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DEVELOPMENT AND DELIVERY OF A STABLE MASTER OSCILLATOR

M. L. Skolnick, et al

United Aircraft Corporation

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DEVELOPMENT AND DELIVERY OF A STABLE MASTER OSCILLATOR

United Aircraft Corporation

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13. ABSTRACT

This report discusses the technical background, design features, hardware, and performance of the stable master oscillator (STAMO) CO_2 Laser System developed under Contract F30602-72-C-0147. This laser which operates with a high degree of frequency stability at a power level of 35 watts has been tailored for use as the driver laser for the high-power laser amplifier at the Rome Air Development Center Floyd Facility. The STAMO configuration uses a low-power master oscillator to injection lock a high-power ring oscillator. This configuration achieves the high degree of short-term frequency stability inherent in the small low-power master oscillator at the 35 watt power level. A feedback control loop is used with a hybrid injection-locking technique to achieve reliable long-term closed-loop operation of the system. Heterodyne measurements of the frequency stability of the STAMO have been made and its stability is shown to exceed the design requirements.

Details of illustrations in this document may be better studied on microfiche.

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DEVELOPMENT AND DELIVERY OF A STABLE MASTER OSCILLATOR

M. L. Skolnick
C. J. Buczek

Contractor: United Aircraft Corporation
Contract Number: F30602-72-C-0147
Effective Date of Contract: 20 December 1971
Contract Expiration Date: 20 August 1972
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Principal Investigator: M. L. Skolnick
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PUBLICATION REVIEW

This technical report has been reviewed and is approved

RADC Project Engineer

TABLE OF CONTENTS

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I. INTRODUCTION

The purpose of this program was to design, fabricat. test, and deliver a medium-power stable cw CO_2 laser source which is tailored for use as a driver oscillator for the high-power laser amplifier at the RADC Coherent Optical Radar Laboratory at Floyd, New York. The stable master oscillator (STAMO) developed and deli- ered under this program has demonstrated all of the required performance characteristics. These design requirements are:

a) Power output: 35 watts in a single line (P_{18}, P_{20} or P_{22}) of the 10.6μ CO_2 branch.

b) Transverse mode: TEM_{00} and collimated to the diffraction limit of the output aperture.

c) Frequency stability: less than 25 kHz (.05 seconds); less than 5 MHz (1 hour).

d) Amplitude stability: 2 percent for 2 minutes.

The method of approach used in the design of the STAMO is based on a separation of the burdens of frequency stability and power generation. A low-power highly stable master oscillator is used to control the frequency of a higher power ring oscillator by means of injection locking. The low-power master oscillator provides 1.5 watts of power; the higher power ring oscillator provides 35 watts of output power. This injection-locking approach results in significantly better frequency stability than can be achieved with the large high-power oscillator operating alone. The CO_2 laser injection-locking techniques used here were pioneered at the United Aircraft Research Laboratories under Air Force Contract F33615-70-C-1481, "Ruggedized CO_2 Packaged Laser." These techniques are discussed in Section II of this report.

Extensive tests of the performance of the STAMO have been conducted. The frequency stability of the STAMO has been measured by optical heterodying its output with the output of a separate low-power stable reference laser. These experiments, which illustrate the importance of separating the frequency stability and power generation functions in moderate power laser sources, indicate all of the performance requirements have been achieved. This STAMO evaluation is described in Section V of this report.

II. TECHNICAL BACKGROUND

The method of approach used in the STAMO is based on using a low-power highly stable master oscillator to injection lock the frequency of a higher power 35-watt oscillator. As discussed in the following paragraphs, this method of approach was more suitable than the alternate methods for building a large oscillator or using a single-pass laser amplifier.

The frequency stability achievable with large laser oscillators is generally poorer than the stability achievable with small oscillators since a higher degree of dimensional stability can be easily achieved in the small laser cavity structures. The short-term frequency stability of a CO_2 laser oscillator depends on the cavity stability and rigidity. This short-term stability cannot be improved by using stabilization techniques referenced to the molecular transition gain profile because the broad frequency width of such a gain profile, typically 60 MHz, limits the realizable bandwidths of feedback control loops to a few Hz. Frequency jitter in the laser output caused by acoustical vibrations of the resonator are usually too fast to be reduced by such narrow bandwidth feedback techniques. Therefore, the use of an intrinsically small stable reference cavity is required in applications where short-term frequency stability is of paramount importance.

A highly stable low-power master oscillator could in principle be used to drive a conventional single-pass laser amplifier such as the high power stage of the RADC transmitter. However, because of the relatively low gain of the CO_2 laser medium ($\sim \frac{1}{2}$% cm) an amplifier path length in excess of 5 meters would, for example, be required to amplify the 1.5-watt master oscillator output power to the required 35-watt level. Because of this long path requirement, the conventional amplifier was not considered an attractive approach for STAMO.

The injection locking of a high-power CO_2 ring laser oscillator to a low-power master oscillator has been studied by United Aircraft Research Laboratories under Air Force Contract F33615-70-C-1481. This work provided the technical basis for the development of the STAMO and the relevant material is discussed briefly below.

The configuration used in the STAMO is a simple Fabry-Perot two-mirror master oscillator whose output is injected into the cavity of a higher power ring oscillator. The ring oscillator is operated in a single direction to prevent its output from being coupled back to the master oscillator. The total ring oscillator output will in general consist of radiation at two frequencies, originating from the two laser oscillators. However, when the ring oscillator is tuned so that its cavity resonance is sufficiently close to that of the injected radiation from the master oscillator, competition effects in the homogeneously broadened CO_2 laser medium result in locking of the self-oscillation frequency to that of the injected signal. This frequency interval over which locking occurs is called the locking range. Under this injection-locked condition the output frequency is determined primarily by the master oscillator. This CO_2 laser injection locking which has many similarities to injection locking of electrical oscillators has been discussed in detail in References (1), (2) and (3).

The use of injection locking to achieve a high degree of frequency stability in a high-power laser oscillator requires that the frequency stability of the large laser itself be sufficient so that its fast frequency fluctuation or jitter is smaller than the injection-locking range. The injection-locking range has been discussed in Reference (3) and is given by:

$$\Delta f_{\ell} = 2\Delta f_c \left(\frac{P_o}{\Delta P_o} \right)^{\frac{1}{2}}$$

where: Δf_{ℓ} = locking range

Δf_c = ring oscillator cold-cavity bandwidth

P_o = injected signal power

ΔP_o = output power of the ring oscillator.

For many cases of interest, such as STAMO, this locking range is on the order of a few MHz. Therefore, fast short-term frequency fluctuations (not correctable with a slow hill-climbing servo) in the higher power laser, which have excursions less than this locking range, can be eliminated by injection locking. Consequently, the output of the high-power oscillator assumes almost the frequency stability of the master oscillator.

To maintain laser injection locking on a continuous basis, so that it is a practical stabilization technique, it is necessary to continuously tune the perimeter of the ring oscillator so that its resonant frequency is within the locking range. The hybrid injection-locking technique used to generate a discriminant which can be used for electronically maintaining this tracking is discussed in Reference (2). This method results in a peak in the laser output power centered on the injection-locking interval. In the hybrid mode of operation, the injected signal from the low-power laser is chosen to be different from the transition in which self-oscillation of the high-power laser is occurring. As a consequence of the strong line competition of the homogeneously broadened laser medium, the injected power can determine the operating transition of the higher power laser. When the laser resonators are properly tuned, the undriven self-oscillation of the higher power laser will be quenched; and only the driven or injection-locked contribution of the laser power will be extracted. A simple hill-climbing servo can be used to maintain the ring oscillator perimeter so that operation occurs on the top of its power output peak.

The hybrid injection-locking technique has been used to provide reliable long-term ring oscillator stabilization in the STAMO. It is implemented by adjusting operating conditions such that the ring oscillator operates on a 9μ CO_2 transition and the master oscillator on a P_{18} - P_{22} 10μ transition. The total power output is sampled and passed through a narrow bandpass (P_{18} - P_{22}) interference filter which separates the injected and self-oscillation components. This is illustrated in Fig. 2 where the total output of the 10.6μ filtered output are displayed as a function of its resonant frequency. The left column in Fig. 2 shows the variation in the output power as the ring oscillator cavity is swept. The apparent output power fluctuations are due mostly to the variation in sensitivity of the gold-doped germanium detector between the 9μ and 10μ wavelengths as the ring oscillator frequency line hops. The output consists of both 9μ and 10μ transitions and the effect of the injected radiation is seen to be small. In the right column of Fig. 2 this same output characteristic is displayed after passing through the narrow 10μ bandpass filter. The line switching between the 10μ and 9μ transitions is clearly evident from their different transitions through the narrow band filter. Also clearly distinguishable is the high signal-to-noise ratio 10μ peak superimposed on a frequency range where 9μ self-oscillation occurs. This 10μ peak occurs as the ring oscillator is tuned through the frequency of the injected signal. The width of this peak is nearly equal to the injection-locking range. Also shown is the quenching effect of injecting a 9μ signal in the region of

10μ self-oscillation. Continuous closed-loop operation of the STAMC on the P_{18} - P_{22} 10μ lines is achieved by controlling the ring oscillator perimeter with a hill-climbing servo so that operation is maintained close to the 10μ peak.

This high signal to background 10μ peak is used to generate a discriminant to lock the ring oscillator perimeter to the injected frequency. A simple hill-climbing servo which uses a small dither or length modulation of the ring perimeter to modulate the output power is used with a synchronous detector to generate the error signal. This conventional type of laser stabilization loop is shown in Fig. 3. The excursion of this dither is chosen to be less than the injection-locking range, i.e., ~ 250 kHz and the frequency of the dither is chosen so that it results in a small phase modulation of the output. The resulting FM is small compared to the inherent short-term frequency stability of the master oscillator.

III. STAMO DESIGN AND CHARACTERISTICS

The STAMO head components are shown diagramatically in Fig. 4. The major components are:

a) the stable master oscillator,

b) the 35 watt ring oscillator,

c) the mode matching telescope,

d) the beam sampler, filter and detector, and

e) the beam expansion telescope.

The design rationale for each of these components is described below:

1. Master Oscillator

The master oscillator is shown in Fig. 5. It operates with an output power of 1.5 watt in a TEM_{00} transverse mode and a short-term frequency stability of 10 kHz over measurement times of 50 msec. It is also characterized by a slow thermal frequency drift of typically 3 MHz/hr. Figure 6 shows the heterodyne beat spectrum of two identical master oscillators.

The master oscillator uses an internal mirror design and incorporates a long-life sealed plasma tube. The resonator structure is made from low expansion coefficient invar to which the cavity mirrors are permanently attached. The plasma tube has a single ended discharge with a grounded cathode. The piezoelectric length transducer is located on the grounded cathode end of the plasma tube.

The output mirror is a plane germanium substrate with a 93 percent reflectivity mirror. The mirror coating was chosen to enhance the 10μ CO_2 transitions. The observed signature as the cavity length is scanned shows the strong tendency for the desired P_{18} - P_{22} lines to operate. The thermal drift rate is such that the laser will operate on a preselected transition for several hours without resetting the cavity length adjustment. The narrow bandpass optical filter and built-in detector used for the hybrid stabilization technique enable tuning the master oscillator to a desired transition without an external spectrometer.

The total reflector of the master oscillator is a 1 meter radius concave mirror having a dielectrically enhanced gold coating. This mirror, which is ruled with a series of fine parallel lines in the coating, is used to determine the plane of polarization of the master oscillator output. The ruled lines have a width of 8μ and a spacing of .5 mm. A typical polarization selecting mirror of this design is shown in Fig. 7.

2. 35-Watt Ring Oscillator

The 35-watt ring oscillator design is also shown in Fig. 4. This laser uses two split discharge plasma tubes and a total active length of 150 cm. The ring cavity is a right triangle which is formed by one curved 5-meter mirror and two plane mirrors. The plane mirror located at the right angle is a partially transmitting gallium arsenide mirror which has a 70 percent reflectivity coating at $\lambda = 9.6\mu$. This coating has been tailored to have a slightly lower reflectivity at 10.6μ resulting in a tendency for the ring oscillation to occur on the 9.6μ CO_2 transitions. This characteristic was chosen to enhance the hybrid-locking technique used in the STAMO in which a 10.6μ signal from the master oscillator is injected in the presence of a 9.6μ self-oscillation of the ring. The ring curvature results in a beam waist of 5.7 mm.

The perimeter of the ring is 250 cm resulting in a free spectral range c/p of 116 MHz. The cavity linewidth Δf_c is determined by this free spectral range and the mirror reflectivity and is about 6 MHz.

The ring oscillator frequency stability has been measured by heterodyning it with a stable reference laser. It has been found to have a low frequency jitter in its output which results in frequency deviations on the order of 500 kHz. Its long-term thermal drift is approximately 10 MHz/hr. The short-term frequency stability of this ring oscillator results in excursions which are less than the injection-locking range (approximately 2 MHz for the STAMO parameters). Accordingly, in closed-loop operation the frequency jitter of the 35-watt oscillator is completely eliminated and the 35-watt output has the short-term frequency stability of the low-power oscillators. The thermal drive of the ring perimeter is sufficiently slow that the servo electronics can maintain injection-locked operation for many hours before manual resetting of the electronic amplifier is required.

3. Mode-Matching Telescope

The locking range of an injection-locked CO_2 laser has been shown to be proportional to the square root of the injected laser power. A large locking range, which is desirable for reliable operation, requires that the effective injected power be maximized. This is accomplished in the STAMO by means of a telescope which matches the master oscillator output beam to the ring oscillator mode.

The optical geometry of the STAMO is shown in Fig. 4. The diameter of the output spot of the master oscillator is 2.4 mm. The diameter of the beam waist of the ring oscillator is 5.7 mm. In the STAMO design a two-power telescope is used near the output of the master oscillator to expand the beam. The resulting power coupling efficiency of this expanded beam into the ring laser mode volume is approximately 50 percent.

Figure 4 also shows the mode-matching telescope. It consisted of two AR coated germanium lenses which can be independently centered on the beam and their separation adjusted to achieve the required focusing.

4. Beam Sampler, Filter, and Detector

The output beam of the STAMO is sampled, filtered and detected by a thermistor bolometer to generate the electrical signals required for slaving the ring oscillator perimeter to the frequency of the injected radiation. The beam splitter used is a NaCl flat at an angle of 70 deg to the plane polarized STAMO output. This angle was chosen so that the Fresnel reflection from the NaCl flat is 5 percent per surface. The reflected sample of the STAMO output is passed through a narrow bandpass filter and impinges on the detector surface. The geometrical arrangement is shown in Fig. 4.

The narrow bandpass filter transmission characteristic is shown in Fig. 8. As evident from this curve, the filter bandpass encompasses the P_{18} - P_{22} 10.6μ CO_2 laser transitions and is essentially opaque for other transitions. This characteristic is used for initially setting the master oscillator to one of these transitions and for generating the discriminant curve for the hybrid injection locking.

The detector used is a thermistor bolometer which has a frequency response of about 500 Hz which is sufficient for detecting the AM in the laser output of the servo at the 100 Hz dither frequency electronics. The output of this detector is avilable from a connector in the electronics panel and is useful in setting up closed-loop STAMO operation as described in the instruction manual.

5. Beam Expansion Telescope

A two-power variable focus telescope, which can be used to match the STAMO output to the laser amplifier mode volume, is included in the STAMO head. This telescope uses a pair of AR coating gallium arsenide meniscus lenses. This telescope expands the output of the STAMO to a 12 mm diameter and can be adjusted so that the position beam waist is controllable.

IV. STAMO HARDWARE

In this section the STAMO harware is described. Detailed operating instructions for the system have been delivered with the hardware.

The inside of the STAMO laser head with the housing and oven side plates removed is shown in Fig. 9. The major components and structural elements are indicated on this photograph. The oven structure which surrounds the entire laser head consists of four magnesium plates to which silicon rubber heating pads are bonded. These pads are used to provide uniform heating to minimize temperature gradients. The wire sensor and controller itself are mounted inside the oven to provide maximum temperature stability. The oven side plates are an integral part of the resonator structure and are designed to provide torsional rigidity. These plates must be place when the system is optically aligned and operated. One plate can be easily removed for plasma tube replacement when required.

The STAMO head structure is built around four low-expansion invar tubes which have been filled with sand in order to suppress resonant vibrations. These tubes locate both the two ribbed endplates containing the optical components which bound the ring oscillator, and the two middle plates which support the plasma tube adjustment mechanisms. The front endplate which contains two of the ring laser mirrors incorporates an invar rib which is used to space these mirrors. The four magnesium plates are attached to the invar tubes through phenolic bushings to provide a mismatch for the flow of acoustical energy through the structure. Additional vibration damping is obtained by use of a damping coating throughout the entire structure. The lower pair of invar tubes also support the master oscillator laser and the mode-matching telescope.

The ring oscillator optical geometry is a right triangle in which the 45 deg mirror is partially transparent and is used for output coupling and the 5-meter curvature mirror is driven by a piezoelectric transducer for length tuning. The third mirror of the ring oscillator is plane. The partially reflective mirror uses dielectric coatings on a gallium arsenide substrate and the total reflecting mirrors use dielectrically enhanced metallic coatings on silicon substrates. The partially transparent output mirror is permanently aligned to the resonator endplate. The other two mirrors of the ring oscillator are angularly and longitudinally adjustable.

The ring oscillator uses two long-life sealed pyrex plasma tubes which have NaCl Brewster windows and which employ split discharges with a common cathode. Also located inside the laser head near the anode pins are noise suppression resistors in series with each of the discharges. The tubes themselves are water-cooled and use a concentric gas ballast volume. A flow sensor is included in the water circuit which prevents operation of the plasma tube discharge without the water cooling. The plasma tubes are held at each end by concentric metal collars which are positioned within the structure by x,y mechanical adjustments.

The master oscillator laser uses a one-piece cast invar resonator and an internal mirror single discharge sealed plasma tube. It contains a piezoelectric transducer for length tuning. The output beam of this master oscillator is expanded by a two-power refractive telescope which is composed of 1 in. and 2 in. focal length AR coated germanium lenses. The separation between the lenses is adjustable by a slide mechanism. This telescope is required to efficiently match the output beam of the master oscillator to the mode of the ring oscillator. The expanded beam from this telescope is then incident on a folding mirror which has x, y and z adjustments which are used to align the master oscillator beam along the optical axis of the ring oscillator.

The output beam from the ring oscillator emerges from the partially transparent mirror perpendicular to the injected beam from the master oscillator and parallel to the housing length. It then passes through a NaCl beamsplitter which reflects a small portion (~ 5 percent) into the detector assembly. The detector assembly and output beam expansion telescope are shown in Fig. 10. The detector mounting bracket contains a narrow passband optical filter and the preamplifier for the thermistor bolometer detector. The major portion of the beam which passes through the beam splitter is then incident on the two power beam expansion telescope. This telescope uses 2 in. and ¼ in. gallium arsenide AR coated meniscus lenses. The separation between these lenses is adjustable by a slide mechanism which is controlled by a fine worm gear adjustment on the outside of the telescope housing. The effective focal length of the telescope can be adjusted for best matching the laser amplifier.

The entire STAMO resonator is shock mounted through rubber bushings inside the STAMO housing. This housing is thermally insulated and forms the outside of the resonator oven. All of the electrical and water connections are brought out through the rear endplate of this housing. The housing is supported by three adjustable feet which are used for leveling and pointing of the output beam.

The electronics module is shown in Fig. 11. It contains the following components:

a) Master Oscillator Power Supply,

b) Ring Oscillator Power Supply,

c) Laser Frequency Controller,

d) Ring Oscillator PZT Driver Amplifier,

e) Plasma Tube Ballast Resistors,

f) Temperature Controller Readout, and

g) Safety Interlocks.

The master oscillator and ring oscillator power supplies are commercially purchased high voltage regulated power supplies. These supplies have normal overload interlocks. In addition they have been interlocked to shut down in the event of insufficient plasma tube coolant flow. The ballast resistors for running the four ring oscillator discharges from the single power supply are mounted in the electronics module. A single ballast resistance circuit is used for the master oscillator power supply.

The laser frequency controller contains a filtered adjustable high voltage supply for driving the master oscillator PZT to set the oscillating frequency to the desired operating point. It also contains a hill-climbing servo which is used to maintain continuous injection locking in the closed-loop mode.

This servo operates by synchronously detecting the power modulation in the output beam sensed by the optical detector in response to a small dither impressed by an ac signal to the ring piezoelectric length transducer. The output of this synchronous detector is applied to a high voltage linear amplifier which drives the ring PZT. Circuit functions are also provided for sweeping and manually tuning the ring oscillator frequency. The high voltage PZT driver amplifier is a commercially purchased component which has been adapted for this purpose.

A readout has been provided for monitoring the temperature of the STAMO head. This also indicates the continuous operating of this controller when the rest of the STAMO is shut off. The entire STAMO electronics has been built in a standard enclosed 19 in. rack cabinet. These electronic components are forced air-cooled by fans located in the top panel of this enclosure. The enclosure stands on casters for ease of movement.

V. PERFORMANCE EVALUATION

The performance of the STAMO was tested by assembling an experiment in which its output was optically heterodyned with the output of an external reference oscillator. The external reference oscillator was a standard UARL mini-laser which has well-established output characteristics.

The first parameter measured was the injection-locking range of the system. This is shown in Fig. 12 which shows the filtered output power versus ring oscillator frequency characteristic. The horizontal scale is 5 MHz/div. The locking range of 2 MHz agrees with the theoretical predictions within the experimental accuracy and is broader than the frequency jitter of the ring oscillator.

The open-loop stability of the 35 watt ring oscillator is shown in Fig. 13(a) which is a 30 second time exposure. The jitter is attributed to residual mechanical vibrations in the large cavity structure.

The closed-loop injection-locked frequency stability of the STAMO is shown in Fig. 13(b) which is also a 30 second time exposure. This output characteristic at the 35 watt power level exceeds the STAMO performance requirements.

The amplitude stability of the STAMO has been measured with a gold-doped germanium detector and the output fluctuations observed to be less than 1 percent for a two-minute measurement interval.

The measurements have clearly shown that CO_2 laser injection-locking techniques result in an overall optimized STAMO source which is suited for driving the high power laser amplifier at RADC.

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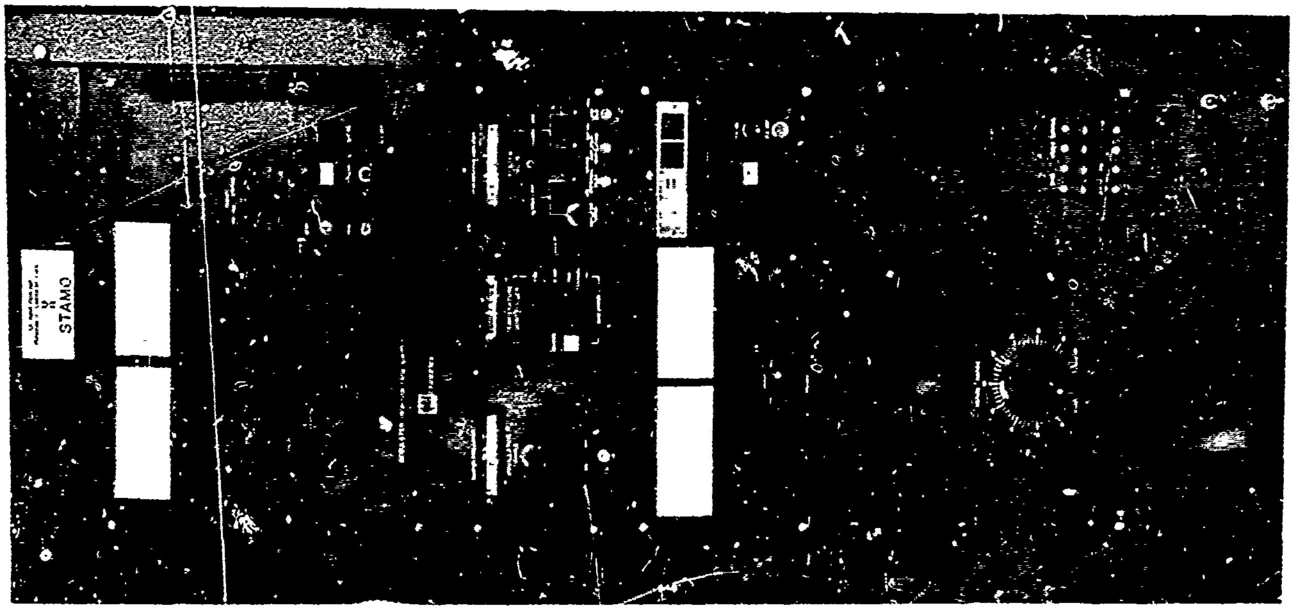
(2) C. J. Buczek and R. J. Freiberg, IEEE J. Quan. Elect. QE-8, 641 (1972).

(3) R. J. Freiberg, C. J. Buczek and M. L. Skolnick, "Ruggedized CO_2 Packaged Laser," Tech. Report AFAL-TR-71-273.

LIST OF FIGURES

L921293-1

FIG. 1



STAMO SYSTEM

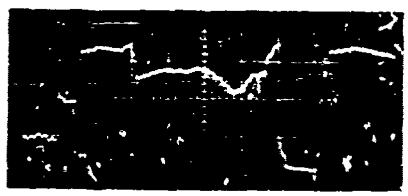
STAMO OPERATION

FILTERED OUTPUT

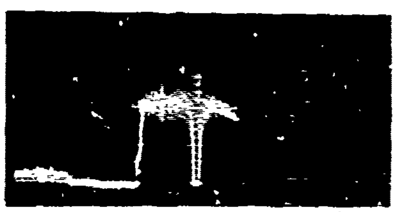
TOTAL OUTPUT

NO INJECTED SIGNAL

MASTER OSCILLATOR TUNED TO 10.6 μ



MASTER OSCILLATOR TUNED TO 9.6 μ



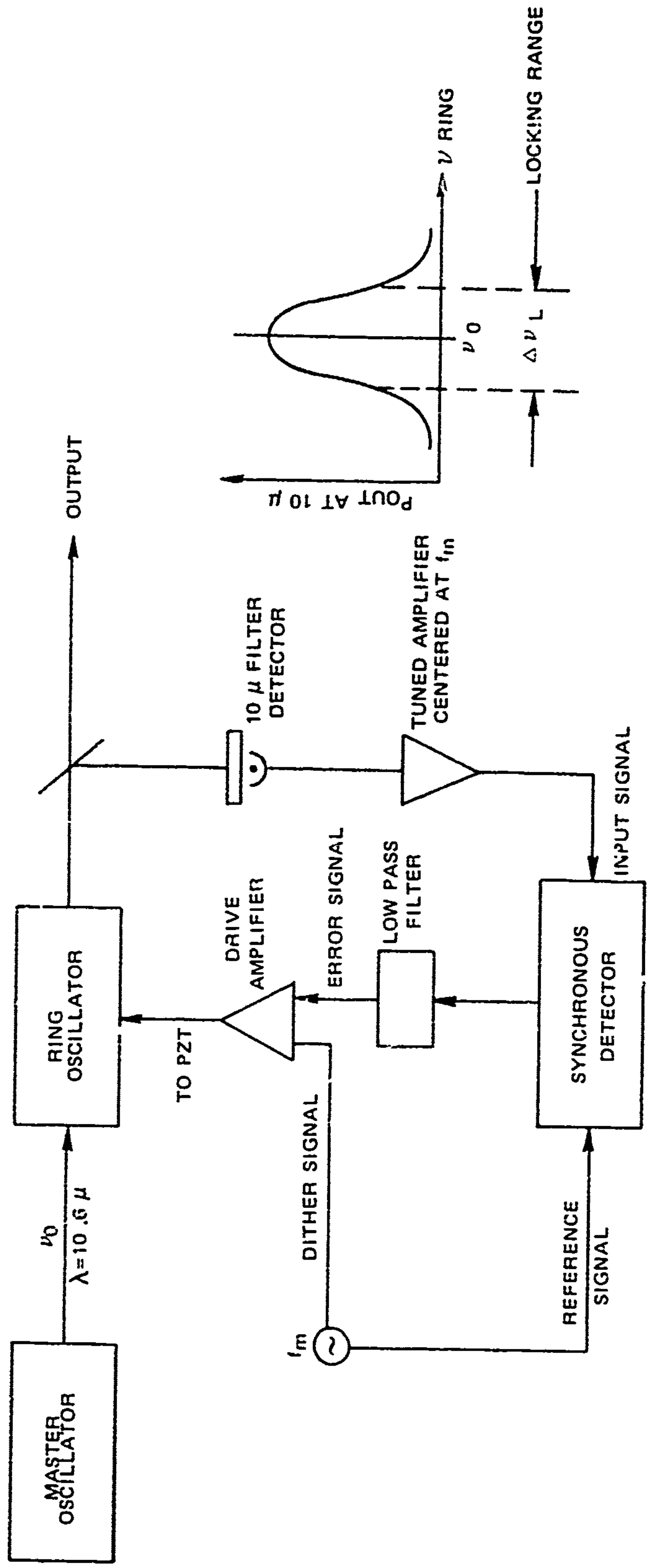
RING OSCILLATOR FREQUENCY

5 MHz/div

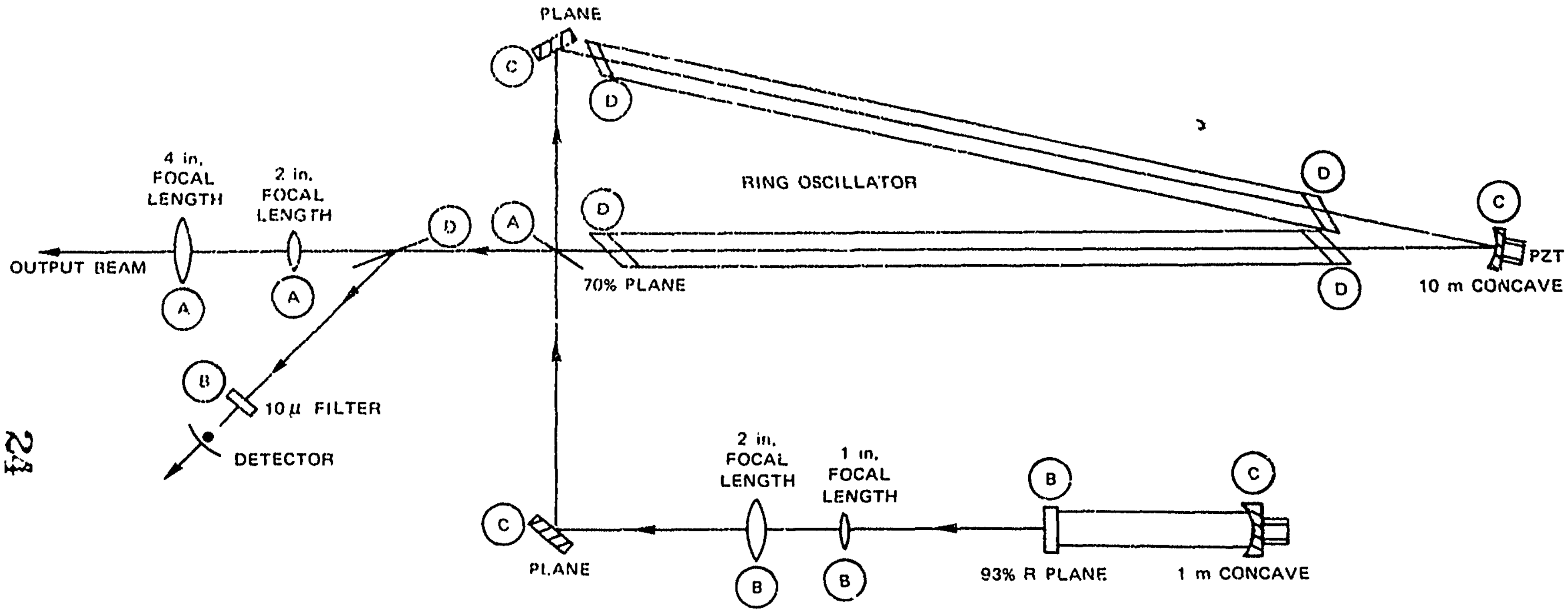
RING OSCILLATOR FREQUENCY

FIG.3

HILL–CLIMBING SERVO



STAMO OPTICAL BLOCK DIAGRAM



(A) GALLIUM ARSENIDE

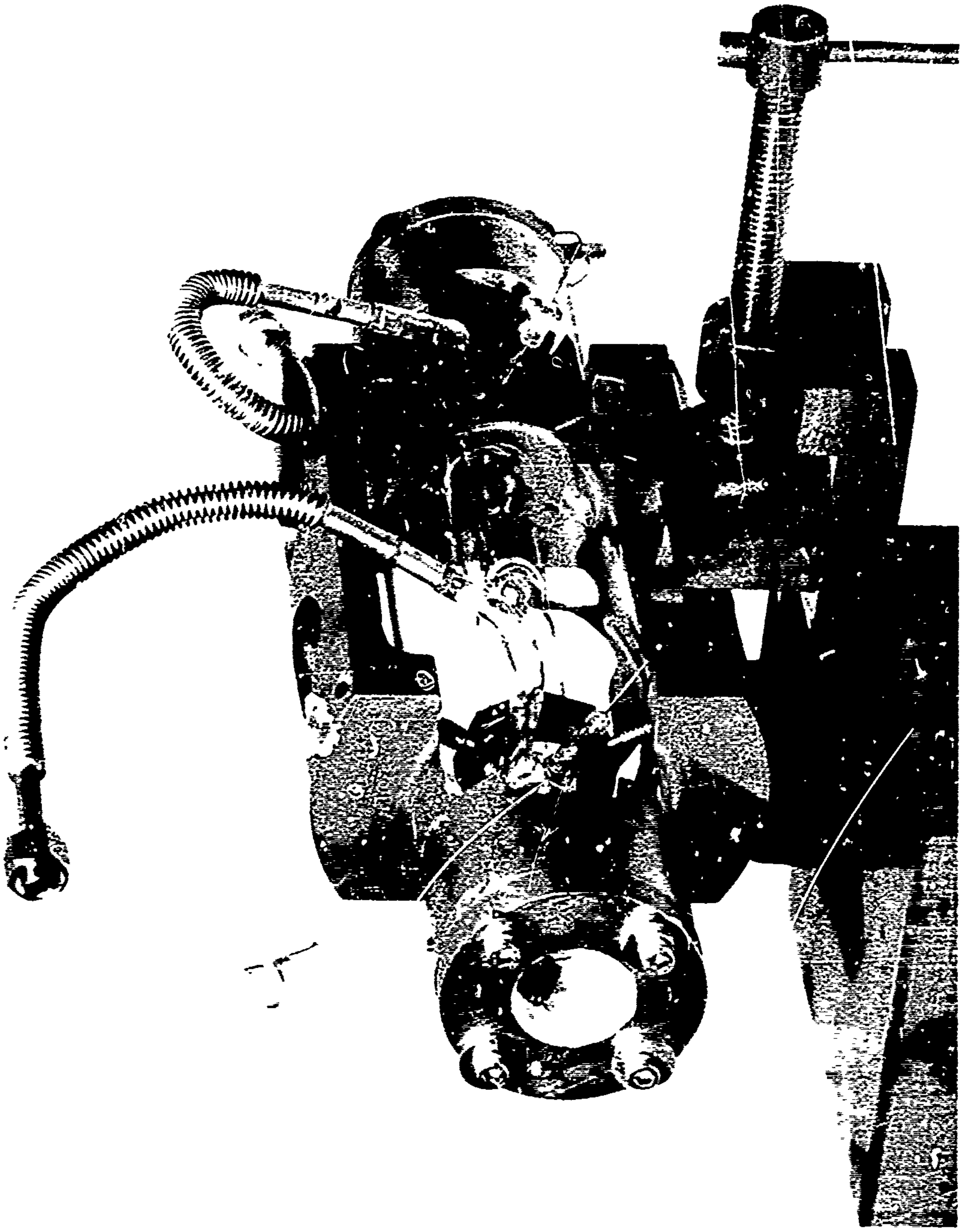
(B) GERMAINIUM

(C) SILICON

(D) SODIUM CHLORIDE

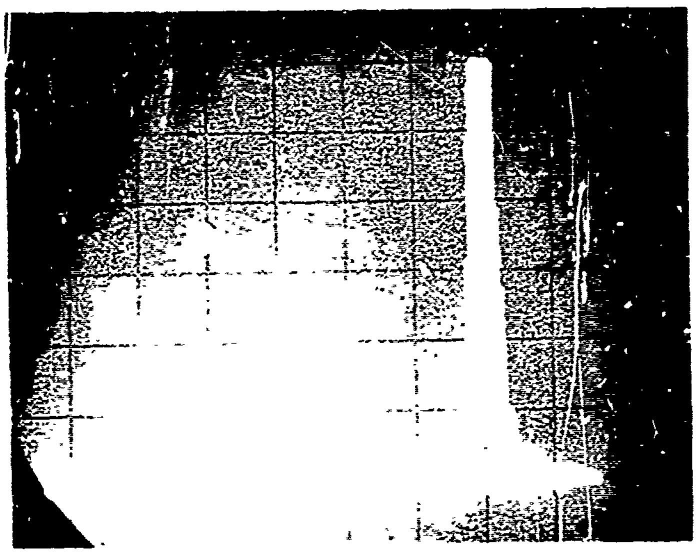
FIG. 4

FIG. 5



MASTER OSCILLATOR

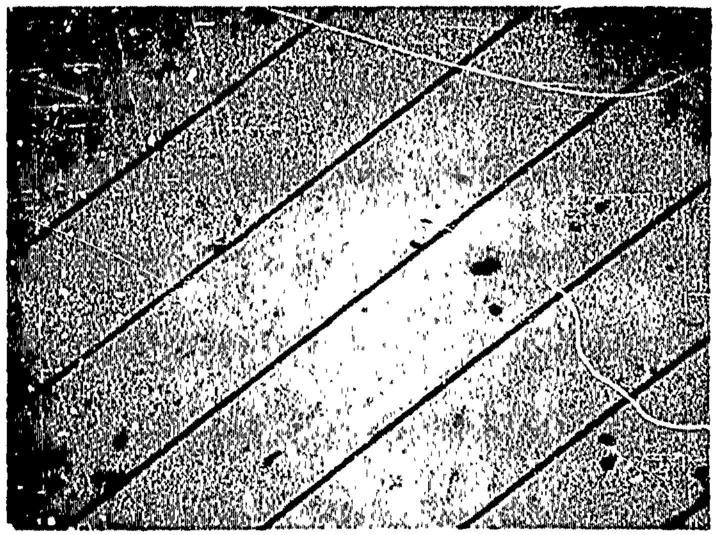
SPECTRUM ANALYZER DISPLAY OF BEAT BETWEEN TWO MINI—LASERS



HORIZONTAL SCALE: 20 kHz/div

FIG. 7

SCRIBED LASER MIRROR FOR POLARIZATION SELECTION

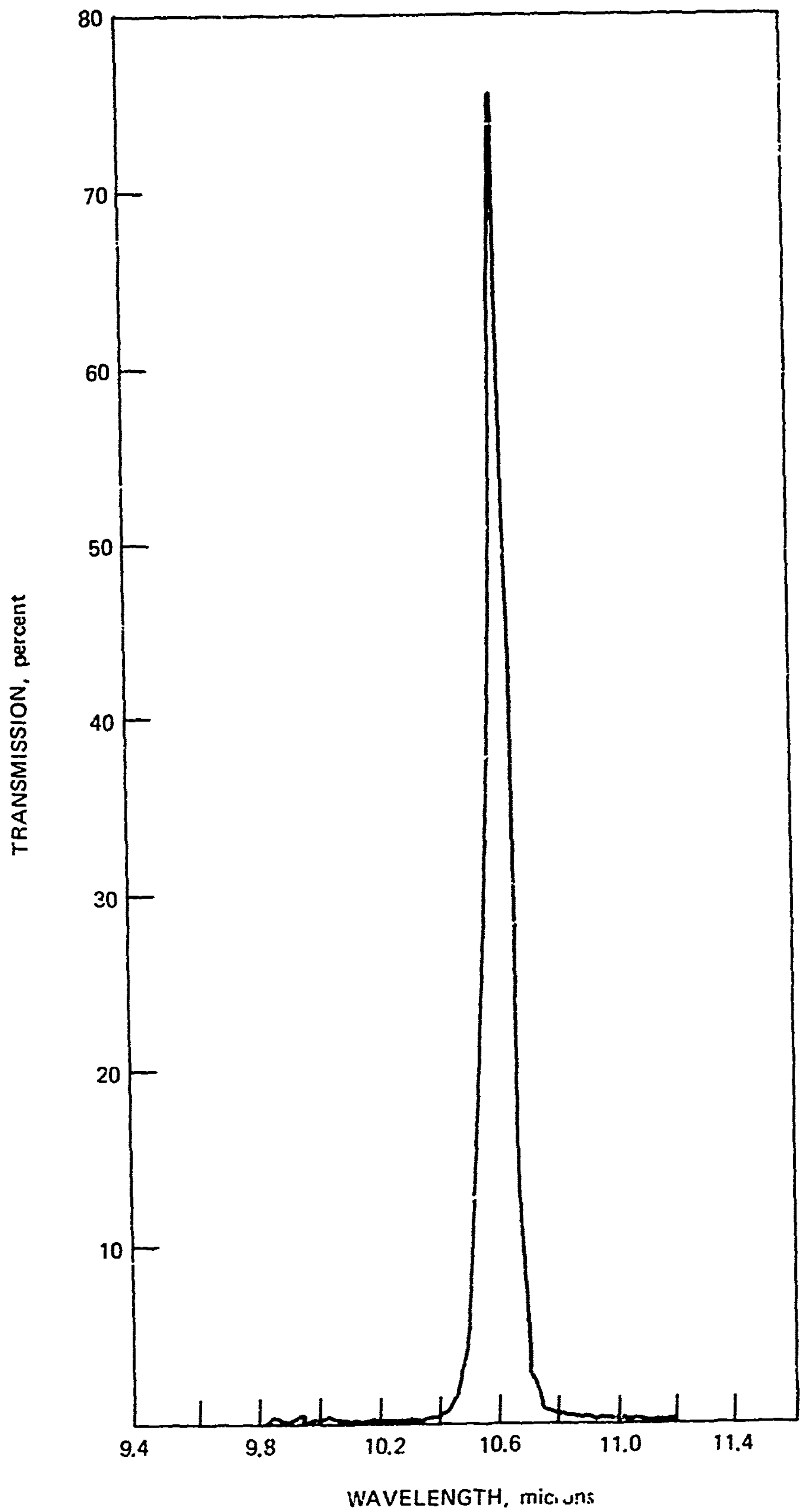


LINE SPACING 0.5 mm

LINE WIDTH 8 μ

L921293-1 FIG. 8

TRANSMISSION VS WAVELENGTH OF BANDPASS FILTER



STAMO LASER HEAD (SIDES REMOVED)

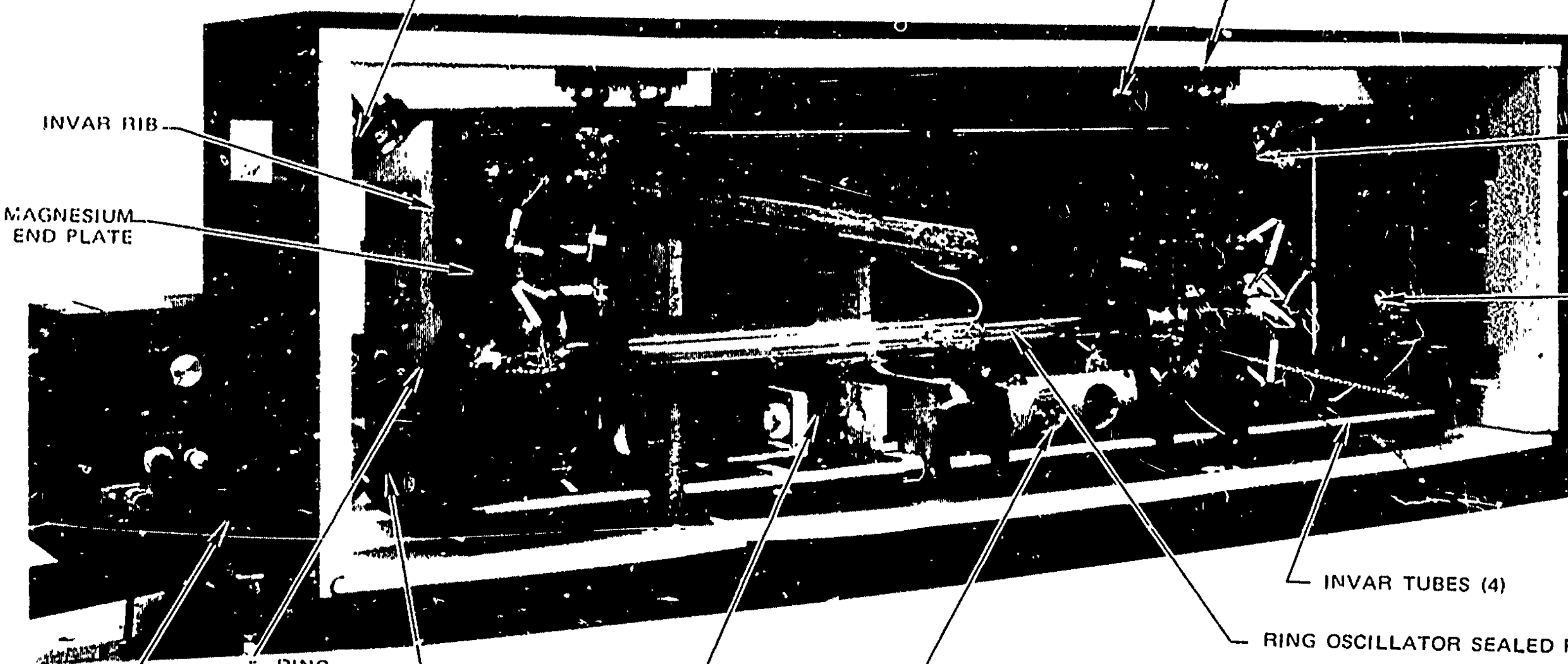
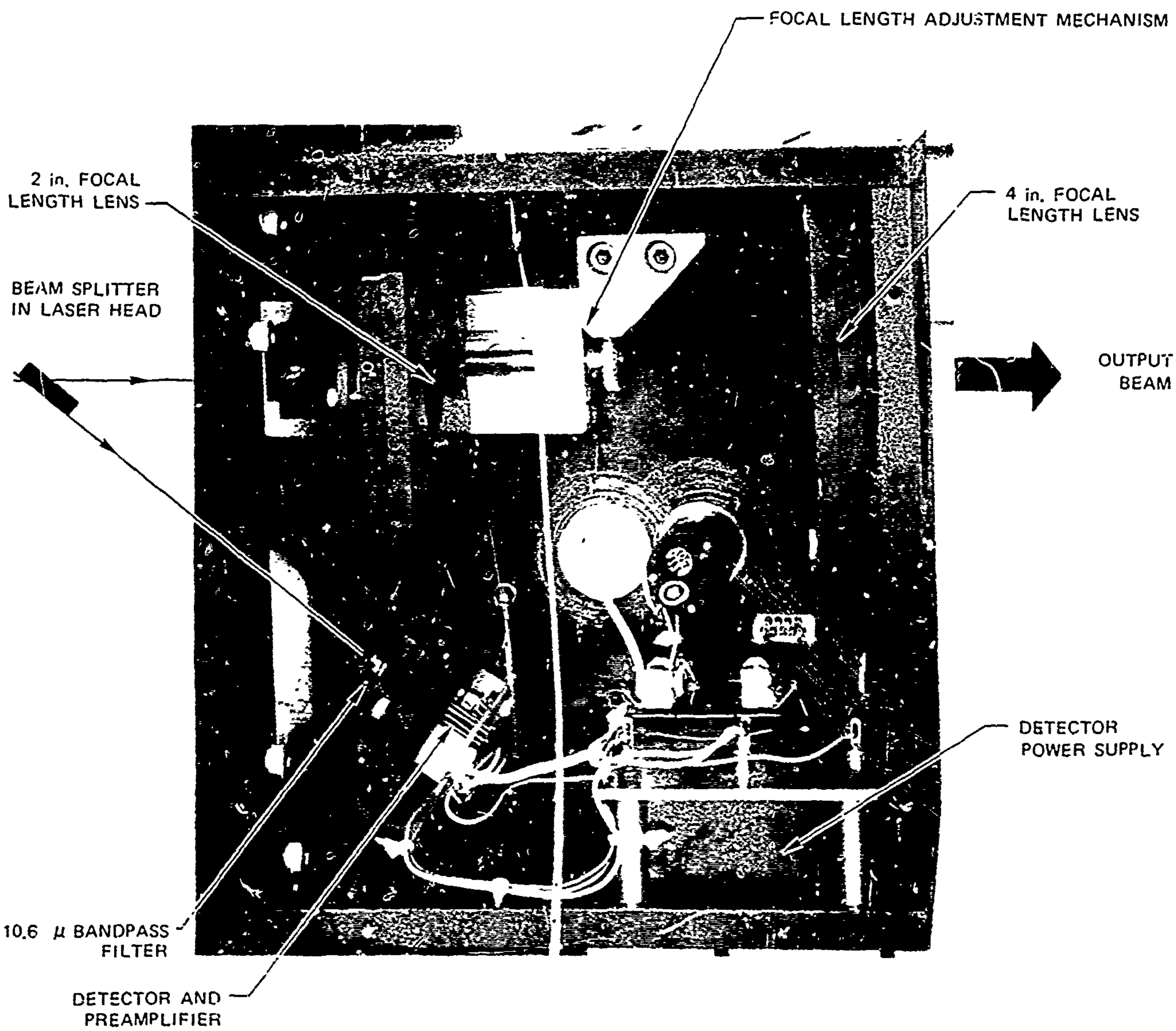


FIG. 9

STAMO OUTPUT BEAM EXPANSION TELESCOPE



STAMO ELECTRONIC'S MODULE

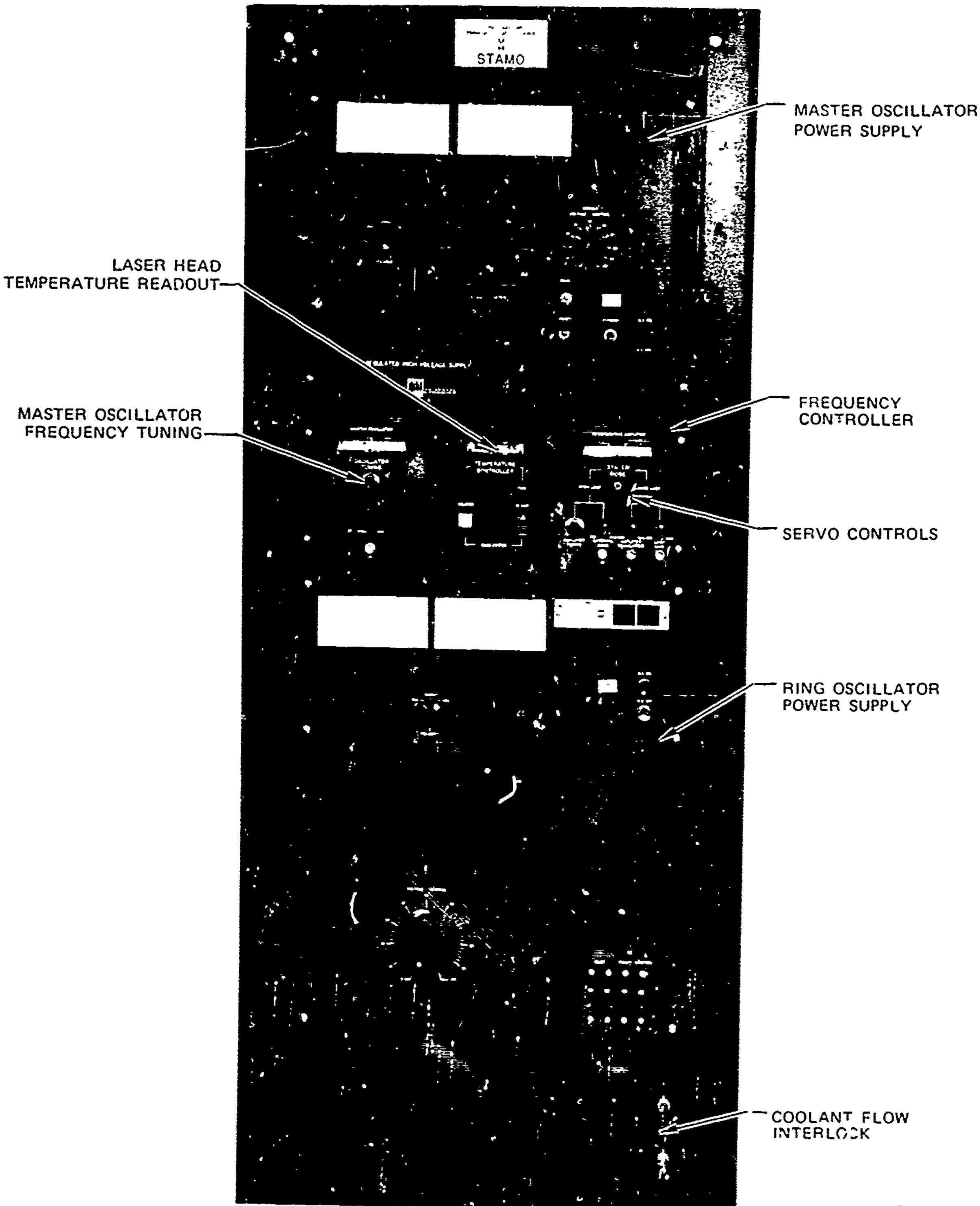


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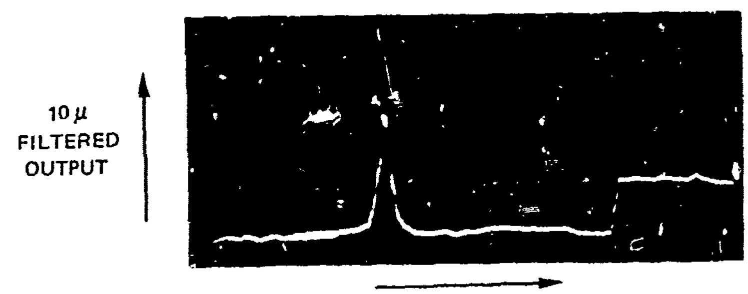
FIG. 12

INJECTION LOCKING RANGE

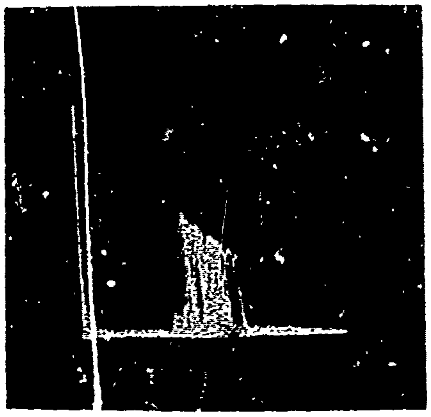


$\Delta\nu_L \approx 2$ MHz

STAMO HETERODYNE FREQUENCY STABILITY MEASUREMENT

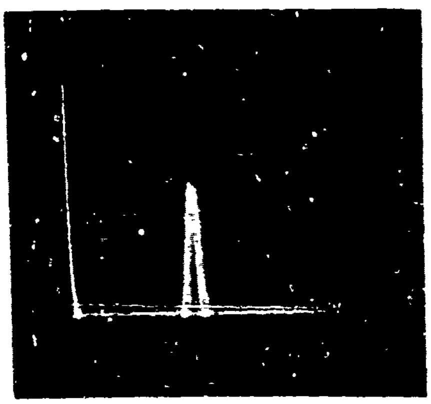
30 sec EXPOSURES

1 MHz/div ——→



a) FREE-RUNNING (OPEN LOOP)

1 MHz/div ——→



b) INJECTION–LOCKED (CLOSED LOOP)