LONG WAVELENGTH $Pb_{1-x}Sn_xSe$ AND $Pb_{1-x}Sn_xTe$ DIODE LASERS*

AS LOCAL OSCILLATORS

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SUMMARY

A breadboard heterodyne receiver is described which has been used to establish the characteristics of lead salt diode lasers pertinent to their use as local oscillators using laser devices operating in the 15-25μm spectral region. Heterodyne detection efficiency has been directly correlated with the transverse mode structure and emphasizes the necessity of stable lowest order mode operation for lasers when used as local oscillators. The results obtained indicate that the continued development of these lasers will provide suitable local oscillators for a variety of applications.

INTRODUCTION

The ability to operate $Pb_{1-x}Sn_xSe$ and $Pb_{1-x}Sn_xTe$ diode lasers at any given frequency over a wide wavelength range (approximately 7-30μm) with a narrow linewidth has resulted in their application to high resolution infrared absorption spectroscopy. These same features provide the basis for their use as local oscillators in heterodyne receivers. However, additional characteristics are required of lasers used as local oscillators which are relatively unimportant in the usual incoherent (direct) detection mode of operation employed in absorption spectroscopy. In particular, the transverse mode structure and mode stability play a key role in the ability of the laser to provide quantum noise limited performance. Diode lasers which operate in the lowest order $TE_{0,0}$ mode provide excellent heterodyne mixing efficiency while those operating in higher order modes are typically inefficient and frequently unstable. These characteristics are of prime importance for heterodyne detection but have little influence on direct detection.

In the following sections, the laser power and mixer characteristics required for optimum heterodyne receiver sensitivity are summarized. The breadboard heterodyne receiver developed for the operation and characterization of lead-salt diode lasers as local oscillators is described in detail and results obtained on commercially available diode lasers presented.

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HETERODYNE SIGNAL-TO-NOISE RATIO

The current signal-to-noise ratio of an optical heterodyne receiver including polarization loss is given by (Ref. 1)

$$\frac{S}{N} = \frac{\left(\frac{\eta e}{h\nu}\right)^2 P_S P_{LO}}{\alpha e \frac{\eta e}{h\nu} P_{LO} B_1 (1 + \eta n_b) + \frac{4kT_N B_1}{G^2 R_A}} \left(\frac{B_1}{B_2}\right)^{\frac{1}{2}} \quad (1)$$

The numerator is the rms current resulting from the mixing of the signal power, P_S, with the local oscillator power, P_{LO}, followed by second detection. B_1 is the bandwidth following the first detector (IF) and B_2 that following the second detector; their ratio represents the signal-to-noise ratio improvement possible through the use of second detection with integration. The denominator contains the shot noise of the local oscillator and a thermal noise term, α equals 2 for a photodiode and 4 for a photoconductor, G is unity for a photodiode and is the photoconductive gain for a photoconductor, η is the mixer quantum efficiency, T_N and R_A the IF amplifier noise temperature and input impedance, respectively, e the electronic charge, k Boltzman's constant, h Planck's constant, and ν the frequency of the radiation. The term n_b is the number of background photons which are in a single spatial mode and within the IF bandwidth B_1 (and which therefore may interact coherently with the local oscillator), and is equal to $(\exp(h\nu/kT) - 1)^{-1}$ where T is the temperature of the background blackbody radiation. Equation (1) considers local oscillator shot noise (only) but does not include any excess noise, and assumes perfect wave-front matching of the signal and local oscillator beams at the mixed. The signal-to-noise degradation resulting from a wave-front mismatch has been treated elsewhere (Reference 2) and is not considered further here. It can be seen that in order to achieve quantum noise-limited operation with a heterodyne receiver, using an idealized local oscillator, the shot noise generated in the mixer by the local oscillator must exceed the thermal noise in the following amplifier. The local oscillator power P'_{LO} required to make these noise contributions equal is

$$P'_{LO} = \frac{4k}{e} \frac{h\nu}{\eta e} \frac{T_N}{R_A} \frac{(1 + \omega^2\tau^2)}{\alpha G_o^2} \quad (2)$$

The power requirement for the laser is a function of the mixer element characteristics and the application, in particular, the IF bandwidth requirement. Diode lasers developed to date have been relatively low power devices (<<1 mW per mode), necessitating optimization in mixer and amplifier selection for a given application. For a variable local oscillator power P_{LO}, the receiver will approach quantum noise limited operation as $(1 + P'_{LO}/P_{LO})$. The actual signal-to-noise ratio achieved depends largely on such inherent laser characteristics as excess noise (mode instability) and transverse mode structure (mixing efficiency) and operational factors such as temperature stability and vibration (shock) isolation, both of which affect the frequency stability. The low diode laser powers available in a single longitudinal mode during the course of this investigation dictated the use of photoconductive mixer elements and relatively low IF bandwidths. Photoconductive HgCdTe mixers were used between 10 μm and 17 μm and Ge:Cu for the longer wavelengths.

DIODE LASER HETERODYNE RECEIVER BREADBOARD

The laser characterization and heterodyne measurements were obtained using the apparatus shown in Figure 1. This system was used for the evaluation of diode lasers produced at Laser Analytics, Inc. (Bedford, MA) and New England Research Center (Sudbury, MA) operating in the 10-25 μm spectral region. The apparatus was also used for blackbody and molecular line radiation heterodyne measurements, and heterodyne detection of semiconductor laser emission at 23 μm and 10.6 μm.

The optics are all reflective (except for KRS-5 lenses in the frequency control loop and in the near-field measurement optical legs) which permits the receiver to be used over a wide wavelength range without refocusing, including the visible for alignment. The entire optical path can be enclosed with a plexiglass cover (not shown) and the system purged with dry nitrogen to eliminate atmospheric absorption. The lasers examined did not exhibit high beam divergence in a given single mode. This is as expected because of the long diffusion lengths and high refractive index in the Pb salts. Thus, the f/2 collection optics were more than adequate. The optical transfer system shown in Figure 1 matches the f/8 monochromator optics. The monochromator is used for spectral analysis and longitudinal mode isolation. The grating in the monochromator can be easily bypassed by a mirror which is used mainly for initial laser alignment. The radiation from the monochromator is collimated by a 4-in. focal length, off-axis, parabolic mirror to reduce the size requirement on the beam splitter. The beam splitter for the 15-μm spectral region consists of ZnSe 50% reflecting on one surface (at 45^{o} angle of incidence) and antireflection coated on the other which is optimum for the weak signal case. Far-field radiation measurements are made in this collimated beam using a small area HgCdTe or pyroelectric detector mounted on an automated x-y stage which samples the cross section of the beam intensity profile. (Far-field measurements were also made at a distance of several centimeters from the diode laser, using no additional optics.) The X10 beam expander is employed to provide a convenient working distance to the focal point of the f/2 focusing mirror. The laser radiation transmitted by the beam splitter is passed through a 1-in. long solid germanium etalon (when used) for accurate tuning rate measurements and the radiation is also passed through a gas absorption cell which is used for accurate laser frequency measurements (referenced to a known absorption line) and for high-resolution spectroscopic measurements (including pressure broadening studies). This signal path also forms one leg of the frequency control loop which will be described below. The signal leg of the receiver can employ a blackbody source (operable in the Dicke switch mode), a heated gas emission cell (which can be operated in the heterodyne absorption mode by use of a blackbody source behind the cell), or a second laser at the positions shown in Figure 1. The emission cell was designed to have a low emissivity. Near-field (mirror radiation) and polarization measurements have also been made as shown.

The major electronic components of the receiver are the laser driver, mixer, IF amplifier chain, and the frequency stabilization control loop. The components and circuits have been custom designed when necessary. All other components involve commercial instrumentation (IF amplifier, spectrum analyzer, lock-in detectors, etc.). The laser driver was designed for low-noise, low-drift output. A measured noise level of 20 μA rms was achieved. Two drivers were built: a manually operated unit for general utility and a remotely controlled unit for use with the stabilization control loop. The Amplica 201 VSL IF amplifier used was thoroughly characterized having 5- to 110-MHz bandwidth, 1.2-dB noise figure, and 50-dB gain. This amplifier was used with the wider bandwidth Ge:Cu mixer. A Plessey SL1205 low noise preamplifier was used with the HgCdTe mixer. This amplifier was specifically designed for use with a HgCdTe detector having a 50-dB gain (nominal), a 6.5-MHz bandwidth and a 0.8 $nV/\sqrt{Hz}$ equivalent input noise voltage. In the direct detection mode, the output of the detector (mixer) circuit is connected directly to a lock-in amplifier and is used to monitor the laser mode power. In the heterodyne mode, the output of the IF amplifier is passed through a second detector which is referenced to the Dicke switch. The output of the IF amplifier can be directly connected to a spectrum analyzer for signal frequency analysis.

The mixers used in the 15 μm spectral region were photoconductive HgCdTe 75 μm and 150 μm square elements mounted on a common heat sink. The peak spectral responsivity occurs at 14.3 μm with good response to 16.5 μm. The 40 nsec response time measured by the manufacturer (SBRC) using an InAs emitter was verified by the generation-recombination (g-r) noise roll-off frequency displayed on a spectrum analyzer and shown in Figure 2. This also demonstrates that the particular diode laser used was capable of generating a g-r noise level that exceeded the amplifier noise. The lifetime of this particular detector was the shortest available in high quality material. It may be possible to reduce the lifetime by compensation to provide a mixer with a wider bandwidth and flat response to higher frequencies, but this is advantageous only when increased laser powers become available. The breakdown field was measured to be 40V/cm which is sufficiently high to ensure attainment of the saturated drift velocity conditions at operational electric fields. The detector properties as a function of bias and background flux as well as responsivity were used to calculate the quantum efficiency ($\eta = 0.6$). The detector impedance is approximately 30 Ω (depending upon bias) and is relatively well matched to the IF amplifier.

The mixer element used for the 23-μm spectral region was Ge:Cu. The lifetime and quantum efficiency were determined from measurements of the responsivity, D^*, and detector resistance at known background flux levels and as a function of bias field. This particular element had an interelectrode spacing of 0.0152 cm, a quantum efficiency of 0.15, a lifetime of approximately 5 nsec, and a saturated drift velocity of 5×10^6 cm/sec, resulting in a photoconductive gain of 1.64. The detector impedance at the flux levels during the experiments was approximately 1 MΩ. This high impedance level resulted in poor coupling to the 50-Ω IF amplifier used (Amplica 201 VSL) and nonlinear response over the amplifier bandwidth. The best 22 μm laser did, however, induce sufficient shot noise to exceed the amplifier noise, as observed on a spectrum analyzer, and provided a good blackbody heterodyne signal-to-noise ratio.

FREQUENCY STABILIZATION AND CONTROL

A significant advantage of a diode laser LO heterodyne receiver over fixed frequency laser systems is the capability to be operated at any frequency in the 3- to 30-μm spectral region. Laser operation at a specific frequency is principally a function of the laser chemical composition, temperature, and drive current. A diode laser can be easily tuned (continuously over a 30-GHz range, for example) by simply changing the laser drive current. This versatility of diode lasers has a price, expecially when used in a heterodyne application for the detection of molecular line radiation. Since the diode lasers are relatively low-power devices and efficient long wavelength infrared mixers presently have modest bandwidths, the laser must be operated close in frequency to the source of interest (within a few hundred MHz, for example) and must be stable to within a few MHz. This requirement makes frequency stabilization and control an important issue. Once the composition and nominal operating conditions have been established for a given device, the problem reduces to operation at a specific frequency with a given frequency stability. Since the laser tuning rates are typically 100 MHz/mA and 100 MHz/mdeg, close control of these parameters is essential. In principal, the absolute laser frequency can be determined by mixing the diode laser frequency with another fixed-frequency laser or harmonics of microwave devices in point contact devices. This technique is considered to be complex, inefficient, and unnecessary for many applications. The use of a secondary frequency standard is considered to be adequate. This standard can be simply a vapor phase molecular absorption which is at (or near) the line of interest. This absorption need not even occur in the same molecular specie as the line radiation of interest, but must be able to be established (isolated) to the required accuracy. Given such an absorption, the frequency stabilization technique investigated during this program involved operation of the desired laser frequency on the edge of the absorption line and use of an electronic feedback control of the laser drive current to maintain the laser output at the desired frequency.

A laser frequency stabilization and control loop was designed, fabricated, and tested. Two techniques were investigated; both are based on the stabilization of the laser frequency on the slope of a reference molecular absorption line. The first control loop utilized a single detector; the second used two detectors. The single mode selected by the monochromator is passed through an absorption cell whose line width can be pressure broadened from the Doppler limit to a few GHz. With the laser diode tuned to a frequency approximately half-way down the absorption line edge, the output voltage of a detector sensing this power transmitted through the absorption cell will increase or decrease proportionately with diode frequency, provided that there is no change in the laser power. The change in detector output is fed back through a controller to change the diode laser current and, therefore, its frequency. This will return the diode frequency to the original value selected on the absorption line. Fluctuations in diode power output will cause errors in the frequency change measurement and an independent measurement of power must be made.

The electronic system based on the single detector technique was bench tested to ensure proper operation of the controller. At this stage of the program, the experimental effort concentrated on the 23-μm spectral region. The frequency control loop was, therefore, operated on the slope of an H_2O absorption line using a diode laser which could be tuned to the absorption line (although the laser power was relatively low at this particular frequency). The performance of the control loop in terms of frequency stability could not be satisfactorily evaluated due to large detector amplitude fluctuations caused by the reflective chopper wheel used in this mode of operation. The metallic wheel was found to have several distorted blades which caused the focused image at the detector to be displaced on and off the detector element. The resulting noise level of the system was too large for effective operation of the control loop. A second system was constructed which made use of two detectors rather than one. The basic principle is the same as for the case of a single detector; the difference is in the complexity of the detailed electronics. The loop was tested electronically but not operated with a laser.

It should be pointed out that considerable effort has been applied to the passive frequency stabilization of the laser output. For example, the laser current source (drive) provides a low-noise, low-drift output and the liquid helium Dewars used for laser cooling have been superinsulated to minimize varying external heat loads. The mechanical refrigerator (Air Products Model CS 202-modified) has a specially designed thermal dampener to reduce temperature fluctuations caused by the piston cycle. Indirect frequency stability measurements of the laser output in the closed cycle refrigerator show that frequency variations greater than a few MHz did not occur in general, although significant laser amplitude (power) fluctuations at the mixer can occur for a poorly mounted refrigerator in addition to excess laser noise induced by the mechanical refrigerator. (Fig. 3 shows a Doppler limited line width was achieved in CO_2.) These amplitude fluctuations were the result of a physical displacement of the laser and its conjugate image at the small mixer element used and were minimized by proper mounting arrangements. In all the measurements to be reported, the only active laser frequency control loop involved temperature stabilization of the mechanical refrigerator.

A more direct measure of the frequency stability attainable using these techniques is shown in Fig. 4. The heterodyne beat note obtained using a CO_2 laser as the local oscillator and a diode laser operating in the modified refrigerator as the signal source is shown. The line width remained unchanged when the refrigerator was turned off and the line position swept thru the IF bandpass as expected. The observed line width of approximately 5 MHz indicates excellent frequency stability.

MECHANICAL REFRIGERATOR MODIFICATION

The manufacture of a diode laser operating at a specific frequency is a time-consuming process. Crystal growth, annealing, junction formation, contacting, and yield limit the number of devices that can meet a given specification. In order to increase the usefulness of a given device's chemical composition and, therefore, reduce the fabrication complexity, lasers are operated in mechanical refrigerators which provide additional convenient (temperature) tuning capability. The use of such a cooler, however, can introduce additional unwanted mechanically induced laser noise. Quantitative measurements were made of the shock and vibration effects in the Air Products refrigerator. The displacment of the cold head due to the piston motion was measured to be 0.015 cm (0.006 in) using a capacitance technique. Shock effects were investigated using an accelerometer attached to the cold head. The data were acquired and analyzed by a Hewlett-Packard 5450A Fourier Analyzer. A typical spectrum and its Fourier transform are shown in Figures 5 and 6 respectively. The analysis shows a relatively complex spectrum having a peak value of approximately 8g with a major component at 1500 Hz. The results of these data were used in the shock/vibration isolator design. This design is similar to that used by Dr. Jennings at NASA Goddard Space Flight Center (Ref. 3), but is more versatile in providing five degrees of freedom in the laser positioning, which we have found to be necessary to provide the proper alignment of the laser in the optical system.

The effectiveness of the shock isolation can be seen from a comparison of Figures 7 and 8. Identical accelerometers were placed on the cold head and the modified laser mount. Figure 7 shows the accelerometer output at the refrigerator cold head and Figure 8 the corresponding data at the modified laser mount. A dramatic decrease in the peak g-value is to be noted as well as a reduction in the high-frequency content. A total of six laser mounts were made to accomodate all presently existing laser package designs and comparative accelerometer data were obtained.

The laser measurements taken with the modified refrigerator included a comparison of the direct detected laser power level (in a given longitudinal mode), the second detection (IF noise) level, and low-temperature blackbody heterodyne SNR measurements when possible. The magnitude and noise level of the IF signal (and, therefore, heterodyne signal-to-noise ratio (SNR)) is a strong function of the longitudinal mode stability which depends upon the laser operating conditions. The SNR attainable for the heterodyne detection of thermal radiation can be directly related to the mode stability. Certain modes of a given laser are quite stable over a wide range of conditions and others are unstable under any condition. A comparison of the IF noise level produced by a laser when operated in the modified refrigerator and a liquid helium Dewar showed that the modification of the refrigerator greatly reduced the random (undesired) noise level but did not eliminate it; i.e., liquid cryogen cooling provides a better heterodyne SNR than mechanical refrigerator cooling. In any case, the modified refrigerator decreased the excess IF noise level to the extent that the inherent mode instability and poor transverse mode structure of the diode lasers become the major limitations in achieving near quantum-noise limited heterodyne performance.

LASER MEASUREMENTS

The diode lasers characterized and used during this program include lasers operating in the 23- and 15-μm spectral regions. Detailed measurements were made on more than 20 lasers. This section will report results obtained on selected devices which typify diode laser characteristics. The I-V characteristics of the lasers had series resistance (Rs) values from tens of milliohms to as high as 180 mΩ. Good I-V characteristics in general did not correlate with laser performance. As an example, lasers having the same Rs value would vary in output power by a factor of 10 and lasers exhibiting the well-known kink, supposedly indicating high radiative efficiency, frequently would have lower power than a laser with a more gradually rising I-V curve. Although a few lasers exhibited an extremely large number of longitudinal modes, a more typical behavior was three to six longitudinal modes operating simultaneously at current levels sufficiently above threshold to provide useful laser power levels. The typical continuous tuning range of a given mode for all lasers examined was approximately 1 cm^{-1} (30 GHz). The power output characteristic for a continuously tunable mode varied considerably. The output power peaked at any point in the range from lasing onset to the disappearance of the mode. The laser which gave the best blackbody heterodyne detection results showed efficient IF noise generation for all modes as shown in Fig. 9.

The beam divergence we have observed has varied from f/1 to f/10 with values larger than f/2 being more common. Some of the observed far-field patterns can be explained by a blockage (reflection) of a portion of the diverging beam by the heat sink, which is a fabrication problem and is not fundamental to the device. All the lasers examined to date are polarized in the plane of the junction and frequently in the lowest order $TE_{0,0}$ mode. The near-field (mirror radiation) pattern of two lasers selected at random showed only one active region and no evidence of filamentary action (which is understandable in light of the long diffusion lengths in the Pb salts).

The major emphasis to date in the development of the lead salt lasers has been concerned with increasing the total output power. Considerable success has been achieved in this area, particularly in the past two years. Output powers in the milliwatt range are common, compared with microwatt levels in the early stages of development. Although a sufficiently high power level is a necessary condition for a local oscillator source, it is not sufficient by itself. The power must be also available in a single longitudinal mode. Unfortunately, the presently available higher power lead-salt lasers exhibit a relatively large number of longitudinal modes, limiting the power available in a single mode. Furthermore, the laser emission radiation pattern frequently consists of several diverging lobes. The angular extent of a given lobe is relatively small as mentioned above, but the total angular extent may be large. This situation is shown in Fig. 10, which is the far-field pattern of a diode laser operating at 15.4μm (cw) obtained from a cross sectional scan of the output beam without using additional optics. Three lobes are evident and each, in turn, could be isolated by the monochromator by using the angular adjustments available in the modified refrigerator laser mount. Although f/1 optics can collect all of this emitted radiation, the available power in a single lobe (mode) is limited.

The lowest order TE mode is required for good heterodyne mixing efficiency and therefore the importance of the transverse mode structure of the laser in determining the mixing efficiency cannot be overstated. A typical result is shown in Figure 11. It can be seen that individual longitudinal modes have varying degrees of mixing efficiency; poor efficiency is correlated with a complex transverse mode structure of an individual longitudinal mode. This particular laser also exhibited significant excess noise resulting in a poor heterodyne signal-to-noise ratio as compared to theoretical predictions. The far-field intensity distribution for a relatively efficient mode is shown in Figure 12(a) and in Figure 12(b) for an inefficient mode. The plots represent a partial cross-sectional scan of the laser beam using a small detector in the collimated beam of the laser. Close inspection of Figure 12(b) reveals a more complex intensity distribution than that in Figure 12(a). These results are general: higher order transverse modes result in poor heterodyne detection efficiency.

The transverse mode structure of a diode laser is only of minor importance in high-resolution spectroscopy and has consequently received little attention in the manufacture of these lasers. In general, to ensure lowest order mode operation, additional optical and carrier confinement is expected to be required over that occurring in the simple diffused junction devices presently manufactured, although homojunction devices which operate in the lowest order mode have been produced which provide excellent heterodyne mixing efficiency. The nature of the mode instability (excess noise) is not well understood at present. It is possible that improvements in material uniformity and crystal perfection will relieve this problem. Self-beating effects have also been observed with individual longitudinal modes and may be due to Fabry-Perot cavity imperfections produced during the cleaving procedure to form the cavity. These effects result in excess noise in the detection process but do not occur for the majority of the modes and can frequently be minimized by changes in the operating conditions.

These results emphasize the importance of the cavity configuration of diode lasers to be used as local oscillators. It is essential that the cavity provide a minimum in longitudinal mode competition as well as a strong rejection of higher order transverse modes.

SUMMARY

A breadboard heterodyne receiver is described which has been used to establish the characteristics of lead salt diode lasers pertinent to their use as local oscillators using laser devices operating in the 15-25 μm spectral region. Heterodyne detection efficiency has been directly correlated with the transverse mode structure and emphasizes the necessity of stable lowest order mode operation for lasers when used as local oscillators. The results obtained indicate that the continued development of these lasers will provide suitable local oscillators for a variety of applications.

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3. Jennings, D. E.; and Hillman, J. J.: A Shock Isolator for Diode Laser Operation on a Closed-Cycle Refrigerator. Goddard Space Flight Center Document X-693-77-143, June 1977.

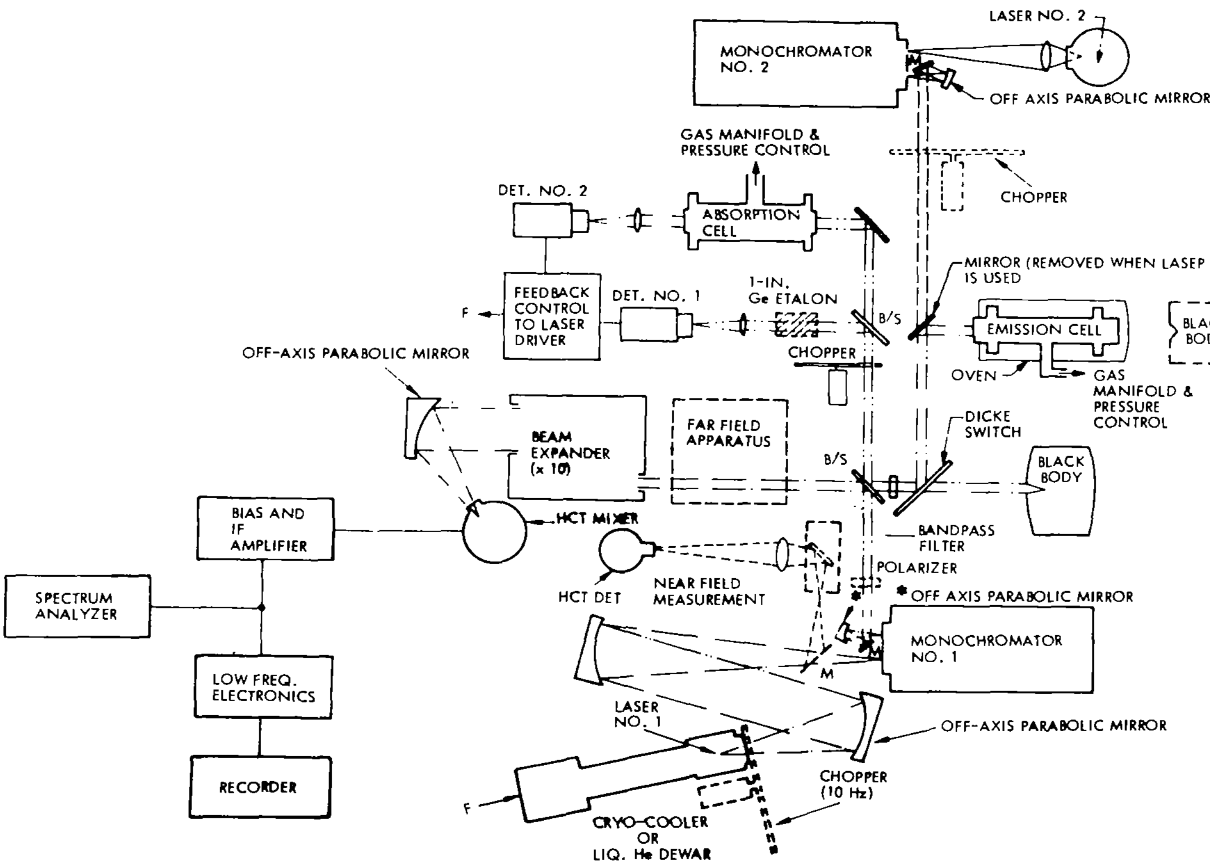


Figure 1.- Diode laser heterodyne receiver breadboard.

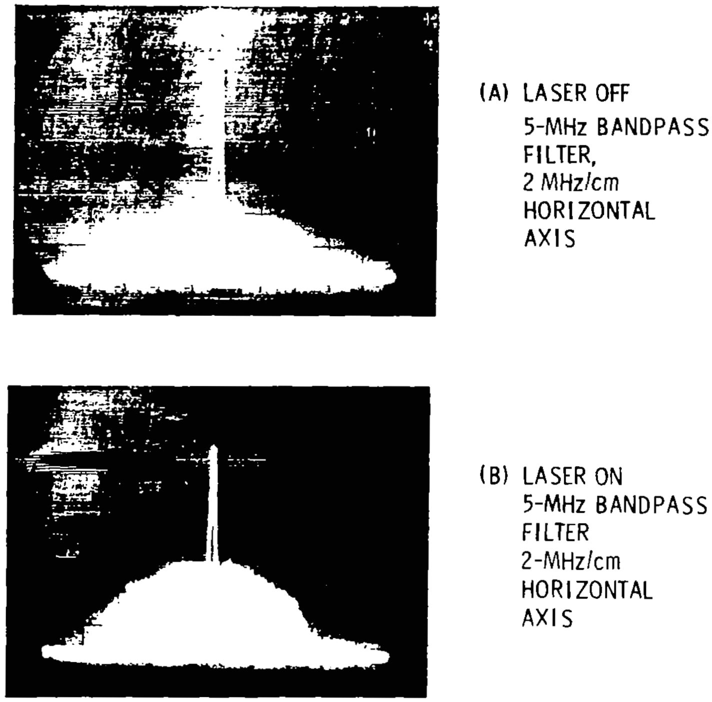


Figure 2.- Generation-recombination noise generated by 15-μm diode laser in HgCdTe.

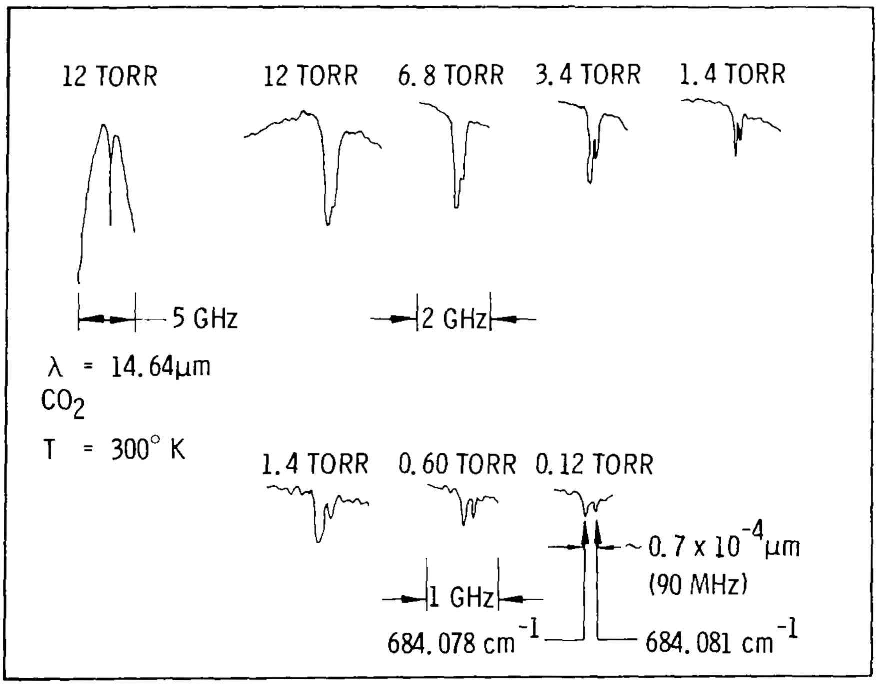
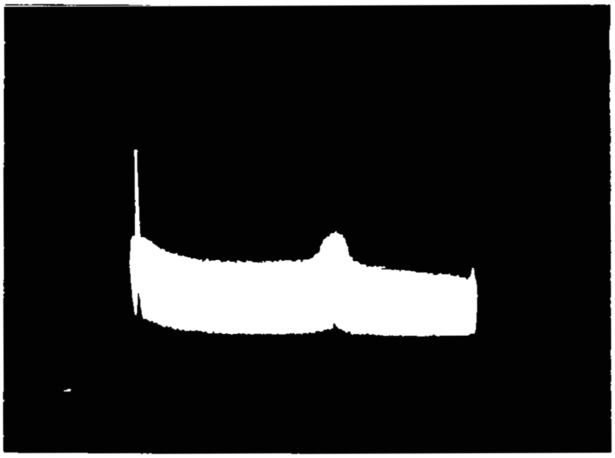


Figure 3.- Frequency stability measurement inferred from Doppler line width.



10 MHz PER DIVISION;
2-ms SWEEP

Figure 4.- Direct frequency stability measurement from heterodyne beat note.

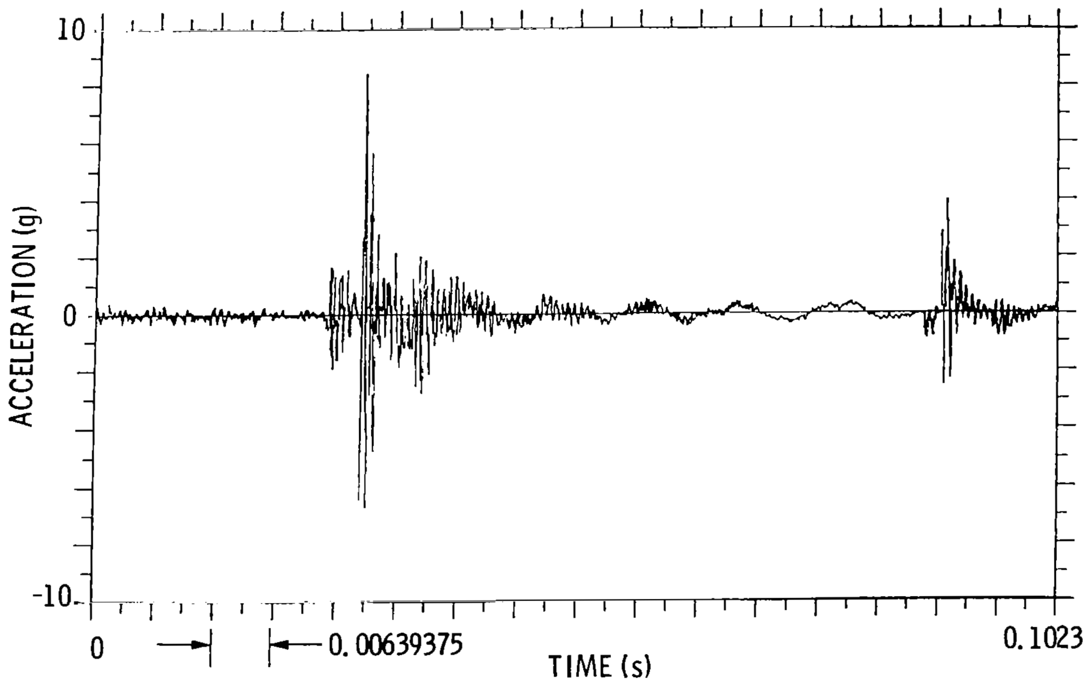


Figure 5.- Refrigerator accelerometer signal.

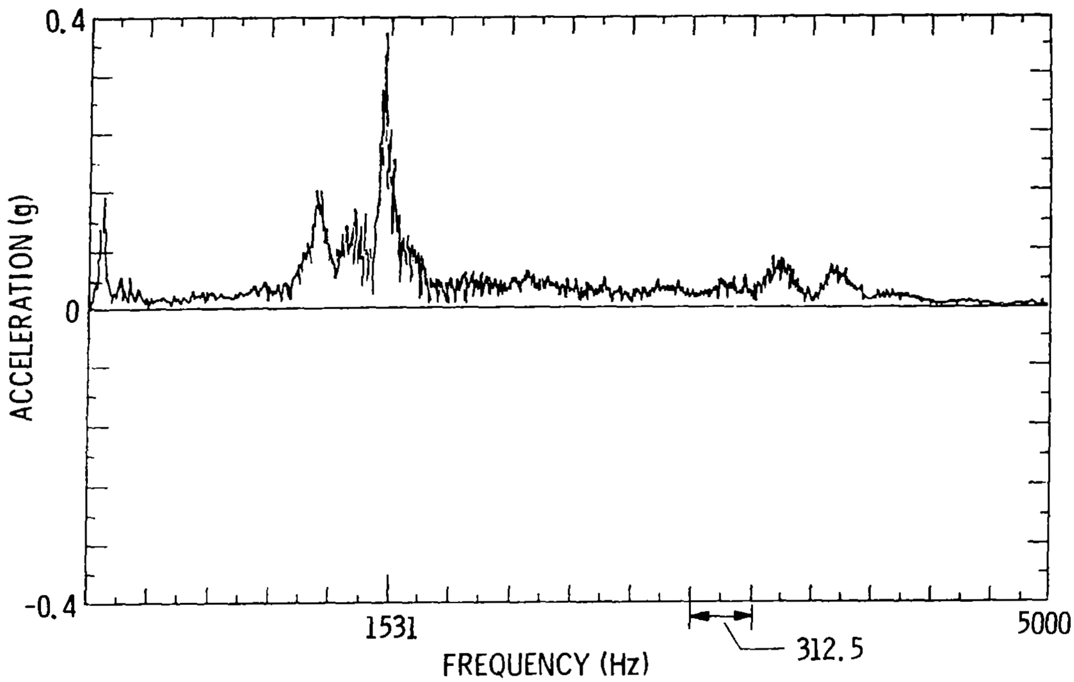


Figure 6.- Fourier transform of accelerometer output.

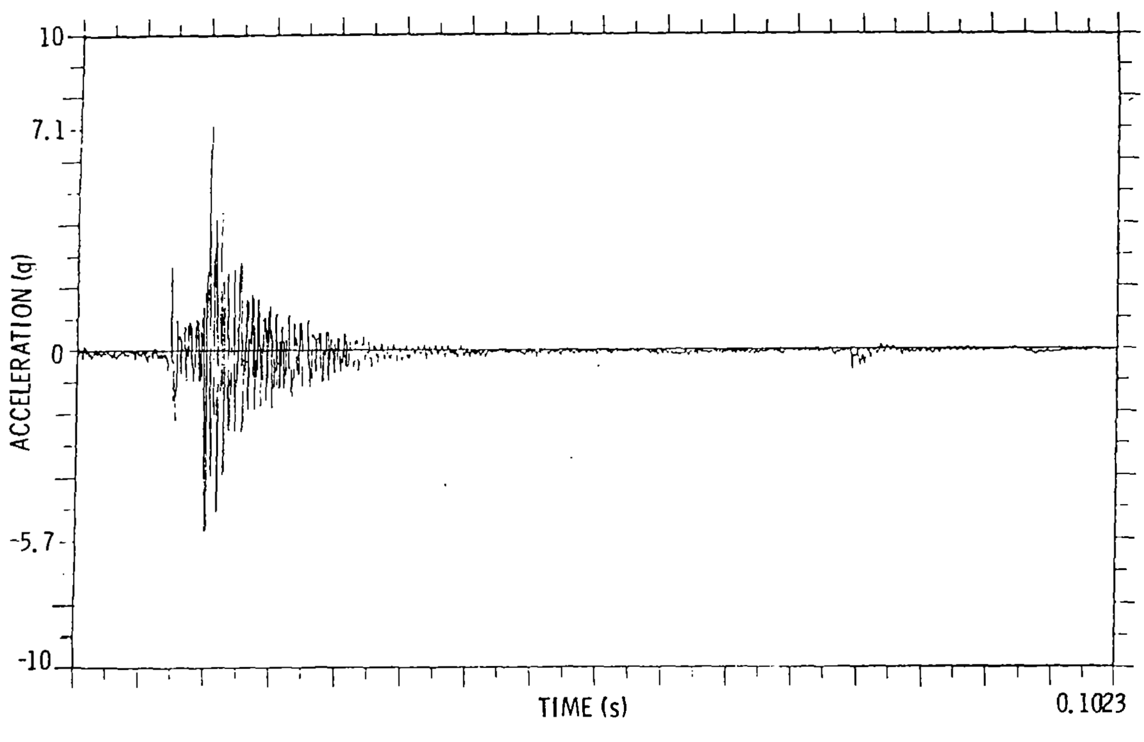


Figure 7.- Modified refrigerator accelerometer signal (at cold head).

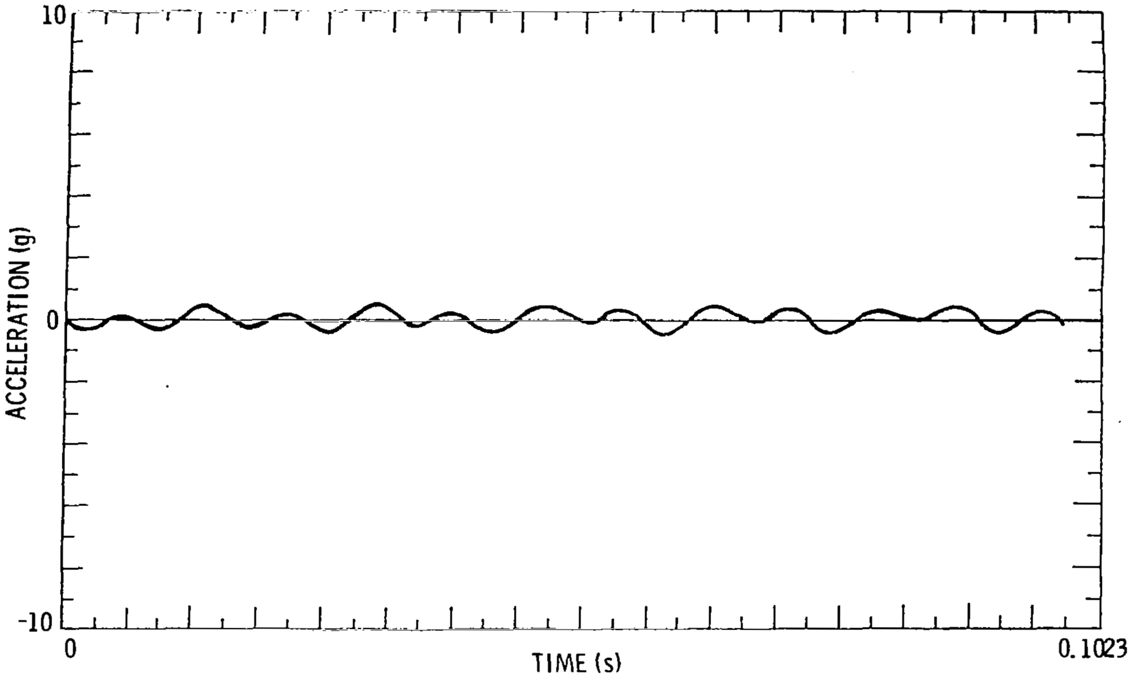


Figure 8.- Modified refrigerator accelerometer signal (at laser mount).

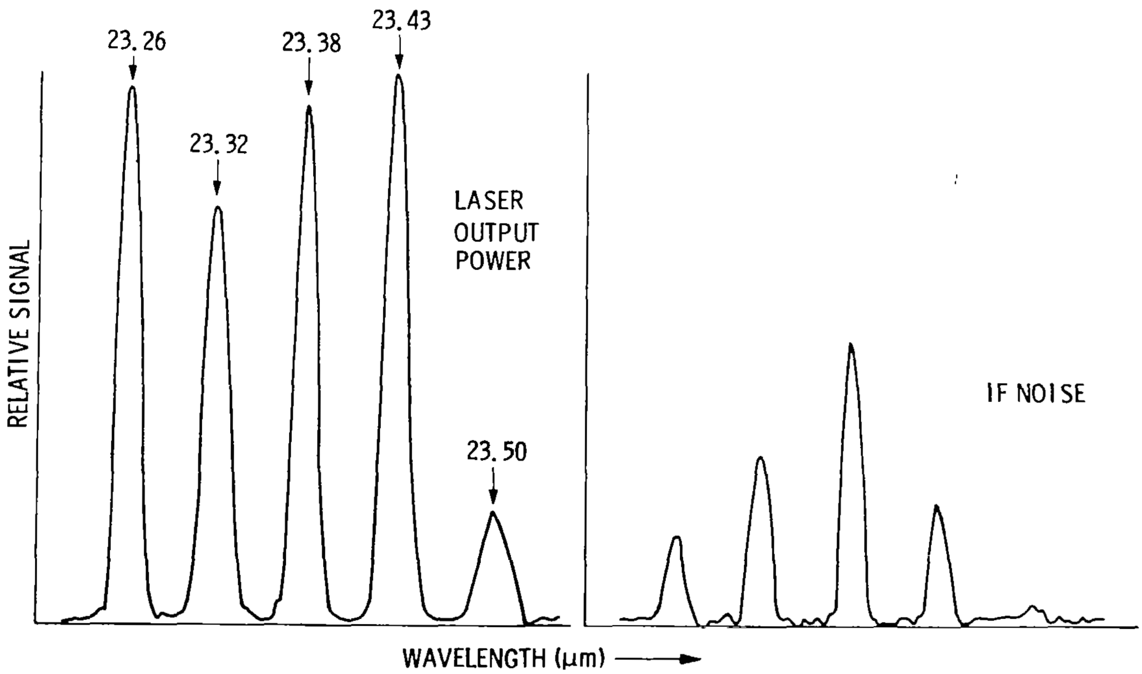


Figure 9.- Correlation of laser mode power and IF noise level.

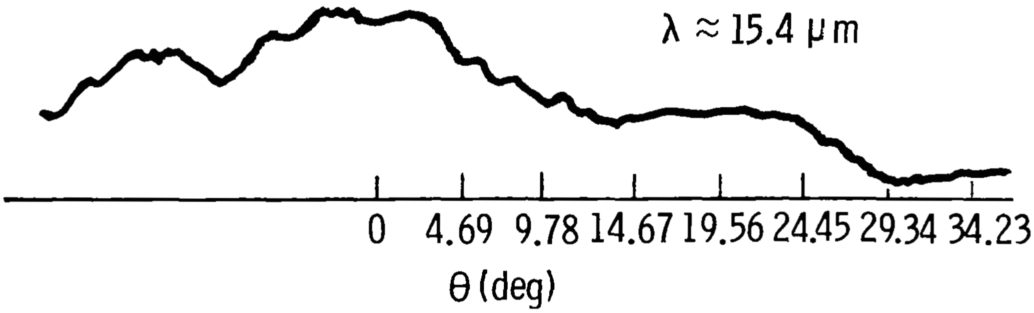


Figure 10.- Far-field beam profile (15-μm laser cw).

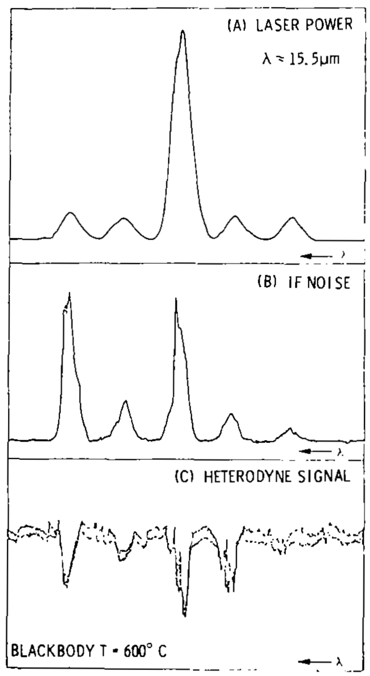
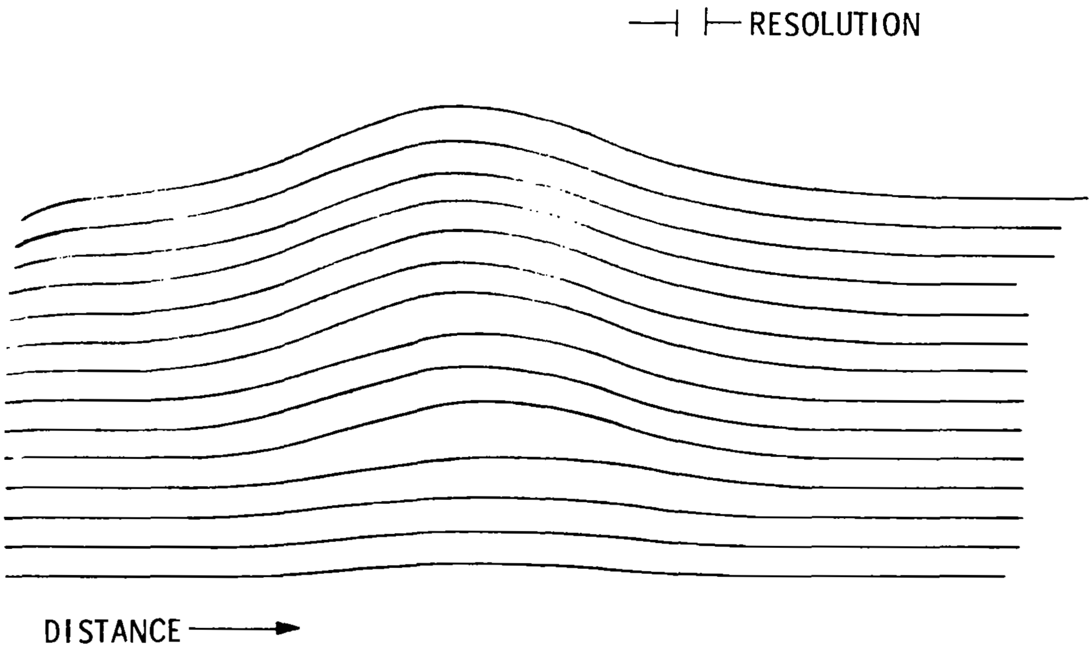
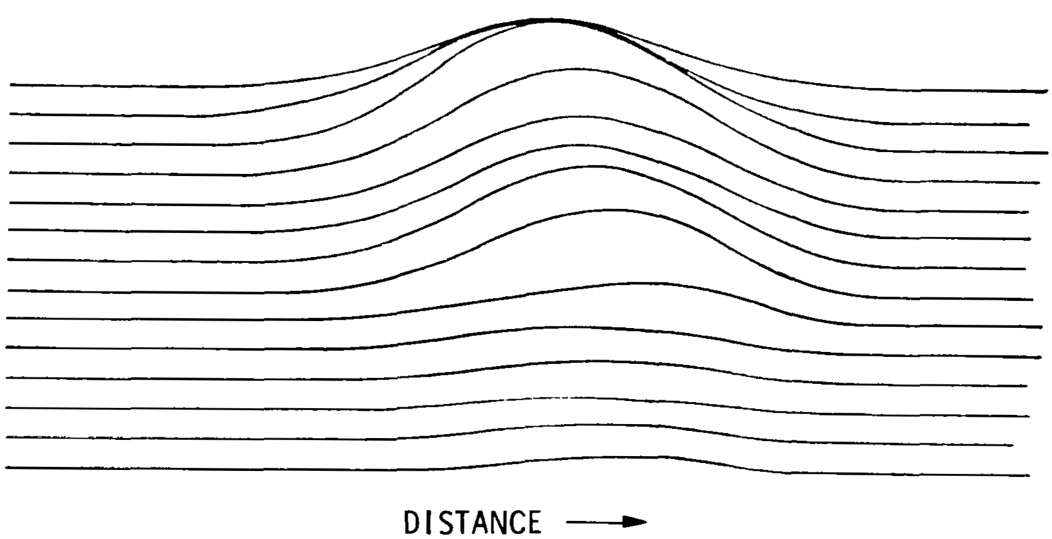


Figure 11.- Heterodyne spectrum as a function of laser power and IF noise level.



(a) Efficient mode.



(b) Inefficient mode.

Figure 12.- Laser far-field profile.