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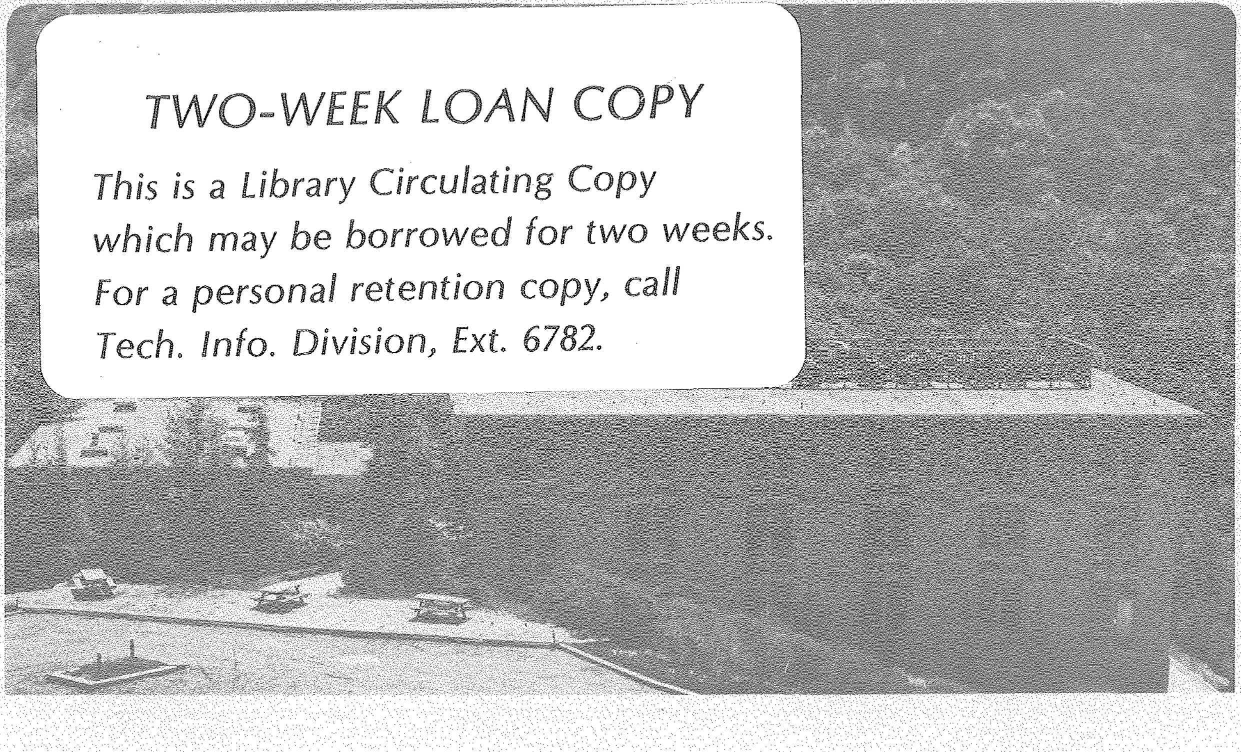

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A Passively Mode-Locked Nd:Glass Laser Oscillator Optimized for TEM_{00} Selectivity and Long Term Stability and Reliability

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ABSTRACT

A passively mode-locked Nd:Glass laser oscillator optimized for TEM_{00} selectivity and long term stability and reliability is presented. The important aspects of the optimized design are explained in detail. A detailed alignment procedure is also included. This laser oscillator is capable of producing TEM_{00}, bandwidth-limited, 5 picosecond pulses for $\geq$ 12 hours.

1. Introduction

Passively mode-locked Nd:Glass laser oscillators are used extensively as a source of high power picosecond light pulses [1]. Limiting this laser oscillator to the TEM_{00} transverse mode is desirable because the TEM_{00} transverse mode produces a uniform and uniphase radial intensity profile, the smallest beam divergence, and the highest power density [2]. Unfortunately, passively mode-locked Nd:Glass lasers restricted exclusively to TEM_{00} operation are notoriously unstable, unreliable and difficult to align.

Although the generation and applications of passively mode-locked picosecond light pulses has been reviewed [3,4] and passively mode-locked Nd:Glass picosecond pulses have been studied [5,6], an optimized, detailed design for a stable, reliable and TEM_{00} selective passively mode-locked Nd:Glass laser oscillator has never been presented. This is particularly unfortunate, because minute details can make extraordinary differences in the laser's performance [7,8,9]. Therefore, knowledge of a detailed design is extremely important to the user of TEM_{00} selective, passively mode-locked Nd:Glass lasers.

In this paper, we report on the design, operation, and performance of a passively mode-locked Nd:Glass laser oscillator which produces essentially bandwidth-limited 5 picosecond pulses and has been optimized for TEM_{00} selectivity and long term stability and reliability. We discuss the important aspects of the design in detail, with special emphasis on the reasons for the design. Because many of the design criteria are not limited to the passively mode-locked Nd:Glass laser, the paper should also be useful to designers of other laser systems. In addition, we include a detailed alignment procedure because proper alignment is critical for stable, reliable and TEM_{00} selective laser operation.

The optimized laser will run stably and reliably in the TEM_{00} transverse mode for $\geq$ 12 hours after initial alignment. This optimized laser oscillator has made possible recent excite and probe experiments [10,11,12] which have demanded spatially coherent, bandwidth-limited $\simeq$ 5 picosecond pulses for $\geq$ 12 hours because of long alignment and data accumulation times. These experiments, which were previously intractable, are now successfully accomplished.

2. Design Criteria

Ever since the original work of DeMaria et al. [13], many problems have plagued the user of passively mode-locked Nd:Glass lasers. These problems have included: irreproducible pulse train envelopes [14]; unreliable mode-locking [7,8]; multiple pulse train mode-locking [14,15]; and unstable and extremely sensitive alignment [8]. Although many experiments have been performed with picosecond pulses from passively mode-locked Nd:Glass lasers [1], these difficulties have limited the laser's utility. This has been especially true for passively mode-locked Nd:Glass lasers restricted exclusively to TEM_{00} operation.

The problems listed above involve many aspects of the passively mode-locked Nd:Glass laser oscillator. These factors include: thermal and mechanical cavity instabilities; thermal distortions in the laser rod; non-linear optical effects in the laser rod; poor flashlamp pumping of the laser rod; poorly constructed laser heads [8]; internal reflections in the oscillator cavity; irreproducible power supply charging voltages; the stochastic nature of the mode-locking process [16,17,18]; inadequate laser head alignment facilities; imprecise and unstable mirror micrometers and mirror mounts; unstable mode-locking dyes; and poor TEM_{00} discrimination.

In order to surmount these difficulties, we carefully considered each aspect of the passively mode-locked Nd:Glass laser. Our design criteria were optimum stability, reliability, and TEM_{00} selectivity, as well as minimum pulse duration.

3. Laser Cavity

Calculations have demonstrated that TEM_{00} transverse mode selectivity is strongly dependent on resonator geometry. TEM_{00} selectivity, using either diffraction or aperature loss mechanisms, is greatest for a confocal or half-confocal resonator and smallest for a plane-parallel resonator [19]. Although confocal and half-confocal resonators are on the edge of stability [20], near confocal or near half-confocal resonators are stable resonators and have also displayed more reliable mode-locking than plane-parallel resonators [7]. Therefore, the optimized laser oscillator cavity is a near half-confocal optical resonator. The front output mirror has a 3 meter radius of curvature and a 60% reflectivity at 1.06 micron. The back mirror is flat and has a 99.7% reflectivity at 1.06 micron [21]. The cavity length is 140 centimeters. The front mirror's relatively high 60% reflectivity reduces the lasing gain threshold and lowers the energy stored in the Nd:Glass laser rod which minimizes the peak power and many possible detrimental non-linear effects which can spectrally and temporally broaden the mode-locked bandwidth-limited light pulse [22].

4. Laser Head

Efficient optical pumping is essential for minimal thermal distortions in the laser rod. In addition, uniform illumination of the laser rod is important for TEM_{00} operation. Therefore, the laser head (see Fig. 1) is a cloverleaf design machined from brass and electroplated with nickel and then gold to provide high reflectivity over almost all the Nd:Glass pumping bands [23]. Four linear zenon flashlamps are mounted slightly off the center of each cylindrical leaf in a close-coupled reflector design that provides uniform illumination of the rod.

The four flashlamps are mounted in cylindrical pyrex jackets which block the flashlamp's UV output. The UV output does not effectively pump Nd:Glass, whereas the UV output does contribute to deleterious thermal distortions in the laser rod which can lead to unreliable oscillator performance. The jackets allow the flashlamps to be air-cooled, whereas the rod is water-cooled for more efficient heat transfer. The water is circulated and temperature regulated at approximately 12 degrees Centigrade by a Lauda K-2/R circulator [24].

The Nd:Glass laser rod has a diameter of 1/4 inch and a length of 6-1/8 inches [25]. The 1/4 inch diameter rod had significantly fewer thermal distortion problems than a previously used 3/8 inch diameter rod. The rod has a rough acid barrel finish and is Brewster-angled at both ends. The Brewster angle configuration introduces a beam displacement of approximately 64 millimeters in the horizontal plane. The front end of the laser rod is positioned approximately 24 centimeters from the curved output mirror because the beam diameter is greatest at the curved mirror. This allows a larger active volume of the laser rod to be utilized.

Accurate alignment is crucial for stable and reliable TEM_{00} operation. For precise and easy alignment, the laser head sits in a stainless steel carriage which is attached to an adjustable stainless steel housing (see Figs. 2 and 3). The carriage allows the laser head to be rotated to align the rod's Brewster angle. The housing can move angularly by pivoting on a central point. The angular alignment is secured by tightening a machine screw which is positioned in a slotted arc connected to the housing. The housing lifts the laser head vertically by means of four adjustment screws which move through four tapped holes in the carriage base plate. The housing translates the laser head laterally by means of four adjustment screws which secure a lateral position inside two sideboard runners. This adjustable housing design facilitates accurate and rapid alignment of the laser head.

5. Flashlamp Driving Circuit

Efficient flashlamp pumping is necessary to minimize thermal distortions in the laser rod which can lead to unstable and unreliable oscillator performance. The most efficient flashlamp driving circuit is determined by: the type of flashlamp; the discharge energy; the discharge pulsewidth; and the circuit damping parameter [26].

Four EG&G FX 47C-5 linear zenon flashlamps in series are used to optically pump the Nd:Glass laser rod. Flashlamp configurations are characterized by K_0, a flashlamp parameter with units of ohm-amps$^{1/2}$ [26]. For zenon flashlamps, $K_0 \simeq 1.275 \times$ arclength/ boresize [27]. The four flashlamps in series have a $K_0 \simeq 50$. Given this K_0 value, a capacitance C= 240 microfarads, a desired discharge energy of approximately 800 Joules, a desired pulsewidth of approximately 650 microseconds [28], and a desired circuit damping parameter, α , approximately equal to 0.75 for critical damping, the discharge circuit inductance, L= 330 microhenries, was determined using the procedure of Markiewicz and Emmett [26].

The capacitor is charged by a regulated power supply capable of giving reproducible charging voltages to approximately one part in a thousand. This accuracy in the reproducible charging voltage is necessary to consistently operate the oscillator at just above the lasing threshold voltage. Experience has shown that optimum mode-locking performance occurs just above the lasing threshold voltage [8].

6. Mode-Locking Dye Solution and Dye Cell

Several studies have shown that satellite pulses are avoided [5, 29] and mode-locking is more reliable [5, 8, 29] when the dye cell is in contact with one of the resonator's mirrors. In addition, several investigations have determined the relationship between dye cell length and pulse duration [6, 29]. These studies have revealed that short dye cell lengths produce the shortest mode-locked pulses. Therefore, the mode-locking dye sits in contact with the back mirror. The dye cell is defined by the back mirror, two narrow teflon shims with a thickness of 300 microns, and a wedged optical flat with anti-reflection coating for 1.06 micron on the surface in contact with the dye. The actual dye cell length is probably $\leq$ 300 microns since the two teflon shims are pressed very tightly between the two glass plates. An illustration of the dye cell assembly is shown in Figure 4. The mode-locking dye cell assembly is constructed entirely of stainless steel in order to minimize thermal instabilities.

The recovery times of saturable absorber dyes commonly used to mode-lock λ = 1.06 micron have been determined [30]. Eastman Kodak Q-switch dye #9860 has the fastest recovery time, $\tau = 7 \pm 1$ picosecond [30]. Because pulse duration is a function of the absorber recovery time, Eastman Kodak Q-switch dye # 9860 in Eastman Kodak Q-switch 1,2-dichloroethane was used as the mode-locking dye solution. Experience has shown that the Q-switch dye is more stable and reliable if the 1,2-dichloroethane is first purified by passage through a column of basic aluminum oxide and then filtered through a 0.45 micron pore size Millipore filter to remove the residual aluminum oxide particulates [31].

The most reliable operation from mode-locking dye solutions occurs when the dye is circulated through the dye cell from a large reservoir [32]. This arrangement provides fresh dye for each laser pulse, assures uniform mixing and constant concentration of the dye, and minimizes thermal effects in the dye cell [33]. The 1,2-dichloroethane is added to a resevoir which is connected to the dye cell and a variable speed magnetic drive gear pump [34]. The total volume of the dye cell, tubing, pump and reservoir is approximately 70 milliliters. Inert, baffled, 1/4 inch tubing [35] is used to connect the reservoir, pump and dye cell, and also to quench vibrations from the pump which can couple into the cavity and lead to mechanical instabilities. In addition, the pump is turned off approximately five seconds before the laser fires to minimize the disturbance from the flowing dye.

Studies have shown that mode-locked pulse durations are the shortest when T, the saturable absorber's low light level transmittance, is as high as possible [8]. We have also determined that the most reliable and reproducible pulse trains occur when the dye solution has an optical density of 1.08 ± 0.02 at a 1.06 micron wavelength in a 0.5 centimeter spectrophotometric cell. This corresponds to the relatively high transmittance of $\geq$ 75% (double pass) in the $\leq$ 300 micron dye cell. Therefore, after filling the dye solution system with 1,2-dichloroethane, Kodak dye # 9860 is slowly added to the 1,2-dichloroethane until the solution has an optical density of 1.08 ± 0.02 at a 1.06 micron wavelength in a 0.5 centimeter spectrophotometric cell. For reproducible, reliable operation, this dye solution should be changed every day.

7. Oscillator Frame Construction

Mechanical and thermal stability are crucial for long term oscillator reliability and stability. Therefore, the optimized laser oscillator is stabilized by four 1-1/8 inch diameter invar rods [36]. These rods are connected to two 1/2 inch thick stainless steel endplates and two 3/8 inch thick stainless steel support plates. The invar rods feed through 1-1/8 inch holes in the stainless steel plates. There is minimal clearance through these holes and initial assembly is difficult because the plates bind unless they remain perpendicular to all the invar rods. After assembly, however, the frame is very rigid. Stainless steel set screws provide additional stability. All parts of the laser oscillator are constructed of stainless steel whenever possible to minimize thermal instability. The invar stabilized oscillator frame is illustrated in Figure 5.

8. Oscillator Frame Connection to the Optics Table

The oscillator frame rests on four stainless steel ball bearings. These ball bearings help to decouple the oscillator from the optics table and also allow the oscillator frame to move freely to relieve possible strain which could lead to oscillator instabilities [37]. One ball bearing sits securely in a hole. Two ball bearings sit in channels which allow for either x-axial or y-lateral movement. The fourth ball bearing sits on a plane which allows both x and y freedom. This design is illustrated in Figure 6.

The ball bearings sit on plates which are mounted to a 160 centimeter Gaertner Corporation precision lathe bed optical bench [38]. The inside housing of the Gaertner lathe bed optical bench is lined with lead bricks to provide enhanced stability.

9. Micrometers and Mirror Mounts

Extraordinary stability and adjustment precision are necessary for TEM_{00} passively mode-locked Nd:Glass laser alignment. These requirements are met by a Burleigh Star-Gimbal stainless steel mirror mount [39] with Lansing differential screw micrometers [40] on the front mirror, and Starrett precision stainless steel micrometers with Delrin knobs [41] on the back mirror stainless steel dye cell assembly. The differential screw micrometers can make translations as small as a millionth of an inch. Experience has shown that, using the Star-Gimbal mirror mount, alignment for TEM_{00} operation must be accurate to within $\cong$ 40 millionths of an inch on the front horizontal Lansing differential screw micrometer, i.e. $\simeq$ 0.4 seconds of arc, for stable, reproducible behavior at the minimum lasing threshold.

10. Alignment Procedure and Aperature Placement

A proper alignment procedure can lead to rapid and reliable operation of a TEM_{00} passively mode-locked Nd:Glass laser oscillator. The following alignment procedure has evolved over the last several years and has been very effective. Refer to Figure 7 during the following discussion.

A 5.0 milliwatt Helium-Neon laser is aperatured to remove off-axis light. The side of the aperature away from the Helium-Neon laser is colored white. The Helium-Neon light beam is brought into the oscillator by a 50% beam splitter located behind the back mirror. The Helium-Neon beam is positioned parallel to the optics cavity. An iris diaphram on an xy micrometer stage mounted on a platform which can slide on the Gaertner optical bench is very convenient for this purpose.

Next the laser head housing is positioned so the Helium-Neon beam is centered on the front and back faces of the laser rod. Positioning the iris diaphram close to the laser head and closing down the diaphram on the Helium-Neon beam greatly facilitates this process. For correct alignment of the Brewster angle, the Helium-Neon beam should reflect off the face of the laser rod and remain in the same plane, at the same height, as the incoming Helium-Neon beam.

After the laser rod is properly aligned, the front mirror is adjusted so the beam reflected from the front mirror is centered on the white-colored aperature positioned in front of the Helium-Neon laser. Part of the beam reflected from the front mirror passes through the 50% beam splitter. A white screen is placed behind the beam splitter to view the reflection from the front mirror. Then the back mirror is adjusted so the reflection from the cavity-defining surface of the dye cell is coincident with the reflection from the front mirror. Sharp, concentric interference fringes should appear when the cavity is properly aligned.

Next the intracavity aperature for TEM_{00} selectivity is placed in the oscillator, on an xy micrometer stage mounted on a platform which can slide on the Gaertner optical bench. The intracavity aperature is positioned approximately 8 centimeters from the dye cell, centered with respect to the Helium-Neon beam [2, 19]. The aperature can be accurately centered by closing the diaphram down on the beam to make a small spot and then centering on this small spot. The aperature has a diameter of 2.18 millimeters. For the position close to the dye cell, aperature diameters smaller than 2.18 millimeters, e.g. 2.08 millimeters, introduce too much light loss and diameters larger than 2.18 millimeters, e.g. 2.26 millimeters, allow the TEM_{01} mode and higher order modes to occur. For aperature positions further from the dye cell, the laser's performance was less reliable.

11. Adjustment for Optimum Lasing Action

Once the laser is aligned, the flashlamps can be fired and the alignment can be adjusted for optimum lasing action. The lasing action can be observed by placing developed Polaroid film near the front mirror and watching for laser burn spots. The power supply voltage should be increased until a burn spot is observed. If a burn spot is not observed the front horizontal differential screw micrometer can be adjusted. If the differential screw micrometer has to be moved more than 250 millionths of an inch, either the voltage is still too low or the initial alignment is faulty. With proper alignment, lasing should occur within ± 200 millionths of an inch, i.e. ± 1.8 seconds of arc, from the initial setting. The voltage threshold is minimized by adjusting the front horizontal differential screw micrometer and observing if the lasing threshold is lowered. The laser oscillator must be operated at its minimum voltage threshold for the most reliable and reproducible laser performance. The front horizontal differential screw adjustment is the only adjustment which should be necessary after initial alignment.

12. Dependability

The optimized, TEM_{00} selective, passively mode-locked Nd:Glass laser oscillator described above is capable of running at a repetition rate of one shot every 20 seconds for $\geq$ 12 hours with only minor adjustments. The repetition rate is limited by the power supply charge time. If the voltage threshold increases significantly, the threshold can generally be brought back down by adjustments of $\simeq$ 30 millionths of an inch on the front horizontal differential screw micrometer, i.e. $\simeq$ 0.3 seconds of arc. We suspect that the need for minor adjustments is related to the fluctuations in the room temperature [8].

If multiple pulse trains occur, the voltage should be turned down. Examples of ordinary and multiple pulse trains observed using a Hewlett-Packard PIN photodiode [42] and a Tektronix 519 oscilloscope are shown in Figure 8. Optimum pulse trains with fairly reproducible pulse train envelopes occur approximately 80-90% of the time when the voltage is just above the lasing threshold voltage.

After amplification and frequency-doubling, single picosecond pulses selected from the rising edge of the pulse trains were found to have a duration of $\simeq$ 5 picoseconds and spectral bandwidth (full width at half maximum) of $\simeq$ 4 cm^{-1}, yielding a bandwidth product of $\simeq$ 0.6. This product indicates that the pulses are essentially bandwidth-limited [18].

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36. The invar was Carpenter Invar 36 available from Carpenter Steel, Redding, Pennsylvania.

37. This design was suggested by Dirk J. Kuizenga, Lawrence Livermore Laboratory, University of California, Livermore, California, 94550.

38. Gaertner Scientific Corporation, 1201 Wrightwood Avenue, Chicago, Illinois, 60614.

39. The Burleigh Star-Gimbal Stainless Steel Mirror Mounts Model Number SG-201 were obtained from Burleigh Instruments, Inc., Fishers, New York, 14453.

40. The Lansing differential screw micrometers, Model Number 22.501, were obtained from Lansing Research Corporation, Ithaca, New York, 14850.

41. The L.S. Starrett Co. stainless steel micrometers Model Number 1263 were obtained from Burleigh Instruments, Fishers, New York, 14453. The Burleigh designation for the Starrett micrometer is Model Number MC-79.

42. The Hewlett-Packard PIN photodiode, Type 5082-4203, was obtained from Hewlett-Packard, 1501 Page Mill Road, Palo Alto, California, 94304.

FIGURE CAPTIONS

Figure 1. Cross sectional view of the close-coupled cloverleaf laser head.

Figure 2. Side view of the adjustable laser head housing.

Figure 3. Top view of the adjustable laser head housing.

Figure 4. Cross sectional view of the mode-locking dye cell.

Figure 5. Side view of the invar stabilized oscillator frame.

Figure 6. Illustration of the decoupling and strain relieving ball bearing design which connects the oscillator frame to the Gaertner optical bench.

Figure 7. Top view of the laser assembly.

Figure 8. (a) Oscillogram of an ordinary pulse train. (b) Oscillogram of a multiple pulse train. Both output pulse trains are taken with a PIN photodiode and a Tektronix 519 oscilloscope at 50 nsec/div.

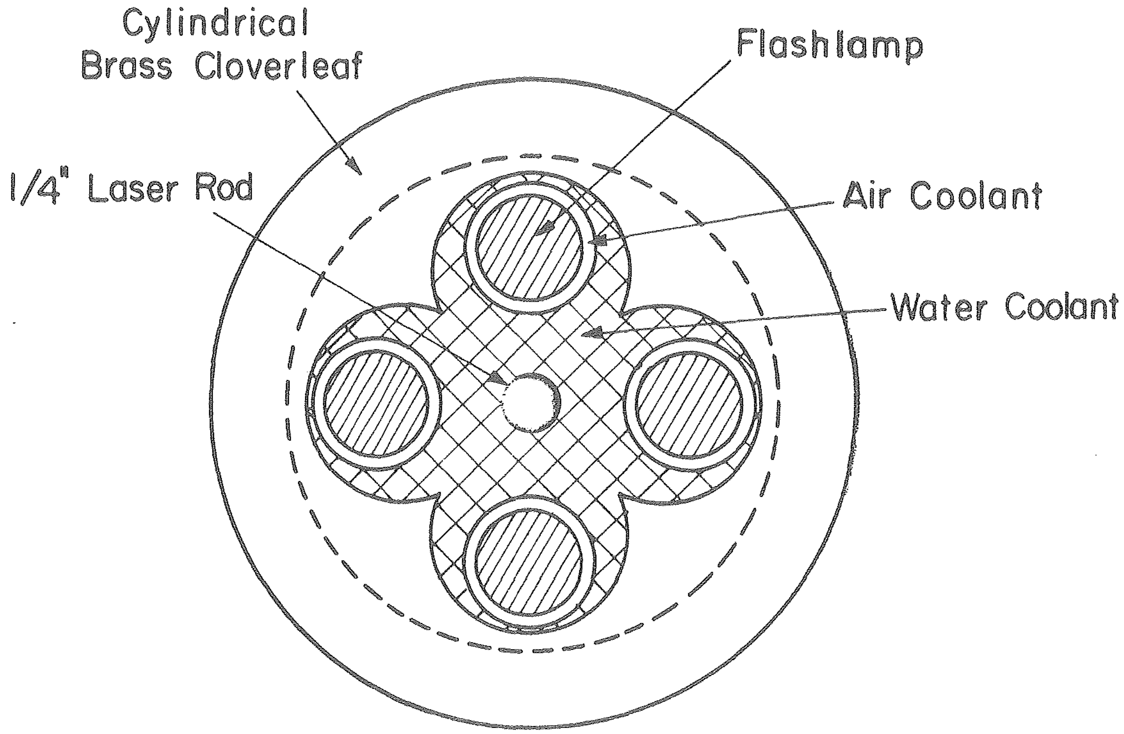

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Figure 1

Adjustable Laser Head Housing
Side View

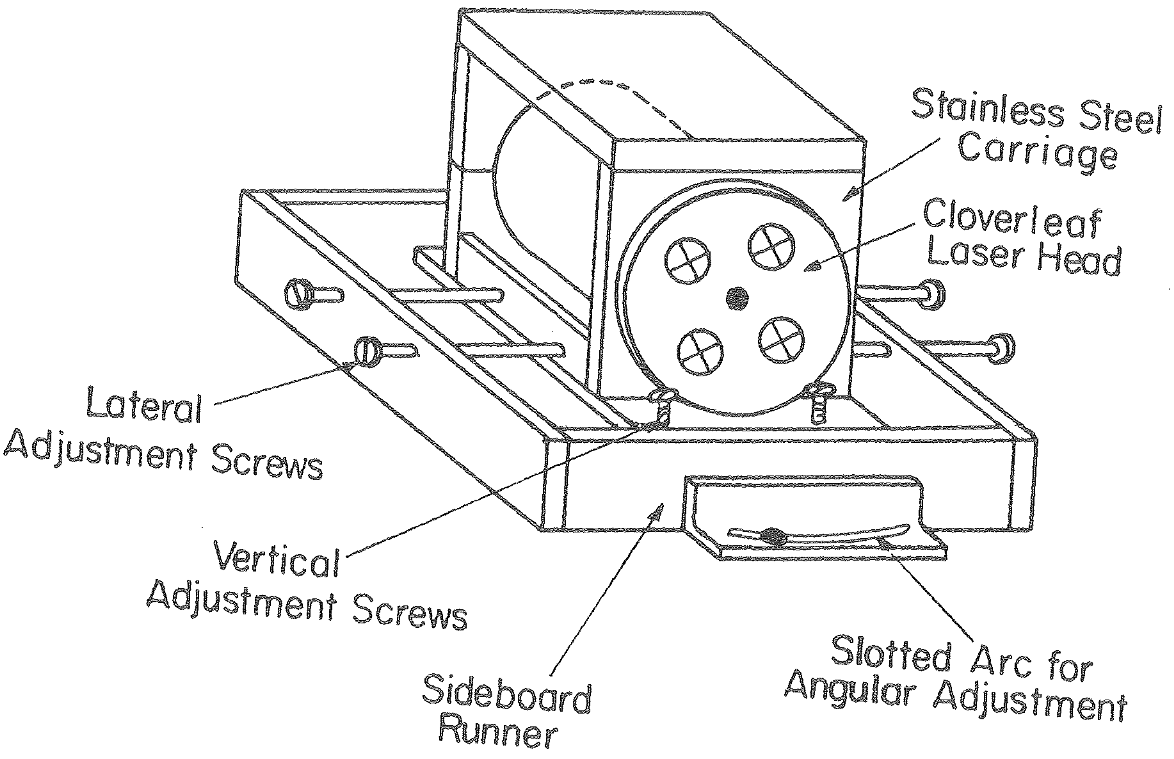

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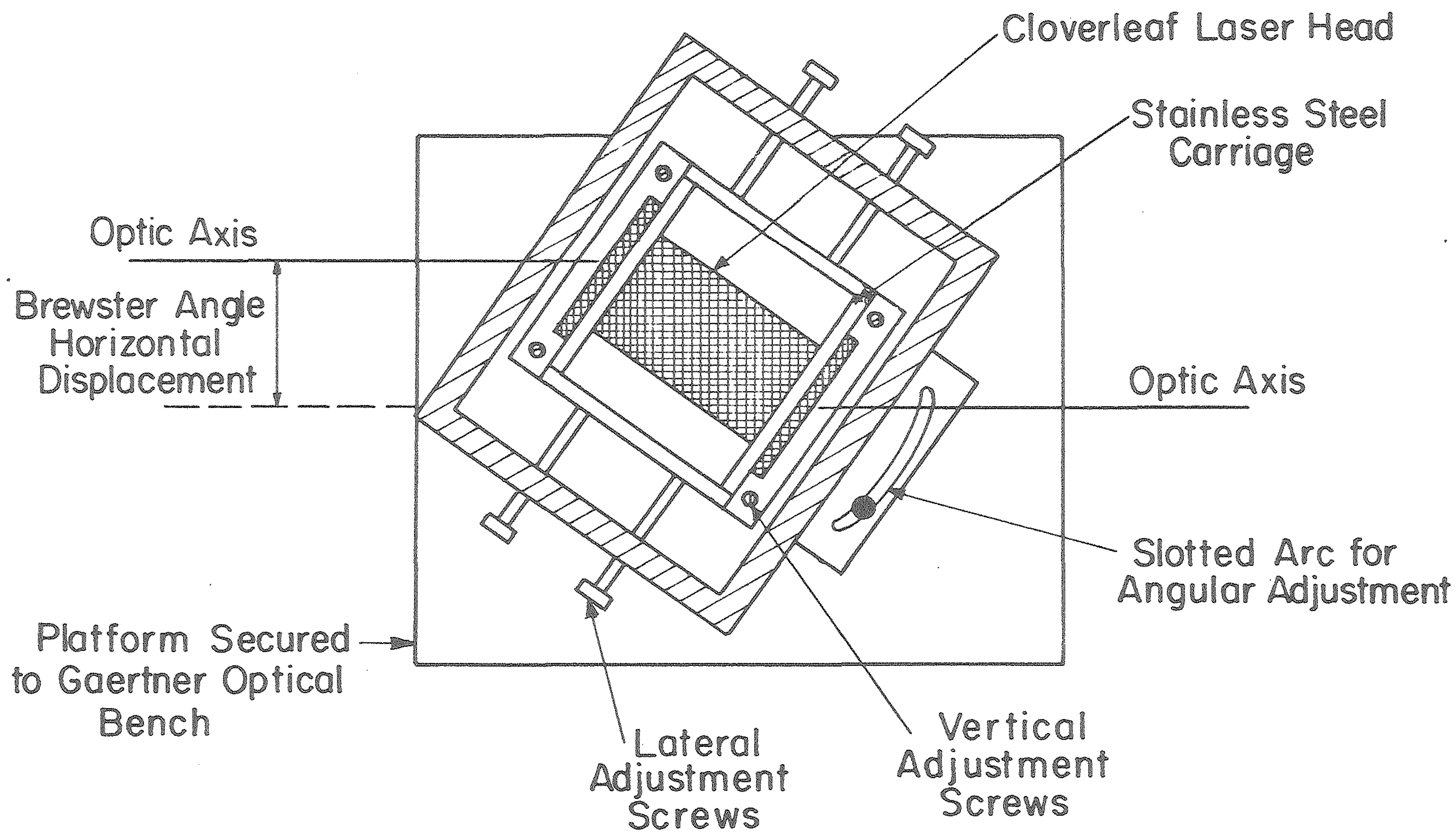
Figure 2



Adjustable Laser Head Housing
Top View

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Figure 3

Cross Section of Dye Cell

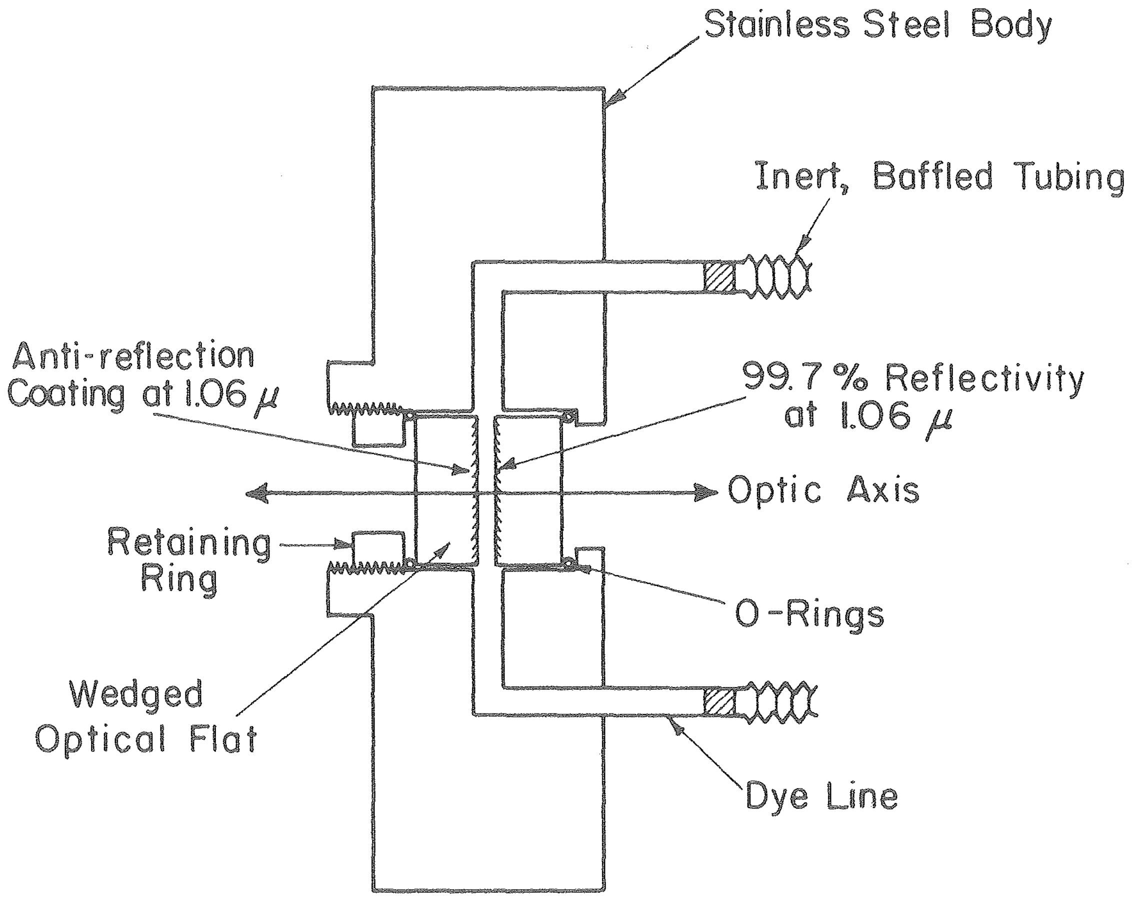

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Figure 4

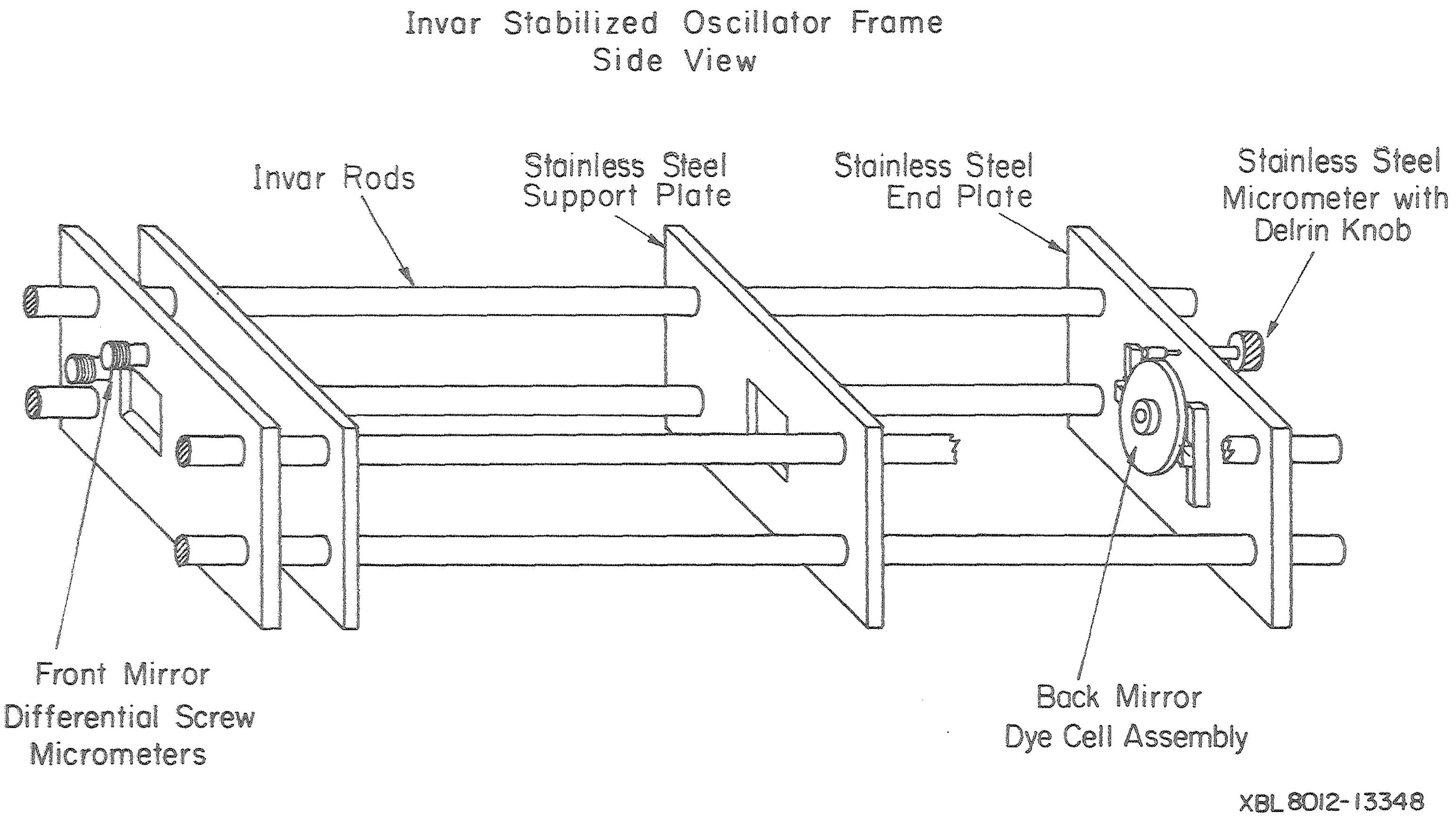
Invar Stabilized Oscillator Frame
Side View
Invar Rods
Stainless Steel Support Plate
Stainless Steel End Plate
Stainless Steel Micrometer with Delrin Knob
Front Mirror Differential Screw Micrometers
Back Mirror Dye Cell Assembly
XBL 8012-13348

Figure 5

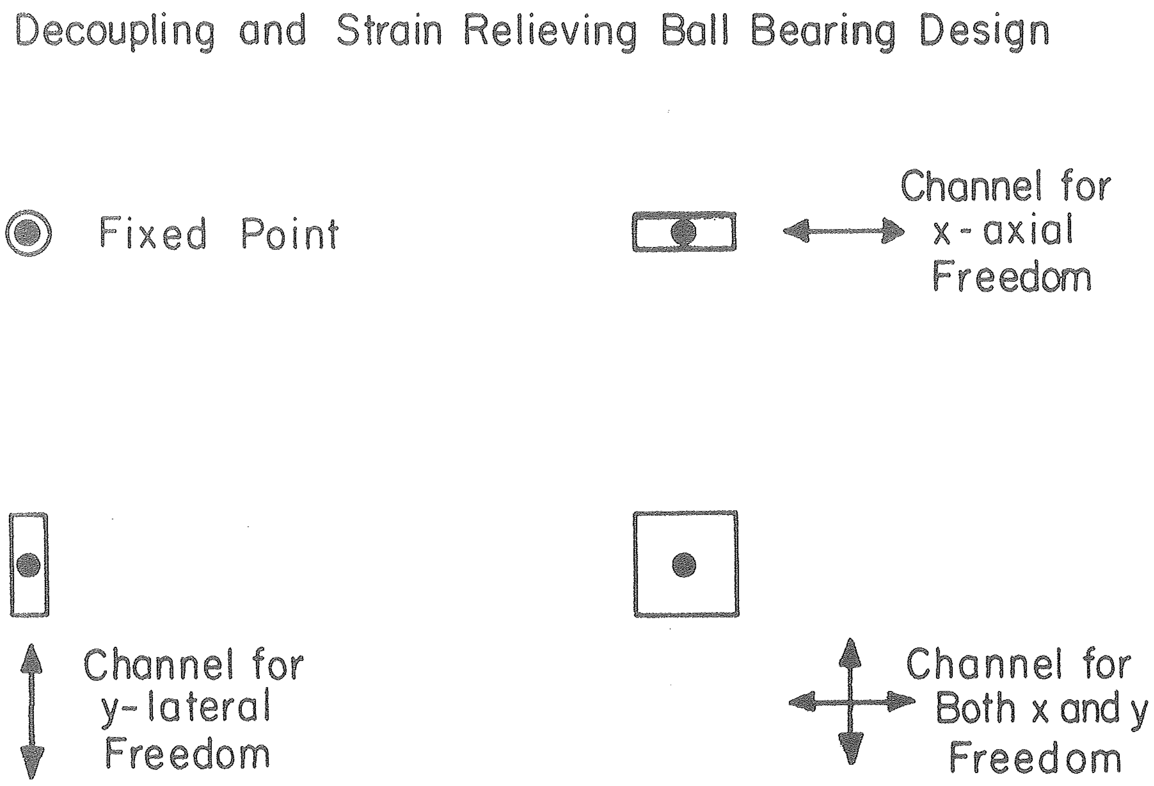

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Figure 6

Laser Assembly
Top View

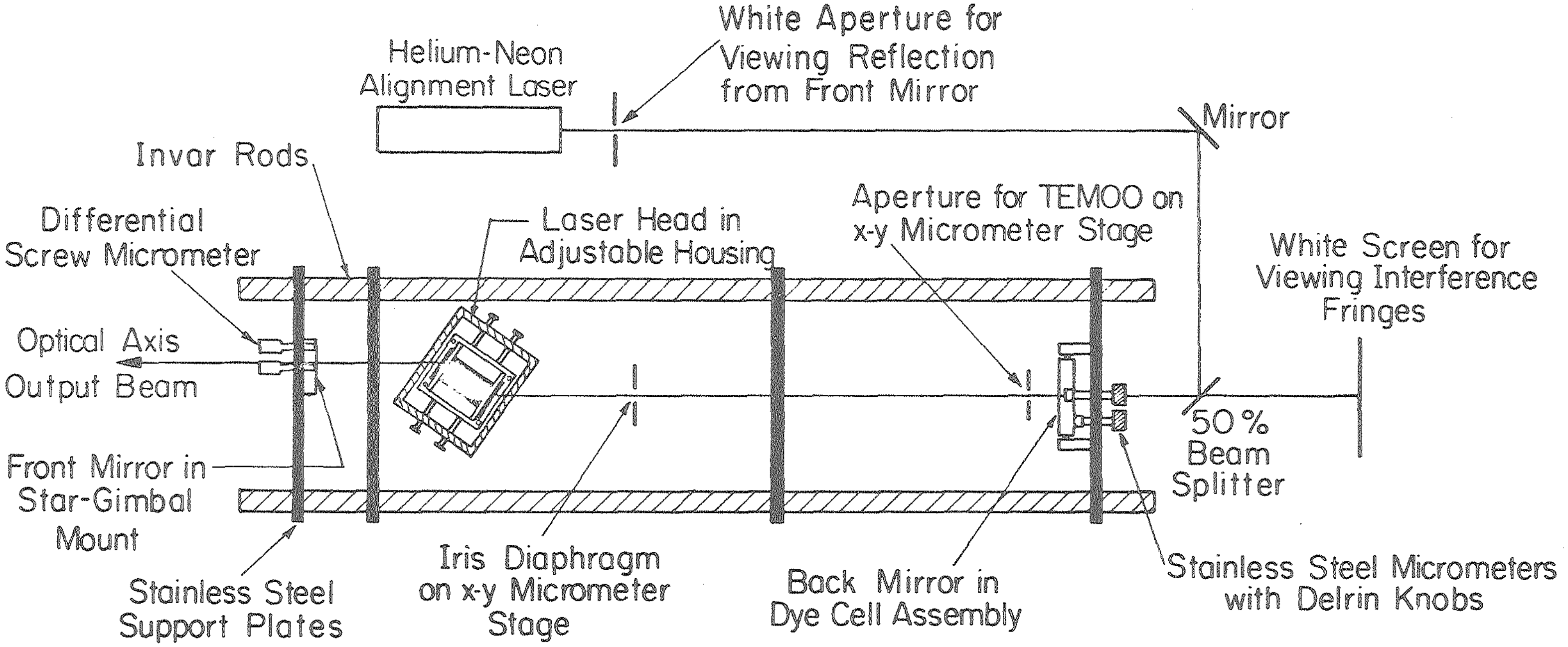

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Figure 7

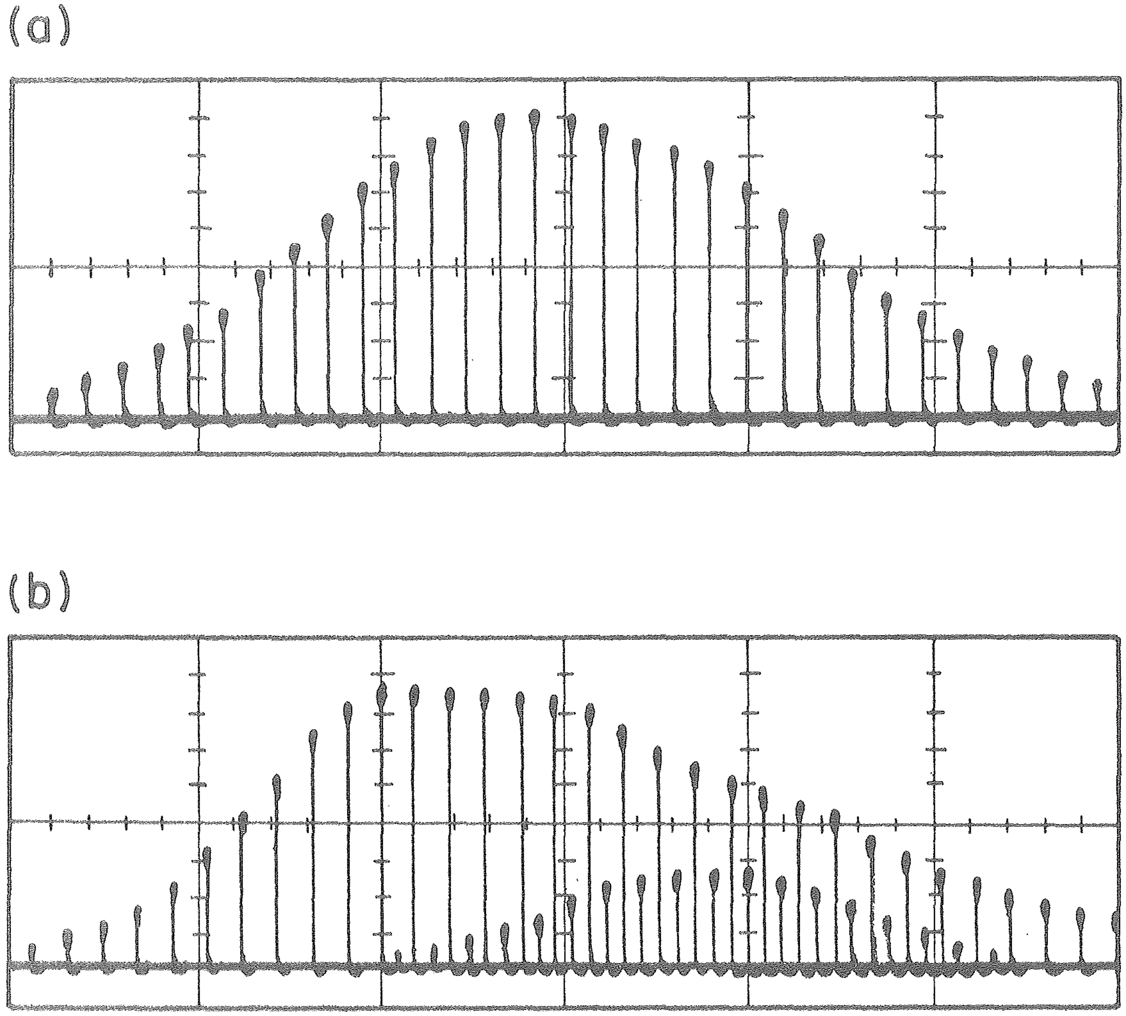

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Figure 8