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NBS TECHNICAL NOTE 620

Frequency and Phase Stabilization of an HCN Laser by Locking to a Synthesized Reference

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Frequency and Phase Stabilization of an HCN Laser by Locking to a Synthesized Reference

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Frequency and Phase Stabilization of an HCN Laser by Locking to a Synthesized Reference

by

Joseph S. Wells and Donald Halford

Infrared frequencies as high as 88 THz have recently been synthesized using diode harmonic mixers with accuracies of parts in 10^9. Stabilized lasers are needed to make frequency measurements of higher accuracy. The HCN laser is the lowest frequency basis laser used in these synthesis schemes and its stabilization has been the subject of recent interest. The laser is stabilized by locking it to a phase locked microwave reference chain. Two servo loops are utilized. The first loop is a relatively slow frequency lock loop with the correction applied to a PZT driver. This loop not only accommodates thermal expansion of the laser, but also serves as an acquisition aiding loop for the second servo. The latter is a phase locked system with the correction applied to the laser discharge current.

Details of the laser design and some noise considerations relative to the microwave reference chain are presented along with some experimental data which indicate the results of the stabilization techniques. Data regarding the system stability and improved fast linewidth are included.

Key words: Fast linewidth; Frequency noise; HCN laser; Infrared frequency synthesis; Laser frequency measurements; Laser linewidth; Laser stabilization; Phase locked laser.

1. INTRODUCTION

The HCN laser is currently the basis laser of lowest frequency that has been used in infrared frequency synthesis (IFS) schemes.[1, 2, 3] The line of greatest interest (337 μm) can be made to oscillate in a 0.000 0070 - THz bandwidth centered at 0.890 761 THz. In order to improve the accuracy of subsequent laser frequency measurements in general and to ultimately increase the accuracy of the methane frequency measurement, it is necessary to stabilize the frequency of the HCN laser to a high degree. To date, workers at Martin Marietta have reported phase-locking the HCN laser to a microwave chain for short periods and obtaining beat note linewidths of less than 50 Hz.[4] The accuracy of the reference was not measured and could possibly be parts in 10^9. A group at NPL in Teddington, England, has recently stabilized the HCN laser to an absorption in difluoroethylene, and obtained a stability of 2.5 parts in 10^8.[5] This note describes the HCN frequency stabilization work at NBS, Boulder. In an effort to put all relevant information into a single document we have included more detail than would be warranted for an external publication.

The description of the technical work is divided into three main areas. The first area involves determining the optimum laser parameters, eliminating sources of frequency fluctuations from the laser, preparing the diode to obtain best signal to noise beat note, etc. The second and most difficult area is to obtain a microwave frequency reference that has the requisite stability in both long and short term. The third area involves active techniques, and includes devising the necessary servos to impose upon the laser the long and short term stability permitted by the reference. Two servo loops have been used simultaneously. A phase lock loop was used to obtain line narrowing, and a frequency lock loop served as an acquisition aiding loop for the phase lock. The frequency lock loop applies a mechanical correction to the laser cavity via a mirror on a piezo-electric translator (PZT). The phase lock loop applies a correction to the laser plasma discharge current. The phase lock was achieved with the aid of two different current controller combinations which we denote as controllers A and B. Since controller A was difficult to work with and required a third order loop to achieve phase lock, we will limit our description to controller B which can be easily duplicated.

2. LASER PARAMETERS

Figure 1 is a block diagram of a representative scheme used to measure the frequency of 337-μm line of the HCN laser. The master oscillator source for the frequency measurement is a stable quartz crystal oscillator. An X-band klystron is phase locked 30 MHz from

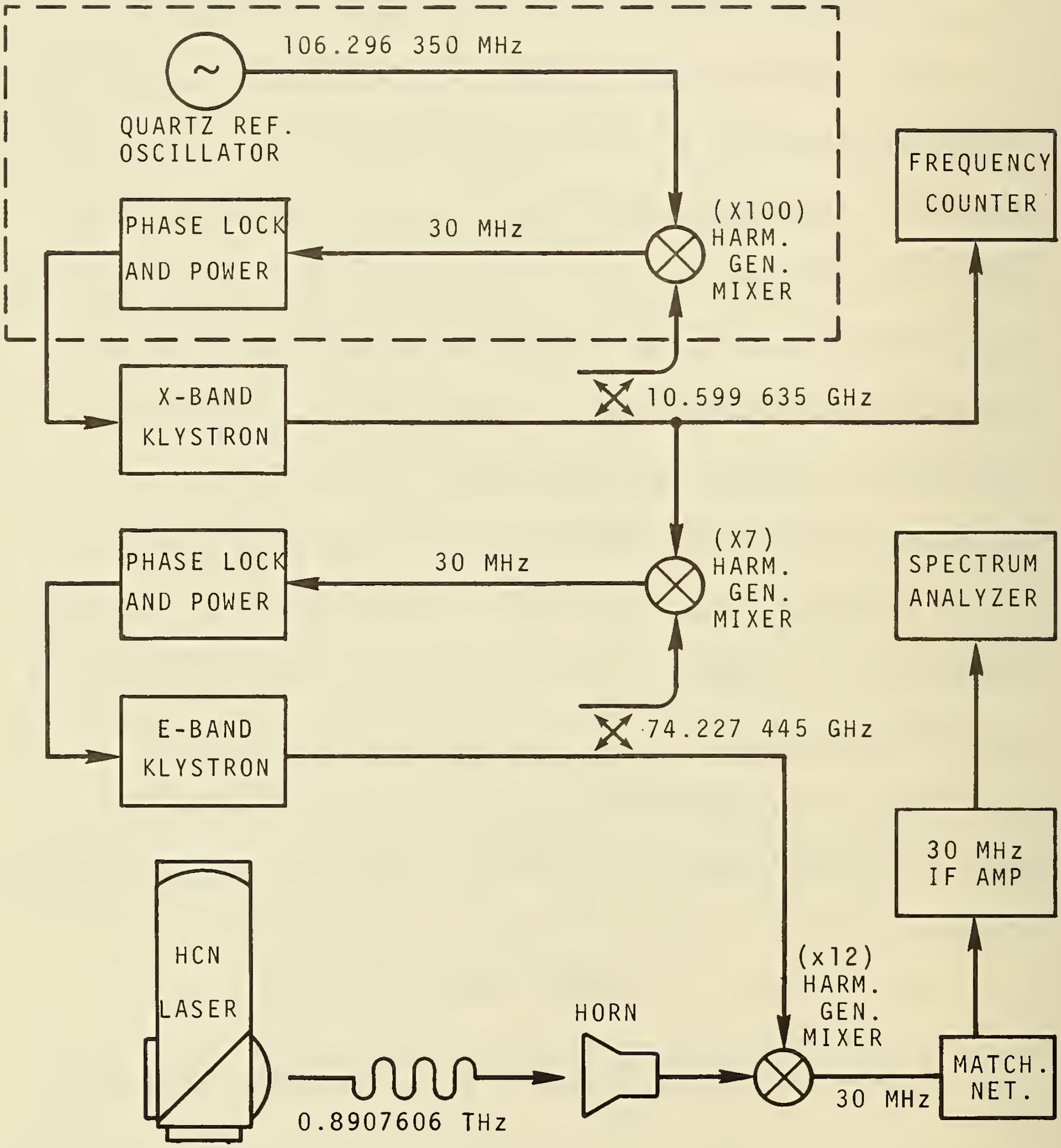


Figure 1. Block diagram of experimental scheme for an HCN laser frequency measurement.

the 100th harmonic of the quartz crystal oscillator. An E-band klystron is in turn phase-locked 30 MHz from the 7th harmonic of the X-band klystron. The output of the E-band klystron goes to a harmonic generator/mixer where its 12th harmonic is compared with the 891-GHz output of the HCN laser and the approximate 30-MHz frequency difference is measured on the RF power spectrum analyzer. In addition to measuring the frequency of the laser, this beat note can be utilized in frequency control. These various laser parameter adjustments are used to obtain the best signal to noise ratio for the beat note as seen on the spectrum analyzer. These techniques are applied to the components in the block diagram in Fig. 1.

A schematic drawing of the 0.1-m diameter, 4-m long folded confocal HCN laser with Michelson coupling output is shown in Fig. 2a.[6] Invar spacers are used to minimize thermal expansion and the high Young's Modulus reduces acoustically induced length fluctuations.[7] Both the laser and the klystrons are supported on an air piston isolation table to decouple the system from building vibrations at 30, 60, and 120 Hz. Without the isolation, the resulting 30-Hz frequency modulation has produced frequency deviations of the 891-GHz output as large as 100 kHz for one particularly unfavorable mounting arrangement. (This occurred when some normally inoperative

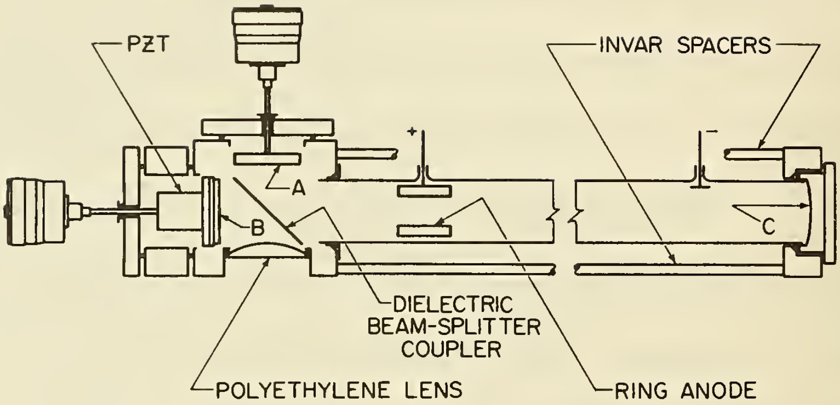


Figure 2.a. Schematic drawing of a frequency controllable HCN laser. The translatable mirror A may be replaced by a window to allow one output for frequency control and the other for synthesis to higher frequencies.

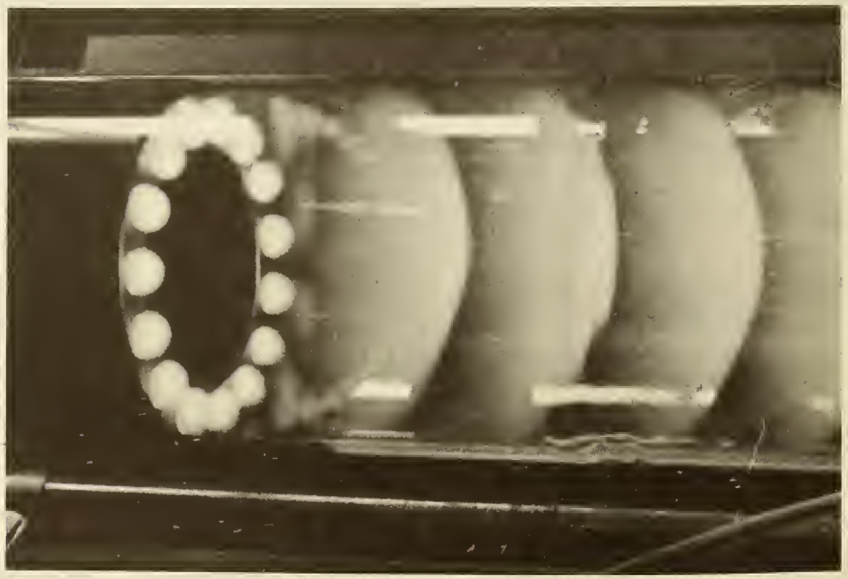


Figure 2 b. Ring anode and resulting stable plasma configuration.

mechanical equipment was working in the room below our laboratory). The beat note amplitude depends (within limits) on the laser power. The output power from the laser is limited by two factors (discharge current and beam splitter absorption) in addition to the design length. To avoid deterioration of the water cooled cathode, the d. c. current is usually limited to 0.6A. This current is maintained by a regulated power supply and is controlled by an external current controller which permits frequency modulation. Modulation experiments with the current controller indicated a drum head resonance at about 250 Hz in the original beam splitter. This unwanted response necessitated going to a thicker beam splitter (0.5-mm to 1-mm polyethylene was sufficiently thick) to avoid the problem. This thicker beam splitter limited the laser power to 65% of the output power with a 0.05-mm beam splitter.

A stable gas discharge in the laser cavity is required because the frequency of the laser output is a function of the resonant frequency of the cavity which in turn depends on the refractive index of the plasma. A turbulent discharge introduces fluctuations of the frequency of the laser. The stability of the plasma is influenced by the d.c. discharge current, pressure of gases, and electrode geometry. The optimum pressures we have found for a current of 0.6A are 0.150 torr (1 torr=

133.3 N/m^2) of methane and 0.275 torr of ammonia. These parameters yield a stable plasma with stationary striations about 2.5 cm apart.

Several anode geometries have been tried. The best plasma stability was obtained by the one shown in Fig. 2b. It consists of an elongated aluminum ring with 9.9-cm O. D. and 7.4-cm I. D. The aluminum is anodized to prevent the plasma from terminating anywhere except on some 15 conducting inserts. The 2.5-cm long inserts are made of stainless steel and the conducting ends are concave with an 11-mm radius. Good electrical contact with the aluminum is obtained by drilling undersized holes which will initially accommodate the inserts only after they have been cooled to cryogenic temperatures.

The one disadvantage of this cathode is the difficulty of renovating it in the event that one of the contacts develops a hot spot. Such a hot spot permanently alters the contact and can cause the discharge to terminate on a single contact. A more recent design permits the anode to be disassembled and the stainless steel surface renovated without damaging the insulating anodized layer. Details of this design are available upon request.

The harmonic generator **mixer** used to mix the E-band signal with the laser output consists of a silicon chip and tungsten catwhisker. The catwhisker is pointed in a 10-molar solution of KOH while applying a small voltage between the whisker and the solution. The chip and whisker dimensions used in the commercial mount and a guide to the proper etching voltage also are available on request. Best results have been obtained after reducing the diameter of the whisker to a slight tapered configuration, although reasons for this are not clear. Several run-in contacts are usually made before one obtains a good junction. One criterion for a contact suitable for harmonic mixing is a fast rise-time square wave of at least 2 mV resulting from the rectification (the antenna is positive for a silicon diode) of the chopped laser beam, which has been optimally directed into the input horn of the mixer. One can sometimes improve the signal by additional pressure by further running-in the differential micrometer screw. The mount is designed to allow one revolution of the screw after contact without deforming the whisker proper. Normally the diode contact is quite susceptible to vibrations, however when located on the vibration isolation table, the diode will generally last three to four weeks without requiring recontacting.

The signal to noise ratio is optimized after a suitable beat note is observed on the spectrum analyzer. The variables are the positions of the 74 and 891-GHz waveguide sliding shorts, laser side-mirror position (mirror A of Fig. 2a), 74-GHz power level, diode contact pressure, laser power, compensation values in the klystron phase lock loops, and laser beam positioning mirror orientation. The signal and noise levels for a typical adjustment are shown in Fig. 3. In order

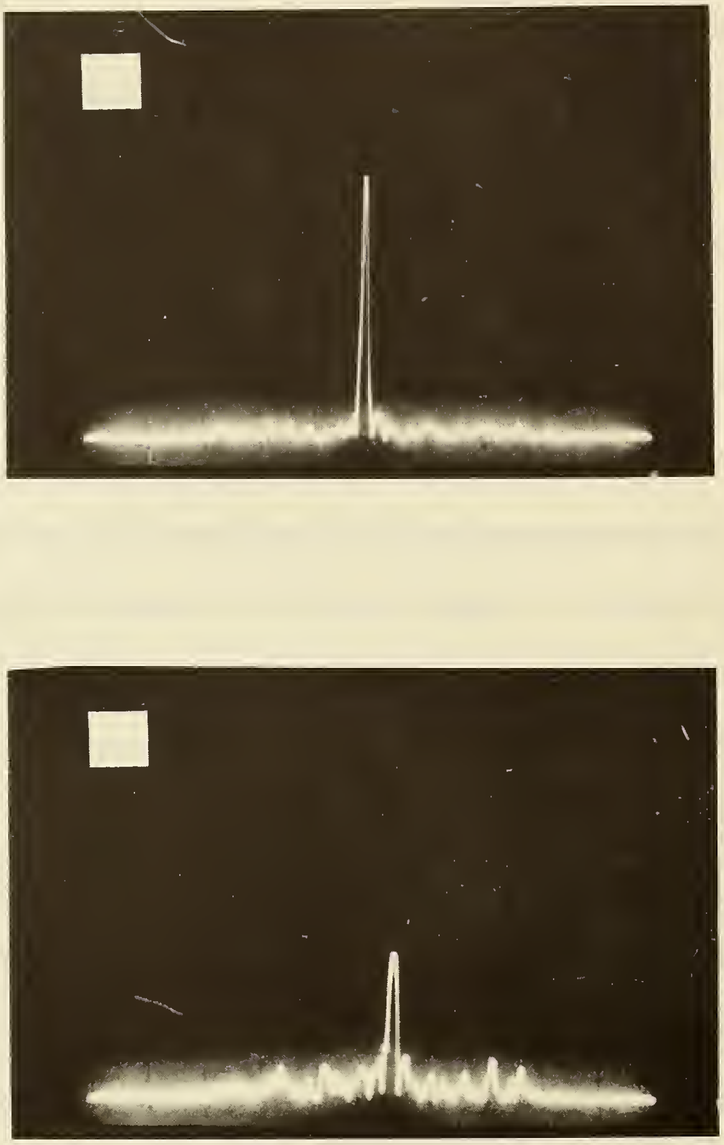


Figure 3. RF power spectrum of beat note between HCN laser and 12th harmonic of 74-GHz klystron. Dispersion is 20 kHz/cm, bandwidth is 1 kHz, and sweep rate is 5 ms/cm. Above, display is linear with 100 mV/cm and input signal attenuated 50 dB. Below, display is logarithmic with 10 dB/cm. Signal to noise ratio is about 25 dB. The white square in the figures denotes 1 cm^2.

to eliminate noise and extraneous beats near 30 MHz (which are picked up from various klystron lock boxes), the output from the IF amplifier has been passed through a 30-MHz crystal filter with a 3-dB band pass of 200 kHz.

3. STABLE FREQUENCY REFERENCE

An immediate objective is to obtain reference stabilities of parts in 10^{10} in both long and short term at one THz. The basic reference chain is as follows: An X-band klystron is phase locked to some harmonic (say the 100th) of a quartz crystal oscillator reference, then an E-band klystron is locked to the 7th harmonic of the X-band source. The HCN laser frequency is then compared with the 12th harmonic of the E-band source. The basic frequency relations and the signs of the offset frequencies in the reference chain are indicated in Fig. 4. (An alternative scheme would go from 10.6 GHz to 0.891 THz using a Josephson junction;[8] however the disadvantages outweigh the advantages at this time.)

The absolute stability of the locked laser depends upon the driving source of the reference chain, a quartz crystal oscillator. To synthesize from a good quality quartz oscillator at 5.06 MHz to the HCN laser at 0.891 THz requires a multiplication factor of 176,400.

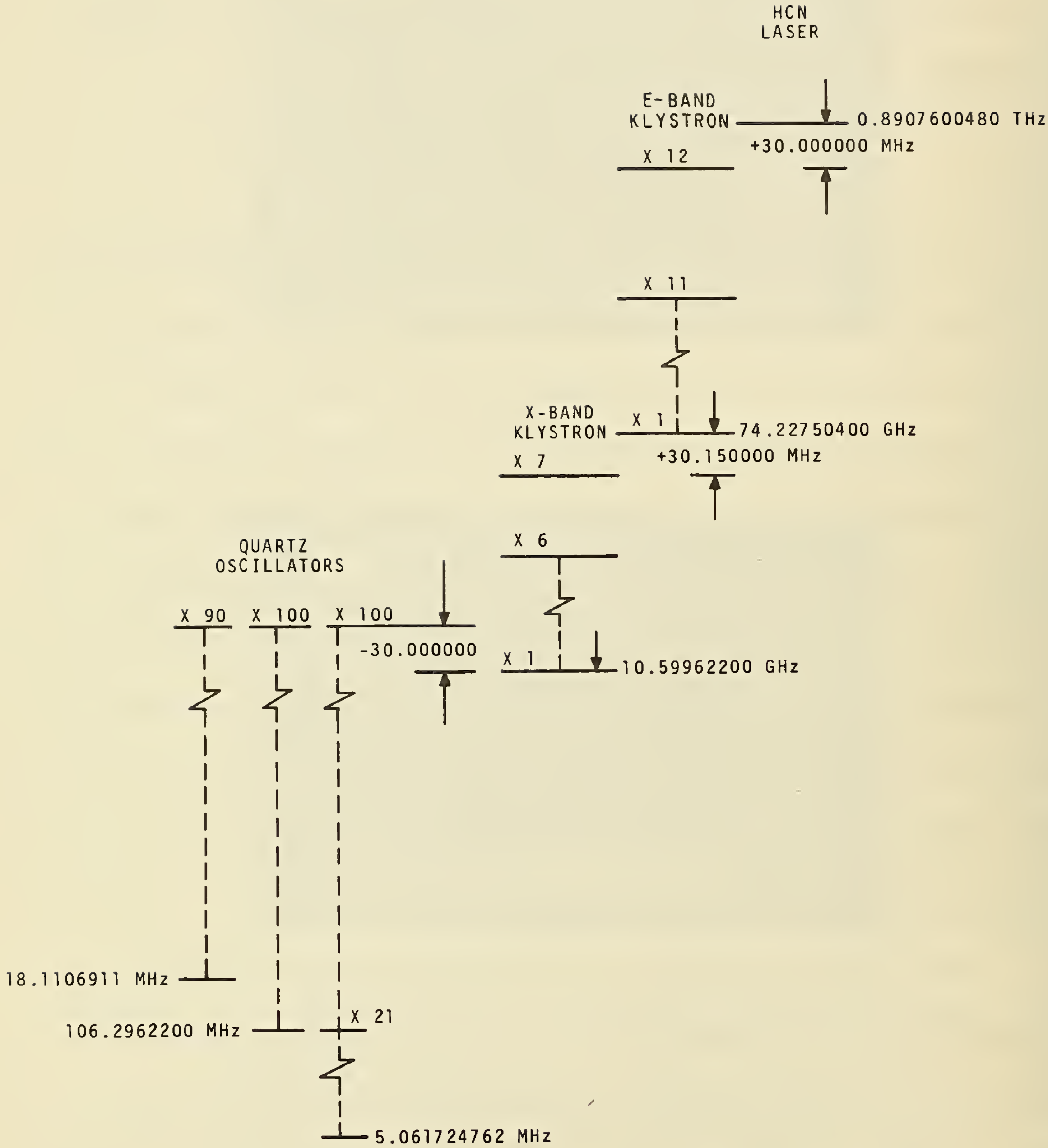


Figure 4. Frequency synthesis scheme for stabilization of HCN laser frequency.

This places some rather stringent requirements on the spectral purity of the quartz crystal oscillator's output.[9]

Our most convenient qualitative check on the short term stability of the reference oscillator (5 MHz to 100 MHz) is obtained by examining the beat note between the multiplied reference signal and the HCN laser at 0.891 THz. When multiplied to this frequency, the short term stability is sometimes such that the multiplied reference linewidth is broader than the laser linewidth (which was to be narrowed by locking to the reference!). Figure 5 shows an extreme example of this, as well as of some sources of noise. These linewidths are to be compared with the 2 to 5 kHz linewidth of a current state of the art HCN laser. The HCN laser is free running in these tests. This sequence of beat notes suggests that a Gunn diode oscillator when stabilized by a superconducting cavity [10] might be the best reference for locking an HCN laser. Another moderately good reference might be a Gunn diode oscillator locked to a high quality quartz crystal oscillator.

3.1. Short Term Stability Requirements

We let a superscript caret ($\wedge$) indicate quantities at the output frequencies, for example, $\hat{\nu}_o = n\nu_o$ (0.891 THz = 84 x 0.0106 THz). A

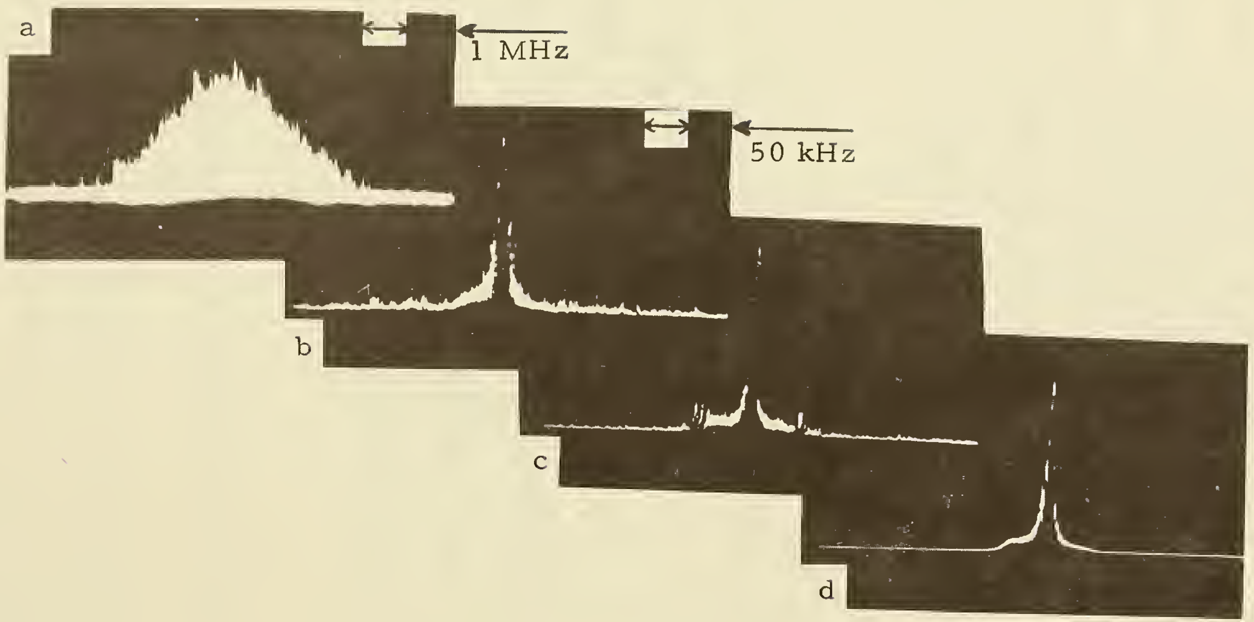


Figure 5. Beat notes of a free running HCN laser versus 12th harmonic of 74-GHz klystron. In a, the 74-GHz is locked to an X-band oscillator which in turn is locked to a multiple of a synthesizer signal at 5.06 MHz. The dispersion is 1 MHz/division. The dispersion for the next three beat notes is 50 kHz/division. For b, the reference is a 5.06-MHz quartz oscillator. However, the multiplier chain going from 5.06 MHz to 106 MHz was not state of the art. In c, the beat note is referenced to a 106-MHz oscillator, and the last beat note, d, results from a free running Gunn diode oscillator at X-band. The last two beat notes are instrument limited by the spectrum analyzer due to the particular dispersion and resolution settings used here. Sweep times are 0.5 s for a and 0.05 s for b, c, and d.

minimally acceptable reference signal should have a linewidth, $\hat{W}_{-3dB}$, at 891 GHz of about 100 Hz or less. If we were to assume white frequency noise in the X-band source, then the requirements on the X-band source would be [9]

$$W_{-3dB} = \frac{\hat{W}_{-3dB}}{(n^2)} = \frac{100 \text{ Hz}}{(84)^2} = 0.014 \text{ Hz} \quad . \tag{1}$$

The 0.014-Hz linewidth requirement on the X-band source can be expressed alternatively in terms of its spectral density of frequency fluctuations, $S_{\delta\nu}(f)$. Since we assume only white frequency noise is present, we may use the well-known relation [9]:

$$W_{-3dB} = \pi S_{\delta\nu}(f) \quad , \tag{2}$$

$$S_{\delta\nu}(f) = \frac{\langle (\delta\nu)^2 \rangle}{B_a} \quad . \tag{3}$$

For a 100-Hz noise analysis bandwidth, B_a, and white frequency noise

$$(\delta\nu)_{rms} = \sqrt{\frac{W_{-3dB}}{\pi} (B_a)} = \sqrt{\frac{(0.014\text{Hz})(100 \text{ Hz})}{\pi}} \tag{4a}$$

$$= 0.668 \text{ Hz in a 100 Hz bandwidth 1000 Hz (or any frequency) from carrier.} \tag{4b}$$

This is a factor of two larger than the 0.3 Hz rms in a 100 Hz bandwidth at f of 1000 Hz as measured for a high quality two-cavity klystron. However, the assumption of white frequency noise is a critical one, and often a 1/f model (flicker noise of frequency) is a better engineering approximation for high quality sources.

Reference [9] is concerned with relevant noise aspects of microwave to infrared frequency synthesis. It uses the concept of the fast linewidth W_f.[1] In its Fig. 7 it summarizes some results for power law noise spectral densities, i.e., spectral densities of the form

$$S_{\delta\nu}(f) = H_\alpha f^\alpha . \tag{5}$$

The coefficient H_α in the f^α power law expression is (numerically) the density evaluated at unity frequency. We now assume that the 0.3 Hz rms frequency fluctuation of the X-band source is due to a flicker of frequency noise, i.e., $S_{\delta\nu}(f) = H_{-1} f^{-1}$ with $\alpha = -1$. The relevant equation for the fast linewidth in Fig. 7 of reference [9] is

$$W_{f,-3dB} = \left[\left(\frac{8\pi}{3\sqrt{3}}\right) H_{-1}\right]^{\frac{1}{2}} \tag{6}$$

[1] The fast linewidth is a measure of the coherence rate of a nearly-periodic signal. For white frequency noise the fast linewidth is the same as the classical linewidth. For detailed discussion, see [9].

or

$$\hat{W}_{f,-3dB} = \left[\left(\frac{8\pi}{3\sqrt{3}}\right) \hat{H}_{-1}\right]^{\frac{1}{2}} . \tag{7}$$

The operation of frequency multiplication increases the spectral density of frequency fluctuations by the factor (n^2). Provided that $B_a << f$,

$$H_{-1} = \frac{\langle(\delta\nu)^2\rangle}{B_a} f , \tag{8}$$

or

$$\hat{H}_{-1} = n^2 \frac{\langle(\delta\nu)^2\rangle}{B_a} f . \tag{9}$$

Hence for flicker of frequency noise

$$\hat{W}_{f,-3dB} = \left[\left(\frac{8\pi}{3\sqrt{3}}\right) \frac{f}{B_a}\right]^{\frac{1}{2}} n\,(\delta\nu)_{rms} . \tag{10}$$

For $n = 84$, with $(\delta\nu)_{rms} = 0.3$ Hz at X-band in a bandwidth B_a of 100 Hz at $f = 1000$ Hz, the fast linewidth is

$$\hat{W}_{f,-3dB} = 170 \text{ Hz}. \tag{11}$$

This is only slightly worse than the desired 100 Hz linewidth.

Another significant source of noise in the reference chain is the flicker of phase noise associated with the quartz crystal oscillator to which the X-band klystron is phase-locked. The spectral density of this noise is

$$S_{\delta\nu}(f) = H_1 f^1 . \tag{12}$$

Unfortunately, the analysis of this flicker of phase noise situation (α equal to unity) is more complicated than for the power law spectral densities where α is less than unity. From equation (38) of reference [9], the fast linewidth for α less than unity is

$$W_{f,-3dB} = 2\left[\frac{\left(\frac{\pi}{2-\alpha}\right) H_\alpha}{\sin \frac{\pi}{2-\alpha}}\right]^{\frac{1}{1-\alpha}} . \tag{13}$$

We can see that the behavior of the linewidth is becoming pathological as α approaches unity.

Due to the f^{+1} behavior of the spectral density, in order to achieve high-order frequency synthesis it is necessary to have some filter with a bandwidth B which furnishes a sharp cutoff at some frequency $f_u \approx B/2$. (This could be a filter or filters say just after the quartz crystal oscillator, at some intermediate stage in the multiplier chain, and/or in the klystron phase lock circuitry.)

If the bandpass filtering of the reference signal is done at a low (carrier)frequency stage, such that at that frequency

$$W_{f,-3dB} << f_u, \tag{14}$$

and if subsequently this signal is frequency multiplied such that at the output frequency

$$\hat{W}_{f,-3dB} > f_u, \tag{15}$$

then we can use a graphical construction similar to Fig. 6 of reference [9] to obtain an estimate of $\hat{W}_{f,-3dB}$. The behavior of the filtered flicker of phase noise is as f^{-1} for f less than f_u, and as f^{-3} (for a single pole bandpass filter) for f greater than f_u.

The corresponding algebraic analysis is as follows:

$$S_{\delta\nu}(f) = H_1 f^1, \tag{16}$$

and therefore

$$S_{\delta\Phi}(f) = H_1 f^{-1} \tag{17}$$

for the unfiltered flicker of phase noise. After filtering by a single pole bandpass filter of bandwidth $B = 2 f_u$, for f greater than f_u the resultant signal is

$$S_{\delta\Phi}(f > f_u)\Big|_{\text{filtered}} = H_1 f^{-1}\left(\frac{f_u}{f}\right)^2 , \qquad (18)$$

or

$$S_{\delta\nu}(f > f_u)\Big|_{\text{filtered}} = f_u^2 H_1 \; f^{-1} . \qquad (19)$$

After frequency multiplication by the factor n we have

$$\hat{S}_{\delta\nu}(f > f_u) = (n^2 f_u^2 H_1)\; f^{-1} , \qquad (20)$$

that is, $\alpha = -1$ and $\hat{H} = n^2 f_u^2 H_1$.

Substituting into the equation for $\alpha = -1$ for the fast line-width (a procedure which is approximately valid provided $\hat{W}_{f,-3dB} \gtrsim f_u$) we obtain

$$\hat{W}_{f,-3dB} \approx \left[\left(\frac{8\pi}{3\sqrt{3}}\right) n^2 f_u^2 H_1\right]^{\frac{1}{2}} . \qquad (21)$$

To multiply from 5 MHz to 0.891 THz, we have n = 176,400. If the flicker of phase noise at 5 MHz has the commonly encountered intensity [11] of

$$S_{\delta\Phi}(f) = (10^{-11.2}\,\text{rad}^2)\; f^{-1} , \qquad (22)$$

then

$$S_{\delta\nu}(f) = (10^{-11.2})\ f^{1} \quad , \tag{23}$$

$$H_1 = 10^{-11.2} \quad . \tag{24}$$

For an assumed bandwidth of 10 kHz, $f_u = 5$ kHz, and

$$W_{f,\,-3dB} \approx 2.20\, n\, f_u \sqrt{H_{-1}} \ , \tag{25a}$$

$$\approx 4.8 \text{ kHz.} \tag{25b}$$

This contribution from the flicker of phase noise is severe. At $\hat{\nu}_o$ = 0.891 THz for our assumed conditions it is a greater contribution to the $\hat{W}$ than is the contribution from the flicker of frequency noise of the X-band klystron. Several methods are available to avoid deterioration of the laser spectrum by the multiplied phase noise. One is to decrease the bandwidth B of the klystron lock loop for example. However, the klystron loses lock if the bandwidth is narrowed by too great a factor.

Recently, we have investigated a scheme similar to that developed by Risley[12] to obtain the best spectral purity for direct multiplication from X-band to frequencies in the 10-THz region. This scheme involves using the quartz referenced klystron as a source to injection lock a second cavity-stabilized klystron. The amount of phase noise on the reference oscillator that is imposed upon the injection locked klystron is dependent upon the level of the injected signal, i. e., the control bandwidth depends on the injected power. The attenuator between the two klystrons is analogous to a variable upper frequency cutoff on a filter.

Risley's source is intended to be multiplied directly to the laser frequency in a Josephson junction. In our case we are using room temperature diode harmonic generators and the 7th harmonic of X-band is used to phase lock a 74-GHz klystron.

Both a cavity-stabilized X-band klystron and a phase locked X-band klystron are connected to a waveguide switch. In position one, the 74-GHz klystron is locked to the phase locked X-band klystron. In position two, the 74-GHz klystron is locked to the cavity-stabilized klystron and the phase locked X-band signal simultaneously fed through an attenuator to injection lock the cavity-stabilized klystron. Sufficient attenuation is available to avoid injection locking. Figures 6a, b show the resulting improvement in the signal to noise ratio of the beat note when using the cavity-stabilized system. At this level of examination, an injecting signal caused no deterioration of the signal to noise ratio. The difference is even more pronounced in Fig. 6c, d where the Lissajous figures are shown when the laser is phase locked.

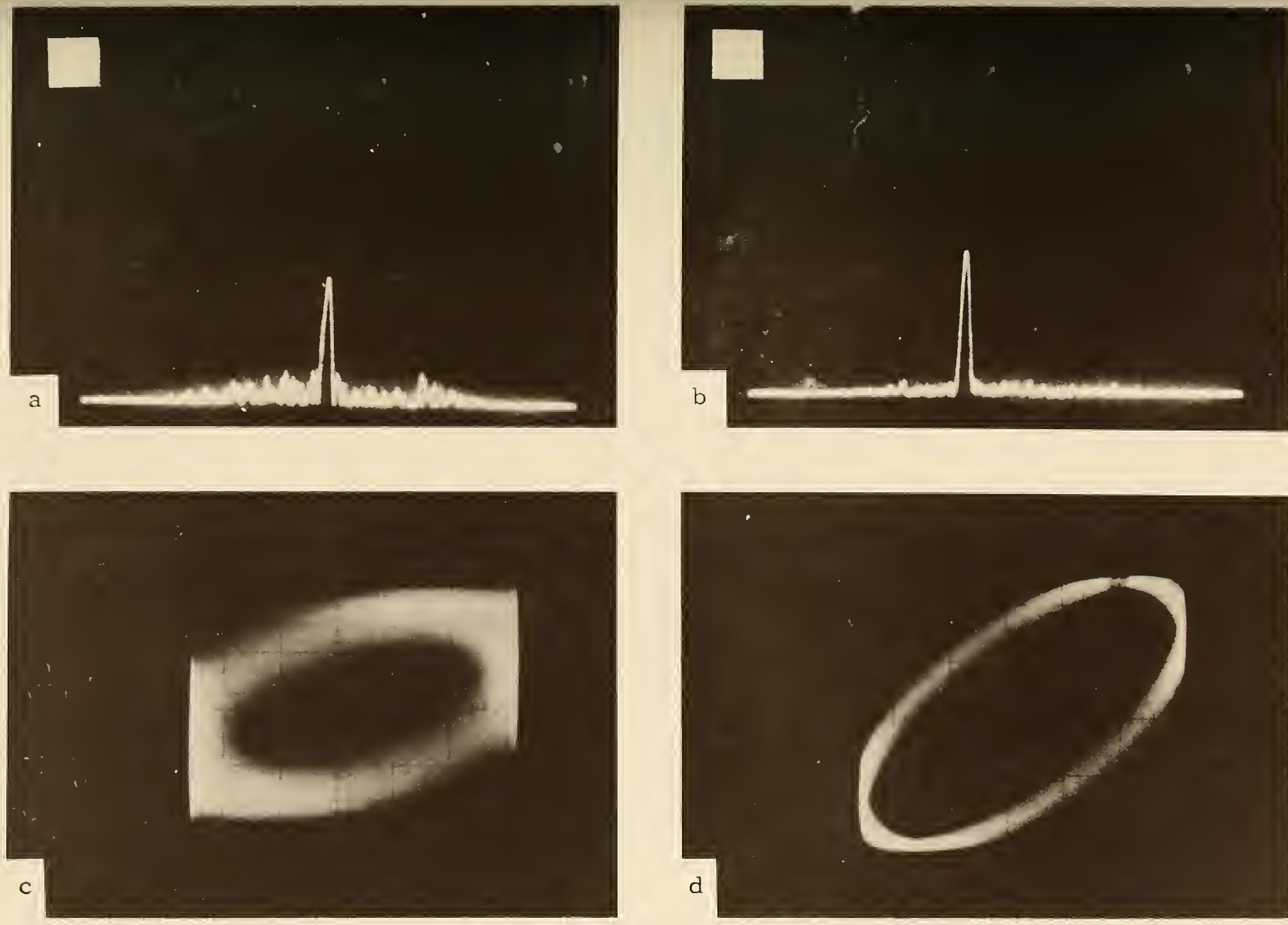


Figure 6. RF power spectrum of 0.891 vs (12 x 0.074)-THz beat note when 74-GHz klystron is locked to a phase locked klystron (a) and a cavity-stabilized klystron (b). Dispersion is 20-kHz/cm and display is logarithmic (10dB/cm). Below are Lissajous figures (Y-axis is down converted beat note, X-axis is phase detector reference) when laser is phase locked with 74-GHz klystron phase locked to a phase locked X-band klystron (c) and a cavity stabilized klystron (d). The white square in the figures denotes 1 cm^2.

(It is pointed out here that the controller A was used in this experiment.) The resulting absolute linewidth of the laser when phase locked to the cavity-stabilized klystron is discussed in the last section of this report.

4. ACTIVE TECHNIQUES

Figure 7 shows a block diagram of the scheme for stabilizing the laser. It consists of two servo loops, one for frequency locking, the other for phase locking. The frequency lock loop consists of a frequency discriminator, preamp and filter, and a translator driver with a slow (up to 100-Hz frequency response) correction applied to the piezoelectric translator (PZT). This loop serves as the acquisition aiding loop for the phase lock system.

The phase lock portion of the scheme is shown on the right. It consists of a filter, a 29.75-MHz quartz oscillator, a balanced mixer, a 250-kHz reference oscillator, a phase detector and filter, and a current controller.

4.1. Frequency Lock Loop

The frequency lock loop is adequate for purposes other than high accuracy frequency synthesis, and can easily be improved with the incorporation of a crystal discriminator (sensitivities like 60 mV/kHz)

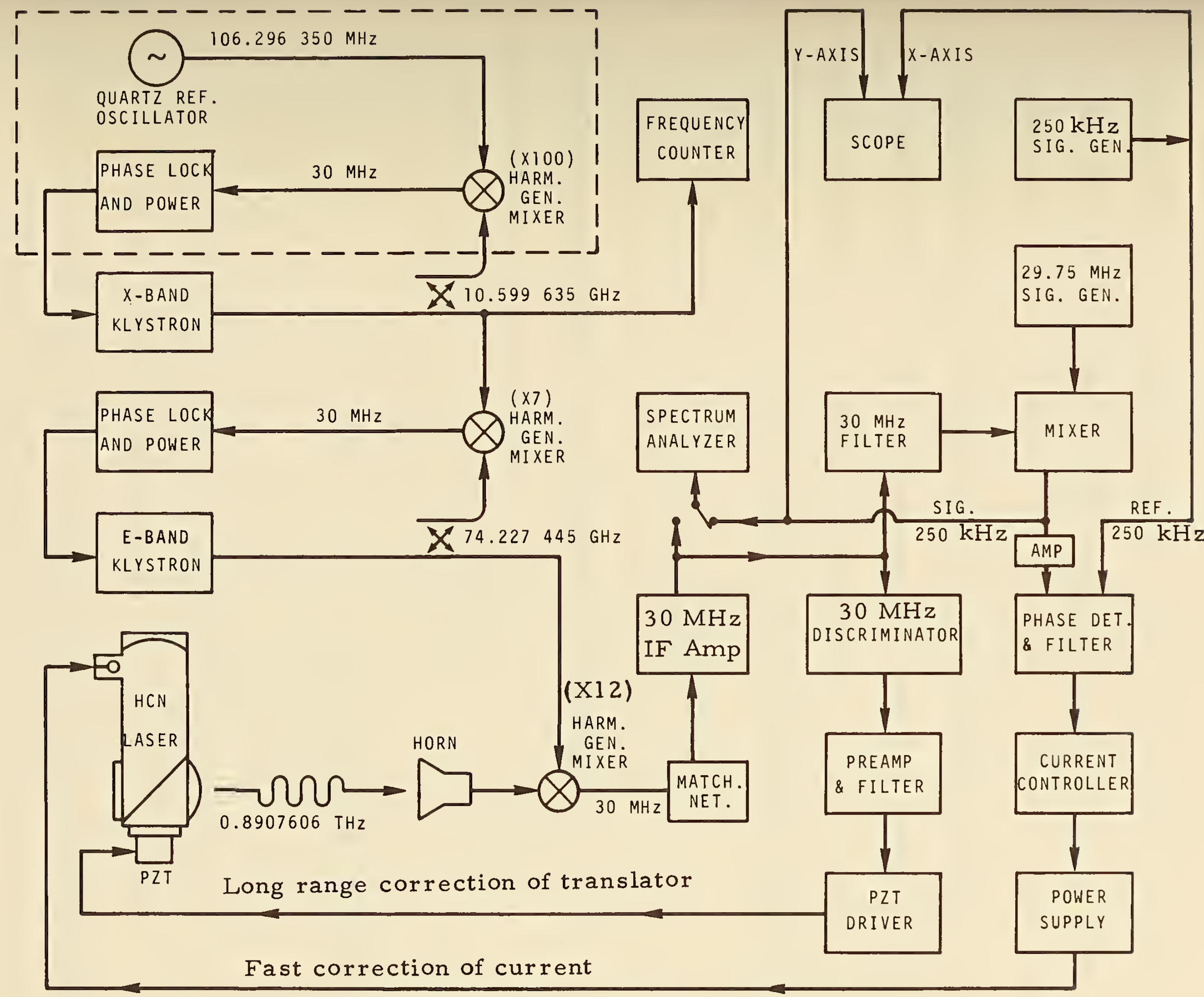


Figure 7. Block diagram of laser stabilization scheme.

or a frequency to voltage converter. The present discriminator (0.11 mV/kHz) requires a 100 to 120 dB IF amplifier to get proper limiting in the discriminator. The resulting amplified Johnson noise, the unwanted ground loops, and the spurious instabilities in the plasma necessitate a high degree of filtering to avoid broadening the laser lines. A time constant of 0.2 s permits servoing out resonant frequencies of the isolation table on which the laser is mounted and at the same time avoiding deterioration of the laser signal due to the loop noise. The frequency control system can serve as an acquisition aiding loop for a phase lock system.

4.2. Phase Lock Loop

To narrow the laser linewidth below the 2 to 5-kHz free-running linewidth requires a narrow reference and a more sensitive discriminator or a phase lock circuit. The phase lock loop shown in Fig. 7 has been used for this purpose. Two different current controllers were successfully used in the experiments.

An initial complication in attempting to phase lock the laser to a microwave chain was the presence of noise primarily arising in the chain. In order to avoid the noise and to test the loop, the laser was initially locked to a second HCN laser.[13] This proved to be a very helpful step in empirically determining the initial gain and filter parameters. It also established that the beat note width was primarily due to the laser rather than the microwave chain used next.

After determining the optimum filter parameters, the second HCN laser was replaced by the microwave chain. The 30-MHz output was filtered by a 200-kHz band pass filter and beat down to a nominal 250-kHz to facilitate use of the 250-kHz phase detector. A 30-MHz phase detector could be used; however, the advantage of being able to monitor the Lissajous on the scope (the scopes available in our lab did not have X-axis deflection at 30 MHz) makes 250 kHz a desirable working frequency. The maximum output of the phase detector, k_d, is 1 volt/rad and the gain of the current controller A -laser combination, k_o, is 10^5 Hz/volt. Hence $k_o k_d = 10^5$ Hz/rad. The transfer function for an ideal controller-laser combination is

$$L(s) = \frac{k_o k_d F(s)}{s + k_o k_d F(s)} \quad . \tag{26}$$

Phase lock was achieved and after empirically adjusting the filter parameters for best lock, it was found that the filter

$$F(s) = \frac{(s\tau_2 + 1)(s\tau_4 + 1)}{(s\tau_1 + 1)(s\tau_3 + 1)} \quad , \tag{27}$$

had zeros at 1.28 kHz and 2.55 kHz and poles at 25 Hz and 130 kHz.

The loop transfer function is then

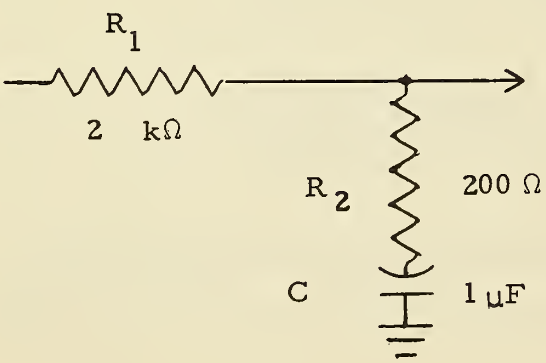
$$L(s) = \frac{K(s)\,K_d\,(s\tau_2+1)\,(s\tau_4+1)}{s^3\,\tau_1\tau_3 + s^2\,K(s)\,K_d\tau_2\tau_4 + sL(s)\,K_d(\tau_2+\tau_4) + k(s)\,K_d} \tag{28}$$

Useful design parameters such as the natural frequency ω_n and the damping factor are not easily extracted from this third order loop expression. Since current controller B is less complicated, more amenable to analysis, and (more importantly) much easier to duplicate elsewhere, we restrict our further description to current controller B. Controller B has a gain constant $k_o = 7.5 \times 10^5$ and the frequency dependence of amplitude and phase are as shown in Fig. 8.

Unlike controller A (which required a unique filter to achieve phase lock) controller B can be locked with a simple filter whose values are not critical, but can be adjusted for optimum damping, etc. A typical filter for controller B is

$$F(s) = \frac{(s\tau_2 + 1)}{s(\tau_1 + \tau_2 + 1)}\,, \tag{29}$$

where the filter parameters are:



$\tau_1 = R_1C = 0.002s$

$\tau_2 = R_2C = 0.0002s$

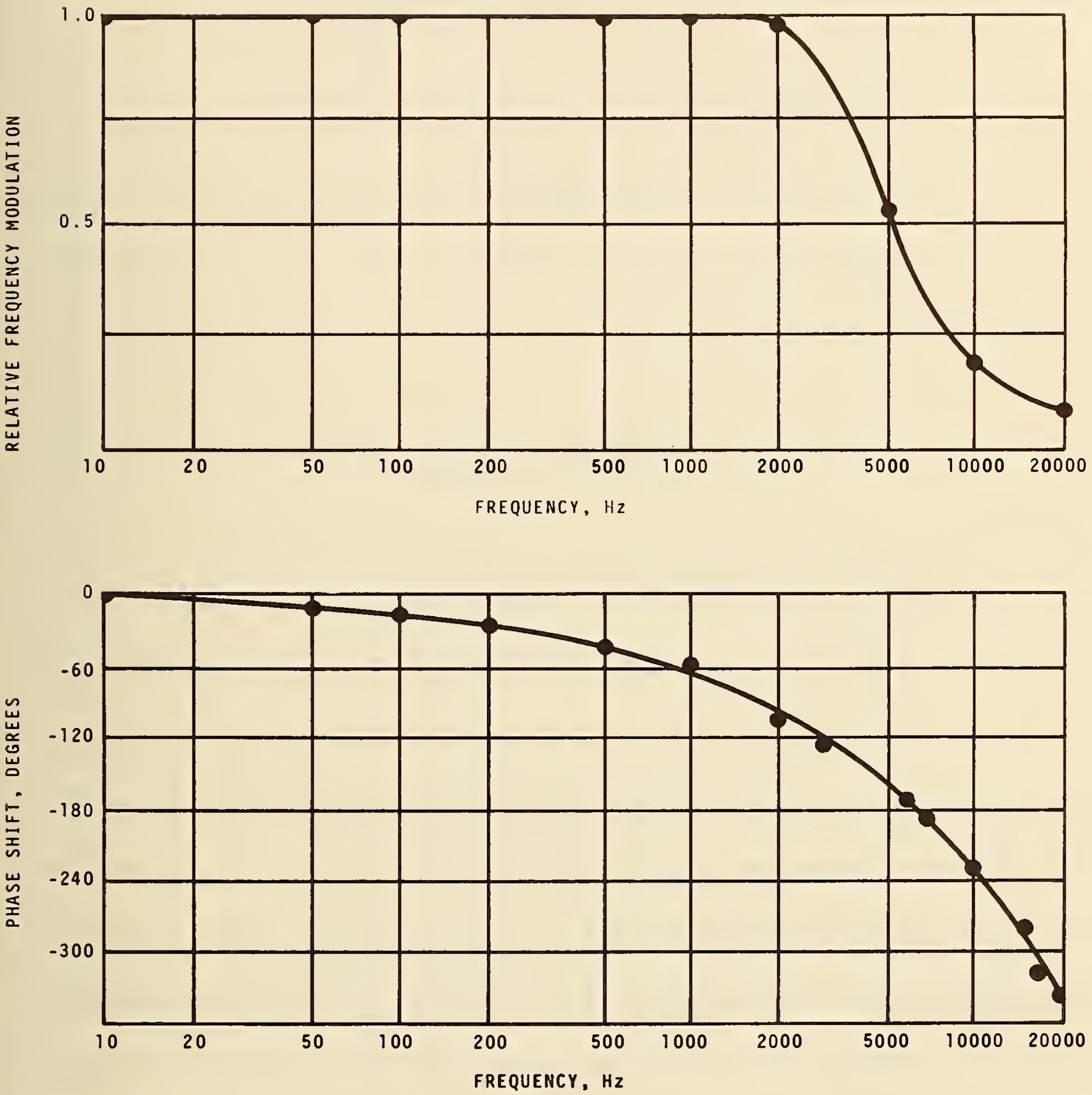


Figure 8. Response of the current controller - laser combination to a fixed amplitude modulation signal.

Then the transfer function is:[14]

$$L(s) = \frac{s\left(2\omega_n - \frac{\omega_n^2}{k_o k_d} + \omega_n^2\right)}{s^2 + 2\,\omega_n\, s + \omega_n^2}\,, \tag{30}$$

where

$$\omega_n = \left[\frac{k_o k_d}{\tau_1 + \tau_2}\right]^{\frac{1}{2}} = 1.8 \times 10^4 \text{ rad/s} \tag{31}$$

and the damping factor is

$$\zeta = \tfrac{1}{2}\,\omega_n\left(\tau_2 + \frac{1}{k_o k_d}\right) = 1.8 \tag{32}$$

This would lead to a pull in frequency of[14]

$$\Delta\omega_p = 2\,(2\,\omega_n k - \omega_n^2) = 1.3 \times 10^4 \text{ rad/s} \tag{33}$$

which is within the range of the acquisition loop. The phase lock loop will hold lock for times of the order of a minute. The acquisition loop increases this time about an order of magnitude, and, while it does not prevent the laser from skipping cycles, it does return it to the locked condition. The 10-minute lock time does permit a frequency measurement which is the objective of the work.

Figure 9 shows the beat note between the HCN laser and the reference when the laser is frequency locked, a, and when the laser is phase locked, b. Controller B was used for this test.

Figure 10a shows the beat note at 30 MHz on an expanded scale for the phase locked condition. The post detection bandwidth is greater than 10 kHz. The probability of seeing the beat note at the center of this 200-Hz window is better than 97% during a 10-minute period and thus the system could be utilized for IFS as is. If it is in the center of the window we know its frequency to within about one part in 10^{11}. In general, one can make about 5 to 10 consecutive frequency measurements with 10 s counting time for each and determine the difference frequency when the beat note is as shown. (In the event that the signal is too weak to count, one can count the 29.75-MHz and the 250-kHz references, the sum of which is the phase locked beat frequency). From the data displayed we infer that the laser is following the reference but we still do not know how wide the laser is.

Figure 10b shows a Lissajous figure where the Y-axis is derived from the beat between the laser and microwave reference chain (down converted 250 kHz) while the X-axis is driven by the phase detector reference oscillator. We reiterate here that there is an advantage to operating the phase lock loop at 250 kHz, as say compared to 30 MHz due to the fact that one can monitor the Lissajous figure

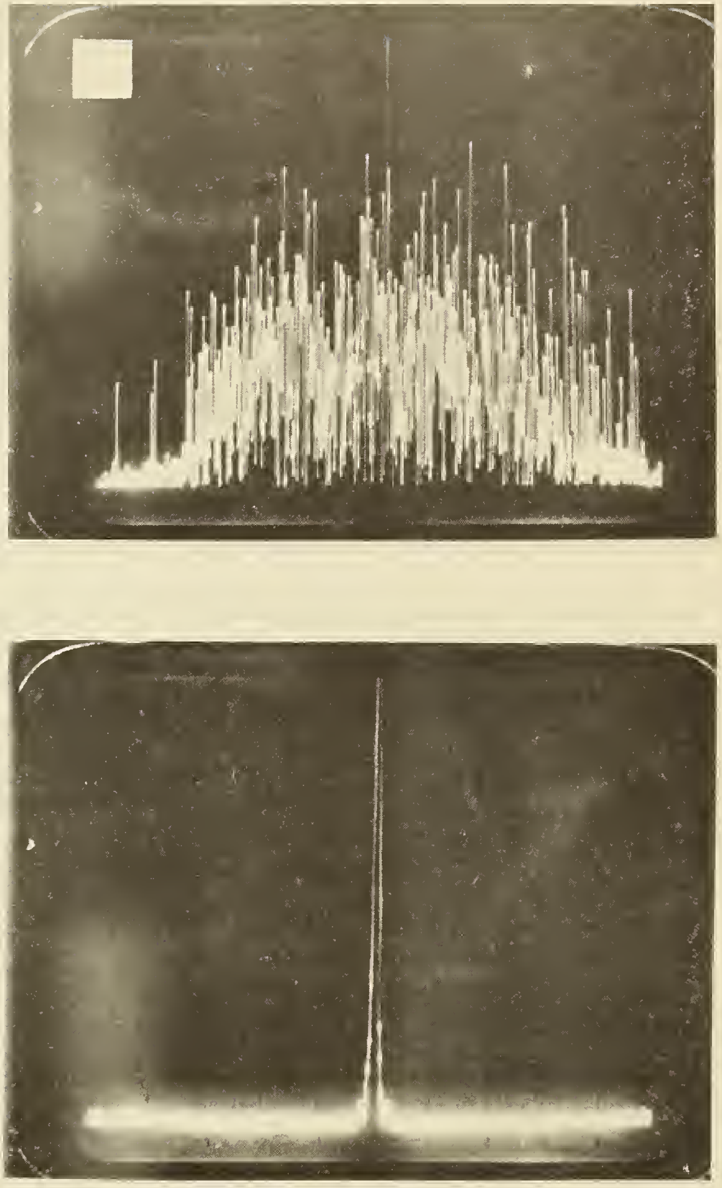


Figure 9. 74-GHz vs HCN laser beat notes. 500 Hz/cm, 30 Hz bandwidth. Sweep rate 1 s/cm. Linear display. Top: frequency lock, 10 mV/cm. Below: phase lock, 20 mV/cm. The white square denotes 1 cm^2.

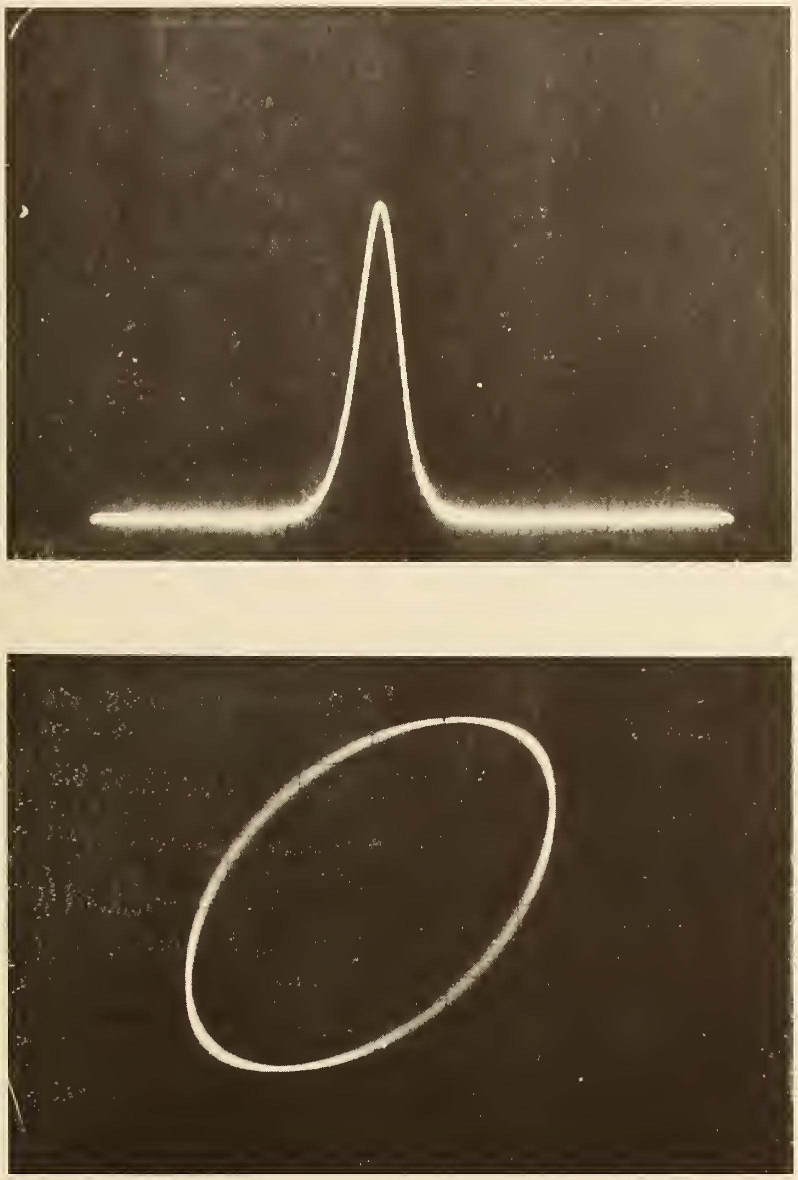


Figure 10. Quality of phase lock of HCN laser.
Top: RF power spectrum of beat between HCN laser and 12th harmonic of 74-GHz klystron with laser phase locked to 12th harmonic. Vertical scale is linear, dispersion is 20 Hz/cm, bandwidth 10 Hz, and sweep rate 1 s/cm (30 MHz is center frequency).
Below: Lissajou figure at 250 kHz where Y-axis is driven by down converted beat note and X-axis is driven by phase detector reference.

while adjusting the filter parameters, gain, etc. for good operating values. The Lissajous figure also tells when the loop becomes unlocked and skips cycles. Of course, with a scope with a 30-MHz X-axis drive capability one could do the same.

Figure 11 shows some preliminary indications of beat frequency fluctuations (square root of an Allan variance) as determined with a commercial computing frequency counter. Each point represents 100 contiguous measurements except for the two points indicated by an asterisk where M = 10. Shown are frequency fluctuations versus averaging time for the HCN laser under three different modes: free running, frequency locked, and phase locked. The rise at 10 s in the phase locked mode is due to the laser dropping out of lock momentarily. The frequency lock loop does cause it to return immediately to the phase locked condition. We are working towards keeping it locked for longer periods, although it is not absolutely essential for our present purposes of IFS. Again, this is a measure of how closely the laser is following the reference, but gives no measure of the laser linewidth.

We have an experiment planned to measure directly the linewidth of the reference (and consequently of the laser) at 1 THz. One would like to beat the 84th harmonic of one X-band klystron with the 84th harmonic from another tuned to a slightly different frequency, but

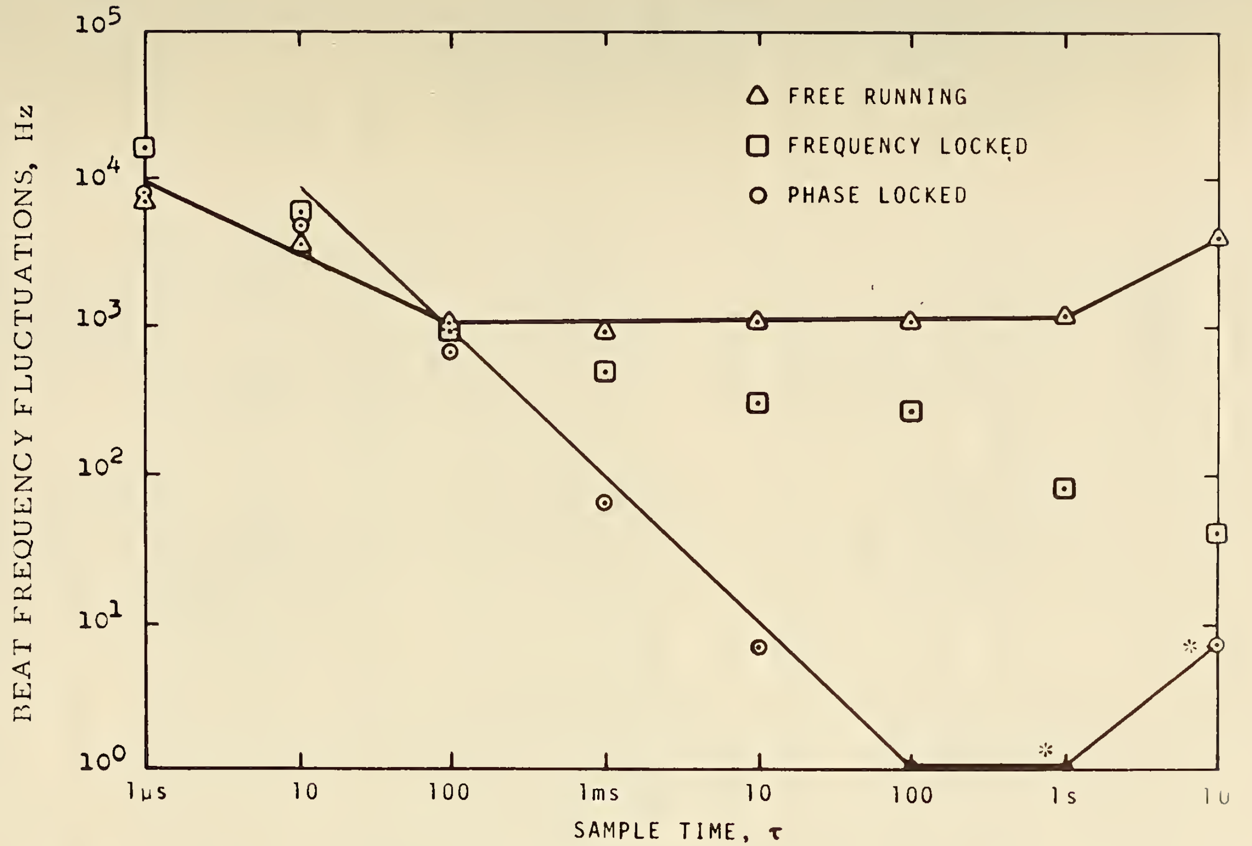


Figure 11. HCN laser stability as measured with a computing frequency counter. The vertical scale is the square root of the Allan variance, $\sigma_{\delta\nu}^2$ (N, T, τ, B) of the frequency fluctuations for N = 2 T- $\tau \approx$ 3 ms, and B = 200 kHz.

there are ambiguities in such an experiment. However, by phase locking an HCN laser to the 84th harmonic of klystron A, all the other harmonics are discarded, and the 84th harmonic of klystron B can be compared with the phase locked HCN laser with a Josephson junction multiplier mixer.

The scheme for such an experiment is indicated in Fig. 12. The HCN laser described earlier has been modified to obtain outputs from both sides of the beam splitter. One output is used in the control loop and the other is used for examination of the spectrum with an independent multiplier chain. Figure 9 showed the gross features of the beat note between multiplier chain A and the laser when the laser is either frequency locked or phase locked as monitored on spectrum analyzer A. Figure 10 gave a better indication of the degree to which the phase of the HCN laser can be made to follow the phase of the reference. Since the laser is tightly locked to the output of the multiplier chain A, the display on spectrum analyzer B really compares the output of the two multiplier chains. This technique provides an experimental means for checking theoretical predictions of the linewidth based upon examination of noise spectra at 5 MHz and 10 GHz and helps to indicate what is needed to achieve the desired linewidth for the HCN laser.

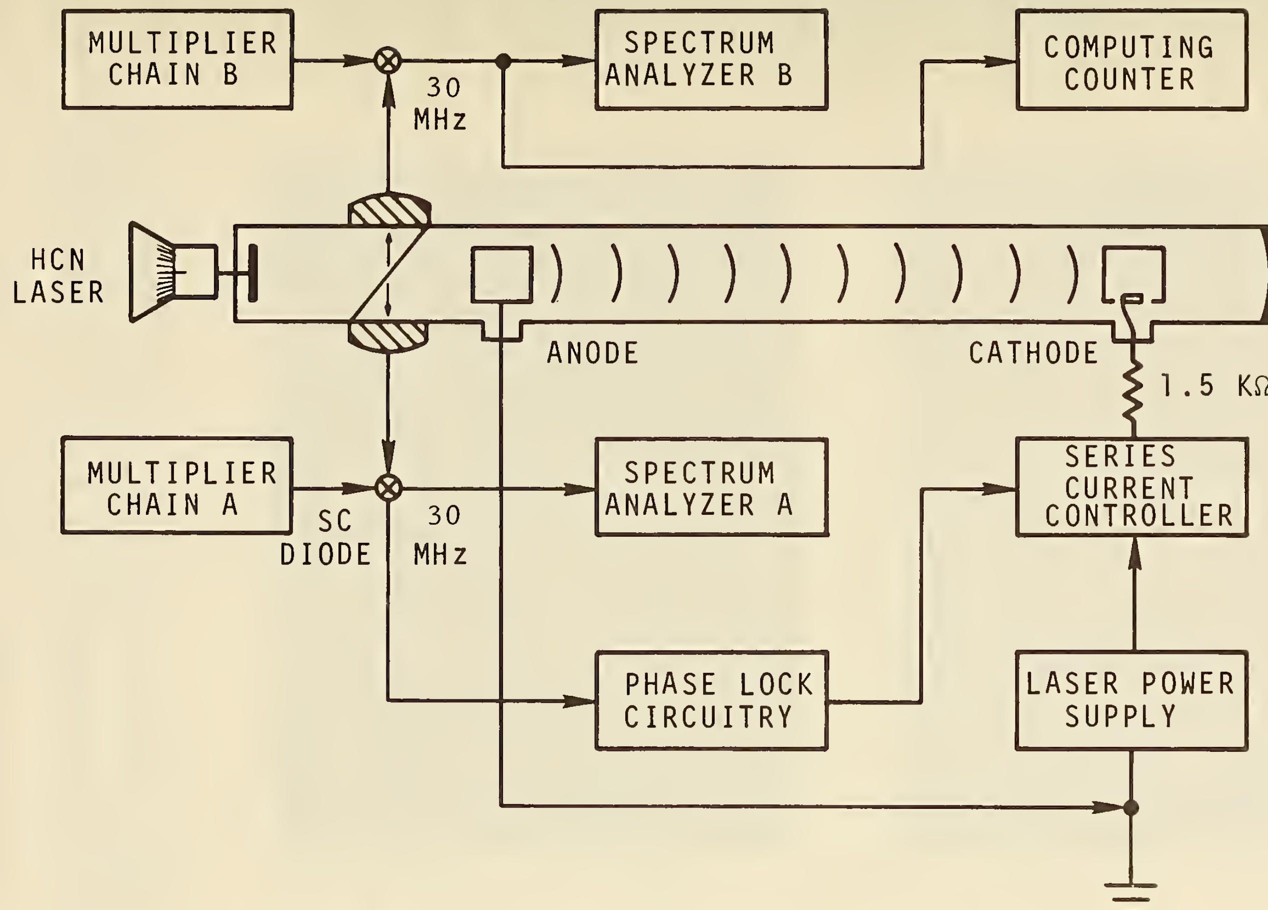


Figure 12. Block diagram of scheme for measuring linewidth and stability of a phase locked HCN laser.

Ideally, one would like the multiplier chains to be identical, however, present economic considerations preclude this. We have nearly identical X-band cavity-stabilized klystrons. These have good short term stability at 10 GHz, however, they need to be locked to a quartz crystal oscillator for good long term stability. The output of multiplier chain A is the 12th harmonic of a 74.2-GHz klystron which is phase locked to the 7th harmonic of a cavity-stabilized X-band klystron (CSKA) at 10.6 GHz. The CSKA oscillator is injection locked (at a low level) to an X-band klystron which in turn is phase locked to the 90th harmonic of a 118-MHz quartz crystal oscillator reference.

The output of interest from multiplier chain B is the 92nd harmonic of a cavity-stabilized klystron (CSKB) at 9.6 GHz. The 92nd harmonic is generated in a Josephson junction which also serves as the mixer to combine the 92nd harmonic with the laser radiation. Oscillator CSKB is injection locked to the output of a multiplier which is referenced to a 5-MHz quartz crystal oscillator. The multiplier chain design is the same as that used in cesium standards work. [15]

A preliminary experiment has been performed on a more modest scale. In this experiment chain A consisted of a cavity-stabilized X-band klystron and an E-band klystron which was phase locked to the 7th harmonic of the X-band signal. Chain B consisted

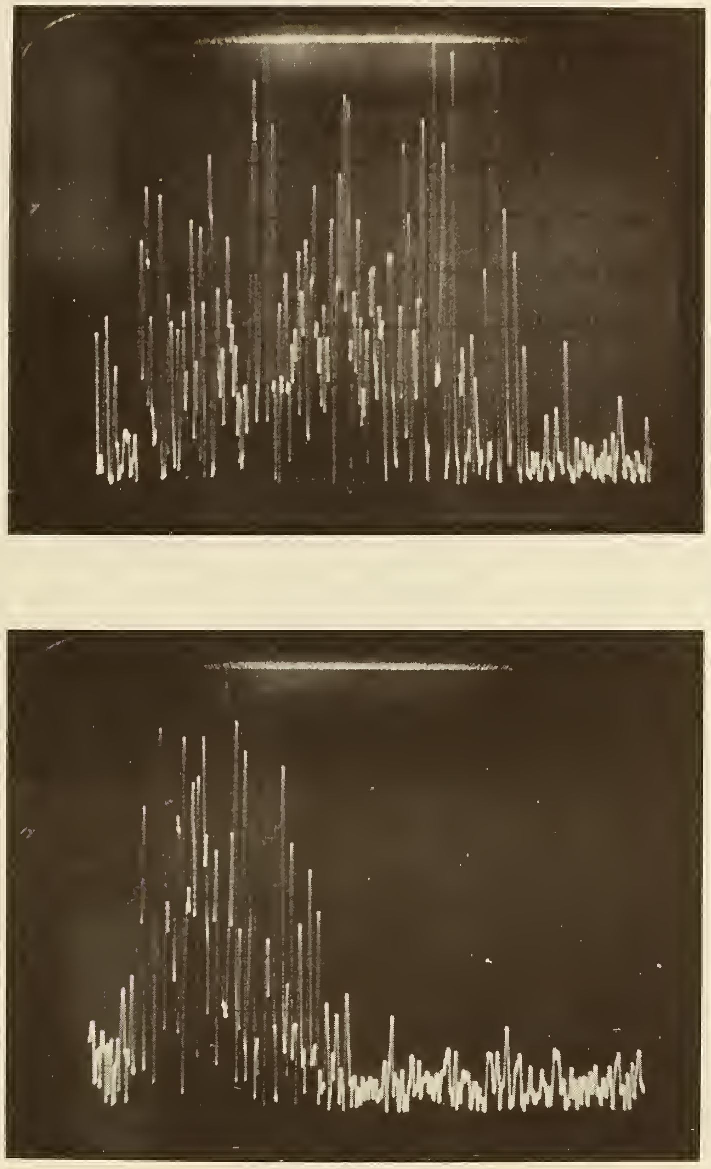


Figure 13. RF power spectrum on analyzer B of beat between laser and multiplier chain B when laser is (a) free running and (b) phase locked to chain A. Dispersion is 500 Hz/cm, bandwidth is 100 Hz, and sweep rate is 0.1 s/cm.

of a 118-MHz quartz crystal oscillator, a phase locked X-band klystron, and a phase locked E-band klystron. The results (shown in Fig. 13) while not spectacular, do indicate that the laser linewidth has been narrowed. Further, problems formerly resulting from slow drifts in the laser frequency are now controlled by the reference, and cycle counting techniques can be used to monitor the frequency of the HCN laser. The computing counter has been programmed to display the laser frequency based upon its measured values for frequencies of the X-band signal and the beat frequency signal (0.891 vs 12 x 0.074 THz).

5. DISCUSSIONS

In addition to being a useful method of stabilizing the HCN laser, the phase locking technique also facilitates a diagnostic technique for determining some of the sources of noise modulation of the laser frequency. As an example, see Fig. 14 which shows photos of traces of the Fourier components of the phase lock correction signal for a series of different changes in the overall system. At the start of the experiment the laser was locked to a phase-locked reference, using controller A for the phase lock correction, and the isolation table was inoperative. The PZT driver was connected to the end mirror. Figure 14a shows 0- and 360-Hz calibration signals

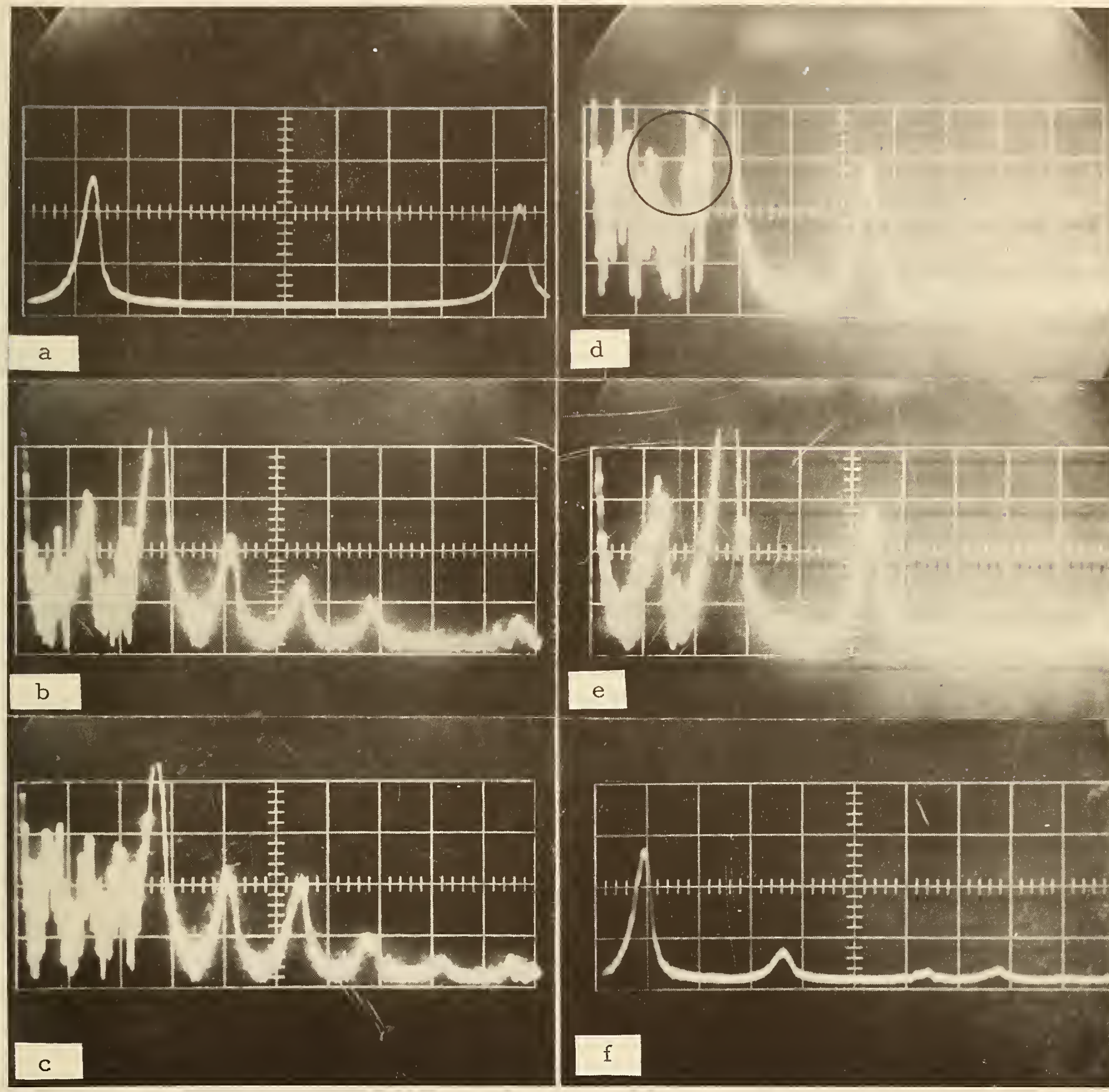


Figure 14. Spectrum of phase lock correction signal under various experimental conditions more fully described in text. a) Calibration marks at 0, 360 Hz. b) Combination ps-scc-A (power supply and series current controller - A) X-band is phase locked. c) ps-scc-A, X-band is cavity stabilized. d) (same as c) except PZT driver is turned off. e) (same as d) except ps-scc-A has been replaced by combination B.

for reference, and Fig. 14b shows correction components at start of experiment. In Fig. 14c, a cavity stabilized klystron was substituted for the phase locked reference; the signal has not changed appreciably. However in Fig. 14d, the PZT driver has been turned off. Gone are the components at 120 and 240 Hz. These were due to 2nd and 4th harmonics of a 60-Hz extraneous signal in the PZT driver. The 3rd harmonic was possibly of such phase that it partially cancelled the 180-Hz component which now appears enhanced. Note the encircled region below 60 Hz which has disappeared in Fig. 14e when isolation table is operative. In Fig. 14f, a new power supply and current controller are put into use and the large 60- and 180-Hz components are no longer present. The correction signal was examined up to 20 kHz, however no appreciable components were found at higher frequencies. Figures 15-17 give details of some of the circuits used in the frequency control equipment.

The techniques described have been recently extended to an 8-m HCN laser, and we are currently operating with only a phase lock correction. Lock times appear sufficient for most of our current experiments.

The stability of our present reference is a part in 10^{10} for 1 s averaging time. Further, since the laser is phase locked to the reference, we can use cycle counting techniques (which are especially convenient with the aid of a programable computing counter) to display its frequency on the counter.

We have demonstrated that the phase of a laser signal can be made to follow quite closely the phase of a reference signal synthesized from the microwave region. The microwave reference could be a superconducting cavity stabilized oscillator for best stability in short-term (narrowest linewidth) coupled with a cesium beam primary frequency standard for highest accuracy and for best long-term stability. We point out that the stabilized laser system which we have described can facilitate greater accuracy in infrared frequency synthesis and measurements.

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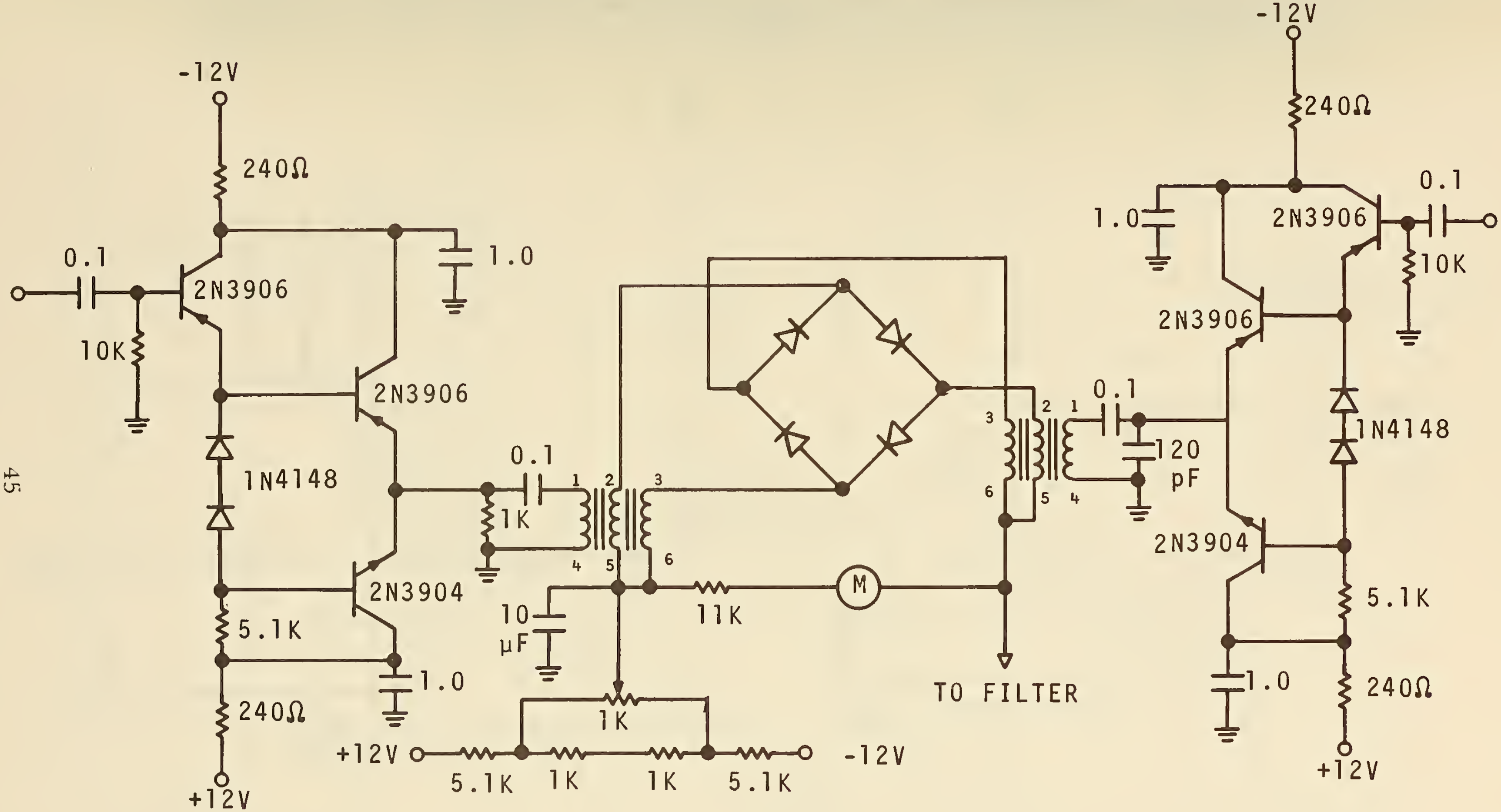

Figure 15. Phase detector circuit used in HCN stabilization. (Courtesy of L. Wood).

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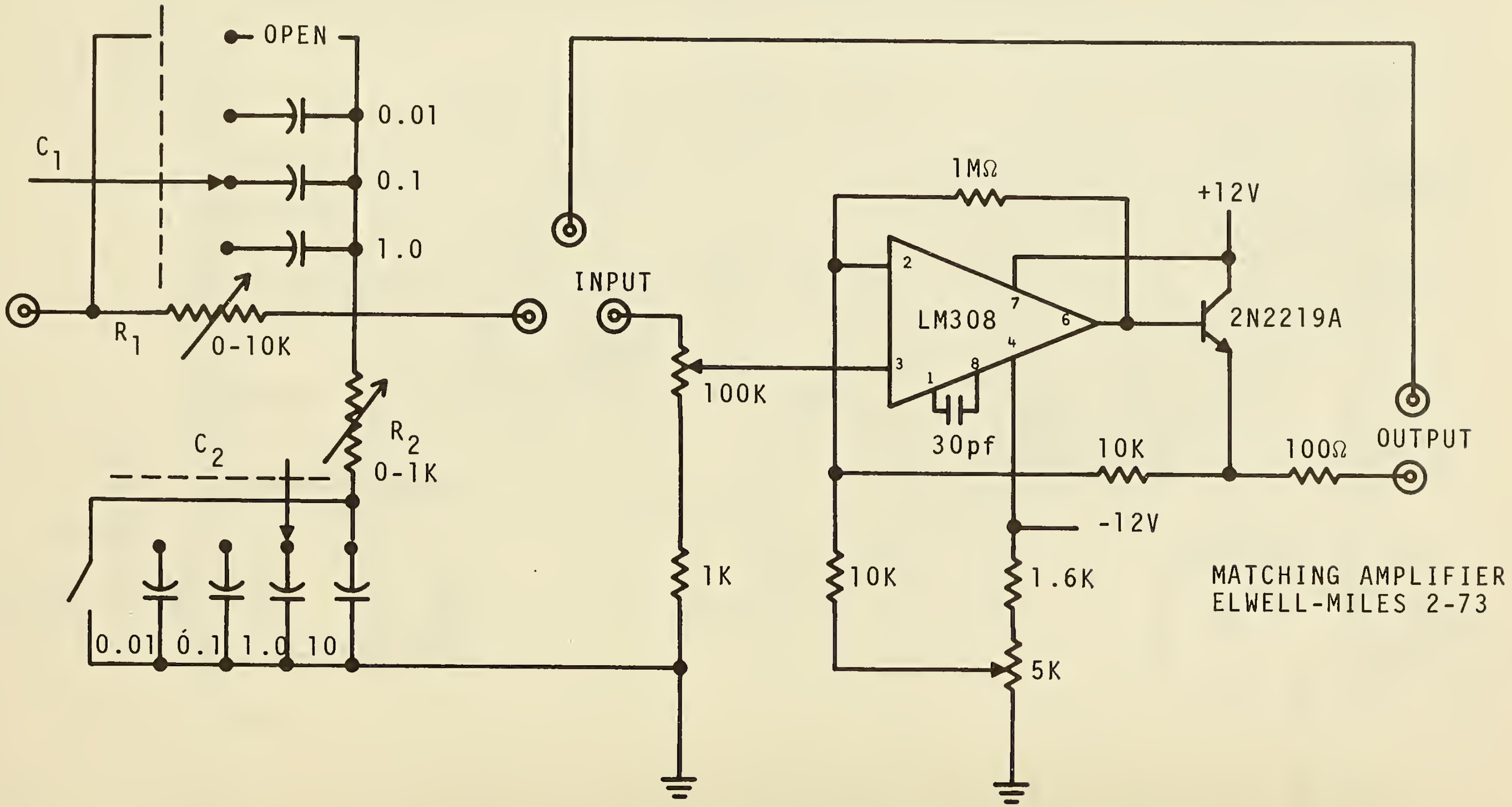

Figure 16. Filter and impedance matching circuit connecting phase detector and series current controller.

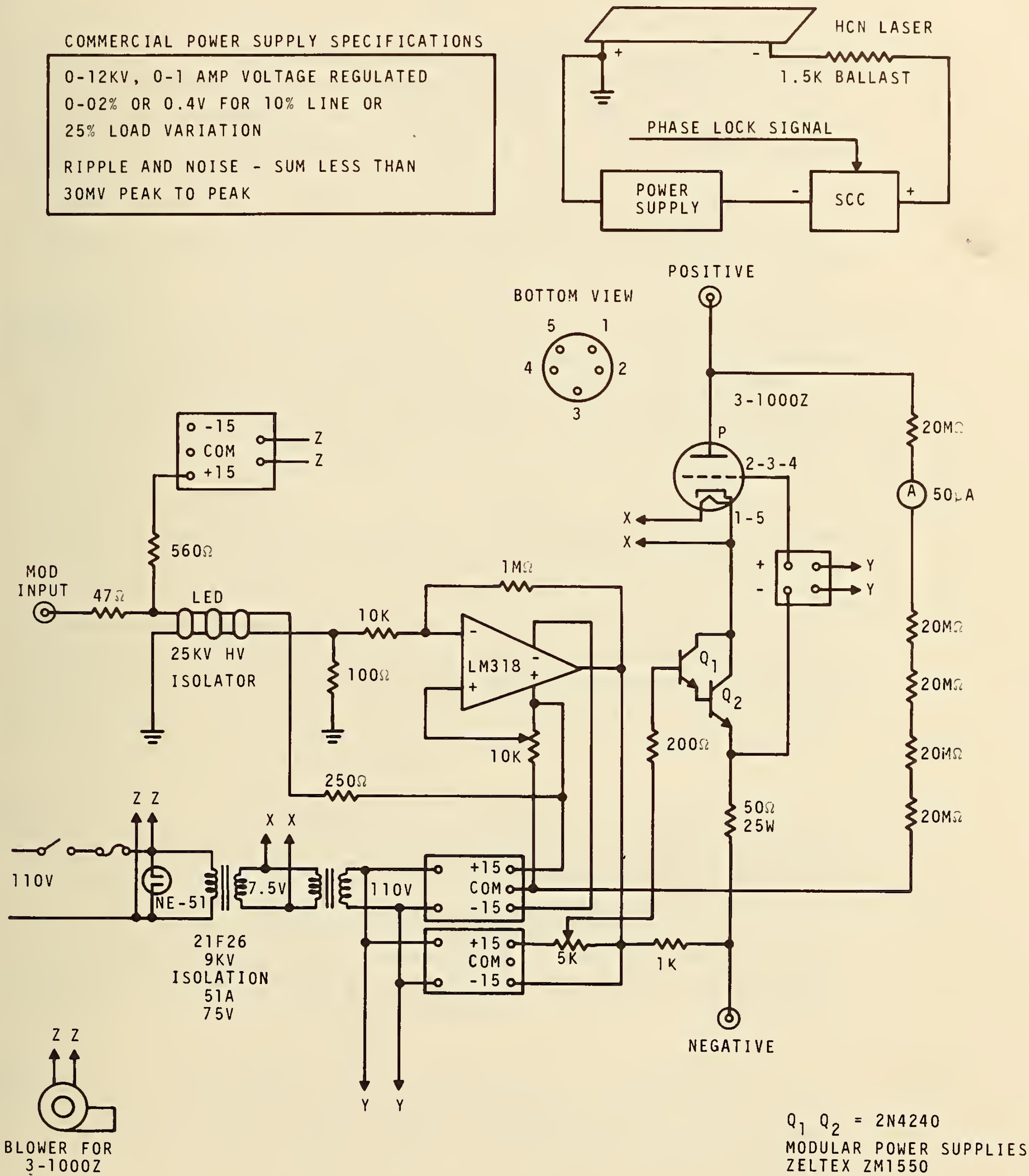

Figure 17. Circuit for series current controller (SCC). Skudler-Elwell 9-72.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Infrared frequencies as high as 88 THz have recently been synthesized using diode harmonic mixers with accuracies of parts in 10^9. Stabilized lasers are needed to make frequency measurements of higher accuracy. The HCN laser is the lowest frequency basis laser used in these synthesis schemes and its stabilization has been the subject of recent interest. The laser is stabilized by locking it to a phase locked microwave reference chain. Two servo loops are utilized. The first loop is a relatively slow frequency lock loop with the correction applied to a PZT driver. This loop not only accommodates thermal expansion of the laser, but also serves as an acquisition aiding loop for the second servo. The latter is a phase locked system with the correction applied to the laser discharge current.

Details of the laser design and some noise considerations relative to the microwave reference chain are presented along with some experimental data which indicate the results of the stabilization techniques. Data regarding the system stability and improved fast linewidth are included.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Fast linewidth; Frequency noise; HCN laser; Infrared frequency synthesis; Laser frequency measurements; Laser linewidth; Laser stabilization; Phase locked laser.

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