STABILIZED CW LASER SYSTEM FOR THE GENERATION OF SINGLE-FREQUENCY LIGHT

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[redacted]

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FOREWORD

This report is the final engineering report summarizing the work performed under NASA Contract NAS8-20558 entitled "CW Laser System," covering the period 11 March 1967 to 11 April 1968. This report was prepared by the Electro-Optics Organization of Sylvania Electronic Systems - Western Division, Mountain View, California. Mr. Russell Targ and Mr. J. M. Yarborough were the principal investigators on this program. Mr. L. E. Wilson provided expert technical assistance in both the design and evaluation of the final laser system, and Mr. J. M. French designed the electronics used in the frequency stabilization system.

All work performed under this contract was administered by the Astrionics Laboratory, NASA George C. Marshall Space Flight Center, Huntsville, Alabama. Mr. Peter Marrero is the principal technical representative for the Laboratory.

ABSTRACT

This final engineering report summarizes the results of the second phase of a research, design, and development program which has resulted in the delivery of a frequency-stabilized argon FM laser. In the first phase of this program, we obtained 150 mW of single-frequency power at 5145Å, using the supermode technique with the argon FM laser. This second phase was devoted to the development of an automatic frequency control system to stabilize the frequency of the FM laser with respect to the center of the 5145Å fluorescence line. Using this control system we have achieved a frequency stability of approximately one part in 10^8 on a long-term basis, with automatic acquisition of lock. An outstanding benefit of this frequency stabilization is that the axial mode beats of the FM laser are very much suppressed with respect to the beats of the free-running laser. In addition to the suppression of the axial mode beats, the laser is quieted by the elimination of the low-frequency intensity fluctuations associated with mode competition and mode pulling. In normal multimode lasers this source of noise predominates at low frequencies and is much in excess of shot noise.

In our experiments with the stabilized FM laser, we found that the axial mode beats up to 1 GHz are suppressed by 30 dB. Further, we observe a 20 dB reduction in the noise due to mode competition over the DC to 300 kHz frequency range. This stabilized FM laser provides a greatly improved source for use in laser tracking, doppler radar, and communications systems, and makes possible long-range heterodyning or homodyning.

The argon FM laser used in this work is an r-f pumped ring-discharge laser, 120 cm long. The frequency control electronics, modulators, and r-f matching circuitry are packaged in the laser head, with the power supplies forming a second chassis.

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I. OBJECTIVE

The objective of this program was the design, development, and delivery of a CW laser system with output in the S-20 photocathode response region. The unique features of this system are the absolute frequency stabilization of its output with respect to the center of the fluorescence line at 5145Å and the suppression of the axial mode beats of the laser, giving a detected r-f spectrum free of excess noise extending up to 1100 MHz.

II. INTRODUCTION AND SUMMARY

The argon ion laser is attractive for a wide variety of communication, radar, and holographic applications. This attractiveness is due to its high CW power output and its operation in the blue-green portion of the optical spectrum, where both photocathodes and film have substantial sensitivity. A multi-axial-mode free-running argon laser, however, has neither the amplitude stability nor the frequency stability required for really satisfactory performance in these applications. In communication applications the excess AM noise due to mode-competition and mode-pulling effects, as well as the presence of several axial modes, so clutters the laser's output spectrum as to reduce its usefulness drastically. In holographic applications one would like to have a laser with a coherence length of several meters, but the 5-GHz oscillating linewidth of an argon laser gives a very much smaller coherence length. We have been able to improve the coherence properties of the argon laser substantially by means of an internal phase modulator which locks the axial modes of the laser with FM phases and allows stabilization of the laser with respect to the center of the atomic gain profile.

In a high-power argon laser, a great number of axial modes tend to oscillate simultaneously. However, because of the 600-MHz homogeneous linewidth in argon, adjacent axial modes (typically separated by 150 MHz) compete considerably for the same inverted atomic population. This competition results in the intermittent and non-simultaneous oscillation of nearest-neighbor modes[1], and the generation of low-frequency AM noise[2]. When the optical signal is detected, r-f beats are produced by the mixing of the axial modes, and these beats, too, are broadened by the competition. Locking the modes together eliminates the effects of this competition and suppresses the low-frequency noise at each of the axial mode beats. Further, many beats can be eliminated altogether by locking the modes in an FM fashion at some multiple (nc/2L) of the axial mode interval.

By locking the modes of the argon laser and stabilizing its frequency to one part in 10^8, we have suppressed the axial mode beats by 30 dB to 1100 MHz and have reduced the low-frequency noise (bandwidth 300 kHz) by 20 dB. To increase the laser's coherence length, we have converted its output to a single frequency via the supermode technique[3]. A monochromatic stabilized output, of course, corresponds to a very great coherence length.

In the sections that follow, we describe the stabilization and quieting we have achieved. In Section III we describe the various types of noise suppression we obtain from stabilized FM operation of the laser. In Section IV we briefly discuss the construction of the argon FM laser used in this work. A detailed description of this laser was given in last year's Final Engineering Report, "CW Laser System for the Generation of Single-Frequency Light," prepared under this same contract[4]. Section IV also describes the origin of the FM discriminant used to stabilize the laser, together with the design considerations and performance of the frequency stabilization system. Section V presents information on the use of the supermode laser in holographic applications.

III. NOISE REDUCTION FOR COMMUNICATION AND RADAR APPLICATIONS

A. INTRODUCTION

The two dominant sources of noise in the argon laser are the axial mode beats and noise due to mode competition. Both of these sources generate noise power 20 to 40 dB above shot noise. One would, of course, like to have a system designed so that the dominant noise source is shot noise from the incoming signal.

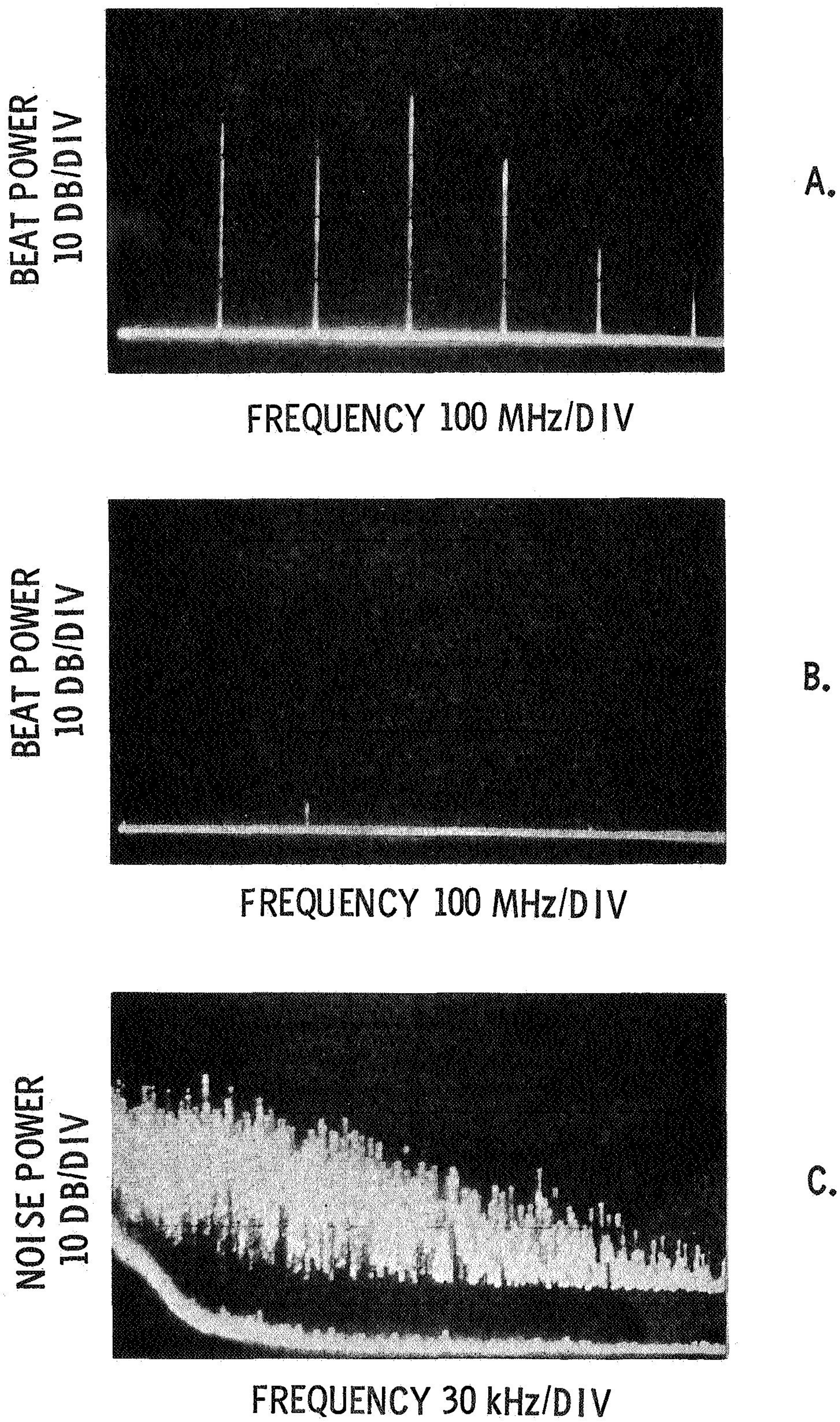
B. AXIAL MODE BEATS

A laser with a one-meter mirror separation will have axial mode beats occurring every 150 MHz, up to a frequency approximately equal to its total oscillating linewidth. In an optical communications receiver these beat signals are in general large compared with the incoming signal modulation, and thus have to be filtered out. The beats also limit the bandwidth that one can use in a broadband system. The free-running axial mode beats are shown in Figure 1a. In this broadband spectrum analyzer display, beats are seen from 150 MHz to 900 MHz. In Figure 1b, we have the same laser power, but the modes have been locked in an FM fashion at 3c/2L. The internal phase modulator driven at 3c/2L = 450 MHz is able to quench two out of every three modes because of the 600 MHz of the homogeneous linewidth in argon[5]. This results in the suppression of all axial mode beats up to 900 MHz. The beats at 150, 300, 600, and 750 are entirely suppressed because no modes are oscillating with these axial mode separations[3]. Further, as explained below, the beat at 450 MHz is suppressed by 30 dB due to the frequency stabilization. The suppression of axial mode beats, as shown in Figure 1b, was one of the main objectives of this program.

C. MODE-COMPETITION NOISE*

Another advantage of locking the modes is the reduction of low-frequency noise due to mode competition[2]. In the free-running laser, modes are able to

*The investigation of techniques for the suppression of low-frequency noise and off-axis modes was supported by the Sylvania Independent Research and Development Program, and made use of the laser developed on this NASA contract.



1. Laser Noise Suppression. 1a. Axial mode beats to 1100 MHz for a free-running laser. 1b. Beat suppression resulting from FM laser operation, with the same output power as in 1a. 1c. Low frequency laser noise, before and after coupling the laser modes. Lower trace showing quieting, has been offset 10 DB for clarity.

oscillate with time-varying relative phases and amplitudes. These modes, separated by c/2L, compete for the same inverted population within the 600 MHz homogeneous linewidth. This competition produces the excess low-frequency noise shown in Figure 1c. The upper trace in this spectrum analyzer display shows the low-frequency noise of a free-running argon laser from DC to 300 kHz. We have perhaps 20 modes oscillating here. The lower trace, offset by 10 dB, shows the 20 dB of quieting achieved by locking the laser modes with the intra-cavity modulator.

The spectrum analyzer sweep speed was 1/30 second, and the exposure time of the photographs was approximately 1/10 second. In both cases the residual noise is essentially indistinguishable from the shot noise, and noise suppression of 20 dB is typical. As long as a single mode-locked spectrum was observed, the suppression was unaffected by the strength and frequency of the internal phase modulation (c/2L, 2c/2L, and 3c/2L) and was also unaffected by the detuning of the modulation frequency required to achieve FM laser operation.

D. SUPPRESSION OF OFF-AXIS MODES

In addition to quieting amplitude noise fluctuations due to mode competition, the mode coupling was also observed to suppress oscillations in off-axis modes (higher order transverse modes). It is well known that in the free-running laser, all modes do not necessarily oscillate simultaneously[1]. We hypothesize that in the usual free-running case, the temporary absence of a given axial mode may allow the emergence of an otherwise below-threshold off-axis mode. Since the axial and off-axis modes share, to some extent, the same inverted population, we can quench the off-axis modes by any mode coupling technique that eliminates competition and guarantees that all of the axial modes oscillate all of the time.

We observed the transverse mode pattern and saw that the off-axis modes were suppressed by the mode locking. In order to determine that the loss generated by the phase modulation was not by itself reducing the off-axis modes below threshold, we introduced an equivalent loss into the cavity and observed that the off-axis modes continued to oscillate. The loss due to the modulator may help to put the off-axis modes below threshold, but mode competition appears to be the primary reason for their suppression in phase-locked and FM operation.

The effect of this mode locking is shown in Figure 2. In Figure 2a we have the beat spectrum of a free-running 50 mW He-Ne laser with c/2L = 75 MHz and with off-axis modes displaced from the axial modes by 15 MHz. In the right-hand portion of the figure, we have locked the axial modes and suppressed the beats with the off-axis modes by 30 dB. Figure 2b shows the beat spectrum of a 300 mW argon laser with off-axis modes, before and after mode locking.

In the mode-locked case there can be no noise due to the combination tones (beats between unequally spaced axial modes)[6], since for both FM and phase-locked operation the modes are equally spaced; each combination tone coincides with a mode and cannot be distinguished from it. Moreover, mode competition is eliminated, the relative phases of the modes are no longer random, and the mode separations are fixed and equal, so there are no more random mode pullings and gross amplitude fluctuations of the individual modes. Of course, some residual noise may still remain after mode locking has been achieved, due to various random fluctuations in the laser elements, as well as to spontaneous emission into the individual modes.

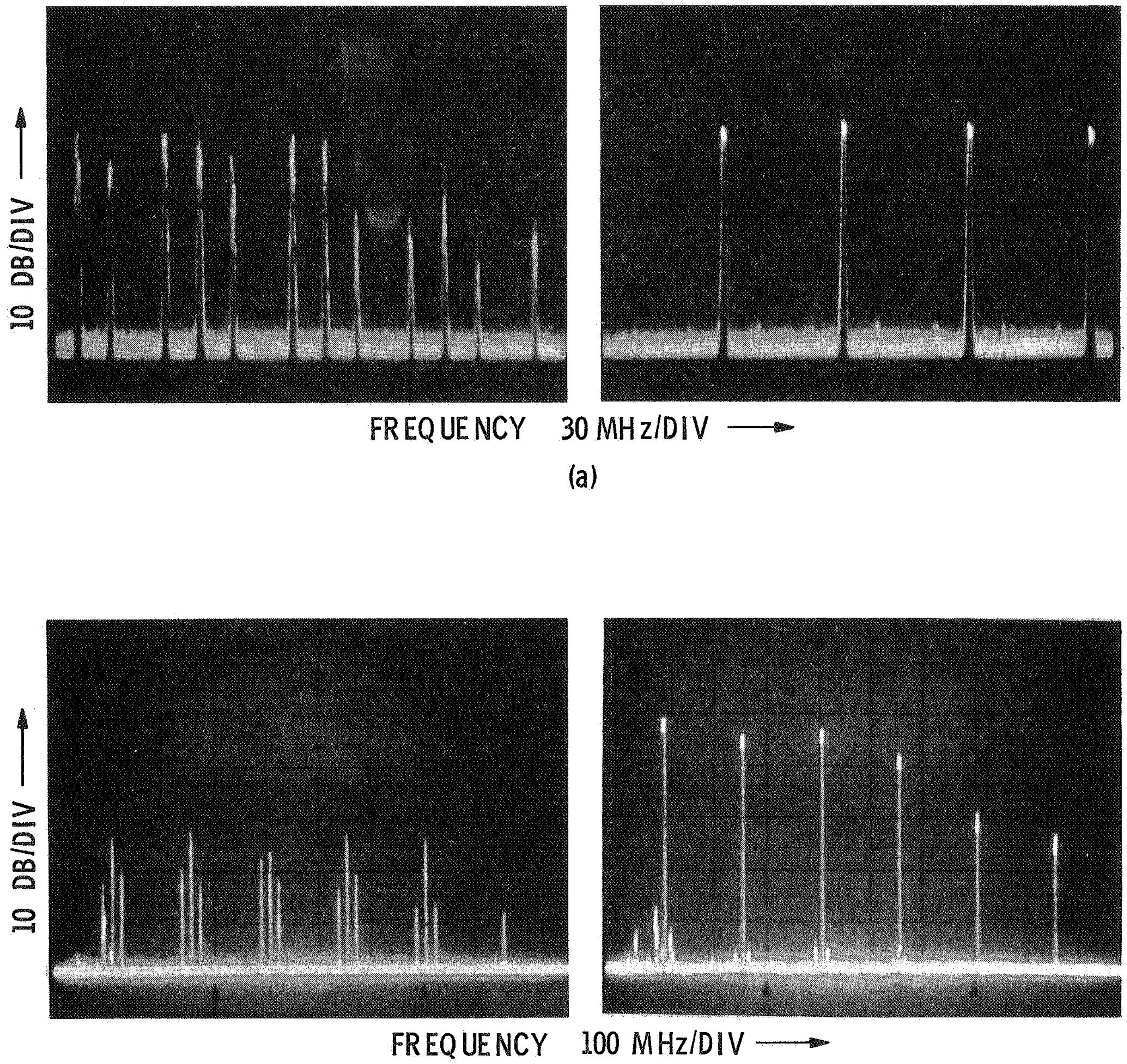


FIG. 2

BEAT SPECTRUM OF LASERS WITH OFF AXIS MODES BEFORE AND AFTER MODE-LOCKING. (a) He-Ne; (b) ARGON.

IV. THE FREQUENCY-STABILIZED LASER

A. INTRODUCTION

In this section we present the design criteria and results obtained with the frequency-stabilized laser system. We first outline the construction of the r-f excited FM laser. An explanation of the FM discriminant is then given, followed by a detailed discussion of the servo-control system. Finally, we present and discuss data taken using the completed frequency-stabilization system.

B. THE ARGON FM LASER

In this section we describe the argon laser and the stabilization system used in the experiments described above. The laser is an r-f-excited, ring-discharge laser[7]. A photograph of the laser, together with its stabilization electronics, is shown in Figure 3. As can be seen, the laser, modulators, r-f matching circuitry, and stabilization electronics are contained in a single package. Laser excitation is provided by an external 5 kW r-f power supply, and both the plasma tube and laser base plate are water cooled.

The discharge length is 40 cm, and the laser is capable of 800 mW at 5145Å with a 4% transmitting mirror at one end and with no intra-cavity modulator. The intra-cavity phase modulator consists of a 4 cm long x 4 mm square crystal of 45^{o} Z-cut KDP[8]. Insertion of the modulator crystal with its measured single-pass loss of 1.5% into the cavity decreased the power of the laser to 350 mW at 5145Å. Driving the modulator so as to produce the desired FM output effected no further power loss.

Driving the modulator at a frequency slightly detuned from the axial mode spacing (c/2L) results in extremely large FM laser modulation indices ($\Gamma \approx 15$) at the gains of interest in argon. At these large Γ's, the FM laser output is quite highly distorted and typically non-quenched (i.e., more than one FM oscillation exists simultaneously). However, a low distortion, quenched FM output with a reasonably low modulation index can be achieved by driving the intra-cavity modulator at a frequency slightly detuned from

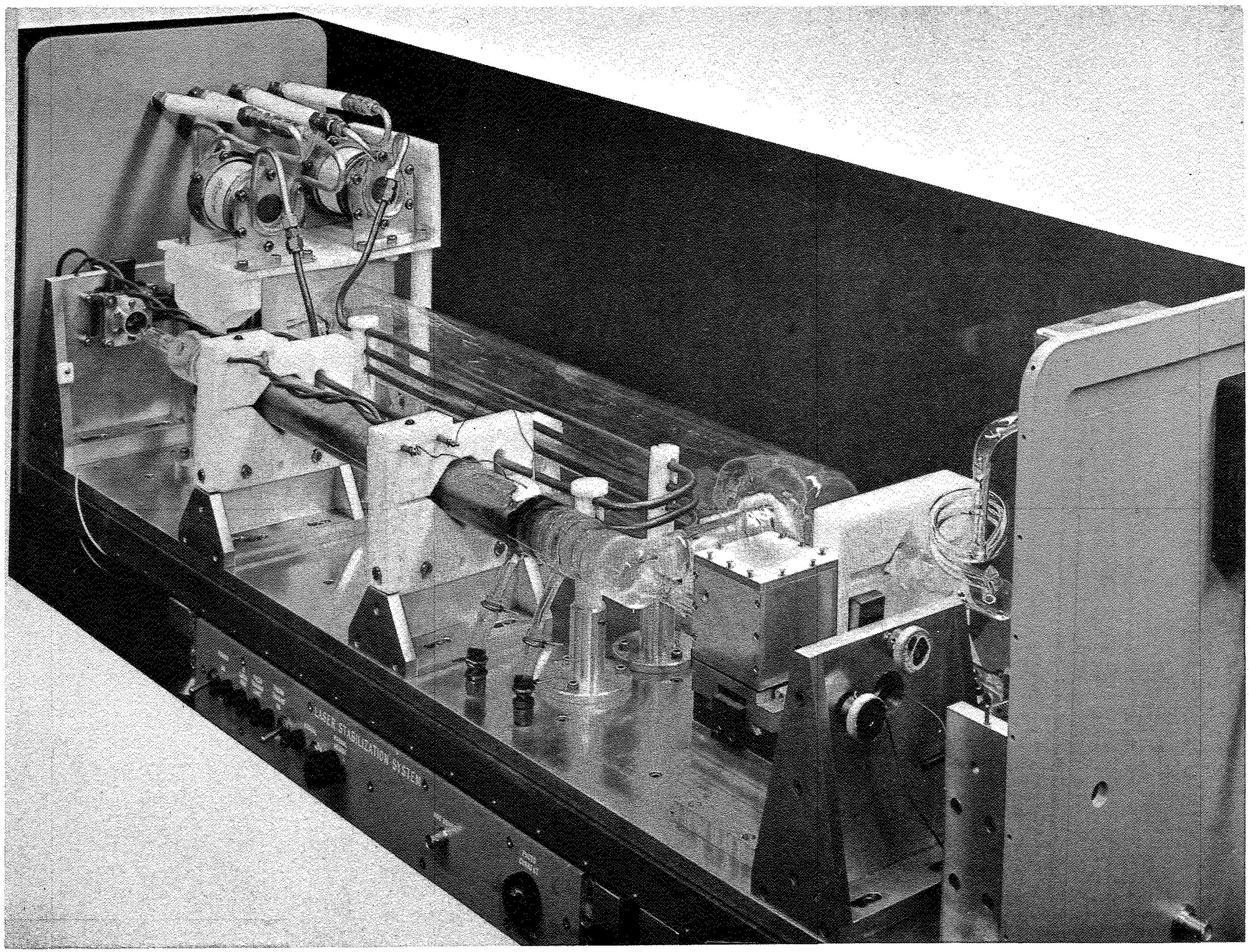


Figure 3. Photograph of Argon Laser, Showing RF-excited, Ring-Discharge Internal Phase Modulator and Control Electronics for Stabilization.

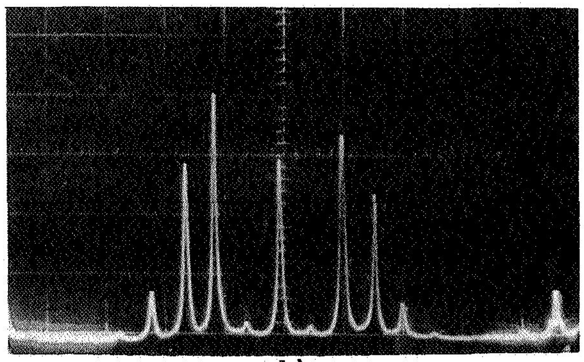
3c/2L (3c/2L for this laser is 467 MHz). In this case the pressure-broadened homogeneous linewidth of argon is sufficient to prevent the simultaneous oscillation of two FM signals with their modes interspersed. The optical spectrum typical of the stabilized FM laser is shown in Figure 4a. Figures 4b and 4c show the spectra of the laser when it is phase-locked at c/2L and 3c/2L, respectively. Figure 4d shows the single-frequency output obtained using the supermode technique. Most of the baseline clutter is due to off-axis modes in the scanning Fabry-Perot interferometer, rather than to residual sidebands.

C. THE FM DISCRIMINANT

As a result of the FM process, the relative amplitudes, frequencies, and phases of the FM laser's spectral components are substantially controlled. However, the entire FM spectrum is free to drift over a range of frequencies at least equal to the axial mode interval of the laser. The control system allows us to absolutely stabilize the frequency of the FM carrier with respect to the center frequency of the doppler-broadened laser gain curve.

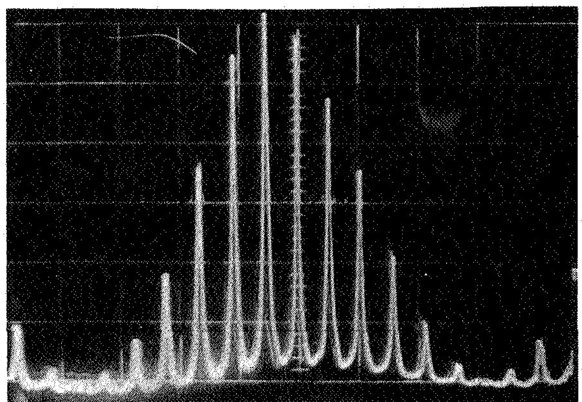
If the FM laser spectral make-up were a perfect, undistorted FM signal, there would be no beat frequencies (between nearest-neighbor modes) present when the laser output is detected. From the theory[9] and from experiments[10] we have performed with the FM laser, it is clear that there is some harmonic distortion in the FM laser spectrum, and this distortion gives rise to a small beat signal in the detected laser signal. The amplitude and phase of this residual beat is a function of the harmonic distortion resulting from shifts in the center of the FM spectrum with respect to the fluorescence line of the laser. Therefore, if the frequency and modulation index of the intra-cavity phase perturbation are held constant along with the excess gain of the laser, then the frequency of the laser can be controlled by holding the amplitude and phase of the harmonic distortion constant, preferably a minimum.

The magnitude of the distortion in the FM signal depends on the difference between the saturation amplitude of each given mode and the amplitude required for the specific FM signal. However, if the center of the FM spectrum drifts with respect to the center of the gain curve, amplitudes and phases will be



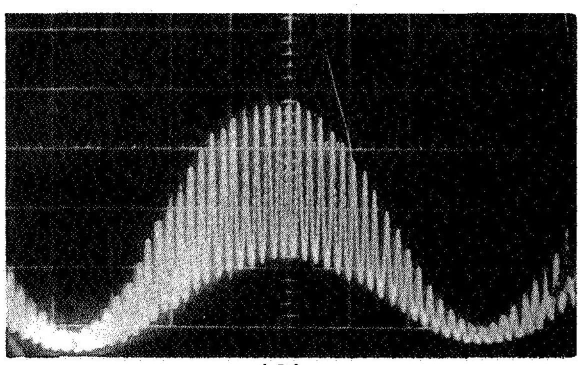
(A)

FM LASER WITH $\Gamma = 3.8$
$\nu_m \simeq 3\, c/2L$



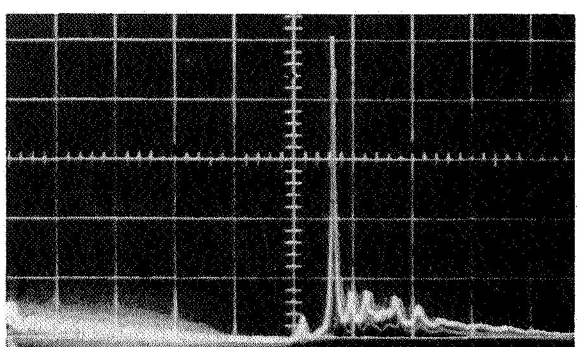
(B)

PHASE-LOCKED LASER
$\nu_m = 3c/2L$



(C)

PHASE-LOCKED LASER
$\nu_m = c/2L = 150$ MHz



(D)

SUPERMODE OUTPUT
OBTAINED FROM A

OPTICAL SPECTRA OF AN FM AND PHASE-LOCKED ARGON LASER AT 5145Å INTERFEROMETER FREE SPECTRAL RANGE = 5.6 GHz.

different for the corresponding pairs of FM sidebands, i.e., those whose undistorted amplitudes would be $J_{+n}(\Gamma)$ and $J_{-n}(\Gamma)$. Only when all the FM sidebands are symmetrically placed with respect to line center will all the odd harmonic beats between the FM sidebands add to zero. Odd harmonic beats from the FM sidebands above the center, or carrier, frequency of the FM oscillation will be exactly cancelled by the contributions from the sidebands below the center frequency of the oscillation. Cancellation will occur when we have 180^o phase difference between the beats from corresponding pairs of modes. When the FM carrier mode shifts from line center due to a change in the laser cavity length, cancellation will not be complete, and a detector will be able to detect an odd harmonic beat whose phase is related to the direction of frequency shift with respect to line center. The effect of this shift is shown schematically in Figure 5.

When the FM carrier drifts from line center, both the mode amplitudes and phases are no longer symmetrical about the FM carrier. Consequently, the beat of J_0 and J_1 are no longer equal to, or exactly out of phase with, the beat of J_0 and J_{-1}. Similarly, the beat of J_1 and J_2 is no longer equal to, or exactly out of phase with, the beat of J_{-1} and J_{-2}, and so on.

Thus, the amplitude of the beat note (arising from AM distortion of the FM laser output) at the intermode separation frequency is proportional to the extent of deviation from line center, and its r-f phase shifts by 180^o as the carrier mode crosses the center of the gain profile. This phase shift of the detected beat signal allows the beat to be used as a discriminant to frequency stabilize the FM laser without need for any "dither" signal, since the beat contains both the necessary amplitude and phase information.

A typical discriminant based on this principle is shown in Figure 6. To obtain this oscilloscope trace, one of the mirrors of the FM laser is driven through an optical half wave, by the same sawtooth voltage that drives the oscilloscope sweep. The abscissa corresponds to one axial mode interval of the laser cavity, $c/2L = 150$ MHz. The ordinate is proportional to the log of

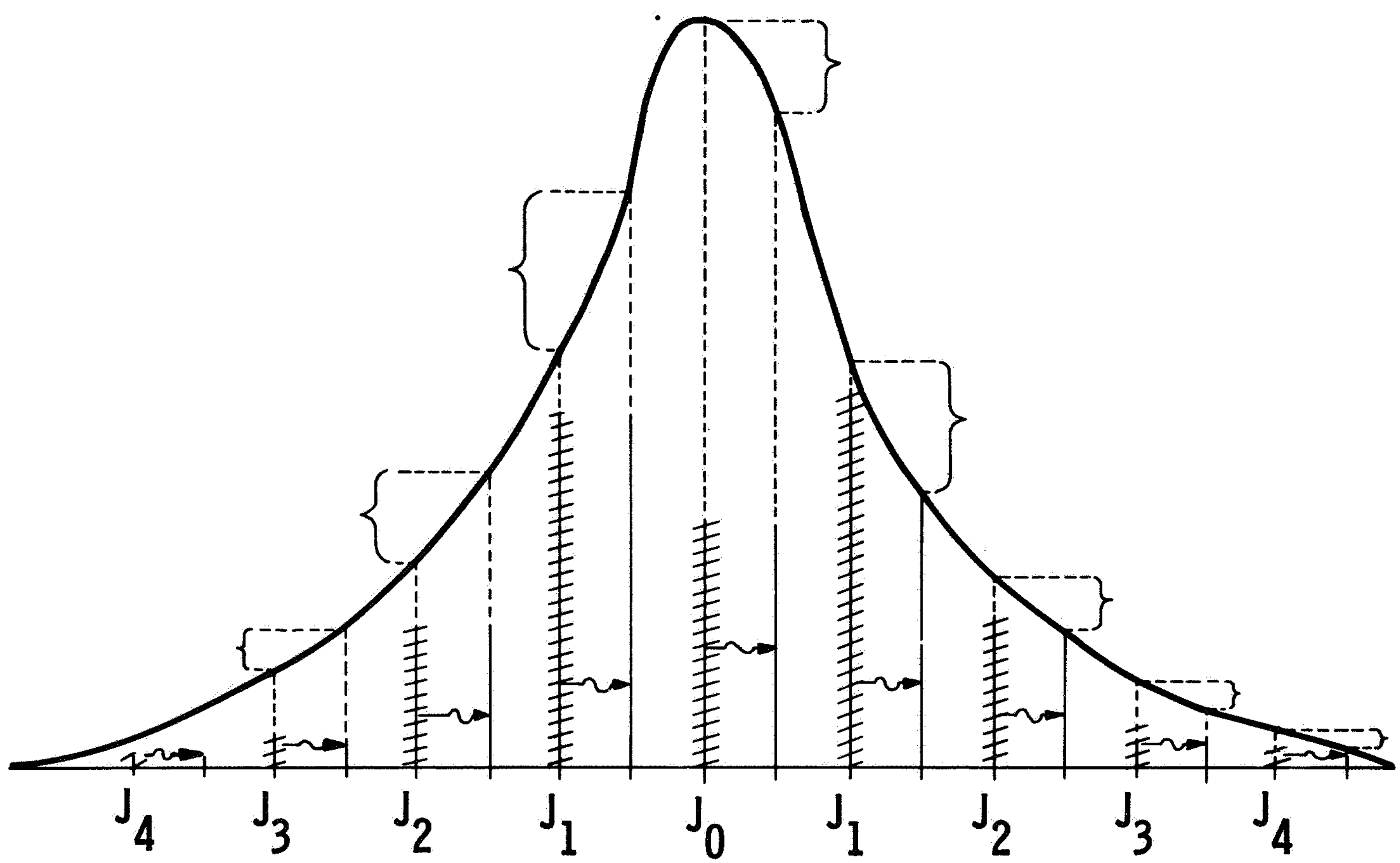


Figure 5. FM Spectrum at Line Center, and After Drifting to the Right by Half an Axial Mode Spacing.

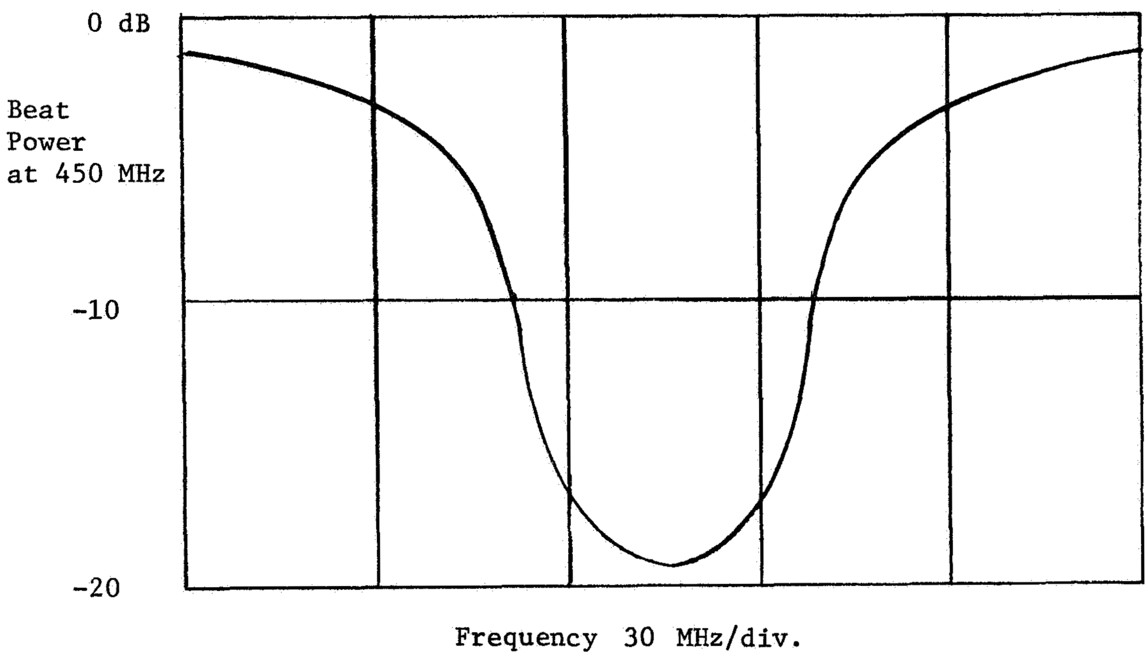


Figure 6. FM Discriminant, Showing Power in the First FM Beat as a Function of Frequency Difference Between the FM Carrier and Line Center. Modulation frequency is at 3c/2L.

the beat power at 450 MHz = 3c/2L. The figure shows that as the laser mirror is moved, the maximum beat power is at least 20 dB above the noise level of the receiver. The receiver used to make this observation is a Hewlett-Packard microwave spectrum analyzer. This instrument was chosen because of its logarithmic amplifier and tunable passband. However, its sensitivity is 15 dB less than the narrow-band detector within our stabilization system (to be shown in the next section).

At a point where the discriminant falls to within 3 dB of the spectrum-analyzer noise, it has a width of about 15 MHz. Since the amplitude of the discriminant is linearly proportional to the frequency deviation from line center, we believe that the 15 dB additional sensitivity of the stabilization system will allow control of the laser frequency to within 1 to 2 MHz, as was achieved using a similar system for the stabilization of a He-Ne laser[10].

D. DESIGN OF THE STABILIZATION SYSTEM

The primary function of the stabilization system is to position the mirrors at either end of the laser cavity so that the mirror separation is independent of thermal and acoustical fluctuations. This condition is achieved by splitting a small portion of the laser output (10 microwatts) and directing it upon a photodiode, as shown in Figure 7. The narrow-band preamplifier centered at 3c/2L = 467 MHz then amplifies this signal by 26 dB with an 8 dB noise figure. The noise figure of the control loop is thus established, and the detected signal has sufficient power to be down-converted to 1 MHz in the mixer. It is then passed onto the 1 MHz IF amplifier where the bulk of the system loop gain is realized. The bandpass characteristics of the 400 kHz bandwidth IF amplifier are important in that any phase or amplitude distortion in the detected signal will cause instabilities in the loop compensation system. It was for this reason that a "maximumly flat" characteristic was chosen.

The output of the IF amplifier is compared with a 1 MHz standard oscillator which yields the phase information as to which direction the piezoelectric transducer must move in order to compensate for any fluctuations in cavity length. The amplitude of this error signal determines the rate of compensation.

An integrator is used between the phase-sensitive detector and the control elements, to convert the entire loop to a first-order system with no net DC positional error.

In order for the system to function correctly, three sinusoidal drive signals are required. The first signal is the 467 MHz modulator drive signal. This signal is supplied to a power amplifier which provides one to three watts of power to the KDP phase modulator used to couple laser modes.

Since the change in phase of the 467 MHz beat signal from the FM laser produces the discriminant which operates the entire loop, we must find a way to heterodyne the detected signal down to a lower frequency and yet preserve all the phase information. This heterodyning is accomplished by phase-locking the 466-MHz voltage-controlled local oscillator to the 467-MHz modulator driver via a 1 MHz standard oscillator. This then means that no matter what precise frequency to which the modulator driver is tuned, we will have a local oscillator signal which is offset by 1 MHz, and the difference between these is precisely fixed in phase with respect to the 1 MHz standard. Therefore, as the optical cavity drifts thermally or acoustically, the change in phase of the 467 MHz beat signal will be detected by the preamp and IF, and will then form the discriminant in the phase detector.

As a result of the phase information inherent in the FM discriminant, the error signal is always of the correct sign. Thus the system acquires lock automatically; and if lock should be lost, it is re-established without manual intervention.

The block diagram as shown is, of course, abbreviated. Located throughout the loop are numerous buffer amplifiers. The main loop integrator has the capability of being converted to a DC positional amplifier with a manually-controlled offset. This enables the operator to manually position the laser mirror and investigate the nature of the FM discriminant without the action of the control loop.

One of the problems inherent in the stabilization of lasers is that the amount of thermal expansion in the laser cavity can be many optical half-wavelengths. The piezoelectric transducer, however, can move through only two or three half-wavelengths with maximum voltage applied. In order to compensate for the slow thermal drifts in the length of the laser cavity, a thermal transducer was placed behind one of the laser mirrors as shown in Figure 6. This transducer is simply an aluminum spool wound with heating wire. When the voltage applied to the piezoelectric transducer begins to exceed the designated range, the transducer amplifier drives current into the heating element, which in turn compensates for expansion and contraction of the laser cavity. This also has the effect of keeping the integrator DC level at a constant level of about 100 volts. The thermal transducer can move the laser mirror through 80 half-wavelengths, and it has a time constant of about 5 seconds. The water flow through the base plate of the laser is adjusted to reduce its thermal drift in order to keep the current levels in the transducer at reasonable levels.

E. OPERATION OF THE STABILIZATION SYSTEM

We verified the operation of the stabilization system by simultaneously recording the magnitude of the residual axial mode beat, and the voltage applied to the piezo-electrically controlled mirror. The theory of the FM discriminant tells us that the detected power in the axial mode beat note is linearly proportional to the FM spectrum's deviation from line center.

The magnitude of the r-f beat at 467 MHz is displayed on a logarithmic scale in the upper trace in Figure 8. The reference level for the unstabilized laser is shown at the left (the loop was disconnected momentarily), and the suppression is seen to be about 30 dB. This suppression, of course, means that the FM spectrum is being held close to the center of the atomic line.

The operation of the thermal transducer is verified by the lower trace in Figure 8, which is a strip chart recording of the voltage applied to the piezo-electric transducer. It is seen that the DC level of the transducer is free of any net drift.

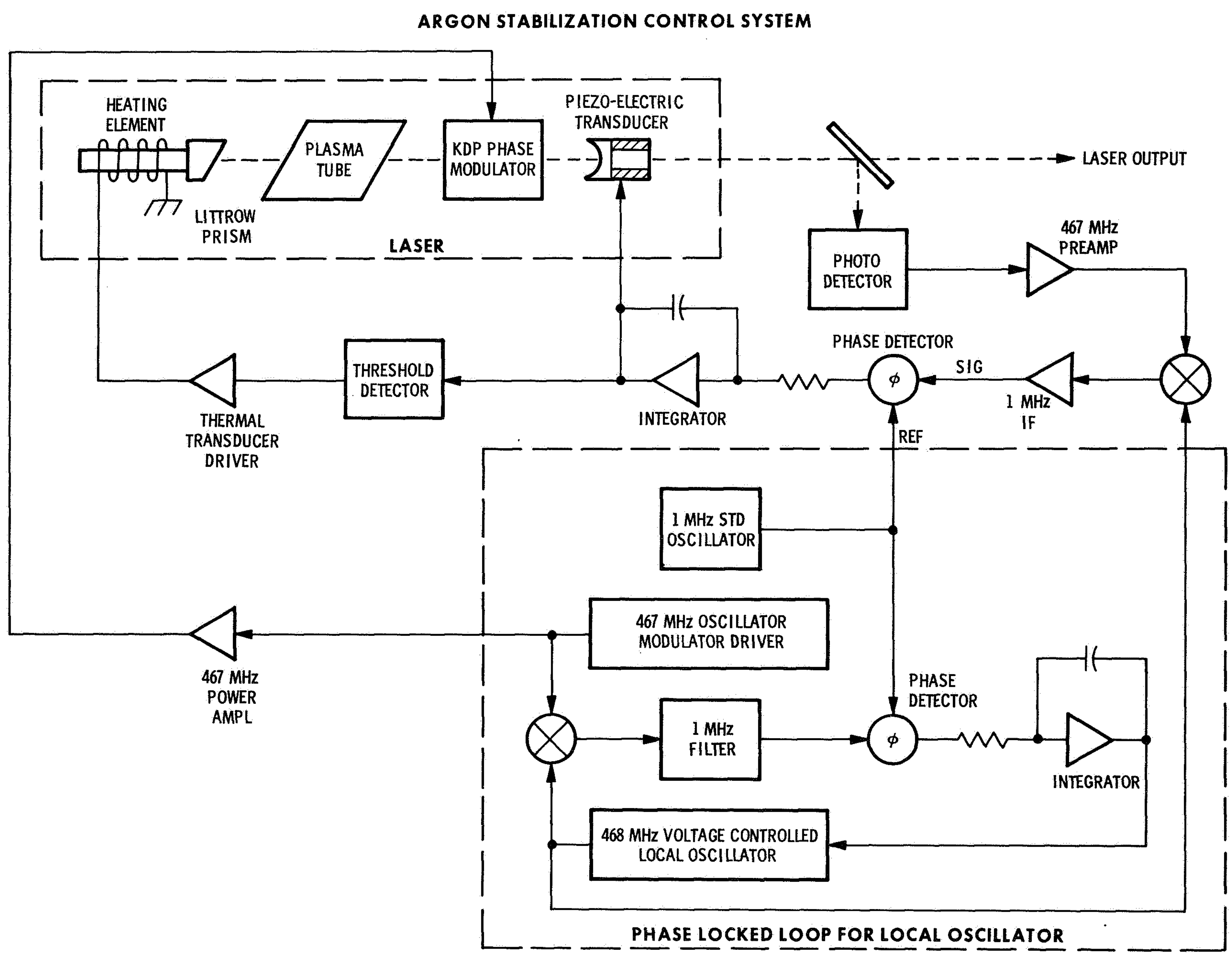


Figure 7. Block Diagram of the Stabilization System.

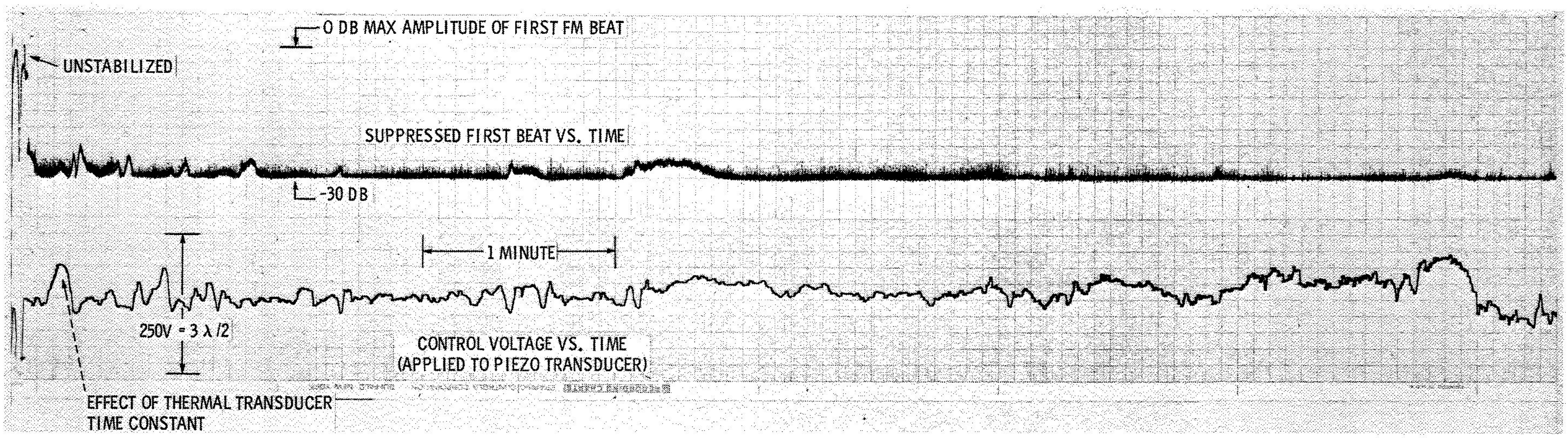


Figure 8. Five-Minute Excerpt from Data Showing Beat Note Suppression and Control Voltages Using the FM Stabilization System.

The time constant of the thermal transducer is shown graphically at the left end of the lower trace. When the system is first locked, the thermal transducer has no current passing through it. This is the case until the piezoelectric transducer voltage crosses a pre-set threshold (about one-third of the maximum permitted voltage). At that time the temperature of the thermal transducer is increased until its expansion sufficiently compensates for the laser drift to allow the voltage on the piezoelectric transducer to fall below the specified value. This operation is clearly shown. The control voltage rises monotonically until it reaches a threshold value, at which time the thermal transducer begins to heat and return the control voltage to its desired control range. This full sequence is seen to take about eight seconds.

Unfortunately, we did not have a second stable single-frequency source at 5145Å to heterodyne with our laser to determine its actual stability[10]. However, we know that a half-wave motion of the piezo-mounted laser mirror will cause a frequency shift of 150 MHz. In such a translation of the mirror, the beat signal is seen to pass through its minimum value. We observe that a displacement of the mirror corresponding to only a few MHz is sufficient to cause the beat signal to rise above its -30 dB value, and we take this measurement as indicative of the stabilization we have achieved.

V. LONG-COHERENCE HOLOGRAPHIC SOURCE

A. COHERENCE LENGTH DEFINITION

In holography, the total available field of view is dependent on the correlation of light scattered from one point in the object to light scattered from another point a distance ℓ away. With a multimode, unstabilized laser, if the time delay, $\tau = \ell/c$, between two points is too great, the two object waves do not interfere with the reference wave in a like manner, and the two points cannot be recorded on the same hologram. There are many formulations for the coherence properties of a light source. One of these which seems particularly relevant to holography is the description of optical coherence in terms of the visibility of the interference fringes produced by mixing portions of the optical signal having experienced different time delays in reaching the point where interference takes place[11].

If light from a multimode laser is introduced into an equal-arm Michelson interferometer, one will observe sharp interference fringes. The visibility of the fringes is defined as:

$$|R| = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where I_{max} and I_{min} are the maximum and minimum intensity.

This function is seen to go to unity when I_{min} goes to zero. As one of the mirrors of the Michelson interferometer is drawn away, causing the arms to be of unequal length, the fringes will be seen with reduced contrast. Mandel and Wolf[12] have defined a generally applicable criterion for coherence length as the difference in path length which will still give fringes whose visibility is greater than 0.88. This difference in path length ℓ is equivalent to the depth of field that one can obtain in a hologram taken with a laser of given coherence length.

B. COHERENCE LENGTH OF THE SUPERMODE LASER

An ideal single-frequency laser will produce sharp interference fringes for arbitrarily large fields of view, corresponding to an infinite coherence length. The coherence length of a laser with a large number of oscillating modes approaches $\ell = c/(4\,\Delta\nu)$, where c is the velocity of light and $\Delta\nu$ is the oscillating bandwidth of the laser. For an argon laser with 5 GHz linewidth, ℓ is approximately 1.5 cm. Because lasers produce an output of regularly-spaced frequencies separated by the axial mode interval $c/2L$, a region of coherence depth ℓ will be found at integral multiples of the laser length.

Single-frequency operation of the argon laser has been obtained with the supermode technique[3]. The supermode output is derived by first locking the modes of the laser to form the sidebands of an FM signal, and then passing this signal through an external modulator driven out of phase with the incoming signal. The resultant output is an FM signal with a modulation index $\Gamma = \Gamma_{\text{FM laser output}} - \Gamma_{\text{external modulator}}$. Hence, the supermode output is really an FM signal with a very low (preferably 0) modulation index. The power in the supermode output is not diminished by the FM or supermode processes.

For an FM laser, the mode amplitudes are given by $E_n = J_n(\Gamma)$ and the frequencies are given by $f_o + n\,\nu_m$, where J_n is the Bessel function of order n, f_o is the frequency of the FM carrier, and ν_m is the modulation frequency. Osterink[13] has derived an expression for the first order coherence function for this case. Here the fringe visibility $R_E(\tau)$ is given as a function of time delay τ in the field of view.

$$R_E(\tau) = J_o(2\Gamma \sin \pi\, \nu_m \tau) = J_o\left(2\Gamma \sin \pi \frac{\ell}{\lambda_m}\right)$$

For any $\Gamma \neq 0$ (non-zero FM sidebands), the coherence function exhibits ripples with a period $\ell = n\lambda_m$. However, the coherence function never falls below 0.88 unless $\Gamma > 0.352$. Consequently, using Mandel's definition of coherence length, an ideal FM laser with $\Gamma < 0.352$ would have an infinite coherence length. From our past experience, it is easy to limit the modulation index of the supermode output to less than 0.2 radian; hence, the supermode laser has the same coherence length as a single-frequency laser.

VI. CONCLUSION

As a result of FM-locking the modes of an argon laser, stabilizing its frequency, and converting the output to a single frequency, the potential of the argon laser has been greatly enhanced under this program.

A number of significant accomplishments have resulted from two years of research and development directed toward frequency stabilization and mode control of the argon laser. Some of the accomplishments resulting from work on this contract are outlined below.

1) An argon FM laser head has been built and packaged in a configuration with no dimension exceeding 120 cm, in accordance with NASA requirements.

2) This laser has been operated with an external $LiNbO_3$ phase modulator whose function was the demodulation of the FM light into a single frequency. 150 mW of single-frequency light has been obtained in this manner. (350 mW with a slightly longer tube)

3) The output of this laser has been frequency stabilized to one part in 10^8 by means of an active stabilization system. The frequency stabilization system uses both piezoelectric and thermal control elements to assure long-term frequency control, and automatic acquisition of system lock.

4) 30 dB of suppression of axial mode beats was obtained from DC to 1100 MHz, as a result of FM laser operation (as compared with the free-running laser).

5) 20 to 30 dB of quieting of DC to 300 kHz mode-competition noise was also obtained.

6) A substantial reduction in the amplitude of off-axis modes was an additional result of FM operation of the laser.

VII. RECOMMENDATIONS

We have found that both the He-Ne and the argon lasers have 20 to 30 dB excess low-frequency AM noise (above shot noise) when they are allowed to operate free-running. It is, of course, very desirable to eliminate these amplitude fluctuations from the laser output. In the course of this program, we have shown that the laser is quieted to approximately shot-noise levels by coupling the modes through the use of internal phase modulation. We have also shown that off-axis modes can be substantially suppressed by this technique.

This work had led us to ask a number of important questions that should be answered by future work in this area:

1) It would be advantageous to be able to quiet a laser without having to introduce a modulator into the laser cavity. We should therefore determine the answer to the question, can the same quieting be achieved with self-locking as with phase-locking?

2) Does self-locking suppress higher order transverse modes as phase-locking does?

3) What, in detail, are the parameters for self-locking of different types of lasers? Under what conditions can self-locking be obtained in argon and in Nd:YAG?

4) Second harmonic generation using Nd:YAG as a pump is of great interest because of the potential of providing a rugged, relatively efficient, watt-level green source. How do intensity fluctuations in the fundamental mirror themselves in the second-harmonic light? Is it a simple squaring process, or are more fundamental noise properties involved?

5) The residual noise (left after phase-locking) has not been experimentally studied. Is a phase-locked laser as quiet as a single-frequency laser, given equivalent cavities and output power? This would be the case if mode

competition accounted for all the noise removed by mode-locking, as we have previously suggested[2].

6) How does quieting (or noise) behave as a function of the number of modes running, the laser material, the cavity construction, the method of excitation, and the environmental conditions? Although some of these questions have been treated in detail for single-frequency lasers, a comprehensive study for the multimode laser should be made as well.

These are, it seems to us, questions of direct relevance to the use of relatively high power (and therefore multi-axial-mode) lasers in communications applications.

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