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Edited by

R. GRISAR, H. BÖTTNER, M. TACKE
Fraunhofer Institut für Physikalische Messtechnik, Freiburg, Germany

and

G. RESTELLI
*Commission of the European Communities,
Joint Research Centre - Environment Institute, Ispra, Italy*

LINE NARROWING AND FREQUENCY CONTROL OF LEAD-SALT DIODE LASERS BY OPTICAL FEEDBACK

M. MÜRTZ, M. SCHAEFER, M. SCHNEIDER, J. S. WELLS[1] and W. URBAN
Institut für Angewandte Physik der Universität Bonn
Wegelerstr. 8, D-5300 Bonn, F.R. Germany

U. SCHIESSL and M. TACKE
Fraunhofer-Institut für Physikalische Meßtechnik
Heidenhofstr. 8, D-7800 Freiburg, F.R. Germany

SUMMARY

We report on a frequency stabilization experiment with lead-salt diode lasers.
An optical feedback technique is used to narrow the diode laser linewidth. A small amount of laser light is retroreflected by an external feedback mirror. In this way narrowing of the linewidth by 2 orders of magnitude (down to 1-2 MHz) is achieved. Frequency stabilization and control of the diode laser is accomplished by frequency-offset locking to a sealed-off CO laser. TDL and CO laser outputs are heterodyned in a HgCdTe detector (1 GHz bandwidth). The resulting beatnote is employed to control the length of the external resonator via an electronic servo loop. The improved spectral properties of the diode laser provide a new tool for accurate frequency measurements and high-resolution sub-Doppler applications in the mid infrared.

1. INTRODUCTION

It is well known that diode lasers are extremely sensitive to small amounts of retroreflected light from external optical elements. Due to the low Q cavity and the strong carrier induced coupling between amplitude and phase of the electrical field, changes in the spectral characteristics of the diode laser occur even for power reflectivities less then 10^{-4}. Uncontrolled optical feedback e. g. from windows or lenses within the beam path can affect both frequency and amplitude stability. Often the sensitivity and resolution of a TDL spectrometer is limited due to optical feedback effects (optical noise).

In the past ten years there was an extensive investigation of effects induced by optical feedback with III-V semiconductor lasers in the near infrared (1)-(11). Stimulated by experiments on diode-to-fiber optical coupling, different groups experimentally investigated and theoretically analysed various feedback setups. Schemes utilizing feedback from mirrors and gratings as well as resonant feedback from a high-finesse cavity were studied. Depending on the feedback conditions (distance of reflector, reflectivity), people found different effects on the spectral properties of the laser radiation: changes of the mode

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[1]Permanent address: Time and Frequency Division
National Institute of Standards and Technology (NIST)
325 S. Broadway
Boulder, Colorado 80303 USA

characteristics, linewidth broadening, enhanced intensity noise, dynamical instabilities (coherence collapse, self pulsations) and also linewidth reduction. The latter, so-called optical stabilization, was obtained with single-mode GaAlAs type lasers coupled to an external high-finesse resonator. This is a powerful way to reduce amplitude and frequency fluctuations up to very high Fourier frequencies[2].

As much less effort has been put into the investigation of Pb-salt diode lasers with respect to III-V semiconductor lasers, their performance is still much worse. For instance lead-salt lasers mostly exhibit multi-mode operation due to their partly homogeneous and partly inhomogeneous broadend gain profile (spectral and spacial hole burning). The object of our investigation was to find out which behaviour is exhibited by lead chalcogenide homostructure diode lasers with optical feedback and whether it is possible to use controlled optical feedback to narrow the linewidth of these lasers. In the following, the experimental setup and the method of the linewidth measurements are described. The results of a line narrowing experiment with optical feedback from an external mirror are presented. Finally we report on stabilizing the center frequency of the narrowed line by a frequency-offset locking technique.

2. EXPERIMENTAL DETAILS

Figure 1 depicts the laser housing. To ensure that we don't get any unintentional optical feedback due to uncontrolled reflections from external elements, we use some non-standard components. The laser crystal is fixed on a special mounting which allows a
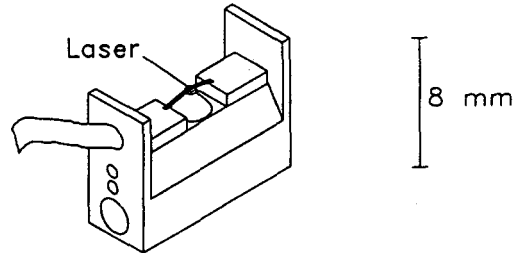

FIG. 1 Laser housing for bidirectional beam output

bidirectional laser beam output. This rules out the possibility of reflections from the backside of the laser as they may occur with the standard mounting which permits beam output in only one direction. Moreover twice the power is available. In our experiments one of the beams was used to examine the linewidth, with the second beam we applied external optical feedback to the laser. This work was done with two homostructure diode lasers which operate near 5 µm at temperatures between 20 K and 40 K. The threshold current is about 180 mA. We usually operated the lasers 40 to 120 mA above threshold

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[2]The response time of the optical feedback loop is given by the distance of the reflector over the speed of light, i. e. a few nanoseconds.

which turned out to be a region with several single-mode operation regimes[3]. The output power was measured by means of a power meter and was in the range between 1 mW and 5 mW.

Vibration-free cooling is performed by a temperature controlled evaporation cryostat, which we modified for bidirectional beam output. The diode laser is mounted at the bottom of the heat exchanger in such a way that both beams emerge unhindered from the cold station. This cryostat can be operated both with liquid helium or liquid nitrogen. The temperature of the laser station is coarsely adjusted by the flow of the coolant. For accurate temperature stabilization we use an electronic temperature controller, employing electrical resistance heating in combination with a silicon diode as a temperature sensor.

To collimate the laser beams we use two off-axis parabola mirrors (focal length = 10.2 mm) which are located inside the vacuum chamber of the cryostat (figure 2).
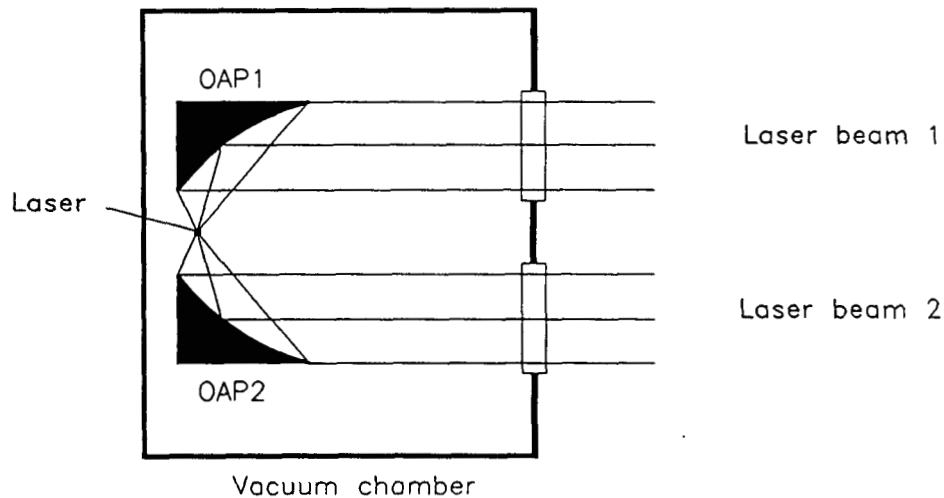

FIG. 2 Collimation of the beams by two Off-Axis-Parabolas

They are adjustable from the outside in the x-, y-, and z-direction. Both collimated beams (diameter: 20 mm) emerge from the cryostat through wedged and tilted CaF_2 windows.

3. LINEWIDTH MEASUREMENTS

We investigated the spectral linewidth of the diode laser by heterodyning the diode laser output with radiation from a sealed-off CO laser (local oscillator). This gas laser provides a few hundred laser lines in the wavelength region from 5 - 8 μm; the output power is 0.01 - 3 W single line and the linewidth is less than 1 MHz. A block diagram of the setup is shown in figure 3. The beams of both lasers were superimposed on a CaF_2

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[3]The proper current/temperature values in order to run the laser nearly single mode at the desired frequency were found with the help of a modechart (12).
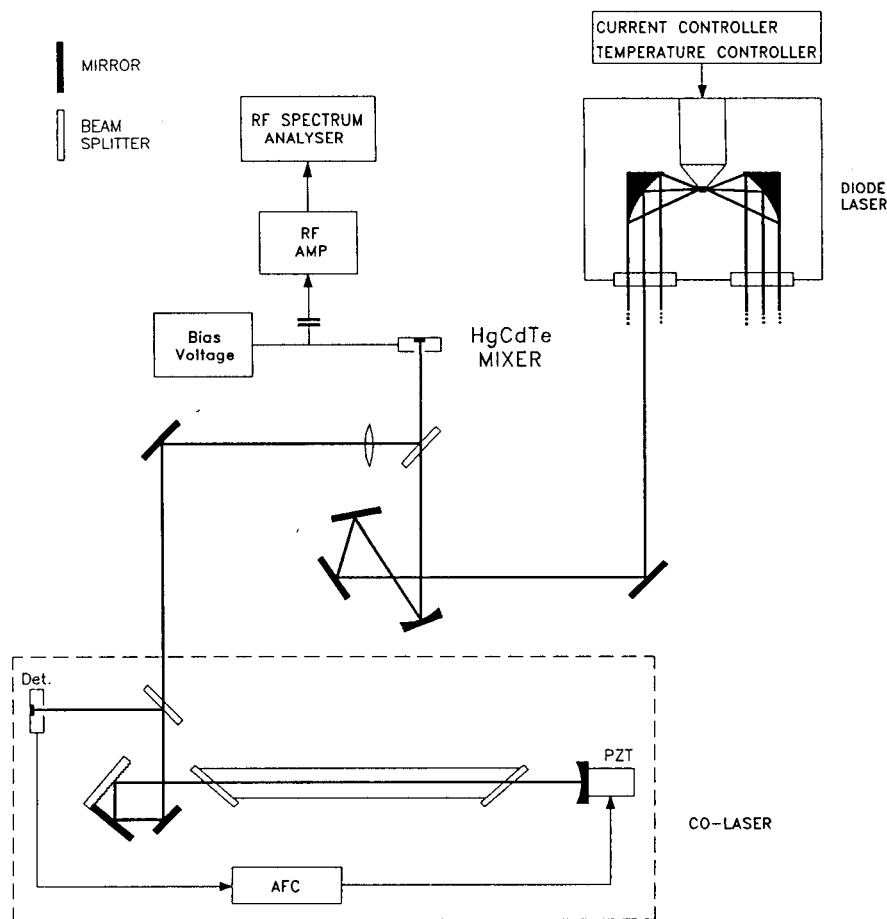
FIG. 3 Schematic setup of the linewidth measurements

beam splitter and focussed on a liquid-nitrogen-cooled photovoltaic HgCdTe detector/mixer. This was done by means of a lens (CO laser beam) and an astigmatically compensated toroidal mirror (diode laser beam) to avoid feedback from a lens to the diode laser. The detector bandwidth is about 1 GHz, under favourable conditions beatnotes up to 5 GHz can be observed. The detector was followed by a microwave amplifier (0.1 - 1.8 GHz, 30 dB). The output of the amplifier was fed to a spectrum analyser, which was mostly operated with 10 ms/div sweeptime.

A typical beatnote, recorded with the diode laser No. 214-B-7, is depicted in figure 4. The center frequency of the beatnote is near 1 GHz. Since the linewidth of the CO laser is less than 1 MHz, the FWHM of the beatnote, which is about 70 MHz, reflects the linewidth of the diode laser. For other temperatures and currents we observed even broader lines, especially in case of multi-mode operation. In earlier experiments with other homostructure diode lasers we found linewidths between 20 MHz and 100 MHz.

In contrast to these measurements the theoretical value for the linewidth, given by the modified Schawlow Townes formula (13), is about 0.1 - 5 MHz (depending on the α-value, output power, etc.). The causes for this huge discrepancy are not well-understood. To ensure that the current supply to the TDL is not responsible for the observed linewidth,
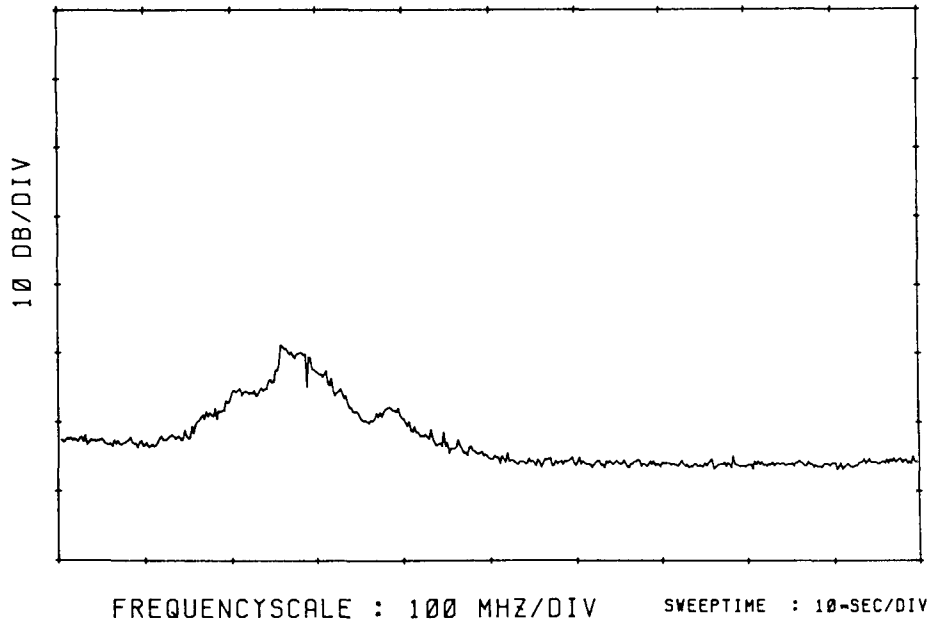
FREQUENCYSCALE : 100 MHZ/DIV   SWEEPTIME : 10-SEC/DIV

FIG. 4 Typical beatnote between a TDL (214-B-7) and a CO laser

it was carefully tested. It turned out that the ripple of the current supply corresponds to 1 - 2 MHz frequency jitter at most. Furthermore we took very much care in avoiding any possible external feedback to the diode, nonetheless one cannot exclude the possibility of slight optical feedback, e. g. coming from the (tilted) photomixer, which might broaden the line. Other authors report linewidths less than 1 MHz for carefully selected diodes (14). This dramatic variation in the linewidths of diode lasers of the same type may be due to a noise generating mechanism inherent to the TDL which produces the observed linewidth. We assume that mode competition noise and carrier density fluctuations are responsible for the linewidth in these gain-guided homostructure laser diodes. Also laser action in different lasing filaments with slightly different frequencies might contribute to the linewidth. By contrast, linewidth measurements of high performance GaAs laser diodes with better electron and photon confinement are in good agreement with the predictions calculated from the modified Schawlow Townes formula (13).

4. LINE NARROWING

In order to investigate the effect of controlled optical feedback on TDL linewidth we placed mirrors and other simple reflectors such as CaF_2 windows in a distance of about 60 cm from the diode into the second beam, while observing the beatnote on the spectrum analyser. The first noticable effects were different kinds of instabilities. The applied
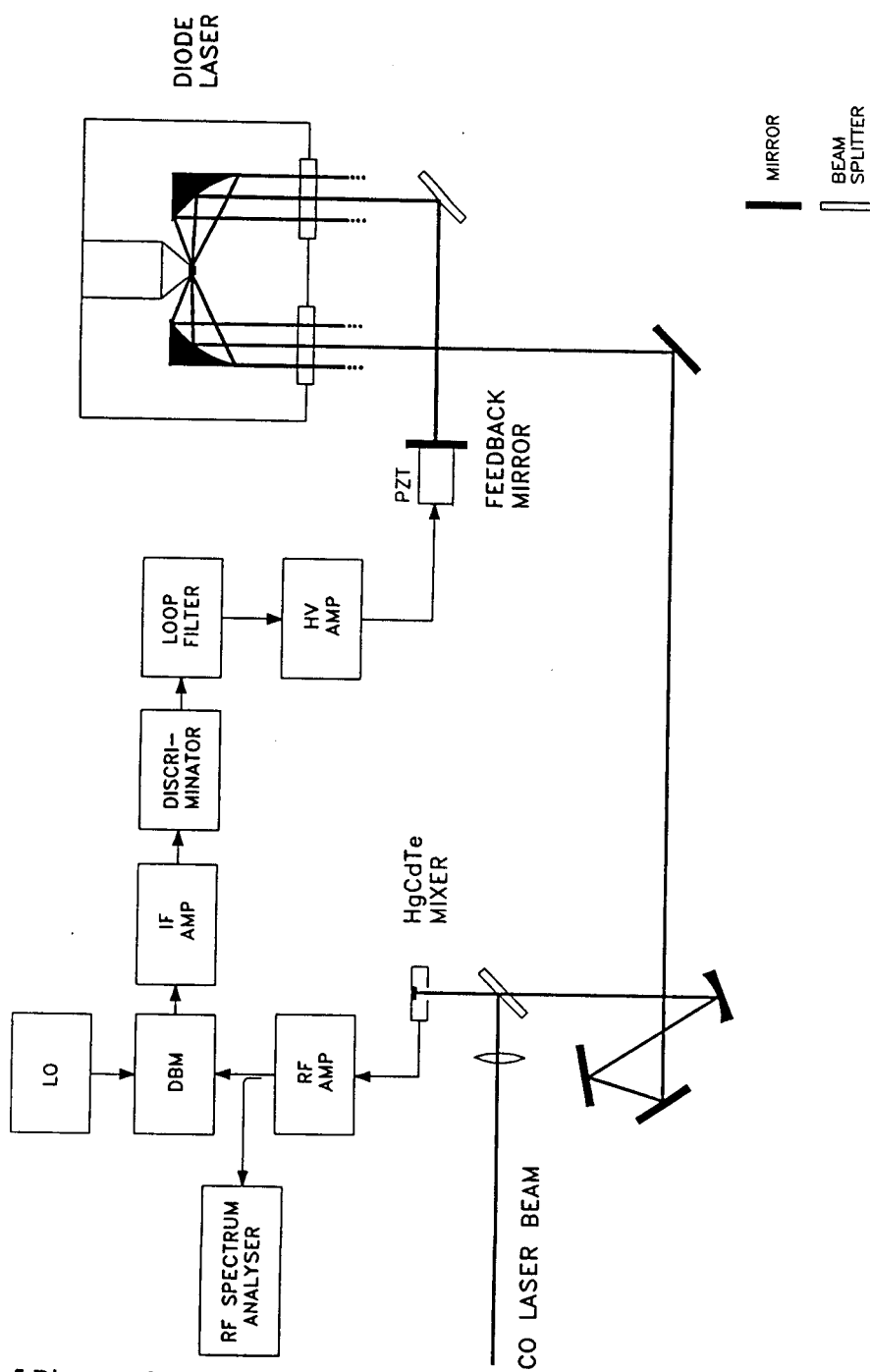
FIG. 5 Diagram of the frequency-offset locking scheme

feedback induced line broadening and in the worst case mode jumps which meant loss of the beatnote. In order to reduce the feedback level we employed a mirror in combination with a beam splitter as external reflector[4] (figure 5). With this setup we found dramatic linewidth reduction by two orders of magnitude down to 1-2 MHz. Figure 6 shows the narrowed beatnote. This linewidth reduction can be explained by the coupling of the diode laser cavity to the external cavity formed by the mirror and one facet of the laser crystal.
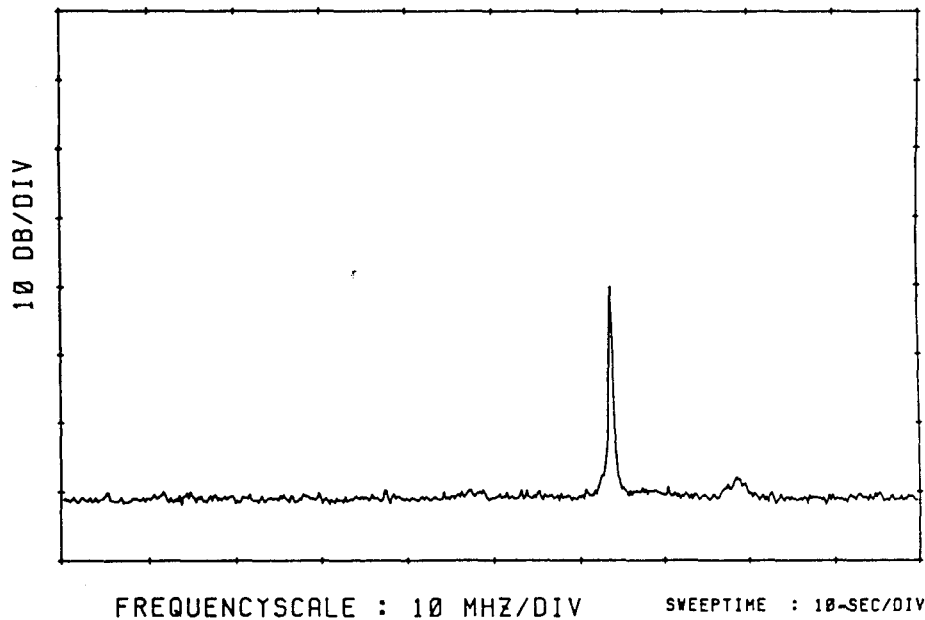

FREQUENCYSCALE : 10 MHZ/DIV   SWEEPTIME : 10-SEC/DIV

FIG. 6 Beatnote after line narrowing by optical feedback

The line narrowing was accompanied with the appearance of external cavity modes: depending on the feedback strength we observed one to three or even more external cavity modes simultaneously with a FSR of about 200 MHz (corresponding to the 60 cm cavity length). It turned out that a defined coupling to the external resonator is not possible if the laser is working multimode, i.e. if there are two or more modes with nearly the same output power. However in the case of near single mode operation[5] the compound cavity laser behaved exactly as predicted by a rate equation model for extended cavity diode lasers (4,5,8,9).

An estimate of the feedback strength was obtained in the following manner. The theoretical analysis of the phase and gain conditions of a compound cavity shows that the tuning rate of the diode laser with optical feedback is decreased by a factor of

[4]This results in a feedback level below 10^{-3}.

[5]I. e. the power level of any other mode was less than 10 % of the dominant mode power level.

$$1+X\sqrt{1+\alpha^2}$$

compared to the solitary laser, where X = feedback strength parameter and α = linewidth broadening factor (5). We found tuning rates of 700 MHz/mA for the solitary laser and 160 MHz/mA for the laser with optical feedback. From these measurements we can deduce the feedback parameter X to be about 1.5 to 2.5 (depending on the α-factor). This corresponds to an external reflectivity of about 10^{-4}. These values are in good agreement with the results of a stability analysis of the rate equations, which predict a linewidth reduction in the case of weak optical feedback ($X \sim 1$) and the onset of instabilities, when a critical value for the feedback strength is exceeded ($X \gg 1$).

Tuning of the extended cavity diode laser can be performed in two different ways. Either one tunes the diode laser cavity by changing the current or one tunes the external cavity by changing its length. As discussed above, the current tuning rate of the extended cavity diode laser is reduced. Moreover we observed discontinuous tuning behaviour. The frequency of a mode can be changed - depending on the feedback strength - up to 50 MHz. When the current is tuned further, a mode hop occurs: the laser emission jumps to the next external mode (1 FSR to higher frequency with increasing current). On the other hand we can tune the laser frequency by changing the length of the external resonator. The feedback mirror can be moved a few microns with a piezo-ceramic transducer (PZT). This results in a continuous tuning range of about 200 MHz (= 1 FSR), followed by a mode hop into the opposite direction. To achieve longer continuous tuning ranges one can either decrease the length of the external resonator in order to increase the FSR or one can tune the external cavity with the PZT and change the current synchronously.

5. FREQUENCY STABILIZATION AND CONTROL

The acoustical noise in the laboratory introduces vibrations of the feedback mirror and the other optical components which are elements of the external cavity. This results in a jitter of the center frequency of the narrowed line, which is visible on the left side of figure 7, where the sweeptime is increased to 1 sec/div[6]. The center frequency jitters over a bandwidth of about 30 MHz. By a detailed experimental analysis we found that this frequency instability is produced by low frequency vibrations of the mirrors below 1 kHz. For the purpose of stabilization we installed a servo loop which offset-locks the TDL frequency to the reference laser frequency. A schematic diagram of the setup is shown in figure 5. This frequency-offset locking technique was used in a different approach by Freed at al. (14).

The beatnote is down-converted by means of a double-balanced mixer and a frequency synthesizer as local oscillator. The frequency of the synthesizer ν_{syn} is adjusted such that the frequency of the down-converted beatnote is roughly 160 MHz. The intermediate frequency (IF) signal is amplified by 70 dB and fed to a discriminator. The difference between the IF and the center frequency of the discriminator (160 MHz) is converted to an error signal with a sensitivity of 100 mV/MHz. The loop filter contains an amplifier with low pass characteristics and an integrator. Moreover we can introduce a

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[6]The peak on the right side of figure 6 is due to the local oscillator described below.
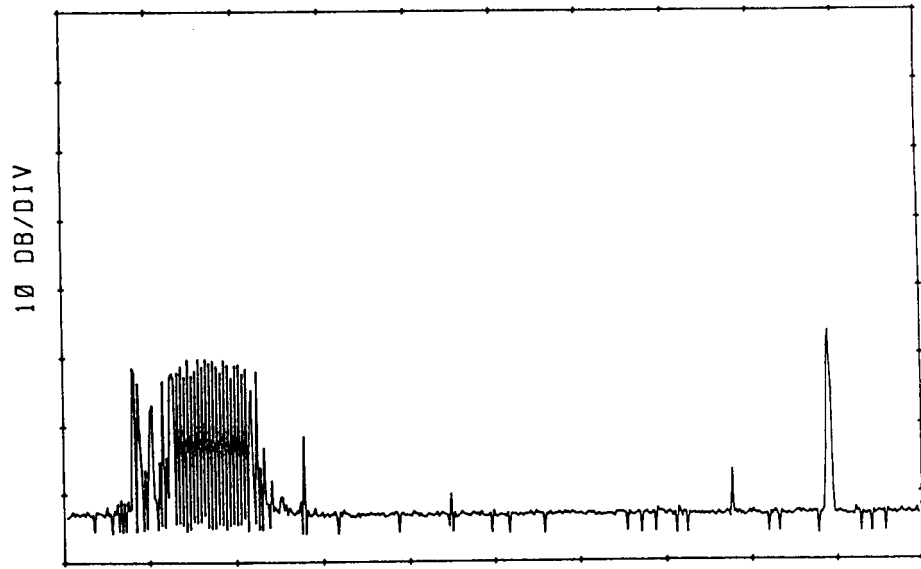
FREQUENCYSCALE : 20 MHZ/DIV   SWEEPTIME : 1 SEC/DIV

FIG. 7 Narrowed beatnote displayed with 1 sec/div sweeptime
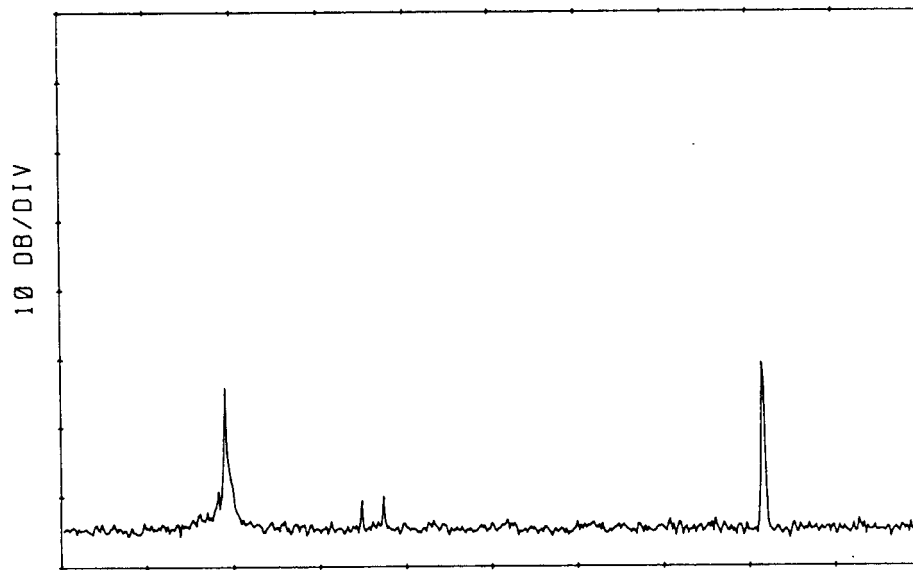
FREQUENCYSCALE : 20 MHZ/DIV   SWEEPTIME : 1 SEC/DIV

FIG. 8 Narrowed beatnote of the offset-locked diode laser

variable offset voltage to the lock loop in order to sweep the frequency of the TDL within the bandwidth of the discriminator (65 MHz). The signal is finally amplified to a high voltage level and fed to the PZT. When the servo loop is closed, the TDL frequency is locked to the reference CO laser frequency[7] with a variable offset of $v_{syn} \pm 160$ MHz, provided that there is no additional offset in the loop. The sign depends on whether we choose v_{syn} either above or below the beatnote frequency. A preliminary result is depicted in figure 8, where the same sweeptime (1 sec/div) was used as in figure 7. The former frequency jitter has disappeared. Optimizing the lock features is still in progress, some improvements concerning the stability of the lock have to be made.

6. CONCLUSION AND PLANS

Our experiments pointed out that it is possible to achieve linewidth reduction for a lead-salt diode laser by applying controlled optical feedback. We combined this method with frequency stabilization and control by offset-locking the TDL to a CO laser. This tunable narrow-linewidth light source in the mid infrared will be a new tool for high resolution spectroscopy with sub-Doppler accuracy. By introducing one or two Lamb dip stabilized CO_2 lasers, we gain the capability to make very accurate frequency measurements (15). We will extend our investigations to shorter wavelengths (3 µm) and to longer wavelengths (10 µm) and also to different diode laser structures (DH-, BH-laser, etc.). Further experiments with improved optical feedback elements like a reflection grating or an external high-finesse cavity are in preparation.

ACKNOWLEDGEMENTS

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