive mode-locked system was used as the injection seed source. An electro-optic pulse slicer, consisting of a $\lambda/2$ pockels cell between a pair of prism polarizers, was positioned after the output coupler to select the center pulse from the mode-locked train. The selected pulse was then sent into a 50% beam splitter where half the energy was directed toward a photodiode for the ring's Q-switch trigger and the other half reserved for injection seeding.

In order for the ring pockels cell SW1 to trigger with the arrival of the seed pulse, an optical delay was required prior to injection through the TFP. The internal trigger delay of SW1 was measured to be more than 80 ns. An optical cavity similar to a White Cell[10] was constructed to create a total optical path length of ~93 ft from 31 passes within the 3 mirrored cavity. This produced an optical delay of ~ 97 ns.

The spatial profile of the seed pulse required variability when it was injected into the ring. This was adjusted by employing a pair of positive lenses on a 3-axis stage to focus the beam in the ring and two 100% reflective flats for beam steering. The 3-part, injection seeded laser system, composed of the injection laser, optical delay, beam steering optics and ring cavity is shown in figure 3.

4. Injection Seeded,Q-Switched Ring Laser Results

When the injected beam neared coalignment with the ring cavity, the Q-switch pulse began to display defined temporal structure on the oscilloscope due to the reduction of longitudinal modes, and the build-up time decreased. By monitoring these parameters, the alignment was optimized. An oscilloscope plot in figure 4 shows 2 pair of photodiode outputs; the top pair are the counter clockwise CCW and clockwise CW

Q-switch pulses in the ring prior to injection seeding, and the bottom pair are after injection seeding. The CW circulating energy was nearly extinguished when seeding in the CCW direction. The initial injection energy was approximately 175 pJ in a 170 ps wide pulse. The beam diameter was about 33 μm as it entered the TFP and had a slight divergence, less than 1°, which was not precisely measured. By spreading the injection beam into a cone, a solid angle section of the diverging beam mode-matched with the ring's resonant single spatial mode. This helped decrease the coalignment sensitivity requirements typical of a regenerative amplifier. Because the electronics developed for the multi-purpose pockels cell induced a relatively slow fall time for the Q-switch, timing was found not to be as critical as expected. If the seed pulse entered the ring during the first 40 ns of the now longer 100 ns Q-switch voltage fall-time, successful seeding was achieved.

Before attempting to dump the seeded Q-switched pulse, the injected pulse's temporal shape had to match the circulating pulse in the ring. The seeded ring pulse had parasitic pulses riding on the original sub-170 ps seed pulse from the injection laser. These parasitics were approximately 200 ps apart and increased the overall pulse envelope to more than 500 ps. An etalon effect was discovered within the pockels cell, which proved to be the source of these pulses. Since the injection seed laser was not assembled for sub-100 ps pulse production, the pockels cell was rotated by 2° around the horizontal axis, perpendicular to the ring's optical axis, which eliminated the etalon effects. Although the pulse temporal purity was regained, we lost the optimum electro-optical efficiency of the cell and some passive birefringence losses arose.

Successful seeding was restored but with longer build-up times and greater Q-switch pulsewidths. The injection seeded ring cavity's dumped output is shown in figure 5. The threshold energy for injection seeding was measured as low as $E_{st} = 2\,pJ$, but there was an unseeded Q-switch pulse oscillating in the non-seeded CW direction of almost equal intensity. Most of the amplification data was taken with seed pulse energies of $E_s = 330\,pJ$ to provide full CCW seeding with almost no detectable CW oscillations. In the seeded but undumped case the energy in the cavity was measured by the leakage of one the mirrors to be $E_{ud} = 4.0\ \mu J$ at the peak. This represented a total gain of $G_{tot} = 1.21 \times 10^4$, or $G_{tot} = 40.8\ dB$. When the injection seeded ring laser is operated in its pulse dumping mode, the output energy in the 170 ps pulse is $E_p = 1.3\ \mu J$, representing a gain of $G_{dump} = 3.79 \times 10^3$, or $G_{dump} = 35.8\ dB$. The optical efficiency was measured at Eff = 0.05% and Eff = 0.16% for the dumped and undumped ring, respectively. These were much lower than expected but are attributed to the small beam volume within the laser crystal and the necessary inefficient alignment of the pockels cell.

5. Conclusions

We have demonstrated a diode array pumped, regenerative ring amplifier consisting of only 5 optical elements, 2 mirrors, 1 TFP, 1 Nd:YAG crystal and 1 pockels cell. The pockels cell performed both as a Q-switch and a cavity dumper for amplified pulse ejection through the TFP. The total optical efficiency was low principally due to the low gain provided by the 2-bar pumped laser head and the 6% loss per round trip. After comparison with a computer model, a real seed threshld of ~10^{-15} J was achieved because only about 0.1% of the injected energy mode-matched with the ring. Much improvement can be made upon the total performance by increasing the gain-per-pass with higher pump powers. This will also lead to better extraction efficiency while decreasing the Q-switch buildup time. A shorter injection pulse or greater anglular displacement on the pockel's cell windows could reduce the etalon effects and decrease the loss due to birefringence.

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Figure Captions

Figure 1. Injection seeded ring cavity configuration: 2 mirrors, 1 thin film polarizer, 1 pockel's cell and diode pumped laser head. The pockel's cell is a two crystal design to lower the required 1/2 wave voltage.

Figure 2. Optical axis view of the Nd:YAG laser head. A 2 mm x 2 mm x 10 mm Nd:YAG slab is pumped by a pair of 40 W linear diode arrays which are collimated by 2 mm diameter fused silica glass rods. The slab is dielectrically coated to provide a double-pass pump geometry.

Figure 3. Schematic of the injection seeded laser system. The three sections from right to left are: Q-switched mode-locked laser injection seed source, optical timing, and the ring cavity.

Figure 4. Unseeded (lower trace pair) and seeded (top trace pair) operation of the diode pumped ring cavity. Note: the Q-switch buildup time is significantly shortened when the ring is seeded and the resulting longitudinal mode structure is noticable. This is the single pulse circling the cavity.

Figure 5. Photodiode output of the ejected regeneratively amplified pulse from the ring cavity. The small structure before and after the pulse shows the individual round trips. It also shows that the amplified pulse was not completely ejected. This was due to the necessary misalignment of the pockels cell which hindered its performance.

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Figure 1

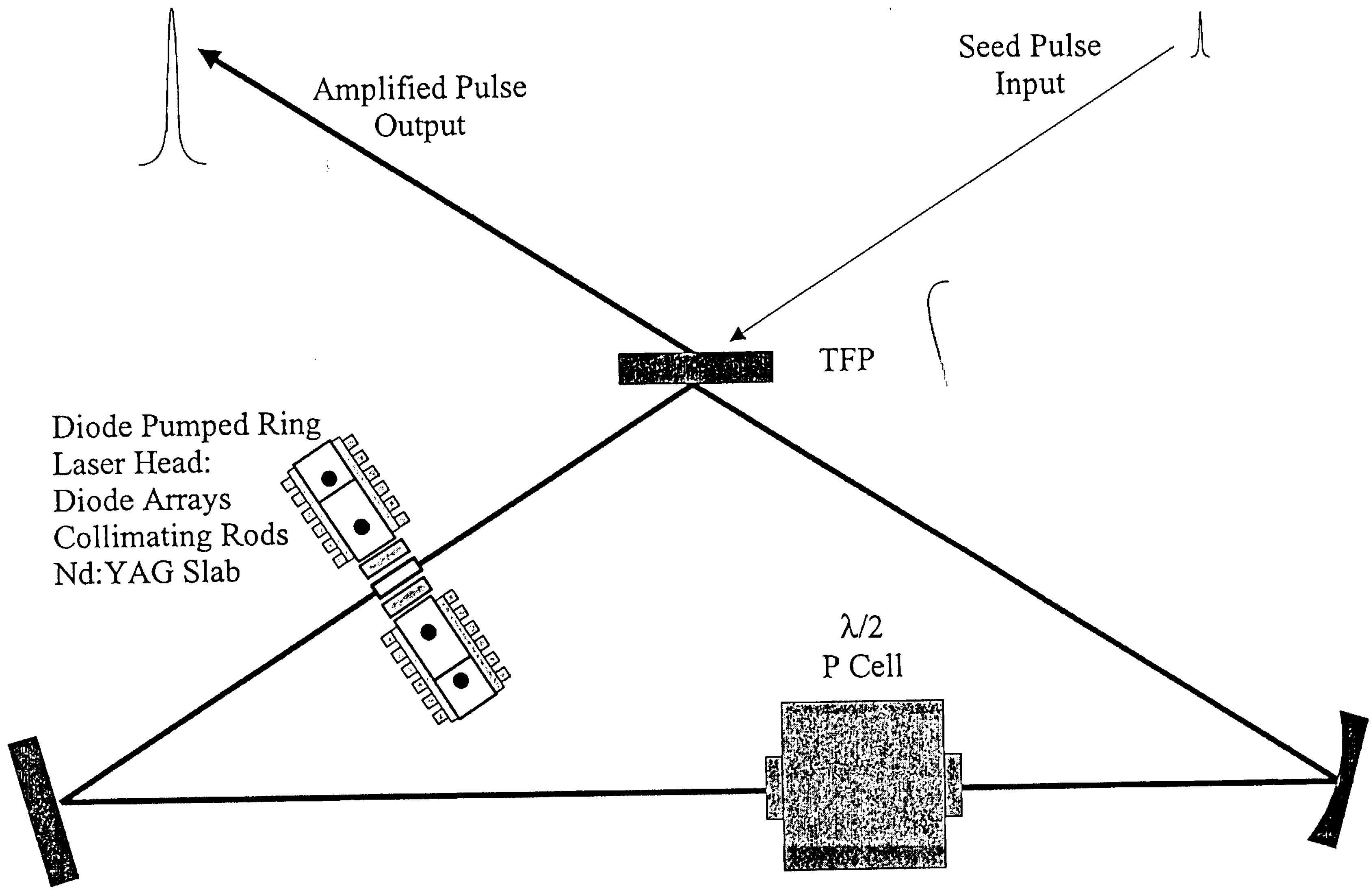

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Figure 2

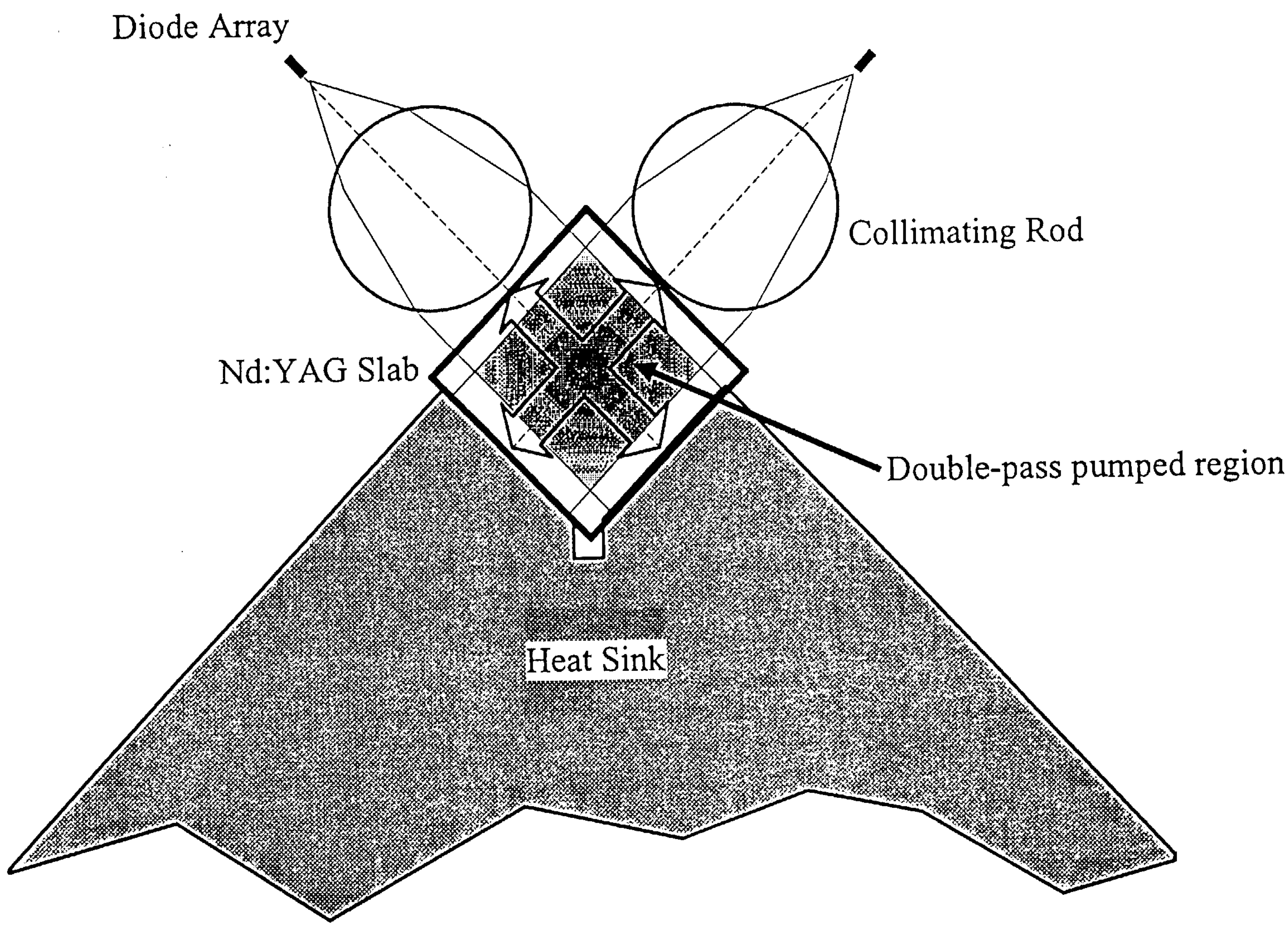

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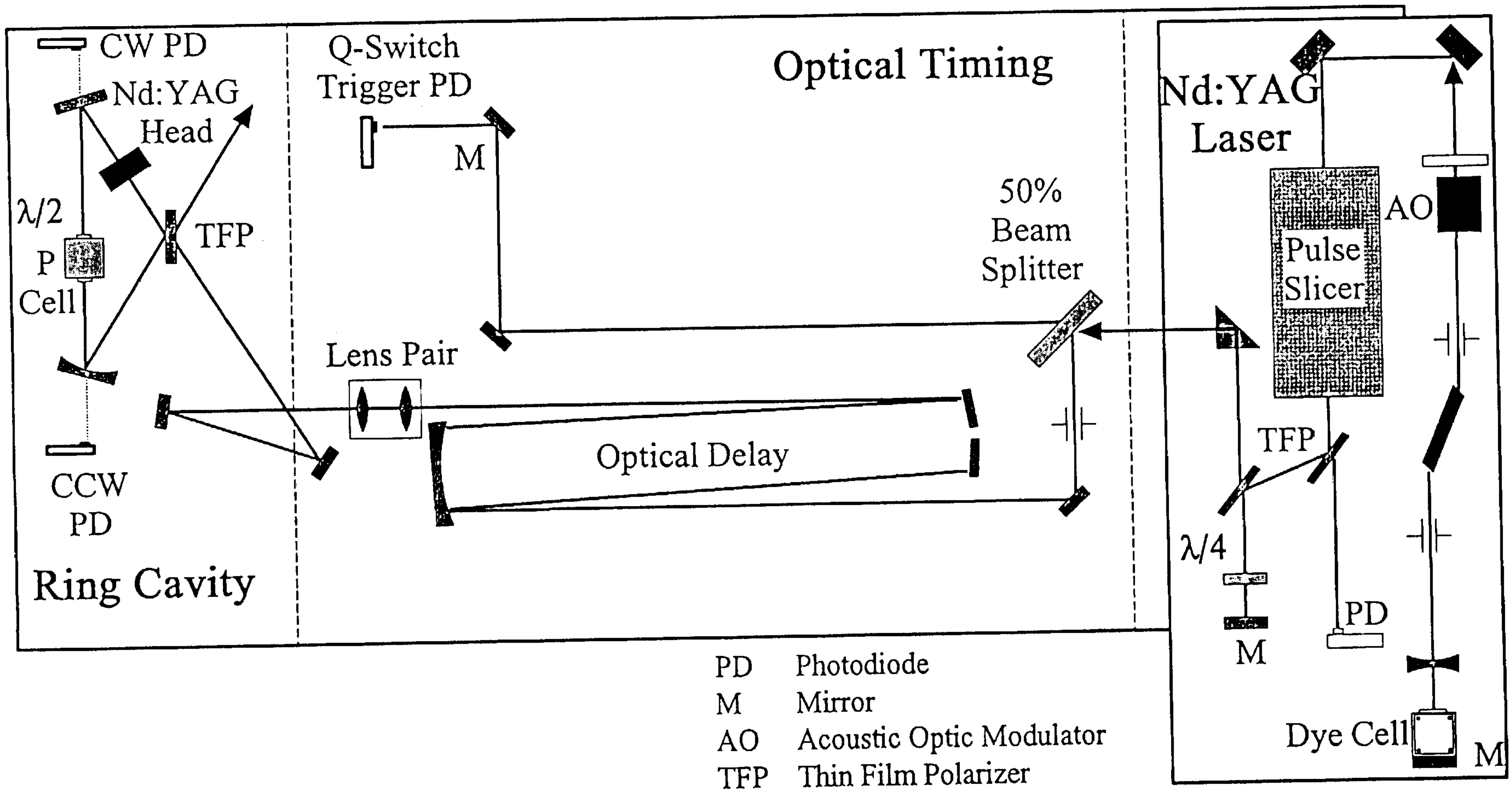
Figure 3



PD Photodiode
M Mirror
AO Acoustic Optic Modulator
TFP Thin Film Polarizer

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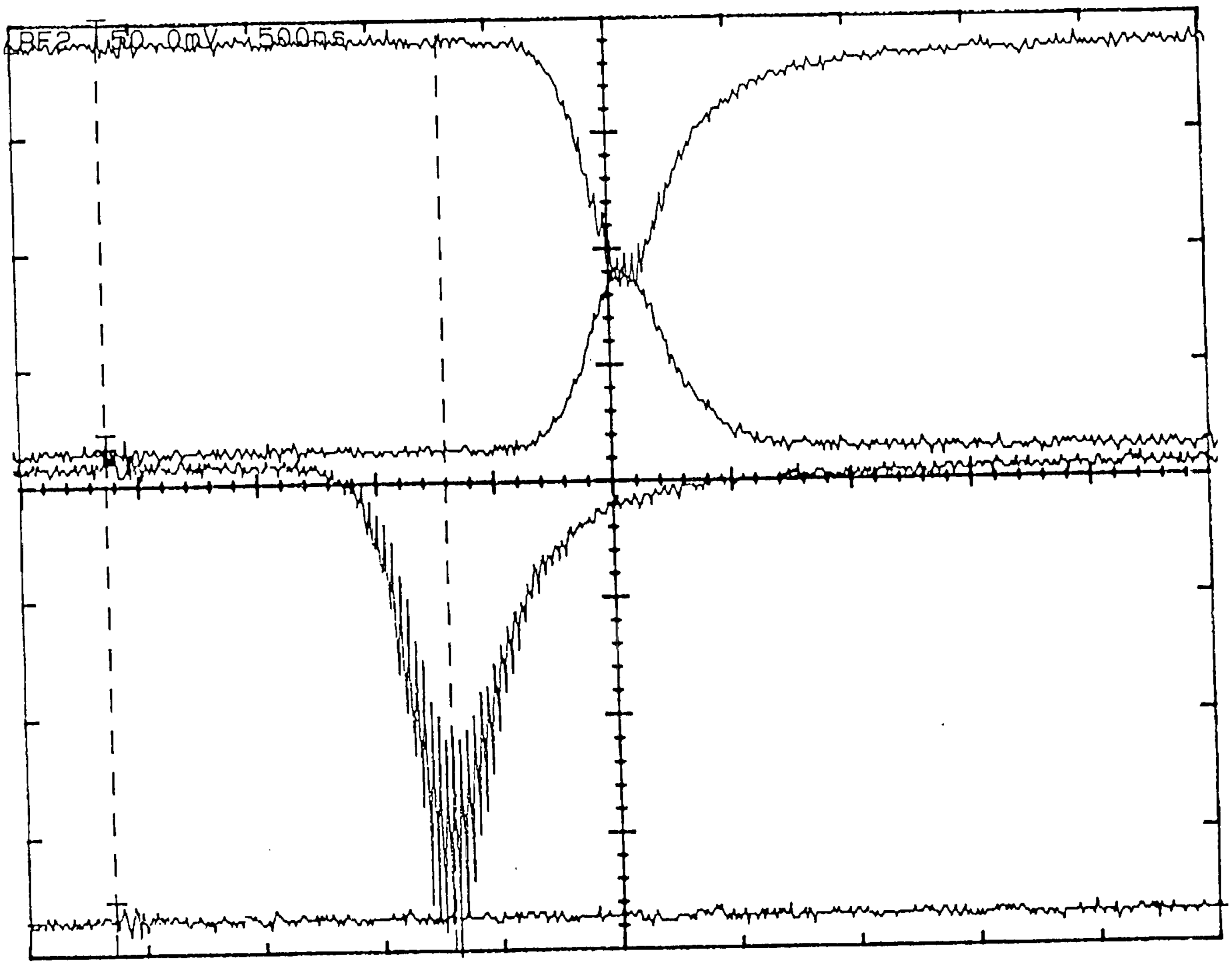
Figure 4



400 NS/DIV

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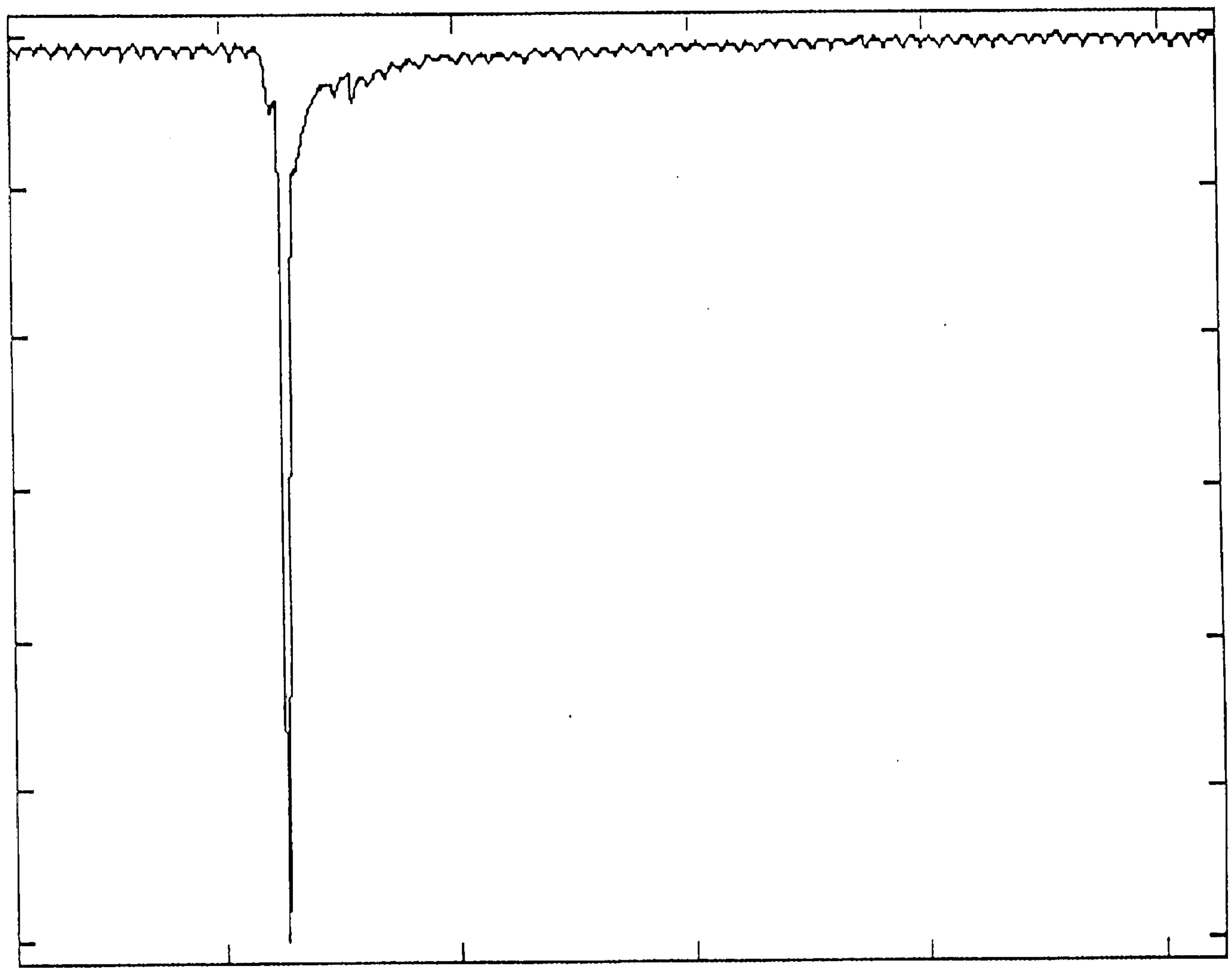
Figure 5



500 NS/DIV